NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 8(1): 71–76
DOI 10.3897/nucet.8.83062

Research Article

Simulating the fuel cycle of a lead-cooled fast reactor*

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Academic editor: Yury Kazansky ♦ **Received** 11 July 2021 ♦ **Accepted** 19 December 2021 ♦ **Published** 18 March 2022

Citation: Balovnev AV, Davydov VK, Zhirnov AP, Moiseev AV, Soldatov EO (2022) Simulating the fuel cycle of a lead-cooled fast reactor. Nuclear Energy and Technology 8(1): 71–76. https://doi.org/10.3897/nucet.8.83062

Abstract

The development of nuclear power with fast reactors is associated with the implementation of a closed nuclear fuel cycle (CNFC). In this regard, one actual task is to simulate the stages of the fuel cycle with study of the neutron-physical characteristics of the core. The design of a reactor for operation in the closed nuclear fuel cycle mode is impossible without the using of verified and certified software packages for calculating fast reactors, capable of simulating all stages of the operation of the reactor facility and the fuel cycle. For the calculations, the FACT-BR software package was used, which has all the necessary capabilities to simulate the operation of the reactor in the closed nuclear fuel cycle mode, taking into account the stages of fuel storage and refabrication. The article presents a technique for modeling the fuel cycle, implemented for the operation of fast reactors with a lead coolant. To demonstrate methodology, a closed nuclear fuel cycle was simulated for the BREST-OD-300 and BR-1200 reactors for the design life. The article describes the scenarios in which the calculation of the burnup of reactor was carried out. In the considered scenarios, it is assumed that the unloading of fuel at the end of the micro campaign is conducted according to the maximum burnup. During the computational modeling the ranges of changes in fuel density and enrichment, reactivity margin, breeding ratio and isotopic composition of plutonium were determined.

Keywords

Fast reactor, fuel cycle, lead coolant, modelling, FACT-BR

Introduction

At present, a design for a lead-cooled fast reactor, BREST-OD-300, with a closed nuclear fuel cycle is being developed (Adamov et al. 2003, 2020, Rachkov et al. 2013). For the large-scale nuclear power development that will meet modern requirements for new generation reactors, a competitive commercial power unit, BR-1200, with an electric power of 1200 MW is being designed.

The CNFC concept provides for complete inner fissile nuclide breeding (BRC~1) without a blanket, efficient use of uranium due to conversion of ^{238}U into ^{239}Pu in the fast reactor spectrum, and the possibility of transmutation of produced minor actinides during recycling. It is impossible to design a reactor for operation in the CNFC mode without using software tools verified and certified for calculations of fast reactors, capable of simulating all the operational stages of the reactor plant (RP) and the fuel cycle.

The system of codes (Balovnev et al. 2020) developed at JSC «NIKIET», which has all the necessary capabilities, is designed to calculate the neutronic characteristics of a

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2021, n. 4, pp. 66–75.

lead-cooled fast reactor, taking into account changes in the fuel nuclide composition during the campaign.

This system is actively used in developing the BREST-OD-300 and BR-1200 projects for calculating the neutronic characteristics and simulating the reactor campaign with fuel assembly inversions and refueling, in particular in the CNFC mode, throughout the complete design life of the reactor. The article presents a description of the developed methods for simulating the fuel cycle of a lead-cooled fast reactor. The operation of the BREST-OD-300 and BR-1200 reactors is considered both at the initial operational stage and in the steady state when the nuclear fuel cycle is closed.

Methodology

The fuel cycle of a lead-cooled fast reactor is simulated using the diffusion certified software package ("FACT-BR"). The program uses a 26-group diffusion approximation to calculate the three-dimensional neutron flux density field and the power distribution. Diffusion equations are solved by Askew-Takeda nodal method. The neutron cross section preparation system, CONSYST, (Golovko et al. 2014, Manturov 2017) with the ABBN 93 library (Manturov et al. 1996) is used as a neutron data block for the FACT-BR software package. Verification was carried out based on comparison of the results of calculations for the software package with the results of experiments at the BFS facility, at the BN-350, BN-600 and BN-800 reactors, as well as with the results of numerical benchmarks and calculations for other software packages.

