NUCET NUCLEAR ENERGY AND TECHNOLOGY

Nuclear Energy and Technology 9(2): 131–136
DOI 10.3897/nucet.9.107762

Research Article

Use of remix spent mixed fuel plutonium in the BN-1200 reactor*

Nikita V. Kovalev[1], Alexander M. Prokoshin[1], Alexander S. Kudinov[1], Vladimir A. Nevinitsa[2]

1 *V.G. Khlopin Radium Institute JSC, 28 2-nd Murinsky Ave., 194021 St. Petersburg, Russia*

2 *Kurchatov Institute NRC, 1 Academician Kurchatov Sq., 123182 Moscow, Russia*

Corresponding author: Nikita V. Kovalev (kovalev@khlopin.ru)

Academic editor: Georgy Tikhomirov ♦ **Received** 11 November 2022 ♦ **Accepted** 1 March 2023 ♦ **Published** 20 June 2023

Citation: Kovalev NV, Prokoshin AM, Kudinov AS, Nevinitsa VA (2023) Use of remix spent mixed fuel plutonium in the BN-1200 reactor. Nuclear Energy and Technology 9(2): 131–136. https://doi.org/10.3897/nucet.9.107762

Abstract

The VVER-1000 thermal neutron reactor can operate on mixed uranium-plutonium fuel with a content of reactor-grade plutonium up to 5% with a 100% loaded core. In this case, plutonium burns up to 56% of odd isotopes. The energy potential of such plutonium is very low, and its further use in thermal reactors is impractical. However, such plutonium can be used in fast neutron reactors. The paper presents the results of investigating the possibility for such isotopic plutonium composition to be used in the BN-1200 thermal neutron reactor and its value be increased for the plutonium recycle in the reactor. For this purpose, a precision model of the BN-1200 reactor has been developed using the Serpent Monte Carlo code. The model has been verified against the reference values of the nuclear fuel burnup and breeding ratios. The study has shown that such plutonium can be used in the BN-1200 reactor MOX fuel. Maintaining the operating cycle length requires the plutonium fraction in the MOX fuel to be increased up to 2%. In the BN-1200 reactor, the isotopic composition has been found to improve for the further recycle of plutonium in the thermal reactor, i.e. odd plutonium isotopes increase. The fewer odd plutonium isotopes at the beginning of the BN-1200 operating cycle, the greater their increase. It can be seen as the result of the calculation that plutonium from VVER-1000 spent mixed fuel must be loaded into the BN-1200 reactor at least twice to increase the fraction of odd isotopes to the level of reactor-grade plutonium.

Keywords

nuclear fuel, REMIX, REMIX-E, MIX, MOX, plutonium, sodium-cooled fast reactor, BN-1200, plutonium improvement

Introduction

REMIX is uranium-plutonium fuel cycled in thermal neutron reactors. There are a number of REMIX fuel concepts. The simplest concept, in terms of mixed fuel fabrication, is REMIX-E (a mixture of enriched natural uranium and reactor-grade plutonium 1–5%) (Kovalev et al. 2020).

A thermal reactor of the VVER-1000 type is capable to operate based on mixed uranium-plutonium fuel containing up to 5% of reactor-grade plutonium with a 100% loaded core (Kovalev et al. 2021). Reactor-grade plutonium herein means plutonium extracted from SNF of thermal reactors using enriched natural uranium fuel. And the neutronic performance of the reactor core is in the limits of the design-basis values. The fuel nuclides in this case are ^{235}U, ^{239}Pu and ^{241}Pu. The fraction of odd isotopes in reactor-grade plutonium, depending on cooling time, is about 66%. Such plutonium being

* Russian text published: Izvestiya vuzov. Yadernaya Energetika (ISSN 0204-3327), 2023, n. 1, pp. 70–81.

used further in a thermal reactor, odd isotopes burn up and their fraction becomes smaller. As the fraction of odd isotopes decreases to 50%, the energy value of such plutonium is fully exhausted. In the event of a VVER-1000 using mixed fuel from the REMIX-E recycling concept with the maximum plutonium content of 5%, the fraction of odd isotopes in the unloaded fuel becomes equal to 56%. The energy potential of such plutonium is extremely low, so it is not reasonable to use it further in thermal reactors. Such plutonium can be however used in fast reactors.

