Calculation of the CPS effectiveness in the high-power fast neutron lead reactor with varying degrees of heterogeneity of the description of reactor model

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Abstract. The object of research in this work is the core of a high-power fast neutron reactor with lead coolant (hereinafter referred to as the BR-1200). The purpose of this work is to determine the effectiveness of the CPS in the core of such a reactor in various states that differ in the type and number of CPS organs, which are simultaneously in the core. An additional goal is to determine the effectiveness of the method of partial heteronization of the fuel assembly structure in the model. In addition, the task is posed to compare the results with the data obtained using other neutron-physical codes and libraries of neutron constants. The calculations were carried out in the KENOVI module of the SCALE code. Neutron constant libraries such as the ENDF / B7 point library and the v7-238 group library were used. This paper describes the creation of full-scale models of the BR-1200 reactor with a homogeneous and heterogeneous description of the fuel assembly structure. The article describes the simulation of fuel assemblies with a homogeneous description of the fuel structure and a heterogeneous description of the structure of absorbing rods. The calculation of such parameters as the effective multiplication factor and the efficiency of CPS organs is carried out.

1. Introduction

Every year, global energy consumption increases and leads to the need to increase electricity production, which, in turn, leads to an increase in the consumption of organic fuels in the construction of power plants operating on this type of fuel, including coal, natural gas and other organic fuels. Given the exhaustion of resources of this type, the question arises about the expansion of the used range of fuel resources.

Only large-scale nuclear power engineering based on fast reactors operating in a closed nuclear fuel cycle can stop the growth of consumption of these resources [1]. As a way of implementing large-scale nuclear power engineering, that meets all the necessary requirements, a high-power reactor plant with a fast lead-cooled reactor and mononitride uranium-plutonium fuel is considered (hereinafter referred to as the BR-1200) [2]. The reactor under consideration must comply with the concept of natural safety [3,4,5,6]. Numerous studies conducted by many countries claim, that it is precisely fast reactors with liquid metal coolant that meet the high requirements of competitiveness and safety [7,8,9].

The peculiarity of such a reactor will be the minimum number of technological safety systems and CPS in the reactor core. It is precisely in connection with a small amount of CPS organs that accurate
calculation of the efficiency of CPS organs in reactor core is an actual work, especially when comparing the results obtained using different neutron-physical codes and using different libraries of neutron constants.

Thus, the purpose of this work is to determine the effectiveness of the CPS organs of a high-power fast nuclear lead-cooled reactor BR-1200 with mononitride uranium-plutonium fuel based on data obtained when calculating the model of this reactor core in the SCALE module KENOVI. In addition, the goal is to compare the calculation results of the reactor core models of the BR-1200 with various descriptions of the fuel assembly structure, the reactor core models of the BR-1200 calculated in various neutron-physical codes and the reactor core models of the BR-1200 calculated using different libraries of neutron constants.

2. Calculation tool
The neutron-physical code SCALE [10] was chosen as the tool for the calculation, one of the distinguishing features of which is the possibility of using both point libraries of neutron constants (for example - ENDF / B7) and group libraries of neutron constants (for example - 238-group v7-238 ). The SCALE code system developed at Oak Ridge National Laboratory (ORNL) is a comprehensive, verified and internationally certified tool for calculating reactor criticality, radiation protection, and uncertainty analysis. In this work, we used the KENO-VI module of the SCALE code. The KENO-VI three-dimensional criticality calculation algorithm, based on the Monte Carlo method, is one of the main SCALE security and criticality analysis tools. The SCALE code system includes several multisection libraries for criticality analysis. The most modern library is the ENDF / B7 neutron constants library.

3. Description of the reactor core structure
The model of the BR – 1200 reactor consists of 547 hexagonal cells arranged in accordance with a given cartogram of the core of the model, which is divided into three subzones - central (CS), intermediate (IS) and peripheral (PS), differing in height of the fuel element in the fuel assembly for alignment of the radial distribution of neutron flux and power. A schematic display of subzones in a vertical section is shown in figure 1.

In the 85 cells of the central subzone, 72 working fuel assemblies, 1 fuel assembly with emergency protection organs (EP organs), 6 fuel assemblies with reactivity compensation organs (RC organs) and 6 fuel assemblies with automatic regulation organs (AR organs) are installed. In the 240 cells of the intermediate subzone, 186 working (staff) fuel assemblies, 18 fuel assemblies with EP organs, 30 fuel assemblies with RC organs and 6 passive negative-reactivity input devices (NRID) are installed. In all 222 cells of the peripheral subzone, working fuel assemblies are installed. The cartogram with the designation of various types of fuel assemblies and their location is shown in figure 2.
In this paper, we consider several states of the active zone, differing in composition and type of CPS organs, which are simultaneously in the reactor core. The base state is characterized by the complete removal of all CPS organs from the core.