In addition to the main calculation core, the FACT-BR software has a graphical module for managing input and output data. The module is responsible for the formation of source files for calculating the reactor steady state and campaign, and makes it possible to set the geometry and nuclide composition of individual elements of the calculation model as well as to regulate the movement of the control elements and the temperature conditions of the reactor plant. Also, using the control module, it is possible to set a refueling scenario.

Before making calculations, it is necessary to enter the initial data describing the reactor material and geometrical characteristics into the FACT-BR software. Corrections are entered into the calculation model. taking into account the heterogeneous effects obtained using the MCU-BR software package ("MCU-BR with MDBBR50 Constant Library"). The initial state is obtained using the diffusion module. Data of the core location map are transmitted to the MCU-BR software package. Based on comparative calculations of the efficiency of the CPS elements for the initial reactor loading carried out using MCU-BR and FACT-BR, correction factors were introduced for the macrosections of the absorbing material of the CPS working element in the FACT-BR model to take into account heterogeneity.

Constants for neutronic calculations are prepared in the CONSYST program, the input data of which are nuclear concentrations and temperatures. Next, calculations are made of K_{eff}, neutron flux density distribution, reaction rates, and neutron spectrum. After the neutronic calculations, the data are transferred to the burnup module to calculate the reactor campaign.

Fuel cycle implementation

In campaign calculations using the FACT-BR software, there are many possibilities for simulating the reactor fuel cycle. When the reactor operation is simulated, refueling is carried out in batches of individual fuel assemblies. The software package implements the possibility of inverting fuel assemblies in the core, unloading them into an in-reactor storage (IRS) facility, unloading them into a storage after conditioning in the IRS, and loading new fuel assemblies with fresh fuel or fuel that has passed the refabricating stage.

Three main fuel assembly unloading modes are supported:

- according to the preset refueling scheme;
- when fuel assemblies reach the specified maximum burnup; and
- manual selection of refueling fuel assemblies.

In the basic version, when simulating the fuel cycle of a lead-cooled fast reactor, it is assumed that the fuel is unloaded at the end of the micro-campaign when the maximum burnup is reached. At the beginning of the micro-campaign, the maximum burnup in all the fuel assemblies of the core is estimated. Next, a linear interpolation of the maximum burnup during the current micro-campaign is carried out using the maximum burnup rate in the considered fuel assembly, obtained in the previous micro-campaign. If the maximum burnup in the fuel assembly exceeds the specified one, this fuel assembly is unloaded into the IRS.

In the course of estimating the maximum burnup in fuel assemblies, the distribution per fuel element is taken into account. Restoration of burnup per fuel element is carried out by seven nodal points in the selected fuel assemblies and six points in neighboring fuel assemblies using quadratic interpolation. To increase the accuracy of the reconstruction of the power release per fuel element and the description of the local features of the fuel assemblies, such as the frame tubes and the casing of the CPS working element, a detailed calculation of the characteristic fuel assemblies according to MCU-BR based on the Monte Carlo method is used as a form function.

The campaign calculation includes the coupled calculation of the FACT-BR neutronic code and IVIS-BR thermophysical code. A combination of neutronic and thermophysical codes makes it possible to track the maximum temperatures during the campaign (Balovnev et al. 2019).

The stages of storage and refabrication of spent fuel assemblies are simulated by the fuel fabrication/refabrication module in the FACT-BR software package. During refueling, burnt-up fuel assemblies are unloaded into the in-reactor storage, and then sent for away-from-reactor conditioning and subsequent reprocessing. Uranium and plutonium isotopes and minor actinides selected in the scenario are returned to the fuel cycle. During the fabrication of regenerated fuel, it is diluted with depleted uranium in a given proportion to obtain the required plutonium enrichment of the fuel. The fuel cycle implementation in a lead-cooled fast reactor is schematically shown in Fig. 1.