Unlike thermal reactors, fast reactors can operate on plutonium with practically any isotope composition since all plutonium isotopes undergo fission in a fast spectrum. It has been shown by Russian and French experts on the example of the BN-800 and ASTRID reactors that fast reactors change the plutonium composition towards an increase in the fraction of odd plutonium isotopes but their efficiency is not sufficient (Eliseev et al. 2020).

A computational model was developed to find out if it was possible to use plutonium from the REMIX-E concept mixed fuel SNF in the MOX fuel of the BN-1200 reactor and to investigate the change in its isotope composition in the process of burnup in the BN-1200 reactor.

BN-1200 reactor

Favorable conditions are established in fast reactors, in the absence of a neutron moderator, for more neutrons to emerge, which are capable to sustain a fission chain reaction and transform efficiently ^{238}U and ^{232}Th fertile isotopes into ^{239}Pu and ^{233}U fissionable isotopes (Kuzmin et al. 2013).

The design of an advanced power unit with the BN-1200 fast sodium-cooled reactor is developed as the basis for the initial stage in deploying, on a series basis, reactors of this type. The development of the BN-1200 reactor is based on the maximum possible use of proven and scientifically justified and engineered technological solutions implemented in the BN-350, BN-600 and BN-800 fast reactor designs (Reactor BN-1200 2022).

Table 1. Key characteristics of the BN-1200 reactor core

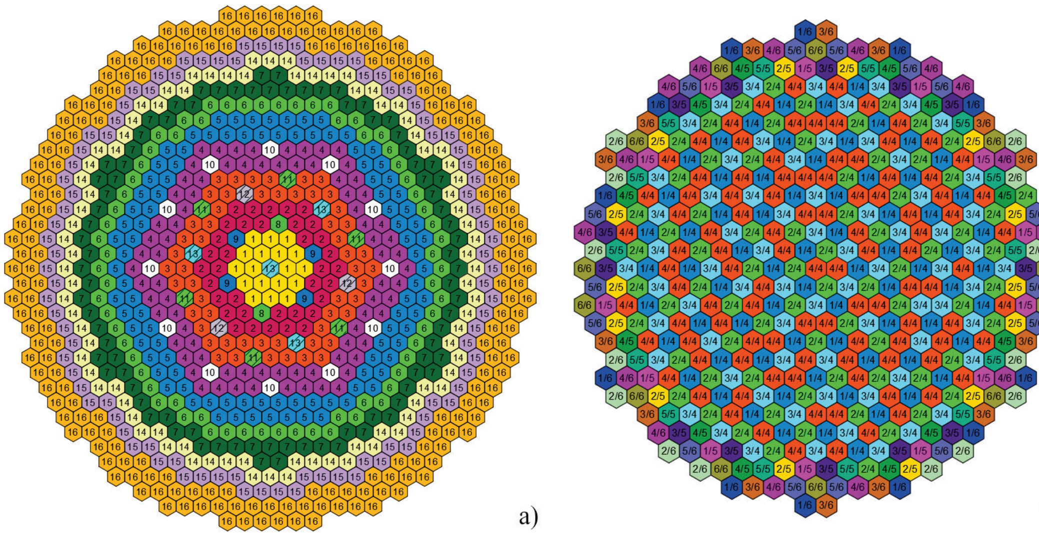
Description	Value
Thermal power, MW	2800
Inlet/outlet sodium temperature, °C	410 / 550
Core height, cm	85
MOX fuel load, t	47.2
Plutonium content in fuel, %	17.2
Breeding ratio, including	1.19
- core	0.92
- axial blanket	0.16
- side blanket	0.11

The key characteristics of the BN-1200 reactor (Vasiliev 2019) are given in Table 1. The reactor core map, and the core FA, side blanket (SB) FA, CPS control member (CM) and absorber rod (AR) designs are presented in Kurashov 2015, Vasiliev et al. 2018, Mosunova 2018, Drobyshev 2021.

BN-1200 reactor calculation procedure and model

The information for the model construction was taken from publicly available sources (Anikin et al. 2015), Kurashov 2015; Mosunova 2018; Vasiliev 2019; Drobyshev 2021).