4. Justification of the calculation parameters of the model in the SCALE code
When performing calculations in the KENOVI module of the SCALE code implementing the Monte Carlo method, it is necessary to indicate the number of simulated neutron generations during the calculation, as well as the number of calculated neutron histories per neutron generation.

The number of simulated neutron generations was chosen in accordance with the recommendations of the developers of the SCALE code, and it is 300 generations. Thus, it is possible to influence the magnitude of the statistical error \(d_{\text{KeFF}}\), when calculating the effective neutron multiplication factor, only by changing the number of calculated neutron histories per one generation \(N_{\text{hist}}\). However, with an increase in the number of \(N_{\text{hist}}\), the time spent on the calculation increases \(t_{\text{calc}}\). After conducting a series of calculations to determine the optimal \(N_{\text{hist}}\) value and analyzing the results, it was decided to use \(N_{\text{hist}} = 2 \cdot 10^4\) in the calculations, since this value \(N_{\text{hist}}\) meets the necessary requirements and minimizes the time spent on the calculation.

5. Creating reactor core models with a different description of the structure of fuel assemblies

5.1. Model of the reactor core with a homogeneous structure of fuel assemblies
When creating a homogeneous model, some assumption was made. The temperature of the fuel assembly elements was taken to be equal to the temperature of the fuel, and the temperature of the reflector was taken to be equal to the temperature of structural materials. figure 3 shows the vertical and horizontal section of the resulting homogeneous model.
5.2. Model of the reactor core with a heterogeneous structure of fuel assembly

When creating a model with a heterogeneous description of the fuel assembly structure, preliminary work was carried out to recalculate the homogeneous compositions used in the model of the BR-1200 reactor with a homogeneous description of the fuel assembly structure.

The main difference between a model with a heterogeneous description of the structure of fuel assemblies and a model with a homogeneous description of the structure of fuel assemblies consists in the physical separation of individual elements of fuel assemblies in a horizontal section. For each of the fuel assemblies, the following were described separately: lead coolant surrounding the external cover of the fuel assembly, the external cover of the fuel assembly, the structure of fuel rods and individual elements of fuel rods, including the shell and fuel of fuel rods. For fuel assemblies with CPS organs, the internal cover of the fuel assemblies, the inner tube, the control organs tube and the structure of absorbing rods, including the casing of absorbing rods and absorbing elements, were also described. An example of the separation of fuel assemblies is presented in figure 4.

![Figure 3](image-url)

**Figure 3.** Vertical (a) and horizontal (b) section of the calculated homogeneous model of the reactor.

**Figure 4.** The separation of homogeneous fuel assemblies into different types of heterogeneous fuel assemblies.

There was a need to create separate fuel rods cartograms and absorbing rods cartograms, with the condition of including one cartogram into another, which in turn was an element of the FAs cartogram of the reactor core model. For each type of fuel assembly, a separate model was created, with its own characteristics and structure. The scheme of this process is shown in figure 5.
5.3. **Model of the reactor core with a homogeneous description of the fuel structure of fuel assemblies and a heterogeneous description of the absorbing rods structure**

A model with a homogeneous description of the fuel structure of fuel assemblies and a heterogeneous description of the absorbing rods structure (hereinafter referred to as a mixed model) was created in order to consider the influence of the heterogeneous structure of absorbing rods on the divergence of the calculated effective multiplication factor values for models with a homogeneous and heterogeneous description of the structure of fuel assemblies.

If, when calculating models with a homogeneous, heterogeneous and mixed description of the fuel assembly structure, under the same conditions, the values of the calculated characteristics of the mixed model are close to the values calculated for the model with a heterogeneous description of the fuel assembly structure, then it means that the heterogeneous description of the structure absorbing rods contributes a large part to the discrepancy between the results of calculating models with a homogeneous and heterogeneous description of the fuel assembly structure. This will allow us to conclude that this model can be used to improve the accuracy of calculations without carrying out large works on creating a model with a heterogeneous description of fuel assemblies.

A fuel assembly model is created similarly to a fuel assembly model with a homogeneous description; however, a heterogeneous site from a fuel assembly model with a heterogeneous description must be placed in the centers. The horizontal section of a fuel assembly with a mixed description of the structure is shown in figure 6.

