COMPUTATIONAL STUDY OF RADIATION CHARACTERISTICS INHERENT IN THE REACTOR GRAPHITE FROM RBMK-1000 UNITS

Selkin S. S., Sharov D. A., Plekhanov R. V., Zinakov D. L.

JSC All-Russian Research Institute for Nuclear Power Plants Operation, Moscow, Russia

Article received on September 28, 2024

The paper focuses on a computational study seeking to estimate the radiation characteristics of reactor graphite from RBMK power units at their decommissioning stage based on the case study of Leningrad NPP and its unit № 2. The calculations performed in the MCU-RBMK software via the Monte Carlo method were verified based on a data array with experimental specific activities of radionuclides found in the reactor graphite. The paper presents the estimated distribution of radioactive waste volumes represented by reactor graphite according to relevant waste categories with due account of amendments introduced into the radioactive waste classification system since January 1, 2024.

Keywords: *reactor plant, RBMK-1000, graphite stack, radionuclides, activation, specific activity, Monte Carlo method, decommissioning, radioactive waste.*

Introduction

Currently, 7 RBMK reactor units are operated at three NPPs in the Russian Federation: Kursk, Leningrad and Smolensk NPP. New power units with this reactor type neither are planned for construction nor were included in the concept of further nuclear power development [1], and some of them (the first and the second power units of the Leningrad and Kursk NPPs) have already been shut down for decommissioning.

In RBMK reactor units, graphite is used as a moderator and neutron reflector and is exposed to intense neutron fields during reactor operation, which drives radionuclide formation due to the radiation capture reaction. Irradiated reactor graphite is specifically characterized by its activity, which is mainly associated with the long-lived carbon ^{14}C isotope with a half-life of $T_{1/2} = 5{,}703 \cdot 10^3$ years. Due to large RW volumes (over 1,700 tons per power unit) generated from RBMK decommissioning, the management of RW and irradiated graphite, in particular, may contribute considerably to the total decommissioning cost [2]. As noted in [3], in terms of specific activity, quite considerable portion of activated reactor graphite corresponds to Class 2 RW requiring disposal in deep geological repositories (DGR) [4]. Owning to new amendments introduced to the RW classification system [5], [6] on January 1, 2024 that reduce conservatism in waste assignment to particular RW classes based on the content of long-lived radionuclides, it seems reasonable to evaluate the distribution of reactor graphite in accordance with the new classification system and taking into account the influencing factors.

This article summarizes the calculations focused on radionuclide activities in the reactor graphite of Leningrad NPP Unit 2, which was shut down to perform necessary pre-decommissioning operations. The calculations were performed based on a full-scale RBMK-1000 reactor model implemented in the MCU-RBMK software [7], [8]. The paper also evaluates the distribution of graphite RW by RW classes established depending on the waste disposal routes by the new classification system. The calculation results were compared with the currently available experimental data. The article also summarizes another study performed to determine the radiation characteristics of metal RBMK-1000 reactor structures and to attribute the RW to certain classes according to the new RW classification system [10].

Calculation model developed for the RBMK-1000 reactor unit

A model of a RBMK-1000 reactor unit was developed to evaluate the radiation characteristics of activated reactor graphite. MCU-RBMK software was used to perform neutron transport calculations, as well as to calculate relevant flux densities and the specific activities of activated radionuclides by the unit elements [7], [8]. This software package consists of several modules and is absolutely identical to the MCU-6 code, which was verified in benchmark experiments when the functionals of a wide class of neutron multiplying systems, including the burnup function, were calculated [11].

To solve a system of nuclide kinetics equations, the MCU-RBMK leverages the BURNUP module [12], [13]. The calculations implied an approximation, in which the neutron flux densities remained constant at a time step.

Based on MCU-RBMK, one can build detailed models of changes associated with particle energy fluctuations during collisions (based on a continuous dependence between the cross-sections and the energy), spectra of prompt and delayed neutrons, the changes in neutron energy during moderation taking into account the resonant nature of absorption.