The BN-1200 reactor model for the neutronic calculations was developed using the Serpent Monte Carlo 3D particle transport code (Anikin et al. 2015) based on energy-continuous libraries. Monte Carlo method uses all currently available knowledge to calculate the particle transport and interaction in conditions of a real 3D geometry with no approximations at all. These peculiarities make the method more precise and independent of the problems solved.



a) b)

Figure 1. a) Map of BN-1200 zones; **b)** BN-1200 core FA reloading map.

The map of the BN-1200 reactor zones (Belov et al. 2014) and the FA reloading map (Egorov et al. 2019) shown in Fig. 1 were used for the simulation. Zones 1 through 7 are the core FAs; zone 8 is an assembly with a control rod (CR); zone 9 is an assembly with the inner ring shim rod (SR); zone 10 is an assembly with the outer ring SR; zone 11 is the emergency protection assembly; zone 12 is the hydraulic passive emergency protection assembly (PEP-H); zone 13 is the temperature passive emergency protection assembly (PEP-T); zone 14 is an SB FA (row 1); zone 15 is an SB FA (row 2); and zone 16 is a biological shielding assembly (BSA) FA. In the core FA reloading map, the first number is the unloading number, and the second number is the reloading frequency. The reloading frequency is four for the core zones 1 through 5, five for zone 6, and six for zone 7. The reloading frequency is eight for the SB (row 1), and ten for the SB (row 2). Due to the absence of detailed data on the SB reloading, it was assumed for the model that all SB FAs are reloaded at a time, once in eight years.

Fig. 2 presents the developed geometrical model of the BN-12000 reactor used in the calculation. The model built was symmetrical (did not include the steel shielding assemblies (SSA) zone). The model does not also include the in-vessel storage (INS) zone and the biological shielding assemblies (BSA) zone. No damaged CPS CMs (Nos. 11, 12 and 13) were used in the model.

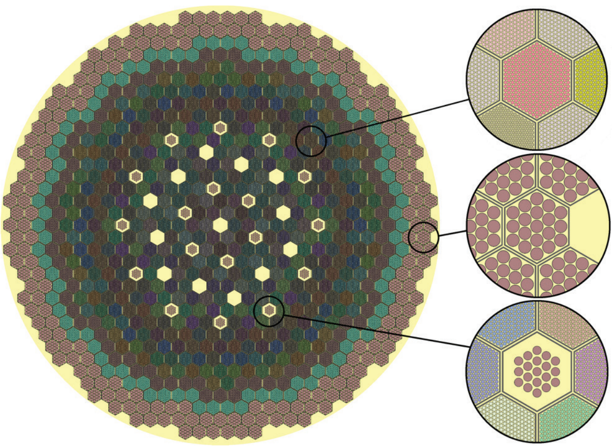


Figure 2. Geometrical model of the BN-1200 core used in the calculation, and the cut is perpendicular to axis Z at a level of 70% H_{core}.

Verification of the BN-1200 calculation model

The calculation model was verified based on the following criteria:

- in the course of the reloading cycle, the reactivity shall be positive and tend to zero as the cycle ends (with no control rods taken into account);
- the neutron spectrum shall correspond to the theoretical spectrum;
- the unloaded fuel burnup be equal to the reference values;
- the breeding ratio shall be equal to the reference values.

The model implements the FA reloading function. The calculation starts with the core fully loaded with fresh fuel. After each reloading cycle, the material composition of all burnup zones is written as a binary file. According to the map (see Fig. 1), FAs are reloaded in the next reloading cycle. Due to different reloading frequencies, a decision was made to calculate 16 reloading cycles of 330 days each. The number of such cycles is defined largely by the FA reloading frequency. At the beginning of the initial reloading cycle, the core in the model is filled fully with fresh fuel, and reactivity is at a high level. Following 8 reloading cycles, however, after all FAs in the core and in the SB go through the reloading cycles, the neutron multiplication factor becomes stable. Each subsequent cycle starts with a reactivity margin of ~2.5% and tends to become zero as the cycle ends, which is in accordance with the first criterion we have defined. In further calculations, the CPS CMs are introduced into the model beginning in the 9th reloading cycle, with their positions chosen such that the effective multiplication factor equals unity throughout the respective cycle, and reactivity is accordingly equal to zero.