![Diagram of creating a fuel assemblies with a heterogeneous structure.](image)

**Figure 5.** Diagram of creating a fuel assemblies with a heterogeneous structure.

![Horizontal cross-section of the fuel assembly of a mixed description.](image)

**Figure 6.** Horizontal cross-section of the fuel assembly of a mixed description.
6. Calculated parameters
In the course of work, for each state by using the KENOVI module of the SCALE code, the value of the effective multiplication factor $K_{eff}$ and the value of the statistical error $d_{K_{eff}}$ in the calculation were calculated.

Also, for each state, the effectiveness of the CPS regulatory organs is evaluated, which is expressed in the introduced negative reactivity compared to the baseline state and is determined by the following formula:

$$\Delta \rho = \frac{1}{K_{eff}} - \frac{1}{K_{eff}^i}, \%$$

(1)

Where $K_{eff}^0$ – effective multiplication factor in the base state, $K_{eff}^i$ – effective multiplication factor in the state in which the effectiveness of regulatory authorities is assessed.

7. Calculation results
To create models, we used the data from the test problem for the TRIGEX code, in which the data were compiled so that the maximum neutron multiplication factor in the reactor did not exceed one. Thus, the expected values of the effective multiplication factor are less than or equal to one.

The core models of the BR-1200 reactor with a homogeneous and heterogeneous fuel assembly description were calculated in the KENOVI module of the SCALE code using the ENDF / B7 neutron constant library. Comparison of the results of calculating these models are presented in table 1.

| State № | Description of state | $d_{K_{eff}}$ | $K_{eff}^{hom}$ | $\Delta \rho^{hom}$ | $K_{eff}^{het}$ | $\Delta \rho^{het}$ | $\Delta K_{eff}$, % | $\Delta (\Delta \rho)$ |
|---------|---------------------|--------------|----------------|------------------|----------------|------------------|------------------|------------------|
| Base state | All CPS organs are removed from the core | $10^{-4}$ | 0.9969 | - | 0.9991 | - | 0.22 | - |
| 3 | 1 EP organ of CS entered in the 35 RC organs are entered in CS and IS of the | $10^{-4}$ | 0.9908 | -0.62 | 0.9953 | -0.38 | 0.45 | -0.24 |
| 7 | 2 · $10^{-4}$ | 0.9615 | -3.7 | 0.9674 | -3.27 | 0.61 | -0.42 |
| 11 | 10$^{-4}$ | 0.9889 | -0.81 | 0.9914 | -0.77 | 0.25 | -0.04 |
| 15 | 10$^{-4}$ | 0.9436 | -5.7 | 0.9546 | -4.66 | 1.15 | -1.01 |
| 16 | All CPS are entered in the core | 2 · $10^{-4}$ | 0.9430 | -5.7 | 0.9537 | -4.76 | 1.12 | -0.97 |

Where $K_{eff}$ – effective multiplication factor, $d_{K_{eff}}$ – statistical error in $K_{eff}$ calculation, $\Delta \rho$ – effectiveness of the CPS organs calculated by the formula (1).

The results obtained correspond to the expectations in terms of the lack of supercriticality in each of the states. The highest value of the effective multiplication factor is observed in the base state, which is associated with the absence of absorbing elements in the reactor core. Similarly, the lowest value of the
effective multiplication factor is observed in state 16, which is associated with the largest number of absorbing elements introduced into the reactor core. 

The largest discrepancy in the values of the effective multiplication factor is observed in states with a largest number of CPS organs introduced into the reactor core. Similarly, the smallest discrepancy in states with a smallest number of CPS organs introduced into the reactor core. A more detailed analysis will be conducted in the conclusion.

To facilitate the visual analysis of results and convenience of perception, charts were created comparing the effectiveness of CPS organs obtained for models with a homogeneous and heterogeneous description of the structure of fuel assemblies. This diagram is shown in figure 7.

**Figure 7.** Comparison of the values of the effectiveness of CPS organs estimated from the results of the calculation of models with a homogeneous and heterogeneous description of the structure of fuel assemblies.

7.1. The results of the calculation of the reactor core model with a homogeneous description of the fuel structure of fuel assemblies and a heterogeneous description of the absorbing rods structure

The mixed model was calculated in the KENOVI module of the SCALE code using the ENDF / B7 point neutron constant library. The calculation of this model should reveal the effect of a heterogeneous description of the absorbing rods structure on the difference of the values obtained in the calculation of models with a homogeneous and heterogeneous description of the structure of fuel assemblies. The diagram with the CPS efficiency values obtained for models with a homogeneous, heterogeneous, and mixed description of the fuel assembly structure is presented in figure 8.

