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Research Article

Comparison of methods for calculating the neutronic characteristics of a VVER-1200 fuel assembly*

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Abstract

This article presents the results of neutronic calculations of a VVER-1200 fuel assembly carried out using the multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code Serpent 2. The study compares neutronic characteristics during the fuel burnup process (1) with and (2) without fuel cooling. In the first option, the FA fuel campaign was simulated with 30-day cooling periods between reactor campaigns. The second option assumed simulating the FA fuel campaign without fuel cooling. In the course of the study, the authors determined the infinite neutron multiplication factors as well as the fuel burnup dependence of the concentrations of xenon, samarium and gadolinium nuclides. In addition, it should be noted that no differences were found in the change in the concentration of gadolinium isotopes, the discrepancy in the values of the multiplication factor, and the accumulation of samarium isotopes during the campaign.

Keywords

Fuel assembly (FA), neutronic characteristics, Serpent, fuel cooling and simulated refueling, Samarium, Xenon, fuel burnup, infinite multiplication factor, deflection, absorption cross-section

Introduction

The question of setting the task is fundamental in the framework of justifying the operation of a particular nuclear power facility. Neutronic calculations can be carried out using different approaches: some researchers believe that there is no need to simulate fuel cooling when studying material burnup (Korkmaz et al. 2014), others, on the contrary, think it necessary to calculate with fuel cooling (Giusti et al. 2013/2014). In this paper, calculations were made by two methods: (1) continuous burnup calculation (without simulated fuel cooling) and (2) burnup calculation with simulated fuel cooling periods between reactor campaigns.

Therefore, the equivalence of the proposed calculation methods seems to be quite a topical issue. If the results differ by values significantly exceeding the statistical error, it is necessary then to choose the most reliable method from the available ones for calculating the campaign, that is, the one that corresponds to real operating conditions. Under such conditions, fuel cooling is carried out to reduce the concentration of neutron absorbers (^{135}Xe, ^{135}I).

Research objectives

The research objectives include as follows: (1) to determine infinite multiplication factors for VVER-1200 fuel as-

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semblies with simulated 30-day fuel cooling periods after every 340 effective days of operation and continuous fuel burnup; (2) to monitor the concentrations of the most important nuclides (in terms of neutron absorption) in fuel elements and fuel rods (^{135}Xe, ^{149}Sm, ^{155}Gd (Mercatali et al. 2014)) and obtain dependences on the burnup depth as well as determine the concentration and time at which the influence of the absorption properties of gadolinium will be insignificant; and (3) to make a conclusion about the reasons for the discrepancy between the values in the compared calculations.

Model

The calculations were carried out using the Serpent 2 software package. The results of calculating the burnup of fuel assemblies with gadolinium for VVER-440 and VVER-1000 reactors are also presented in (Lötsch 2014, Novak et al. 2017, Vnukov et al. 2020). The burnup calculations for a VVER-1200 hexagonal fuel assembly (Abu Sondos et al. 2019, Vnukov et al. 2021) based on the Serpent code give sufficiently accurate results compared to the results obtained using other proven codes. Thus, the burnup calculations using the Serpent code lead to reasonable and sufficiently accurate characteristics of fuel assemblies, which makes the choice of software relevant (Stroganov et al. 2014).

The selected model was calculated using the multi-purpose three-dimensional continuous-energy Monte Carlo particle transport code Serpent 2. Each cycle contained a packet of 10,000 neutrons, 50 inactive and 750 active cycles. The following burnup steps per day were set: 1, 5, 10, 15, 40 and further up to 340 effective days in increments of 30 days. The frequency of the initial dividing is due to the need to track changes in the concentrations of xenon, plutonium and other important isotopes. In the study, the concentrations of the mentioned elements were also monitored to substantiate the processes occurring in the fuel and their influence on the multiplication factor. An infinite lattice of fuel assemblies, which is analogous to real BelNPP lattices, was chosen as the computational geometry (VVER-1200 reactor core, Frybortova 2019). Fig. 1 shows the horizontal (*x*-*y*) and vertical (*xz*) sections of the FA lattice.