The BN-1200 neutron spectrum calculated based on the model is presented in Fig. 3. It has a good fit with the theoretical spectrum (Nuclear Physics and Reactor Theory (1993)). For comparison, the figure also presents the calculated VVER-1000 spectrum.

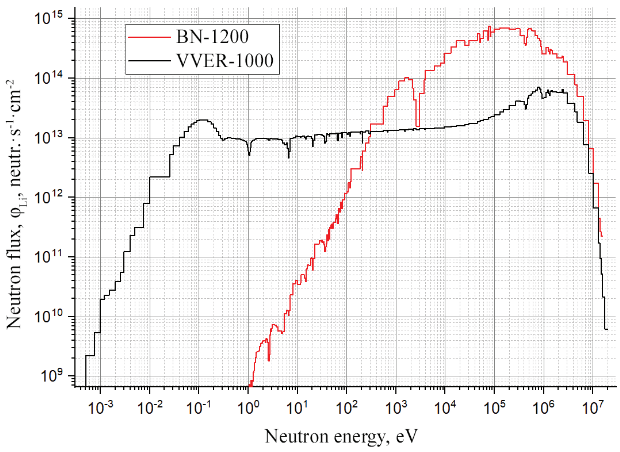


Figure 3. Calculated VVER-1000 and BN-1200 neutron spectrum.

As the result of the FA power density data processing, burnup values have been obtained for the unloaded fuel. Table 2 presents the unloaded fuel average burnup values from several sources. It can be seen that the calculated value has a good fit with the reference value. The table also presents the calculated core burnup value and the maximum core burnup without the axial blanket (AB) and side blanket (SB) taken into account.

Using the information on the reaction rates obtained, breeding ratios can be obtained for different zones in the

Table 2. Unloaded BN-1200 fuel burnup

	Reference values	Calculation
	MW·day/kgHM	
B *	95 (Vasiliev 2019)	92.27
	90 (Babushkin et al. 2020)	
	93 (Vasiliev 2010)	
B_{core} **		99.25
B_{MAX} ***		109.22

* - Core average burnup value with AB taken into account;
** - Core average burnup without AB taken into account;
*** - Core maximum burnup without AB taken into account.

calculation model. The breeding ratios were calculated using the following formulas:

$$BR = (N_c^{U238} + Nc^{Pu240})_r/(N_{c,f}^{Pu239} + N_{c,f}^{Pu241})_r, \quad (1)$$

$$BRC = (N_c^{U238} + N_c^{Pu240})_{core}/(N_{c,f}^{Pu239} + N_{c,f}^{Pu241})_{core}, \quad (2)$$

$$BRS = (N_c^{U238} + N_c^{Pu240} - N_{c,f}^{Pu239} + N_{c,f}^{Pu241})_{sb}/(N_{c,f}^{Pu239} + N_{c,f}^{Pu241})_{core}, \quad (3)$$

where N_c, N_f are the capture and fission reaction rates for the isotope under consideration, and $N_{c,f} = N_c + N_f$; "r", "core", and "sb" are the "reactor", "core" and "side blanket" zone indices.

The calculated breeding ratios compared with the reference values are presented in Table 3.

As the result of a computational study, the identified criteria for the calculation model verification were met, and the model can be used for computational studies of the fuel isotope composition change in the process of burnup.

Table 3. BN-1200 breeding ratios

	Reference value (Vasiliev 2019)	Calculation
BR	1.19	1.19
BRC	0.92	0.91
BRS (AB)	0.16	0.16
BRS (SB)	0.11	0.12

Determination of the fraction of plutonium in the BN-1200 MOX fuel from REMIX-E spent fuel

The usability of plutonium from the REMIX-E concept mixed fuel SNF in the BN-1200 reactor MOX fuel was studied, and the fraction of plutonium in MOX fuel was determined for preserving the design duration of the reloading cycle. Table 4 presents the isotope composition of plutonium extracted from spent uranium and uranium-plutonium (1–5% Pu) nuclear fuel of VVER-1000 reactors after 5 years of cooling. It can be seen from the table that the larger is the initial content of plutonium, the fewer odd isotopes of value for a thermal reactor remain.