When calculating the changes in the isotopic composition, the entire period of material irradiation is divided into successive time intervals, during which the power of the studied system is assumed to be constant. The calculation system is divided into zones, within which the reaction rates required to calculate the changes in the isotopic composition of the fuel at a given time interval are recorded. In each zone, the average isotopic composition at the end of the time interval is calculated. Thus, the problem is split into two subproblems:

- the zone-averaged nuclide reaction rates at the beginning of the time interval are calculated via the Monte Carlo method;
- changes in the nuclide composition of the zone are calculated at recorded reaction rates on different nuclides.

The MDB650 constant library provided constant support to the MCU-RBMK software. The library provides for a set of sections that can be used in calculations involving different particles and different submodules of the composite physical module.

The MDB650 library consists of the following sections:

ACE — a library providing data on the cross-sections of neutron interactions with nuclei for different nuclides in the epithermal energy region as a pointwise representation uploaded from ENDF/B-VI files and other sources;

LIPAR — resonance parameters of nuclides in the resolved resonance region;

KORT — a library of featured neutron-physical constants in the low-energy region (pointwise representation, upper limit — 5 eV);

VESTAM — a library used to model neutron collisions with moderator nuclei in the thermalization region; presented in the form of probability tables evaluated based on the scattering laws $S(\alpha,\beta)$;

BOFS6 — a library of generalized phonon spectra of moderators;

DOSIM — a library of activation cross-sections presented in a pointwise manner;

BURN6 — contains information required to solve the nuclide burnup problems: half-lives of nuclei, yields of fission fragments, chains of radioactive transformations, etc.

Full-scale calculation models of the RBMK-1000 reactor unit (Fig. 1) were built in MCU-RBMK taking into account a transition to more enriched fuel and full compliance of the operating mode with the thermal power levels scheduled for the power unit No. 2 of the Leningrad NPP.

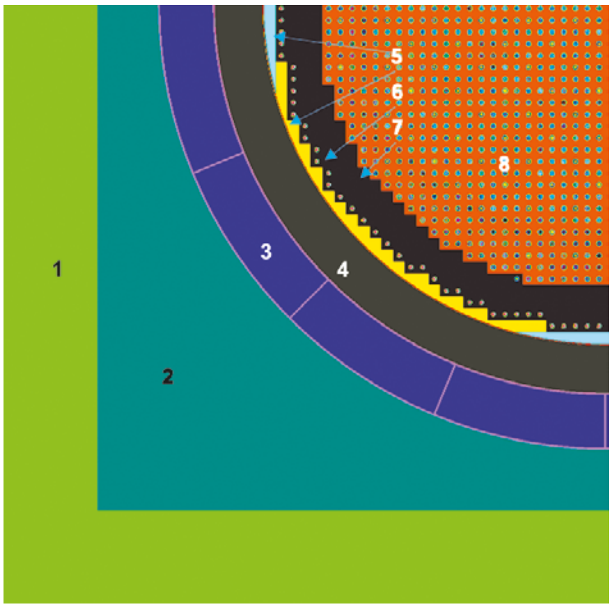

Fig. 1. Cross-section fragment of the reactor core (RC) and the simulated structure (SS): 1 – concrete shaft, 2 – sand, 3 – water biological shield tank, 4 – gas cavity, 5 – gas cavity inside the reactor jacket (RJ), 6 – cooled reflector channels, 7 – reflector columns, 8 – RC channels

Initial chemical composition of graphite and its characteristics

Chemical composition of system elements exposed to the neutron fluxes is seen as a main parameter of the calculation model [14]—[18]. To calculated it, relevant scientific literature sources were analyzed [19]—[29]. The composition of reactor graphite revealed based on this analysis was refined. For this purpose, the inverse problem was solved based on the best description of the experimental parameters.