A hexagonal FA of the Z49A2 type was considered, containing 300 fuel rods with a ^{235}U concentration of 4.95% and 12 fuel rods with a ^{235}U concentration of 3.6%. In the fifth ring (from the center) there is a measuring channel, in the fourth and sixth rings there are six and twelve guide channels. Fuel rods in the tenth and eleventh rings were selected to track the flux non-uniformity. A geometry infinite in height and radius (set bc 2) (Status Report, Khoshahval et al. 2016, Khrais et al. 2019) was used; therefore, the values of K_{inf} were estimated in the work. The calculations were made with 30 days of fuel cooling after every 340 effective days (Model 1) and without cooling, continuously within a four-year fuel campaign (Model 2). During the simulation, the *dep butot* option was used for fuel burnup, and the *dep decstep* option for fuel cooling.

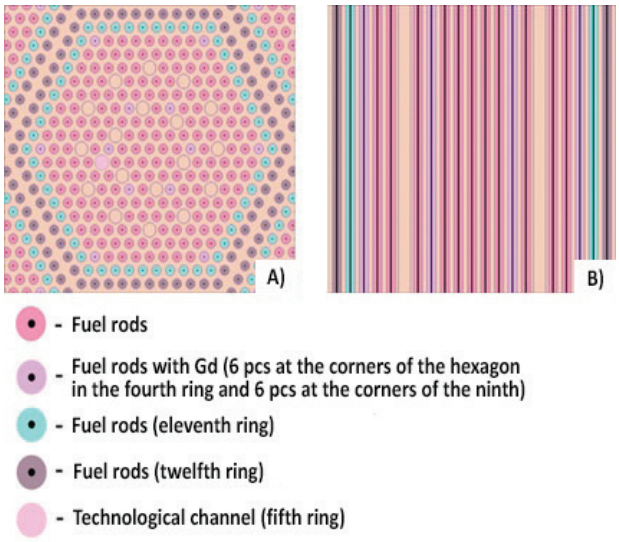

Figure 1. Sections of the FA lattice: **a.** Horizontal; **b.** Vertical.

Results and discussion

Fig. 2 shows the dependence of changes in the K_{inf} values between the models with and without fuel cooling during the fuel burnup process.

The significant deviations in the K_{inf} values between the models are explained by transient processes: when the calculation is started at the initial burnup steps, the xenon concentration is non-stationary. It can be seen from the graph that Model 1 gives results lower than Model 2 by 12, 24, 36 MW·day/kg.

The deviations were determined by analogy with (Stroganov et al. 2014) according to the formula:

$$\frac{K_{inf2} - K_{inf1}}{K_{inf1}} * 100\%$$

where K_{inf1} is the value close to real operating conditions (Model 1); and K_{inf2} is the value compared with the "optimal" value (Model 2).

One can observe the following trend: throughout the entire fuel assembly campaign (excluding the beginning of the 2nd, 3rd and 4th reactor campaigns), the deviation grows evenly. An apparent difference in the values between the models can be seen in Fig. 3.

The difference between the values accumulates, and in the third and fourth years it exceeds the statistical error. This is presumably due to the fact that the concentration of the strong absorber in the stationary areas for Model 1 deviates more and more from the corresponding values of Model 2 after the burnup year, and, by the end of the fourth year, this difference becomes maximum. Therefore, the value of K_{inf} for the model without fuel cooling turns out to be greater than for the model with fuel cooling. To test the hypothesis, the concentrations of such strong

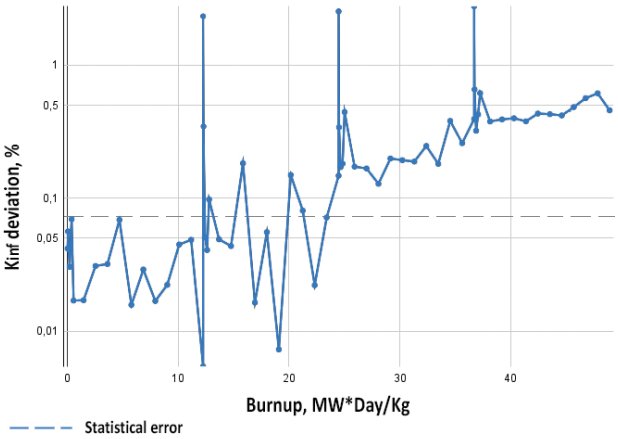

Figure 2. Changes in the K_{inf} deviation during the fuel burnup process.