The MOX fuel loaded into the BN-1200 reactor is a mixture of depleted uranium and plutonium. Due to the variable isotope composition of plutonium, the content of plutonium in the BN-1200 MOX fuel has been chosen such that the duration of the operating cycle remained at the same level. The results are presented in Table 5.

It was found in the course of the study that plutonium from the REMIX-E concept mixed fuel SNF can be used in the BN-1200 reactor MOX fuel. To preserve the design duration of the operating cycle, the fraction of plutonium in MOX fuel needs to be increased to 2% depending on the isotope composition of plutonium (see Table 5).

Determination of the change in the isotope composition of plutonium unloaded from the BN-1200 fuel

The developed BN-1200 reactor model was used to investigate the increase in the plutonium isotope composition value for its return to a thermal reactor.

It is not possible to improve the isotope composition of plutonium with a breeding ratio of less than unity. The BN-1200 BRC, without taking into account the blankets, is equal to 0.92 (see Table 1). However, since the BN-1200 FAs in-

Table 4. Isotope composition of plutonium in the BN-1200 loaded fuel, %

Isotope	VVER-1000 spent nuclear fuel type					
	UO_2	REMIX-E				
		Pu 1%	Pu 2%	Pu 3%	Pu 4%	Pu 5%
^{238}Pu	2.88	3.29	3.52	3.63	3.66	3.66
^{239}Pu	54.49	49.77	45.77	43.29	42.03	41.57
^{240}Pu	23.87	23.68	24.85	26.19	27.27	28.02
^{241}Pu	11.93	12.69	13.62	14.22	14.51	14.58
^{242}Pu	6.84	10.57	12.24	12.67	12.53	12.17
Sum of odd isotopes	**66.41**	**62.46**	**59.39**	**57.51**	**56.54**	**56.15**

Table 5. Content of plutonium in the BN-1200 MOX fuel, %

	VVER-1000 spent nuclear fuel type					
	UO_2	REMIX-E				
		Pu 1%	Pu 2%	Pu 3%	Pu 4%	Pu 5%
Content of Pu in BN-1200 MOX fuel	17.2	18.0	18.6	18.9	19.1	19.2

Table 6. Isotope composition of plutonium in unloaded BN-1200 fuel (no cooling), %

Isotope	VVER-1000 spent nuclear fuel type					
	UO_2	REMIX-E				
		Pu 1%	Pu 2%	Pu 3%	Pu 4%	Pu 5%
^{238}Pu	1.60	1.83	1.98	2.05	2.07	2.08
^{239}Pu	62.85	59.93	57.49	56.00	55.19	54.87
^{240}Pu	24.19	23.82	24.36	25.10	25.74	26.22
^{241}Pu	5.47	5.70	6.07	6.34	6.52	6.60
^{242}Pu	5.90	8.72	10.10	10.51	10.47	10.24
Sum of odd isotopes	**68.31**	**65.63**	**63.57**	**62.34**	**61.71**	**61.46**

cludes the AB, the breeding ratio for such FAs will be more than unity. The maximum effect from the isotope composition improvement will be achieved through reprocessing of both the main SFAs and the side blanket SFAs.

After the BN-1200 fuel life if over, the unloaded fuel includes 1/4 of the main core FA, 1/5 of the core FAs in the row next to the last row, and 1/6 of the core FAs in the last row, as well as 1/8 of the SB FAs (row 1) and 1/10 of the SB FAs (row 2). The isotope composition of plutonium in the unloaded SFAs is presented in Table 6.

Fig. 4 presents the sum of odd plutonium isotopes in loaded and unloaded BN-1200 fuel depending on the type of the used plutonium from the VVER-1000 SNF. It can be seen that the isotope composition 'improves' for the further plutonium recycle in the thermal reactor, that is, the fraction of odd plutonium isotopes increases. And the smaller is the fraction of odd plutonium isotopes in the loaded fuel, the more it increases. Thus, the use of plutonium from the REMIX-E concept mixed fuel SNF with the initial plutonium content of 5% leads to a 5.3% increase in the fraction of odd plutonium isotopes.

