The effect of burnable absorbers (Gd and Eu) on the neutron-physical characteristics of fuel assemblies of VVER-1000 reactors

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Abstract. The problem of the use of burnable absorbers (BAs) in VVER-type reactors is considered to reduce the volume of "liquid" regulation of excess reactivity margin for fuel burnup. As such, natural gadolinium and europium are considered in the form of Gd₂O₃ and Eu₂O₃, placed in integrated form with uranium fuel in fuel rods. The ratio of fuel rods with BAs and conventional fuel elements is 1:6. Variants of both the homogeneous location of the BAs and heterogeneous, including for the mixed use of these BAs were considered. The strong influence of the BAs composition and their location in the fuel elements on the dependence of the multiplication factor on fuel burnup is shown.

1. Introduction

The main sources of energy for the nuclear power plants (NPP), which are operated and constructed in the present, are light water reactors (such as VVER-1000). Similar plants are planned to be used in the future of the construction of the nuclear power plants in different countries, regardless of the specifics of the national plans for the development of the nuclear energy.

One of the main goals of the scientific and technical developments related to the fuel cycle of power reactors is increasing the depth of the fuel burnup. Usually it is achieved by increasing the initial enrichment and applying partial overloads. To compensate for excess reactivity, a "liquid" system is used, based on the addition of a boric absorber to the coolant and, in addition, burnable absorbers of various types.

Burnable absorbers are 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. The negative reactivity of the burnable absorbers decreases during the campaign of the reactor due to a reduction in its concentration. In the ideal case, it should decrease at the same rate as a decrease in the reactivity reserve with burnable of the fuel.

As the burnable absorber in reactors of type VVER (PWR) & (BWR) used gadolinium Gd₂O₃ and Eu₂O₃ europium. Isotopic composition of natural gadolinium and europium and cross-section of absorption of thermal neutrons at energy 0.0253 eV of their separate isotopes together with the main isotopes of uranium are given in the table 1.
Table 1. Natural isotopic composition of the BAs and of the absorption cross section for thermal neutrons [6].

| Isotope | Percent, % | $\sigma$, б |
|---------|------------|-------------|
| $^{152}$Gd | 0.2 | 735 |
| $^{154}$Gd | 2.1 | 85 |
| $^{155}$Gd | 14.8 | 61100 |
| $^{156}$Gd | 20.6 | 1.5 |
| $^{157}$Gd | 15.65 | 259000 |
| $^{158}$Gd | 24.8 | 2.2 |
| $^{160}$Gd | 21.8 | 0.77 |
| $^{151}$Eu | 47.77 | 9100 |
| $^{153}$Eu | 52.23 | 312 |
| $^{235}$U | 72.75 | 680 |
| $^{238}$U | 99.275 | 2.68 |

The burnable absorbers are used for:

- Compensation of reactivity reserve for fuel burnable;
- Equalization of energy release in the core;
- Reduction of boron concentration in the coolant at the beginning of the campaign, which is important for safety. [11]

Usually gadolinium and europium are located in a small number of fuel elements (fuel elements with Gd are "Pings" or with Eu are "Pines"), but with a relatively high concentration of the absorber, to reduce the rate of its burnable and to extend the range of its influence on reactivity. In the Pings or Pines, the burnable absorbers are placed homogeneously over the fuel pellet. Fuel tablets containing a homogeneous mixture of Gd$_2$O$_3$ or Eu$_2$O$_3$-UO$_2$ (solid solution of Gd$_2$O$_3$ or Eu$_2$O$_3$ in UO$_2$) are easy to manufacture and allow for a long time to temporarily compensate for excessive reactivity.

Further development of water-cooled reactor technologies is aimed at the use of various burnable absorbers and optimization of their placement in fuel elements in the core. However, the homogeneous distribution of the burnable absorbers in the fuel leads to a decrease in the value of the thermal conductivity of the fuel elements and the melting point of the fuel. In addition, the presence of strong absorbers in fuel elements raises the coefficient of unevenness of energy release by fuel assemblies. In works [1-5] analyzed various aspects of the use of BAs: the possibility of using granulated Gd$_2$O$_3$ in a UO$_2$ matrix, which practically does not impair the thermal conductivity of the fuel and allows to reduce the rate of gadolinium burnup, the placement of Gd$_2$O$_3$ as a wire in the central hole of the fuel rod, the effect of Gd$_2$O$_3$ and Eu$_2$O$_3$ on the characteristics nuclear reactor fuel PWR.