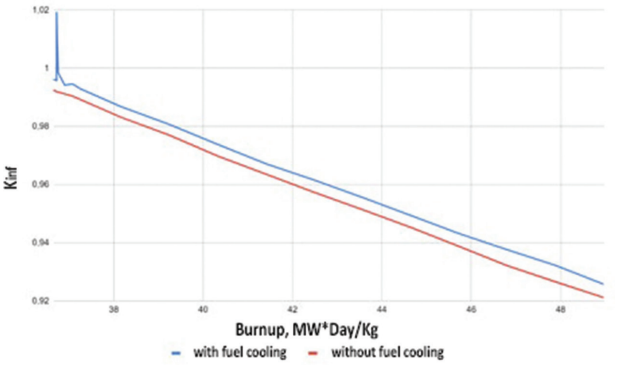

Figure 3. Burnup K_{inf} dependence: 1) model with fuel cooling; 2) model without fuel cooling.

absorbers as ^{135}Xe, ^{149}Sm and ^{155}Gd were compared. It is clear that ^{157}Gd is a stronger absorber than Gd-155, and since the concentration of gadolinium oxide in the fuel assemblies is low, it almost completely burns up by the end of the first microcampaign. Thus, it cannot affect the K_{inf} change in the final microcampaigns.

Fig. 4 shows changes in the ^{135}Xe concentration during the fuel burnup process.

The difference in the ^{35}Xe concentration values between the models appears only in the fuel cooling periods. This is due to the fuel decay. In the process of stationary burnup, the concentrations are identical. This means, that this nuclide does not contribute to the difference in the K_{inf} values between the models.

Fig. 5 shows changes in the ^{149}Sm concentration in the models with continuous fuel burnup.

Before the simulation of the first fuel cooling, the calculations are identical; therefore, the dependences on the graph reflect the process after 10 MW·day/kg. The significant deviations (up to 17% at 12, 24, 36 MW·day/kg) are explained by the accumulation of samarium in the model with fuel cooling: in the absence of power, the neutron flux decreases significantly but the concentration of ^{149}Sm increases. During the simulation of the next reactor campaign, the concentration of ^{149}Sm first drops sharply, then rises until equilibrium is established. This behavior

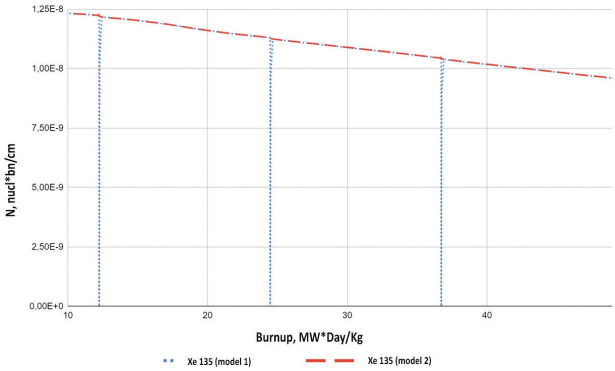

Figure 4. Changes in the ^{135}Xe concentration during the fuel burnup 1) model with fuel cooling; 2) model without fuel cooling.

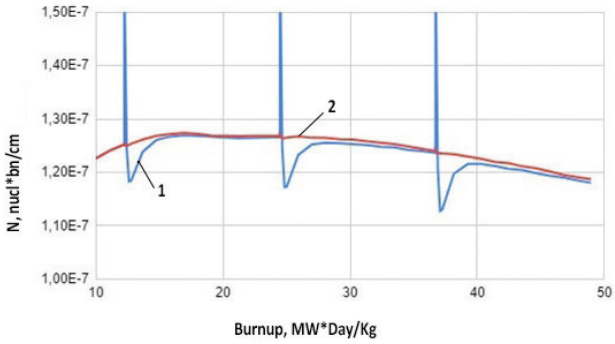

Figure 5. Burnup ^{149}Sm concentration dependence 1) model with fuel cooling; 2) model without fuel cooling.

affects the K_{inf} values. Since the process of establishing the equilibrium concentration takes a considerable time, the process of fuel burnup occurs differently for the two considered models due to the specifics of the calculation method using the Serpent software package (Leppänen 2012, Leppänen et al. 2014, SERPENT – MCRPBCC): initially, at a certain point in time, the neutron flux density is calculated, then the concentrations are recalculated with this value to the next time point. Next, the neutron flux density is refined, after which the concentrations are recalculated. Thus, we obtain an iterative process with the remaining time points. Due to the time difference between the ^{149}Sm concentration models, the neutron flux density is distorted, which causes differences when the concentrations of burnable materials are recalculated. In this regard, it is relevant to check the contribution of ^{155}Gd to the characteristics of the campaign in the models with and without fuel cooling. Fig. 6 shows changes in the ^{155}Gd concentration during the fuel burnup for both models.