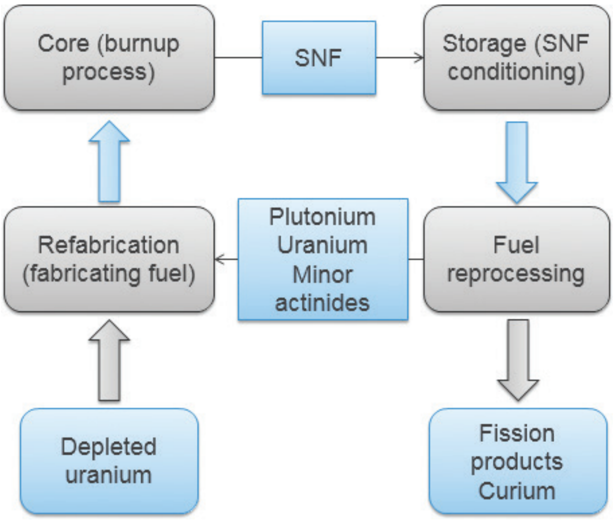

Figure 1. Diagram of the fuel cycle implementation in a lead-cooled fast reactor

Fuel cycle simulation in BREST-OD-300

The calculation model of the BREST-OD-300 reactor includes the fuel part of the core, a side reflector, and an in-reactor storage of fuel assemblies. For this reactor, a layout consisting of 169 fuel assemblies is considered. To equalize the radial distribution of the neutron flux and power, 169 cells in which fuel assemblies are installed are divided into two radial subcores: (1) central subcore (CS) and (2) peripheral subcore (PS). Profiling is carried out by varying the fuel element diameter. In the CS fuel assemblies, fuel elements of a smaller diameter are used and, in the PS fuel assemblies, fuel elements have a larger diameter, with the same fuel composition and density in all the fuel assemblies of the core.

The campaign of the BREST-OD-300 reactor is calculated for the entire operating period at the nominal power level. In the course of computational simulation, the transition from the initial operational stage to the established partial refueling in a closed nuclear fuel cycle is reproduced. This transition implies an increase in the maximum fuel burnup from 6 to 10% of heavy atoms (h.a.) and the duration of the micro-campaign. At the initial operational stage, the duration of the micro-campaign is 150 eff. days and, in steady state, it is 300 eff. day; at the end of each micro-campaign, a shutdown is made for 33 and 65 days, respectively.

During refueling, burnt-up fuel assemblies are unloaded into the IRS for conditioning during one micro-campaign and, at the beginning of the next micro-campaign, they are sent for out-of-reactor conditioning and subsequent reprocessing.

In the accepted scenario, the fuel is conditioned in an out-of-reactor storage for two years at the initial operational stage and a year in the CNFC mode. Further, the fuel assemblies are sent for SNF reprocessing and refabrication. Fission fragments and curium are completely removed from the spent fuel. To obtain the mass fraction of plutonium and americium specified according to the calculation results, depleted uranium is introduced into the purified fuel. From the resulting fuel, fuel assemblies are formed with the density and mass fraction of plutonium specified by the developer. The calculation was carried out on average fuel compositions.

Fig. 2 shows the dependence of the change in the reactivity margin on time for the design life. Starting from the fifth year of operation, refueling uses its own regenerated fuel and, from the seventh year, the share of loaded regenerated fuel approaches 100% (the closure of the nuclear fuel cycle is fully implemented). For the fabrication of fuel for the first reloads, power plutonium of the initial composition is used.