^{14}C is the radionuclide providing the key contribution to the specific activity of graphite [25]. This radionuclide can be generated both in neutron radiation capture reactions on stable carbon $^{13}C(n, \gamma)^{14}C$ and in reactions on nitrogen, which is present in graphite as an impurity. In this case, due to the large neutron capture cross-section, the reaction on nitrogen $^{14}N(n, p)^{14}C$ may turn to be the dominant mechanism responsible for ^{14}C occurrence in graphite. In addition to the basic inventory of nitrogen impurities ($4{\cdot}10^{-4}$ wt. % [16], [20]) found in the graphite stack, certain effect may be produced by the cooling mixture of helium-nitrogen gases filling the sealed RU area that may get absorbed into graphite pores at an excess pressure of 1.5 kPa at the inlet of the reactor space. In addition, it is possible to use nitrogen purging alone during reactor operation at a power capacity of up to 800 MW [37]. The flow rate in this case should be 300—400 m^3/h. Nitrogen purging at a flow rate of up to 1,000 m^3/h and a pressure of up to 6.0 kPa is allowed during stack drying. Estimates show [21] that in the case of GR-280 graphite with a porosity of 23 % and a pressure of 1.5 kPa, the additional nitrogen component in the pores of the graphite stack is expected to be equal to $5.96{\cdot}10^{-3}$ wt. % and, given a pressure of 6.0 kPa, it may account for $2.38{\cdot}10^{-2}$ wt. %. Since this component may be of decisive importance as regards ^{14}C generation, the most conservative indicator presented in the literature [19]—[29], i. e., $1{\cdot}10^{-2}$ wt. %, [24] was used in the calculations.

Table 1 presents the graphite composition considered in the calculation model.

Graphite density of 1.71 g/cm3 was adopted in the model, which is close to the average density recorded during the operation of power unit No. 2 [36] and is considered optimal based on previous neutron-physical calculations performed to verify the MCU software [11].

Table 1. ***Composition of GR-280 graphite assumed in the calculation model***

Element	Li	B	N	O	Na	Mg
Chemical compos., % wt.	$4{\cdot}10^{-6}$	$3{\cdot}10^{-4}$	10^{-2}	$1,8{\cdot}10^{-3}$	$1,7{\cdot}10^{-3}$	$1,1{\cdot}10^{-3}$
Element	Al	Si	Cl	K	Ca	Sc
Chemical compos., % wt.	$3{\cdot}10^{-5}$	$3,3{\cdot}10^{-3}$	$3,2{\cdot}10^{-3}$	$3{\cdot}10^{-3}$	$3{\cdot}10^{-2}$	$5{\cdot}10^{-6}$
Element	Ti	V	Cr	Mn	Fe	Co
Chemical compos., % wt.	$5{\cdot}10^{-4}$	$1,3{\cdot}10^{-6}$	$4,1{\cdot}10^{-6}$	$6{\cdot}10^{-6}$	10^{-3}	$9{\cdot}10^{-7}$
Element	Ni	Cu	Zn	As	Zr	Nb
Chemical compos., % wt.	$3{\cdot}10^{-5}$	$3{\cdot}10^{-5}$	$2,6{\cdot}10^{-4}$	$1,05{\cdot}10^{-5}$	$5,7{\cdot}10^{-5}$	$6{\cdot}10^{-7}$
Element	Mo	Ag	Cd	Sb	Cs	Eu
Chemical compos., % wt.	$6{\cdot}10^{-6}$	$3,5{\cdot}10^{-6}$	$1,5{\cdot}10^{-4}$	$3{\cdot}10^{-7}$	$2{\cdot}10^{-8}$	$2{\cdot}10^{-7}$
Element	Hf	Ta	W	Th	U	C
Chemical compos., % wt.	$5,8{\cdot}10^{-7}$	$1,9{\cdot}10^{-7}$	$4{\cdot}10^{-6}$	$2,5{\cdot}10^{-7}$	$7{\cdot}10^{-6}$	$9,99{\cdot}10$

Calculated induced activity of the graphite stack

Calculations performed based on the operational data available on the second power unit of the Leningrad NPP after one year of cooling showed that the total specific activity of beta-emitting radionuclides in the graphite blocks was ranging from $1.19{\cdot}10^4$ (in the side reflector) to $2.79{\cdot}10^6$ Bq/g (in the central section of the reactor core), which is explained by the spatial anisotropy of the neutron flux density (Fig. 2 shows its distribution in the graphite blocks by height (a) and radius (b) of the reactor core). During the cooling period that may last for up to 1,000 years, graphite activity in the blocks is expected to correspond to the total specific activity of beta-emitting radionuclides and, within a timeframe of thousands of years, would be still referred to the category of intermediate-level waste (ILW) according to the criteria set forth in the OSPORB-99/2010 [30].

Fig. 3 shows the dependence between the average specific activity of radionuclides in graphite blocks and the cooling time.