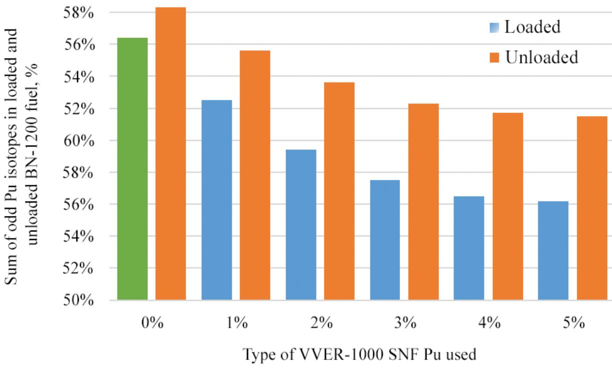


Figure 4. Sum of odd Pu isotopes in loaded and unloaded BN-1200 fuel depending on the VVER-1000 SNF Pu type.

used in the BN-1200 MOX fuel. To preserve the design duration of the operating cycle, it is required to increase the plutonium fraction in MOX fuel to 2% when using the REMIX-E concept mixed fuel SNF plutonium with the initial plutonium content of up to 5%.

The developed BN-1200 reactor model was used to investigate the increase in the plutonium isotope composition value for its return to a thermal reactor. The isotope composition improves in the BN-1200 reactor for the further plutonium use in the thermal reactor, that is, the fraction of odd plutonium isotopes increases. And the smaller is the fraction of odd plutonium isotopes in the loaded fuel, the more it increases. It can be seen from the calculation results that plutonium from the VVER-1000 mixed fuel is required to be loaded into the BN-1200 reactor at least twice for increasing the fraction of odd isotopes to the level of the reactor-grade plutonium level extracted from the SNF of thermal reactors using enriched natural uranium fuel.

Discussion of results

A precision model of the BN-12000 reactor was built using the Monte Carlo Serpent code. The model was verified against the reference values of the nuclear fuel burnup and the BN-1200 breeding ratios.

The model was used to investigate the usability of the plutonium isotope composition from the REMIX-E concept mixed fuel SNF in the BN-1200 reactor. It was found in the course of the study that such plutonium could be

References

- Anikin AYu, Kuryndin AV, Sinegribov SV, Stroganov AA (2015) Verification of the Serpent software tool for assessing the nuclear safety of nuclear facilities. Proc. of the IX-th International Scientific and Technical Conference "Ensuring the Safety of Nuclear Power Plants with VVER", Podolsk, May 19–22, 2015. [Available at:] http://www.gidropress.podolsk.ru/files/proceedings/mntk2015/documents/mntk2015-109.pdf [accessed Oct. 17, 2022] [in Russian]
- Babushkin SV, Vasiliev BA, Vasyaev AV, Vorontsov VE, Dushev SA, Zverev DL, Kiryushin AI, Marova EV, Sedakov VYu, Staroverov AI, Timofeev AV, Shepelev SF (2020) Reactor installations with sodium-cooled fast reactors for two-component nuclear energy. Atomic Energy 129(1): 8–17. https://doi.org/10.1007/s10512-021-00705-y
- Belov SB, Kiselev AV, Marova EV, Farakshin MR, Frolov VM, Malysheva IV, Peregudov AA, Semenov MYu, Stogov VYu, Tsibulya AM, Alekseev PN, Boyarinov VF, Zizin MN, Nevinitsa VA, Timoshinov AV, Fomichenko PA (2014) Results of verification of programs for calculation of neutron-physical characteristics of the core of BN-1200 reactor. VANT. Ser. Yaderno-Reaktornyye Konstanty 4: 66–76.