It can be seen that the change in the reactivity margin lies within 1 β_{eff} over the entire time range. The reactivity margin at the beginning of each micro-campaign is controlled by adjusting the average density and the plutonium fraction of the loaded fuel batch. The average fuel density throughout the campaign is in the range of 12.3–12.5 g/cm^3. The mass fraction of plutonium in the loaded fuel varies from 13 to 14%. During the simulation, the power release field is aligned along the core to prevent the fuel cladding temperature from exceeding 670 °C.

During reactor operation, as a result of the ^{238}U isotope burnup, as well as the accumulation of plutonium and fission products in the fuel, the core reproduction rate decreases towards the end of the micro-campaign (Fig. 3).

During operation, the core reproduction rate lies in the range from 1.085 to 1.025. At the initial operational stage, fresh fuel with a higher core reproduction rate is used to reach the steady state mode of partial refueling on the burnt core. At the beginning of each micro-campaign, the neptunium reactivity effect is realized, which must be taken into account when the campaign is simulated. The neptunium effect is associated with a delay in the conversion of ^{238}U to ^{239}Pu, since the half-life of the intermediate ^{239}Np nucleus is 2.35 days. In the first few days after startup and reaching power, there is a loss of reactivity. The neptunium reactivity effect is 0.22 β_{eff}.

