Irregularity of plutonium isotopic composition of the BREST-OD-300 initial load

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Abstract. This article is dedicated observation of irregularity of plutonium isotopic composition of the BREST-OD-300 initial load. The purpose of the research is to study the effect of the plutonium isotopic composition in the nitride fuel of the BREST–OD-300 reactor core starting load on the reactivity reserve. The calculations is creating by writing simplified three-dimensional geometry of the BREST-OD-300 reactor in software package “SERPENT”. There are five options in the fuel assemblies locations are considered with different cases of using the plutonium isotopic composition with deviations for some isotopes. Calculations have shown that the deviation of the plutonium isotope composition from the design values of the fuel loading of the BREST-OD-300 reactor does not affect the stability of reactivity during fuel burnout within the effective fraction of delayed neutrons. In the course of the research, changes in the effective multiplication coefficient are obtained over five years of reactor operation. The value of this indicator does not depend much on the plutonium deviation in the considered variations in the arrangement of fuel assemblies in the reactor core.

1. Introduction

In December 2019, the contract between Siberian Chemical Plant and Concern Titan-2 engineering company was signed for construction of The Pilot-demonstration energy complex (PDEC) under the Proryv project. The PDEC consists of a power unit with a BREST-OD-300 lead cooled reactor [6] and an on-site closed nuclear fuel cycle facility is being built at the in JSC «Siberian Chemical Combine» site in Seversk.

Before the reactor campaign, it is planned to manufacture fuel for the initial loads of the BREST-OD-300 reactor from plutonium extracted from the spent nuclear fuel (SNF) of the WWER-440 reactor, which is stored at the PA “Mayak”. Plutonium is stored in containers of not more than 3 kg, which is limited by the risk of a self-sustaining chain reaction and the coolability. In research [3], it is stated that the plutonium isotopic composition can be different. The measurement of plutonium isotopic composition is made difficult from the strong gamma background from the accumulated $^{241}$Am. In connection with these limitations, it is almost impossible to obtain a homogeneous isotopic composition.

The BREST-OD-300 reactor plant is planned to use nitride uranium-plutonium fuel, where plutonium is used as the main fissile isotope. Plutonium can be extracted from SNF or be extracted plutonium for other purposes. Each of the plutonium isotopes has a different half-life, resulting in a different isotopic composition. The isotopic composition also depends on the storage time.
Currently, it is planned to produce fuel for the BREST reactor plant from recycled SNF from WWER-440.

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2. BREST-OD-300 reactor model

A special attention in the reactor development and design is paid to confirmation the neutron-physical parameters and justification of the main design approaches and serviceability of the reactor core and its components using calculations. The continuous-energy Monte Carlo reactor physics burnup calculation code «SERPENT» is specifically designed for lattice physics applications.

The «SERPENT» can be used for modelling any critical reactor type or for various reactor calculations at core level, pin, and assembly, such as [1]:

- changes in the nuclide composition of nuclear fuel and their characteristics during fuel;
- neutron multiplication factor of any complex systems, using two- or three-dimensional geometry;
- energy distribution;
- spent nuclear fuel activities;
- vacuum reactivity effects;
- different reaction rates;
- values of different particle fluxes;
- characteristics of isotopes depending on their temperatures.

In «SERPENT», the calculation code is created by writing either a two-dimensional or three-dimensional model. This feature makes it possible to simulate the reactor feed up to a single fuel element. You can model either a single reactor cell or the entire reactor core.

The «SERPENT» reads cross-section from ACE format data libraries based on converted files of the estimated values JEFF-2.2, JEFF-3.1, ENDF/B-VI.8, ENDF/B-VII and ENDF/B-VIII.

The calculation code "SERPENT" is a certified software package, has a certification passport issued by the FBU "STC NRS" for a period up to 16.12.2025, which recognizes the possibility of using systems with nuclear fuel and nuclear fissionable materials for calculating the effective multiplication coefficient.