In this paper, several fuel variants (V1-V7) presented in table 2 have been studied. The calculations were performed with the standard parameters of the fuel assemblies (FA-A) (439GT) and fuel rods of reactor VVER-1000 are presented in table 3 and figures 1-4.

Table 2. The concentrations of the isotopes fuel’s in the considered variants of calculations.

| Variant | The amount of fuel rods | Isotope | Concentration (a/barn·cm$^{-1}$) |
|---------|-------------------------|---------|---------------------------------|
| V$_1$   | 312 - 4.4% ($^{235}$U) | $^{235}$U | 1.0208E-03                      |
|         |                         | $^{238}$U | 2.2179E-02                      |
|         |                         | $^{16}$O  | 4.6399E-02                      |

| V$_2$   | 270 - 4.4% ($^{235}$U) | $^{235}$U | 1.0006E-03                      |
|         | 42 - 4.4% ($^{235}$U)  | $^{238}$U | 2.1740E-02                      |
|         | with 1.5% Gd$_2$O$_3$  | $^{16}$Gd | 5.1659E-04                      |
|         |                         | $^{16}$O  | 4.6257E-02                      |
| Variant | The amount of fuel rods | Isotope | Concentration (a/barn·cm²) |
|---------|-------------------------|---------|---------------------------|
| V₃      | 270 - 4.4% (²³⁵U)       | ²³⁵U    | 9.9803E-04                |
|         | 42 - 4.4% (²³⁵U) with 1.5% Eu₂O₃ | ²³⁵U | 2.1684E-02 |
|         |                         | ¹⁰⁰O   | 5.2990E-04                |
|         |                         |        | 4.6160E-02                |
| V₄      | 270 - 4.4% (²³⁵U)       | ²³⁵U    | 9.9931E-04                |
|         | 42 - 4.4% (²³⁵U) with 0.75% Gd₂O₃ and 0.75% Eu₂O₃ | ²³⁵U | 2.1712E-02 |
|         |                         | ¹⁰⁰O   | 2.5796E-04                |
|         |                         |        | 2.6529E-04                |
|         |                         |        | 4.6208E-02                |
| V₅      | 270 - 4.4% (²³⁵U)       | ²³⁵U    | 9.9931E-04                |
|         | 42 - 4.4% (²³⁵U) with 1.5% Gd₂O₃ in the center of rods | ²³⁵U | 6.106519 g/cm³ |
|         |                         | ¹⁰⁰O   | 0.933481 g/cm³             |
| V₆      | 270 - 4.4% (²³⁵U)       | ²³⁵U    | 9.9931E-04                |
|         | 42 - 4.4% (²³⁵U) with 1.5% Eu₂O₃ between clad and fuel | ²³⁵U | 4.546182 g/cm³ |
|         |                         | ¹⁰⁰O   | 0.717818 g/cm³             |
| V₇      | 270 - 4.4% (²³⁵U)       | ²³⁵U    | 9.9931E-04                |
|         | 42 - 4.4% (²³⁵U) with 0.75% Gd₂O₃ in the center of rod and 0.75 % Eu₂O₃ between clad and fuel | ²³⁵U | 6.106519 g/cm³ |
|         |                         | ¹⁰⁰O   | 0.933481 g/cm³             |
|         |                         |        | 4.546182 g/cm³             |

Table 3. The basic geometric parameters of FA-A.

| Parameter                      | TBC-A (439GT) |
|--------------------------------|---------------|
| Fuel stack length, mm          | 3530          |
| Fuel mass (UO₂), kg            | 497.98        |
| The density of fuel (g/cm³)    | 10.4          |
| The density of water (g/cm³)   | 0.72          |
| Fuel pin (312 pieces/FA)       |               |
| Enrichment (wt%)               | 4.4 %         |
| Pellet ID/OD (mm)              | 1.4/7.57      |
| Cladding ID/OD (mm)            | 7.73/9.1      |
| Cladding material              | alloy Э110    |

Central tube

| ID/OD (mm) | Material |
|------------|----------|
| 11.0/13.0  | alloy Э635 |

Guide tube (18 pieces)

| ID/OD (mm) | Material |
|------------|----------|
| 10.9/12.6  | alloy Э635 |
The density of fuel in variants $V_1$, $V_2$, $V_3$ and $V_4$ - 10.4; 10.35; 10.32 and 10.34 g/cm$^3$ respectively.