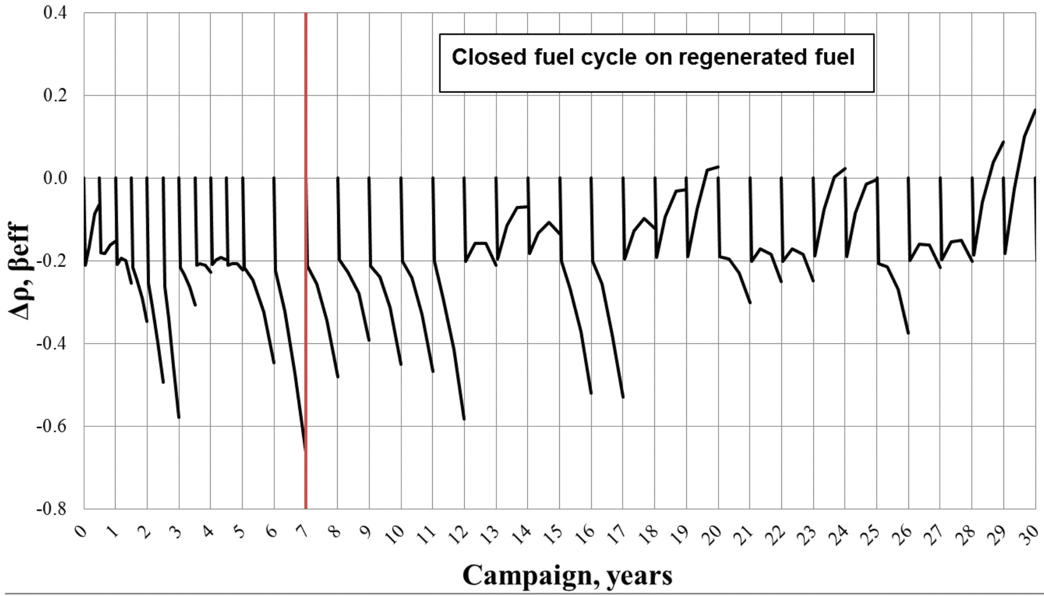

Figure 2. Time dependence of the reactor core reactivity change

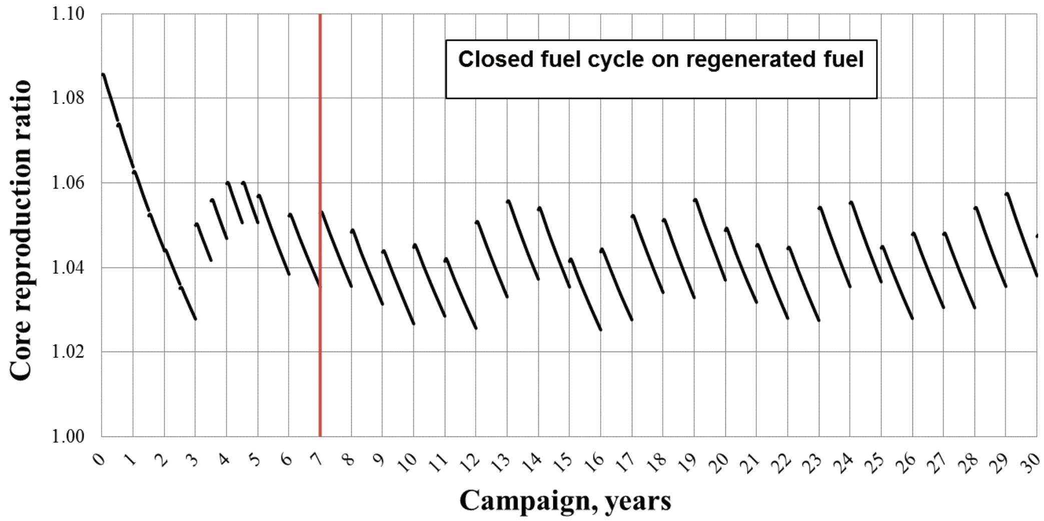

Figure 3. Time dependence of the core reproduction rate

During reactor operation in the CNFC, the isotopic composition of plutonium changes (Table 1) and accumulation of ^{241}Am and ^{240}Pu is observed, which introduces negative reactivity into each loaded fuel batch. At the same time, the share of ^{239}Pu in the fuel decreases, the shares of ^{238}Pu and ^{241}Pu practically do not change. To compensate for the negative effects associated with a change in the plutonium vector, the plutonium enrichment in the loaded fuel is gradually increased in the refueling mode. At the end of the design life of the BREST-OD-300 reactor, the composition of plutonium is as follows: ^{238}Pu = 1.0%; ^{239}Pu = 65.1%; ^{240}Pu = 26.5%; ^{241}Pu = 2.8%, ^{242}Pu = 2.9%, ^{241}Am = 1.7%. The results obtained are consistent with the study carried out in (Vasyukhno et al. 2016).

Table 1. Changes in the isotopic composition of plutonium and americium in the core

Isotope	Lifetime, years						
	0	5	10	15	20	25	30
^{238}Pu	1.2	0.9	0.8	0.8	0.8	0.9	1.0
^{239}Pu	68.3	67.5	67.0	66.3	65.9	65.1	65.1
^{240}Pu	23.2	24.3	24.9	25.5	25.9	26.4	26.5
^{241}Pu	2.8	2.8	2.9	2.7	2.8	2.8	2.8
^{242}Pu	4.2	3.7	3.6	3.3	3.1	3.0	2.9
^{241}Am	0.3	0.8	0.9	1.3	1.4	1.7	1.7

Fuel cycle simulation in BR-1200

The calculation model of the BR1200 reactor includes the fuel part of the core, a side reflector, and an in-reactor storage of fuel assemblies. For this reactor, a layout consisting of 397 fuel assemblies is considered. To equalize the radial distribution of the neutron flux and power, 397 cells in which fuel assemblies are installed are divided into three radial subcores: (1) central subcore (CS), middle subcore

(MS) and (2) peripheral subcore (PS). Profiling is carried out by varying the diameter of the fuel element. In the CS, fuel elements of a smaller diameter are used while, in the MS and PS fuel assemblies, fuel elements have a larger diameter with the same fuel composition and density in all the fuel assemblies of the core.

The campaign of the BR-1200 reactor is calculated for the entire operating period (60 years) at the nominal power level. The article considers a scenario with the accepted maximum burnup limit of 12.5% h.a. The duration of the micro-campaign in the calculations is 330 eff. days. During the first micro-campaign, it is necessary to carry out a two-time shutdown of the reactor with the inversion of the constant reactivity compensators to optimize the characteristics of the core. At the end of each micro-campaign, a shutdown for 35 days is made. In this study, refueling was carried out with an average fuel composition.