A simplified model of the BREST-OD-300 reactor core model is prepared. The simplified model means that all elements of the core had the simplest three-dimensional geometry without detailed elements. The placement of fuel assemblies in the core is performed symmetrically.

It’s considered that during the reactor life, nuclear fuel assemblies do not change their position. The volume fractions of materials in the reactor core of the BREST-OD-300 are presented in Table 2.

The calculation model uses nitride uranium-plutonium fuel (U-Pu)N consisting of 83% UN and 17% PuN. The BREST-OD-300 reactor project uses waste uranium (238U – 99.8%, 235U – 0.2%) as fuel [2]. The operation period is 5 years.

Figure 1 and figure 2 shows longitudinal and cross-sectional plans of the BREST-OD-300 reactor model with an average plutonium composition.
Figure 1. Cross-sectional plans of the BREST-OD-300 reactor model:
1 – reactor core; 2 – fuel assembly tops fitting; 3 – fuel assembly bottoms fitting; 4 – gas cavity; 5 – end reflector; 6 – side reflector; 7 – steel suction head.

Figure 2. Longitudinal plans of the BREST-OD-300 reactor model: green and purple color – central part; orange and dark-blue color – peripheral part; 1 – control rods; 2 – emergency shutdown rods; 3 – compensation reactivity rods.

The reactor core model has the dimensions that are designed in the project. The construction of the model was divided into two distinctive parts. The peripheral and central part of the core has different name codes for the nuclear fuel assembly, although they may have the same composition. The composition depends on the chosen placement scheme. The nuclear fuel assemblies with Control Rod Drive Mechanism were built in the model.

3. Calculation of neutron-physical characteristics of the initial loading of the BREST-OD-300 reactor

3.1 Plutonium isotopic composition
The paper shows the research carried out on a simplified model of the BREST-OD-300 reactor core. For calculations, the isotopic composition was selected so that the fuel enrichment for plutonium corresponds to the design values (Table 1). at the same time, the isotopic composition of plutonium has deviations only for the isotopes $^{239}$Pu and $^{240}$Pu. These isotopes make up the majority of plutonium and their deviations make significant changes in the neutron-physical characteristics of the BREST-OD-300 reactor. The isotopes $^{238}$Pu, $^{241}$Pu, and $^{242}$Pu are present in small amounts relative to other isotopes, so their deviation will not be noticeable and could have been neglected.

Due to the simplification of the BREST reactor model when modeling in the «SERPENT», the value of the effective multiplication coefficient differs from the design one. But to compare the effect of fuel compositions this simplification can be applied.
Table 1. Range of isotope concentration in plutonium and in the core of the BREST-OD-300 reactor project, % mA.

| Isotope | Concentration in plutonium | Concentration in the core of the BREST-OD-300 reactor project |
|---------|-----------------------------|---------------------------------------------------------------|
| $^{238}$Pu | 0.5÷3.0 | 1.2 |
| $^{239}$Pu | 57÷75 | 68.3 |
| $^{240}$Pu | 15.5÷26.4 | 23.2 |
| $^{241}$Pu | 2.0÷13.4 | 2.4 |
| $^{242}$Pu | 1.0÷7.0 | 4.2 |
| $^{241}$Am | 0.1÷13.0 | 0.7 |

In the reactor core, all plutonium consisted of two baskets. The composition of each basket was designed with concentrations symmetric about composition of initial loading in operation. The deviation was designed by the range of isotope concentration in plutonium. Based on the minimum and maximum concentration of the $^{240}$Pu isotope of 23.2% and 26.4%, respectively, we assume a possible deviation of $\pm 3.2\%$ for it. The plutonium fuel deviations are shown in Table 2.