The activity of graphite is mainly contributed by the radionuclide ^{14}C with an average specific activity of $8.01{\cdot}10^5$ Bq/g assuming a cooling time of 1,000 years. It was found that within 10—20 years, a large portion of it would account for the isotope ^3H (up to 25 %) with a specific activity of $2.52{\cdot}10^5$ Bq/g formed due to (n, a) reaction on ^6Li impurities. However, as noted in [31], the values calculated for the graphite stack may be somewhat overestimated due to high tritium mobility.

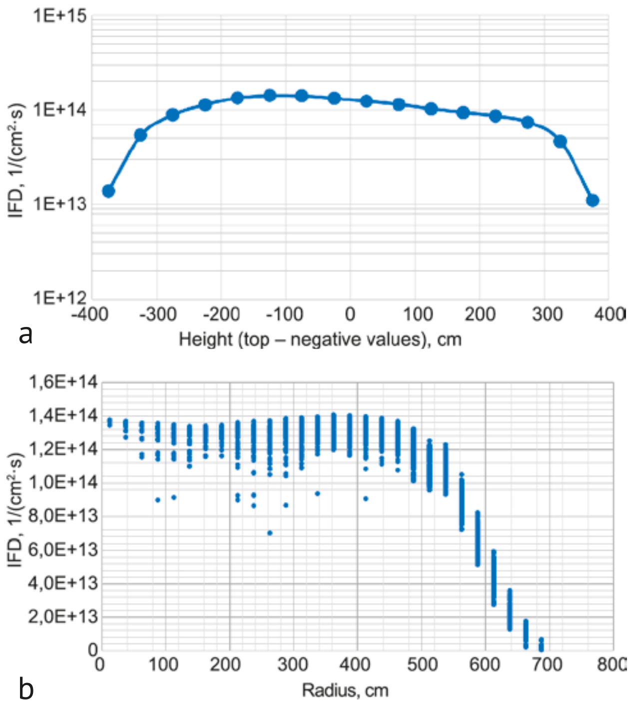

Fig. 2. Integral neutron flux density (IFD) in graphite blocks and its distribution by height (a) and radius (b) of the reactor core

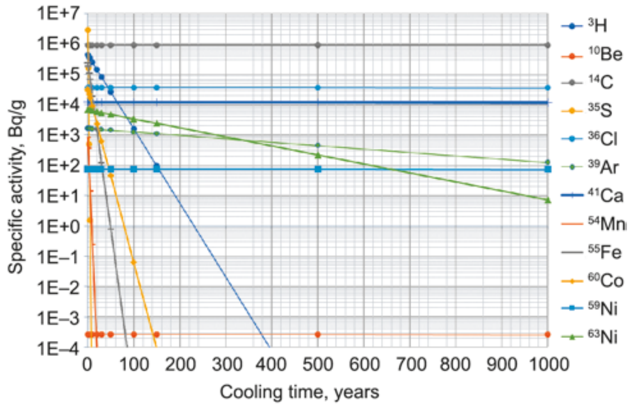

Fig. 3. Dependence between the average specific activities of radionuclides in graphite blocks and the cooling time

In keeping with the former classification system that was effective until January 1, 2024, in terms of specific activity, graphite inventory mostly (99 %) corresponded to RW Class 2. Calculations performed under the new RW classification system showed that the graphite stack of the RBMK power unit can be divided into RW classes as follows: 36 % belongs to RW Class 2; 63 % — to RW Class 3; 1 % to — to RW Class 4. Fig. 4. represents the above distribution graphically (vertical section through the central part of the graphite stack).

RW Class 2 shall be disposed of in a DGR, whereas RW Class 3 is subject to disposal in near-surface disposal facilities [4], [32]. As of 2024, the disposal tariff for RW Class 2 accounted for 858,198.59 rubles, which is 4.6 times higher than the one established

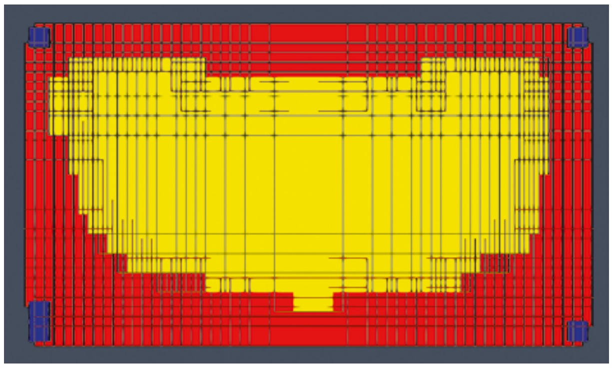

Fig. 4. Graphic representation of RW distribution by classes (yellow color — Class 2, red — Class 3, blue — Class 4)

for RW Class 3 [33]. Thus, the new classification system [5] may considerably reduce the overall disposal costs when it comes to spent reactor graphite. At the same time, the challenge associated with the development of appropriate graphite RW processing and conditioning methods still remains to be addressed.