The figure does not show the burnup steps after 25 MW·day/kg, since after 16 MW·day/kg (after the first microcampaign) the absorber burns up almost completely. At the same time, it is not an accumulated isotope in the process of fuel burnup; therefore, it does not have jumps like ^{149}Sm. Since the difference in the K_{inf} values in the models occurs after the second cooling, when there is no more gadolinium left in the FA (Fig. 7), it can be concluded that the only isotope that affects the K_{inf} deviations between the models is ^{149}Sm.

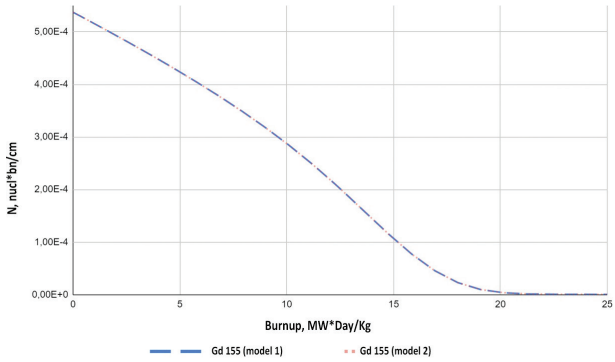

Figure 6. Changes in the ^{155}Gd concentration during the fuel burnup process: 1) model with fuel cooling; 2) model without fuel cooling.

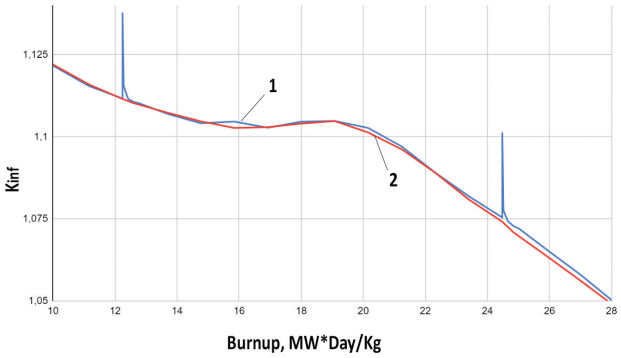

Figure 7. Changes in K_{inf} during the fuel burnup process (at the time of significant burnup of ^{155}Gd): 1) with fuel cooling; 2) without fuel cooling.

The absence of the ^{149}Sm contribution to the change in the ^{135}Xe concentrations can be explained by the low equilibrium concentration of the isotope in the system and its insignificant contribution to the campaign (excluding transients). In contrast to the ^{155}Gd concentration, the non-equilibrium ^{149}Sm concentration makes no contribution either, since, after the first microcampaign, there is practically no burnable absorber left, and it has practically no effect on the criticality of the model. The same effect is achieved in the works of other researchers (Abu Sondos et al. 2019a).

Conclusions

The authors have calculated the burnup of the Z49A2 FA model for a VVER-1200 reactor with a four-year fuel campaign. As part of the study, options were modeled: (1) with fuel cooling between microcampaigns lasting 340 effective days and without fuel cooling. The K_{inf} showed discrepancies between the models starting from 24 MW·day/kg. The discrepancies increase as the burnup progresses.

The evaluated concentrations of the poisoners (^{135}Xe, ^{149}Sm) and the burnable absorber (Gd-155) showed the ^{149}Sm contribution to the K_{inf} deviation between the models.

Significant jumps in the K_{inf} deviation between the models by 12, 24, 36 MW·day/kg are explained by the ^{135}Xe decay in the model with fuel cooling. The equilibrium ^{135}Xe concentration is reached faster as compared to ^{149}Sm. The difference between the models in the poisoner concentration over a long period of time introduces significant changes in the fuel burnup process and the model criticality calculation. For this reason, when calculating burnup, one should use the model that provides the closest approximation to the real conditions of the phenomenon under study. In this case, the model with fuel cooling is the most correct. Of course, it is important to take into account the differences in simulations and under real operating conditions and fuel reloading, since this comparison leaves out the features of the neutron spectrum during fuel burnup or the cooling procedure at a particular nuclear power plant, regulated by the relevant acts and regulatory documents. In this regard, further studies should be directed to the consideration of the effects, taking into account the existing differences, and the comparison of indicators using different characteristics of the core.

Acknowledgement

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