[Available at:] https://elibrary.ru/item.asp?id=22905474 [accessed Oct. 17, 2022] [in Russian]
- Egorov AV, Khomyakov YuS, Rachkov VI, Rodina EA, Suslov IR (2019) Minor actinides transmutation in equilibrium cores of next generation FRs. Nuclear Energy and Technology 5(4): 353–359. https://doi.org/10.3897/nucet.5.46517
- Eliseev VA, Klinov DA, Camarcat N, Lemasson D, Meriot C, Pershukov VA, Troyanov VM, Velardo H (2020) On the Possibility to improve mixed uranium-plutonium fuel in fast reactors. Nuclear Energy and Technology 6(2): 131–135. https://doi.org/10.3897/nucet.6.51587
- Drobyshev YuYu (2021) Hybrid Fuel Loading of a High-Power Fast Neutron Reactor. Cand. Sci. Engineering Diss., Moscow, VNIIAES Publ., 200 pp. [Available at:] https://ds.mephi.ru/documents/762/Дробышев_Ю_Ю_Текст_диссертации.pdf [accessed Oct. 17, 2022] [in Russian]
- Kovalev NV, Prokoshin AM, Yakovlev VA, Sidorov NM, Holupenko EI, Kudinov AS (2021) Neutron-Physical Characteristics of Loading the Core of the VVER-1000 Reactor with Uranium-Plutonium Fuel REMIX-E. Proc. of the X[th] Russian Youth Conference “Scientific research and technological development to ensure the development of nuclear technologies of a new generation”, Dimitrovgrad, RIAR, March 17–18, RIAR Publ., 33–36. [in Russian]
- Kovalev NV, Zilberman BYa, Goletsky ND, Sinyukhin AB (2020) A new approach to the reuse of spent nuclear fuel from thermal reactors within the framework of the REMIX concept. Izvestiya vuzov. Yadernaya Energetika 1: 67–77. https://doi.org/10.26583/npe.2020.1.07 [in Russian]
- Kurashov SS (2015) Numerical Simulation of Heat Transfer in Fuel Assemblies of the BN-1200 Reactor. Slide 4, Diploma Presentation, IATE MEPhI. [Available at:] https://theslide.ru/uncategorized/chislennoe-modelirovanie-teploobmena-v-tvs-reaktora [accessed Oct. 17, 2022] [in Russian]
- Kuzmin AM, Shmelev AH, Apse BA (2013) Simulation of Physical Processes in Power Nuclear Reactors on Fast Neutrons. MEI Publ., Moscow, 128 pp. [ISBN 978-5-383-00733-4] [in Russian]
- Mosunova NA (2018) Development of Scientific and Methodological Foundations and Development of an Integrated Software Package for Modeling Fast Reactor Installations with Liquid Metal Coolants. Dr. Sci. Engineering Diss., Moscow, IBRAE RAN Publ., 333 pp. [Available at:] http://www.ibrae.ac.ru/docs/108/dissertatsiyaimosunovoy_n.a.pdf [accessed Oct. 17, 2022] [in Russian]
- Nuclear Physics and Reactor Theory (1993) Nuclear Physics and Reactor Theory. U.S. Department of Energy Publ., Washington, 142 pp.
- Reactor BN-1200 (2022) Reactor BN-1200. [Available at:] https://ippe.ru/nuclear-power/fast-neutron-reactors/122-bn1200-reactor [accessed Oct. 17, 2022] [in Russian]
- Vasiliev BA (2010) Evaluation of the effectiveness of design solutions for fast sodium reactors and their development in new projects. Proc. of the VII-[th] International Scientific and Technical Conference “Safety, Efficiency and Economics of Nuclear Energy”, Moscow, May 26–27, 2010. Moscow, Concern Rosenergoatom Publ.: 25-28. [Available at:] http://www.reamntk.ru/mediafiles/u/files/Archive/SbornikTrudov2010.pdf [accessed Oct. 17, 2022] [in Russian]
- Vasiliev BA (2019) Goals and Objectives of the Development of BN reactor cores. All-Russian Scientific and Technical Conference “Neutron-Physical Problems of Nuclear Energy”, Obninsk, Nov. 27–29, 2019. [Available at:] https://www.ippe.ru/images/science_info/conference/neutron2019/presentation/plenary-session/Vasiliev-development-active-zones-fast-reactors.pdf [accessed Oct. 17, 2022] [in Russian]
- Vasiliev BA, Farakshin MR, Belov SB, Kiselev AV (2018) Analysis of the spatial perturbation of the neutron field of the active zone of the BN reactor during normal operation. VANT. Ser. Yaderno-Reaktornyye Konstanty 2: 62–70. [Available at:] https://elibrary.ru/item.asp?id=35123517 [accessed Oct. 17, 2022] [in Russian]