2. The aim of work
A computational analysis of the effect of the heterogeneous arrangement of Gd and Eu in the fuel elements, including the mixed placement of these burnable absorbers in fuel, to reduce the volume of liquid regulation of the reactivity reserve by influencing the dependence of the fuel assembly multiplication factor in fuel burnup. The nature of the dependence of the multiplication factor of fuel assemblies on fuel burnup is mainly determined by three factors. This is the value of the average cross section for the absorption of the burnup absorber, the amount of absorber in the fuel elements and the fuel assemblies, and the ratio of the number of fuel rods per Pings or Pines. The higher the absorbed absorber cross section averaged over the 2 spectrum, the smaller the number of fuel elements with the BAs.

3. The results
All calculations were performed using the beta version 2.1.29 of the SERPENT 2 code [7], based on the solution of the neutron transport equation by the Monte Carlo method, for the assembly of FA-A type 439GT [8]. The main attention is paid to the analysis of the dependence of the neutron multiplication factor $K_{\infty}$ on the burnup and distribution of the energy release field for the selected fuel assembly.

The average linear power of the fuel element was assumed to be 166 W/cm [10], calculation statistics - 2,000,000. Burnup was calculated for 74 steps with a range of 0.0; 0.085; 0.255; 22·0.5; 0.66 and 48·1.0 MW·day/kgU. Nuclear data were obtained from the library of nuclear constants ENDFB7 [9].
3.1. The neutron multiplication

Figure 5 presents the coefficients of the neutron multiplication $K_{\infty}$, depending on the burnup.

![Figure 5. The neutron multiplication factor $K_{\infty}$ in depending on the burnup.](image)

Variant $V_1$, in which there is no BAs, was chosen as a reference for comparison with the others, since in this variant a completely liquid control of the reactivity reserve is assumed. The selected ratio of fuel elements and corresponds to the most optimal for the application of natural Europium as BAs. Gadolinium is mainly used in Russian reactors. The best for the Pings and Pines on variants $V_2$ and $V_3$ correspond to the homogeneous arrangement of the burnable absorbers in the fuel pellet. For the chosen concentration of gadolinium, the effect of blocking the neutron flux in the block with BAs is small. Therefore, the initial value $K_{\infty} = 1.098$, but then, due to the high burnup rate of the gadolinium isotopes (Figure 6a), the reactivity retardation is formed up to the value $K_{\infty} = 1.27$. For the variant using europium, the burnup rate of its isotopes is much less than for gadolinium, which leads to the presence of a region of approximately constant $K_{\infty}$ as a function of the burning factor. This option can lead to a significant decrease in the share of liquid control of the reactivity reserve.

Variant $V_4$ corresponds to the case of homogeneous placement of both BAs (Gd and Eu) in one fuel element the total content of each BAs are reduced by half. Since gadolinium is a stronger absorber, at the beginning of the campaign it burns faster, which leads to a retreat of reactivity, and the role of europium is reduced to a limitation of the run-out value with respect to variant $V_2$.

Variants $V_5$ and $V_6$ correspond to the heterogeneous arrangement of BAs, gadolinium is located in the central hole of the fuel element, and europium, in the gap between the tablet and the clad. The number of BAs in a fuel rod is the same as for a homogeneous case. Since the entire gadolinium is located in a small volume, a strong blocking of the neutron flux in the gadolinium region appear, which changes the character of the $K_{\infty}$ dependence on the burnup (Figure 6a). In this case, the initial $K_{\infty} = 1.32$, which is substantially higher than for the homogeneous case. This option provides a smaller reduction in the volume of liquid regulation. The variant with the heterogeneous location of europium completely coincided with the variant of its homogeneous placement in the fuel element.

In the joint heterogeneous arrangement of both BAs in the same fuel element, in the same amount as for homogeneous co-location, the approximate constancy of $K_{\infty}$ at the beginning of the campaign is also provided, but with a larger value than for variant $V_3$, and with its subsequent decline and approaching the reference dependence $V_1$. 
Figure 6 (a). Mass of $^{155}$Gd and $^{157}$Gd in depending on the burnup for variants $V_2$, $V_4$, $V_5$, $V_7$.