Verification

To verify the calculation results, the following experimental data on the specific activity of graphite samples were used:

- 31 samples for ^{14}C and ^{36}Cl [34];
- 15 samples for ^{54}Mn, ^{60}Co, ^{95}Nb, ^{134}Cs and ^{137}Cs [35];
- 15 samples for ^{54}Mn, ^{59}Fe, ^{60}Co, ^{95}Zr, ^{95}Nb, ^{134}Cs, ^{124}Sb, ^{137}Cs [9].

The calculation results were compared based on the available data on the inventory of the above-mentioned radionuclides in graphite samples. In general, their convergence turned out to be satisfactory. The discrepancy in the individual samples could be explained by uneven distribution of impurity elements according to their content both in different graphite batches and by the volume of individual stack elements, which was also noted in [18].

^{14}C is the radionuclide responsible for the graphite stack radioactivity (from 51 % in the first year of cooling and up to 95 % after 1,000 years). The contribution of other isotopes to the specific activity of graphite is much smaller, and they usually originate from the activation of impurity elements, the content of which varies widely across the stack. In this regard, and also given that the class of graphite RW mainly depends on the ^{14}C inventory, data on radiocarbon content may be reasonably considered in the first place when one needs to verify the graphite stack calculations.

In the verification process, it was found that the relative deviation of the measured ^{14}C activities from the calculated ones averaged some 24% with a standard deviation of 36%.

The calculated activity of ^{14}C largely (70—90%) [18] depends on the amount of activated nitrogen included in the calculation model, which is found as a graphite impurity that tend to get accumulated in the pores and on the surface of blocks and graphite rings during reactor operation. The systematic exceedance of the calculation results over the experimental data by 24% can be primarily attributed to somewhat overestimated initial concentration of nitrogen activated in the graphite pores, as well as its variation both along the graphite block volume and between the individual blocks [25].

To determine the content of activated nitrogen in graphite pores one should solve a complex multifactorial problem with its result being contingent on:

- graphite purging background;
- graphite operating temperature conditions;
- the initial graphite structure and its deformation during reactor operation.

Given considerable uncertainty in the amount of nitrogen found in graphite in its initial state and its changes during reactor operation, a discrepancy between the calculated and measured values of 24% with a standard deviation of 36% appears to be quite satisfactory and confirms the adequacy of the applied algorithms and the calculation model.

Moreover, to reduce the discrepancy between the calculation and measurement results, it is advisable to increase the representativeness of the experimental data sample. Currently, Rosenergoatom Concern is running R&D to evaluate the residual radioactive contamination of irradiated graphite from RBMK reactor units. These studies are expected to provide more detailed experimental data on the specific activities of radionuclides in graphite, based on which the verified calculated values can be further refined.

Conclusion

Calculations were performed based on a full-scale reactor model implemented in the MCU-RBMK Monte Carlo software package to determine the induced activity of a graphite stack. The calculated values were found to be in good agreement with the experimental data available on the ^{14}C radionuclide governing its radioactivity within a timeframe of thousands of years.

It was found that under the newly introduced RW classification system, a large graphite inventory (up to 64%) can be categorized as RW Class 3 or even Class 4, which greatly facilitates the task of its disposal and paves the way for some practical steps providing for graphite RW transfer for disposal to the National Operator after the corresponding conditioning methods are identified.

At the same time, the study revealed great degree of uncertainty in the calculated data resulting from the inaccuracy of information on activated impurities found in graphite.