The scenario for implementing the CNFC in the BR-1200 reactor is carried out similarly to that considered for the BREST-OD-300 reactor. Fig. 4 shows the dependence of the change in the reactivity margin on time for the entire design life. Starting from the fifth year of operation, refueling uses its own regenerated fuel and, from the seventh year, the share of loaded regenerated fuel approaches 100% (the closure of the nuclear fuel cycle is fully implemented). It can be seen that over the entire time range, the change in the reactivity margin per micro-campaign does not exceed 1 β_{eff}. The average fuel density throughout the campaign is in the range of 12.0–12.5 g/cm^3. The mass fraction of plutonium in the loaded fuel varies from 13 to 14.6%.

During reactor operation, the core reproduction rate decreases towards the end of the micro-campaign (Fig. 5). The core reproduction rate lies in the range from 1.11 to 1.018. The neptunium reactivity effect is 0.31 β_{eff}.

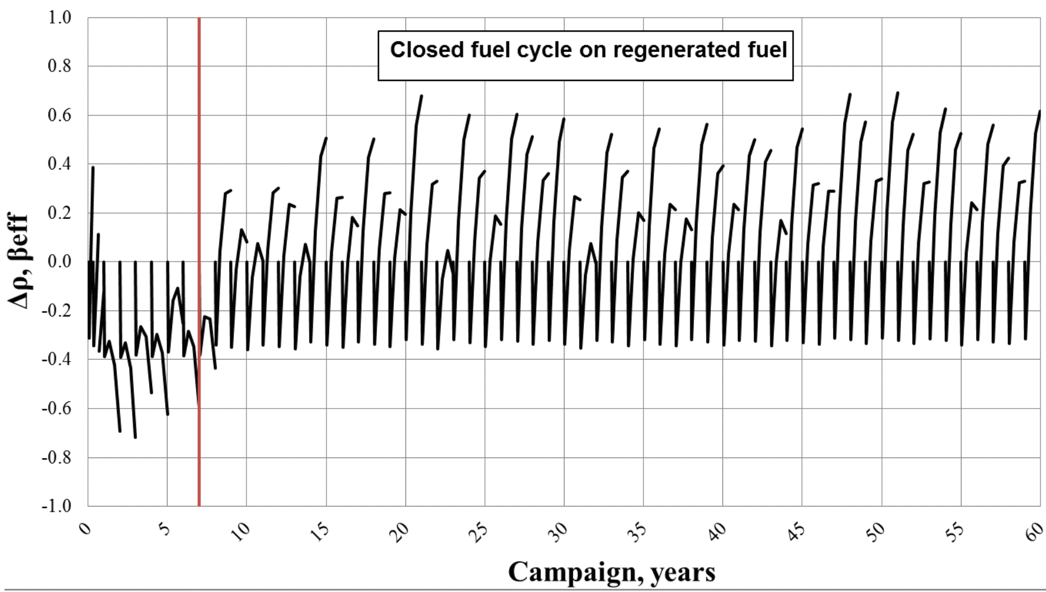

Figure 4. Time dependence of the reactor core reactivity change

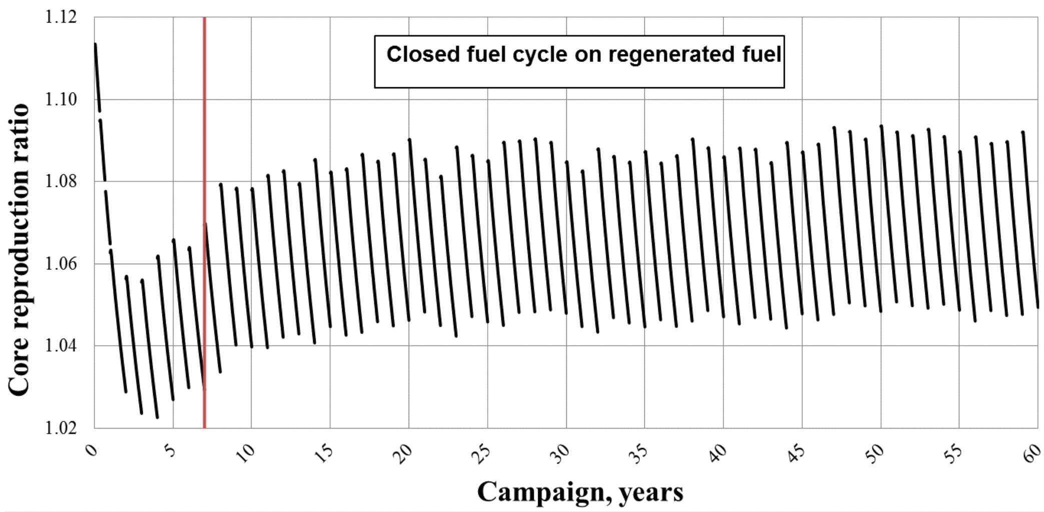

Figure 5. Time dependence of the core reproduction rate

The plutonium isotopic composition of the BR-1200 reactor approaches the equilibrium value during operation (Table 2). As the campaign progresses, the proportion of odd isotopes of plutonium decreases, but the proportion of even isotopes of plutonium and americium increases. At the end of the BR-1200 design life, the following plutonium composition is formed in the core: ^{238}Pu = 1.1%; ^{239}Pu = 62.4%; ^{240}Pu = 28.8%; ^{241}Pu = 3.8%, ^{242}Pu = 2.4%, ^{241}Am = 1.5%.

Table 2. Changes in the isotopic composition of plutonium and americium in the core

Isotope	Lifetime, years						
	0	10	20	30	40	50	60
^{238}Pu	1.2	0.7	0.8	0.9	1.0	1.1	1.1
^{239}Pu	68.3	65.6	64.3	63.5	63.1	62.4	62.4