**Figure 8.** Comparison of the values of the CPS efficiency obtained for models with a homogeneous, heterogeneous and mixed description of the structure of fuel assemblies.
After analyzing the obtained results, we can conclude that the values obtained are closer to the values obtained when calculating a model with a heterogeneous description of fuel assemblies than to the values obtained when calculating a model with a homogeneous description of fuel assemblies. From this, it follows that a heterogeneous description of the absorbing rods structure contributes most to the difference between the results of calculating models with a homogeneous and heterogeneous description of the structure of fuel assemblies. This means that the use of a model of this type will improve the accuracy of the model calculations by detailing it, without carrying out long work on creating a model with a completely heterogeneous description of the structure of fuel assemblies.

7.2. Comparing the results of different codes
This paper compares the results obtained in the calculation of models with a homogeneous and heterogeneous description of the structure of fuel assemblies in the SCALE code and the MCU-FR code. The calculations were carried out with equal calculation parameters (the number of simulated neutron histories per generation and the number of generations) and the same models. The analysis of the comparison results of the values obtained in the calculation of models with a homogeneous and heterogeneous description of the structure of fuel assemblies in the SCALE and MCU-FR codes is given in the conclusion of this work.

8. Conclusion
The purpose of this work was to determine the effectiveness of the CPS organs in various states of the BR-1200 reactor core, differing in the type and number of CPS organs that are simultaneously in the reactor core. An additional goal was to determine the effectiveness of the model with a homogeneous description of the fuel structure of fuel assemblies and a heterogeneous description of absorbing rods. Additional tasks were put to compare the results with data obtained using other neutron-physical codes and libraries of neutron constants.

As a result of comparing the values obtained when calculating the models of the BR-1200 reactor with a homogeneous and heterogeneous description of the fuel assembly structure in the KENOVI module of the SCALE code, we can draw the following conclusions: The maximum discrepancy between the values of the effective multiplication factor is observed in the state 16 (All CPS organs are entered in the core) and it is \(\Delta K_{eff}, \% = 1.15\%\). In the same state, there is a maximum discrepancy between the values of the effectiveness of the CPS organs and it is \(\Delta(\Delta \rho), \% = 1.2\%\) of efficiency.

As a result of comparing the values obtained in the calculation of the models of the BR-1200 reactor core with a homogeneous and heterogeneous description of the structure of fuel assemblies in neutron-physical codes SCALE and MCU-FR, we can draw conclusions: The maximum discrepancy between the values of the effective neutron multiplication factor and the efficiency of CPS organs for a model with a homogeneous description of the fuel assembly structure calculated in the SCALE code and the MCU-FR code are observed in state 16 and the values are \(\Delta K_{eff}, \% = 0.18\%\) and \(\Delta(\Delta \rho_{hom}) , \% = 0.34\%\). The maximum discrepancy between the values of the effective neutron multiplication factor and the efficiency of CPS organs for a model with a heterogeneous description of the fuel assembly structure are observed in state 15 and the values are \(\Delta K_{eff}^{SCALE-MCU}, \% = 0.22\%\) and \(\Delta(\Delta \rho), \% = 0.3\%\).

Considering the results of calculating the model with a homogeneous description of the fuel structure of fuel assemblies and a heterogeneous description of the absorbing elements structure, we can conclude that a heterogeneous description of the structure of absorbing elements introduces most of the difference between the results of the calculation of a model with a homogeneous description of the structure of fuel assemblies and a model with a heterogeneous description of the structure of fuel assemblies. Thus, the use of this model allows you to improve the accuracy of the calculations, without creating a complex model with a completely heterogeneous description of fuel assemblies.

Comparing the results of the model calculation with a homogeneous description of the structure of fuel assemblies, using point (ENDF / B7) and group (v7-238) libraries of neutron constants, we can...
conclude that the maximum difference in the effectiveness of CPS organs is maximally up to 0.37%, with no less than ~ 0.2% difference because of the difference between the libraries data, and the remaining ~ 0.17% difference because of impossibility of interpolating the temperature data in the point library of ENDF / B7 neutron constants.

The results obtained are relevant data that can be used both for crossverification of data in various neutron-physical codes testing, and for scientific work aimed at improving the neutron-physical parameters of the BR-1200 reactor. In particular, these results can be used in work on changing the location of CPS organs in the core of a BR-1200 reactor to increase the efficiency of CPS organs or in works on combining neutron-physical and heat-hydraulic codes when calculating the parameters of the BR-1200 reactor.

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