Figure 6 (b). Mass of $^{151}$Eu and $^{153}$Eu in depending on the burnup for variants $V_3$, $V_4$, $V_6$, $V_7$. 

3.2. Power distribution.

The spatial (in fuel elements) distribution of energy release and the overall the radial coefficient of unevenness in fuel assemblies as a function of burnup are presented in Table 4.

| Burnup (MW·day/kgU) | V₁  | V₂  | V₃  | V₄  | V₅  | V₆  | V₇  |
|----------------------|-----|-----|-----|-----|-----|-----|-----|
| 0.0                  | 1.0692 | 1.2494 | 1.2003 | 1.2503 | 1.1047 | 1.1761 | 1.1622 |
| 9.84                 | 1.0681 | 1.0782 | 1.1454 | 1.1047 | 1.0887 | 1.1386 | 1.1038 |
| 20                   | 1.0737 | 1.0705 | 1.1071 | 1.0923 | 1.0727 | 1.1078 | 1.0828 |
| 30                   | 1.0646 | 1.0646 | 1.1052 | 1.0806 | 1.0670 | 1.1007 | 1.0873 |
| 40                   | 1.0612 | 1.0666 | 1.0938 | 1.0867 | 1.0614 | 1.0902 | 1.0802 |
| 50                   | 1.0622 | 1.0737 | 1.0701 | 1.0717 | 1.0609 | 1.0796 | 1.0721 |
| 60                   | 1.0643 | 1.0632 | 1.0751 | 1.0670 | 1.0632 | 1.0742 | 1.0658 |

It should be noted a significant increase in the coefficient of unevenness of energy release over fuel assemblies in the case of the use of BAs. Naturally, for gadolinium, the degree of depression of the neutron flux in fuel elements located near the fuel elements with Gd is greater than for fuel elements near the fuel elements with Eu. Therefore, the coefficient of unevenness for variants with europium is lower than with gadolinium. However, as the absorber burnables, the unevenness coefficient decreases, approaching the value for the reference variant. In addition, for variants with a heterogeneous distribution of the BAs over the fuel element, the degree of unevenness of the energy release decreases.

4. Conclusion

The use of BAs in the nuclear fuel causes both positive and negative effects. These effects depend on which burnable absorbers were used; the concentration of BAs in the fuel, the number of the fuel elements contains BAs and the placement of BAs in fuel elements. In this work, we compare the effect of the burnable absorbers on the use variants presented in Table 3.

The use of Gd as a burnable absorber reduces the neutron multiplication factor $K_\infty$ only in the initial campaign period, and the use of Eu reduces $K_\infty$ practically for the entire campaign period, but the fuel then goes subcritically at a lower burnup (i.e., at an earlier stage). The combined use of Gd and Eu as burnable absorbers with different versions of their placement in fuel elements stabilizes the behavior of the reproduction coefficient $K_\infty$ in the supercritical position ($V_4$ and $V_7$), and an even better result is achieved when Gd is placed in the central hole of the fuel elements ($V_7$).

The comparison of the calculation options shows that the variants of sharing burnable absorbers $V_4$ and $V_7$ have the best characteristics and safety conditions for the operation of the reactor, and the addition of Gd to the central hole of the fuel elements gives additional advantages. The $K_\infty$ value remains in a critical state before the burnup of 27 MW·day/kgU, which will require less boron during the operation of the reactor during the campaign and a reduction in economic costs. The use of Gd in the central hole of fuel element stabilizes the change in the neutron multiplication factor at the beginning of the campaign.

The stability of $K_\infty$ provides additional nuclear safety limits during operation, exception of the beginning of campaign; the first cycle of fuel in the reactor doesn’t require change the concentration of boric acid or the inserting or withdrawal control rod to conserve the criticality state of fuel and that will reduce in the economic costs. And by using 72 fuel elements with BAs in the FA and with 1.5%Gd of fuel in the central hole of the fuel element and Eu 0.15% of fuel as shown in figures 7.a and 7.b. We obtain more of the stability in the values of $K_\infty$ up to 16 MW·day/kgU as shown in the figure 8.
Figure 7 (a). The mesh of the FA-A.  
Figure 7 (b). The geometry of the FA-A.  

Figure 8. The neutron multiplication factor $K_{\infty}$ in depending on the burnup.

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