To increase the reliability of the calculated radiation characteristics of reactor graphite in RBMK units undergoing decommissioning, some further experimental studies can be recommended, including:

- a study focused on the chemical composition of reactor graphite seen to determine the boundaries for the impurity element concentrations;
- a study focused on the specific activity of the key radionuclides and their distribution by the graphite stack volume for reactor units with different operating histories to compile a verification matrix;
- a study focused on the effect that nitrogen purging has on the graphite stack in terms of its induced activity.

References

1. *Rasporyazhenie Pravitel'stva Rossijskoj Federacii ot 9 iyunya 2017 g. No. 1209-r “Ob utverzhdenii General'noj skhemy razmeshcheniya ob"ektov ehlektroehnergetiki do 2035 g.”* [Order of the Government of the Russian Federation No. 1209-r of June 9, 2017 On the Approved General Siting Layout for Electric Power Facilities Valid Until 2035].

2. Volkov V. G., Safronova N. N., Morozov F. T., Komarov E. A., Zimin V. K., Bylkin B. K., Zverkov Yu. A., Pavliuk A. O., Kotlyarevsky S. G., Kan R. I. O probleme zaklyuchitel'nogo etapa obrashcheniya s obluchennym grafitom blokov AES s vodografitovymi reaktorami [On the Challenge Associated with the Final Stage of Irradiated Graphite Management from Water-Graphite NPP Reactor Units]. *Radioaktivnye otkhody — Radioactive Waste,* 2021, no. 2 (15), pp. 10—20. DOI: 10.25283/2587-9707-2021-2-10-20.

3. Dorofeev A. N., Komarov E. A., Zakharova E. V., Volkova A. G., Linge I. I., Utkin S. S., Ivanov A. Yu., Pavliuk A. O., Kotlyarevskij S. G. K voprosu zakhoroneniya reaktornogo grafita [On Reactor Graphite Disposal]. *Radioaktivnye otkhody — Radioactive Waste,* 2019, no. 2 (7), pp. 18—30. DOI: 10.25283/2587-9707-2019-2-18-30.

4. *O kriteriyakh otneseniya tverdykh, zhidkikh i gazoobraznykh otkhodov k radioaktivnym otkhodam, kriteriyakh otneseniya radioaktivnykh otkhodov k osobym radioaktivnym otkhodam i k udalyayemym radioaktivnym otkhodam i kriteriyakh klassifikatsii udalyayemykh radioaktivnykh otkhodov* [On criteria used to

categorize solid, liquid and gaseous waste as radioactive waste, the criteria for radioactive waste categorization as non-removable radioactive waste or removable radioactive waste, and classification criteria for removable radioactive waste] : Government Decree of the Russian Federation of October 19, 2012 No. 1069.

5. *O vnesenii izmeneniy v postanovleniye Pravitel'stva Rossiyskoy Federatsii ot 19 oktyabrya 2012 g.* [On amendments to the Government Decree of the Russian Federation of October 19, 2012] No. 1069 : Government Decree of the Russian Federation of October 29, 2022 No. 1929.

6. Ivanov E. A., Korotkov A. S., Sharov D. A., Kuryndin A. V., Sharafutdinov R. B. Aktual'nye voprosy vnedreniya novoj sistemy klassifikacii udalyaemykh radioaktivnykh otkhodov [Actual problems of implementation of a new classification system for radioactive waste to be removed]. *Yadernaya i radiacionnaya bezopasnost' — Nuclear and Radiation Safety,* 2023, no. 4 (110), pp. 47—56. DOI: 10.26277/SECNRS.2023.110.4.004.

7. Druzhinin V. E., Bychkov A. S., Plekhanov R. V., Ivanov I. E. *Verifikatsiya PS MCU-RBMK so vtorym kanalom podgotovki iskhodnykh dannykh KDMK* [Verification of the MCU-RBMK software with the second channel for KDMK initial data preparation]. Verification report of JSC VNIIAES, inv. No. Ot-2056-011/2016. Moscow, 2016.

8. *Attestatsionnyy pasport programmnogo sredstva MCU-RBMK s bankom dannykh MDB650 (s kanalom podgotovki iskhodnykh dannykh KDMK)* [Certification passport for the MCU-RBMK software with the MDB650 data bank (with the channel for KDMK initial data preparation)], reg. No. 430 of February 27, 2018.