^{240}Pu	23.2	26.3	27.5	28.1	28.4	28.8	28.8
^{241}Pu	2.8	3.4	3.6	3.6	3.7	3.8	3.8
^{242}Pu	4.2	3.2	2.8	2.6	2.5	2.4	2.4
^{241}Am	0.3	0.8	1.0	1.3	1.4	1.5	1.5

Conclusion

The article considers the actual problems of implementing the fuel cycle of a lead-cooled fast reactor. Specialized modules have been developed for simulating the CNFC, which make it possible to investigate and analyze nuclide fluxes in the reactor and out-of-reactor parts of the fuel cycle. A comprehensive simulation of the fuel cycle of the BREST-OD-300 and BR-1200 reactors for the design life was carried out, taking into account the limitations on the maximum burnup and reactivity margin. Computational simulation made it possible to determine the ranges of changes in the fuel density and enrichment, the reactivity margin, the core reproduction rate, and the isotopic composition of plutonium.

In the BREST-OD-300 and BR-1200 reactors, starting from the fifth year of operation, refueling uses its own regenerated fuel and, from the seventh year, the share of loaded regenerated fuel approaches 100% (the closure of the nuclear fuel cycle is fully implemented). At the entire stage, the range of changes in the reactivity margin was controlled within 1 β_{eff}. During the simulation, temperature conditions were controlled to prevent the fuel cladding temperature from exceeding 670 °C.

At the end of the design life of the BREST-OD-300 reactor (30 years), the plutonium isotopic composition did not fully reach the steady-state values while, in the BR-1200 reactor, the plutonium vector was practically stabilized over 60 years. The performed computational simulation of a lead-cooled fast reactor for the design life shows the possibility of closing the nuclear fuel cycle, taking into account the chosen scenario.

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