Table 2. Plutonium isotopes fractions in the fuel of the BREST-OD-300 reactor, %.

| Isotope | $^{238}$Pu | $^{239}$Pu | $^{240}$Pu | $^{241}$Pu | $^{242}$Pu | $^{241}$Am |
|---------|------------|------------|------------|------------|------------|------------|
| Deviation $^{239}$Pu and $^{240}$Pu | + | 1.2 | 71.5 | 20.0 | 2.4 | 4.2 | 0.7 |
| - | 1.2 | 65.1 | 26.4 | 2.4 | 4.2 | 0.7 |

The accepted deviations and the resulting plutonium isotope compositions are represented by: (+) - positive deviation; (-) - negative deviation. Only two extreme cases of possible isotopic composition were selected, while in reality the fuel may be between critical values.

Note that the variation of the compositions in height was not considered.

3.2 Proposed options for the location of fuel assemblies with different deviations of the plutonium isotopic composition

The possibility of using the plutonium isotopic composition with deviations for some isotopes with different options in the fuel assemblies locations are considered. Extreme cases are identified (figure 3):

- Option 0. Start fuel loading;
- Option 1. Fuel assemblies in the reactor core with a positive deviation;
- Option 2. Fuel assemblies with a negative deviation in the central part of the core, and fuel assemblies with a positive deviation are located on the peripheral part;
- Option 3. Fuel assemblies in the reactor core with a negative deviation;
- Option 4. Fuel assemblies with a positive deviation in the central part of the core, and fuel assemblies with a negative deviation are located on the peripheral part.

It is worth noting that the probability of full core cover with the same deviation is extremely small, which means that research is necessary.
Figure 3. Longitudinal plans of the reactor zone of THE BREST-OD-300 with the identifications of the fuel assembly location.

4. Neutron-physical characteristics of the core of the BREST-OD-300 reactor
In the course of the research, changes in the effective multiplication coefficient are obtained over five years of reactor operation (figure 4). The value of this indicator does not depend much on the plutonium deviation in the considered variations in the arrangement of fuel assemblies in the reactor core.

During fuel cycle in a BREST-OD-300 reactor, the effective multiplication coefficient increases over three years due to the conversion of $^{238}\text{U}$ to $^{239}\text{Pu}$, which in turn does not allow the amount of fissile material to decrease, but rather increases, since the fuel multiplication coefficient in this reactor type is higher than 1. About 3 years later of burnout time, the effective breeding rate reaches a plateau that lasts about a year and then begins to decrease, but the rate of decline is lower than the rate of growth at the beginning of the campaign.
Figure 4. Dependence of the effective multiplication coefficient on time for 0-4 options.

For the analysis of a reactor with a lead coolant, BREST-300-OD is an important value of the reactivity margin [5]. The equilibrium fuel regime implies stability of reactivity during fuel burnout within the effective fraction of delayed neutrons ($\beta_{\text{eff}}$) in the time interval between the next overloads (during the cycle), taking into account all the processes accompanying the reactor operation.

The calculated value of $\beta_{\text{eff}}$ at the start of campaign for different options for the location of plutonium in the fuel assembly is 0.0035± 0.0001. The highest value of reactivity at the start of the reactor operation - 0.0039 is achieved when the entire core is filled with fuel assemblies with a positive deviation of plutonium concentration, and the smallest reactivity- 0.0034 is observed when the center of the core has a deviation in the positive direction, and the peripheral part in the negative. Comparing the maximum and the minimum, we get a difference of 0.0004.

5. Conclusion
The research of influence of the plutonium isotopic composition in the initial loading of nitride fuel of the reactor core were conducted and the neutron-physical parameters of the BREST–OD-300 reactor are obtained and studied.

Deviations of $^{239}$Pu and $^{240}$Pu make the extreme contribution to the reactor core characteristics, are considered. $^{238}$Pu, $^{241}$Pu, and $^{242}$Pu are not considered, as their content is extremely low. Also, for a fast reactor that breed fissionable material, it is the $^{239}$Pu isotope that is the main fissionable material. It influences on neutron-physical parameters is due to its good fission capacity and its amount in the fuel. Calculations have shown that the deviation of the plutonium isotope composition from the design values of the fuel loading of the BREST-OD-300 reactor does not affect the stability of reactivity during fuel burnout within the effective fraction of delayed neutrons.
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