9. Pavliuk A. O., Kotlyarevsky S. G., Kan R. I., Volkova A. G., Zakcharova E. V., Komarov E. A. Podhody k kharakterizacii po gamma-izluchayushchim radionuklidam grafitovykh blokov i ikh kontejnerizacii pri demontazhe kladok UGR [Approaches to graphite block characterization by gamma radionuclides and their packaging during UGR stack dismantlement]. *Radioaktivnye otkhody — Radioactive Waste,* 2021, no. 3 (16), pp. 30—43. DOI: 10.25283/2587-9707-2021-3-30-43.

10. Sel'kin S. S., Sharov D. A., Plekhanov R. V., Zinakov D. L. Opredeleniye radiatsionnykh kharakteristik metallicheskikh konstruktsiy RU RBMK-1000, ostanovlennykh dlya podgotovki k vyvodu iz ekspluatatsii [Radiation characterization of metal structures in RBMK-1000 reactor plants shut down for pre-decommissioning activities]. *Vestnik Moskovskogo energeticheskogo instituta — Bulletin of the Moscow Power Engineering Institute,* no. 5 (2024), DOI: 10.24160/1993-6982-2024-5-149-158.

11. *Verifikatsiya programmy MCU-6 na osnove mezhdunarodnogo banka dannykh kriticheskikh eksperimentov i kriticheskikh sostoyaniy reaktora VVER-1000* [Verification of the MCU-6 software based on an international data bank for critical experiments at WWER-1000 reactor unit and its critical states]. Report by SRC KI. No. 241-07/22-14 of October 22, 2014.

12. *Opisaniye primeneniya i instruktsiya pol'zovatelya komp'yuternogo koda MCU-6* [Description of the application and user manual for the MCU-6 computer code]. NRC Kurchatov Institute. Amended as of October 22, 14. Moscow, 2020.

13. Yudkevich M. S. Paket prikladnykh programm BURNUP dlya raschota izotopnogo sostava materialov rabotayushchego reaktora [Package of Applied Programs for Calculating the Isotopic Composition of the Materials of Operating Reactor]. *Voprosy atomnoy nauki i tekhniki. Seriya: Fizika yadernykh reaktorov — Physics of Atomic Nuclei,* 2011, no. 4, pp. 24—28.

14. Remeikis V., Plukis A., Plukienė R., Garbaras A., Barisevičiūtė R., Gudelis A., Gvozdaitė R., Duškesas G., Juodis L. Method based on isotope ratio mass spectrometry for evaluation of carbon activation in the reactor graphite. *Nucl. Eng. Des.,* 2010, vol. 240, iss. 10, pp. 2697—2703. DOI: 10.1016/j.nucengdes.2010.06.020.

15. Plukiene R., Plukis A., Puzas A., Remeikis V., Duškesas G., Germanas D. Modelling of impurity activation in the RBMK reactor graphite using MCNPX. *Journal of Nuclear Science and Technology,* 2011, vol. 2, pp. 421—426. DOI: 10.15669/pnst.2.421.

16. Bylkin B. K., Davydova G. B., Krayushkin A. V., Shaposhnikov V. A. Raschetnyye otsenki radiatsionnykh kharakteristik obluchennogo grafita posle okonchatel'nogo ostanova AES s RBMK [Calculated radiation characteristics of irradiated graphite after the final shutdown of a NPP with a RBMK power unit]. *Atomnaya energiya — Atomic Energy,* 2004, vol. 96, no. 6, pp. 451—456.

17. Narkunas E., Poskas P., Šmaižys A., Norris S. Estimation of the inventory of 14 C and other key radionuclides in irradiated RBMK-1500 graphite based on limited measurements and full 3D core modeling. *Radiocarbon,* 2018, vol. 60, no. 6, pp. 1849—1859. DOI: 10.1017/RDC.2018.122.

18. Kan R. I., Kotlyarevskaya A. S. *Osobennosti prostranstvennogo raspredeleniya klyuchevykh radionuklidov aktivatsionnogo proiskhozhdeniya v obluchennom grafite uran-grafitovykh reaktorov* [Features specific for the key radionuclides of activation origin and their spatial distribution in the irradiated graphite of uranium-graphite reactors]. Scientific dire tor A. O. Pavliuk / *Izotopy: tekhnologii, materialy i primeneniye : sbornik tezisov dokladov VII Mezhdunarodnoy nauchnoy konferentsii molodykh uchenykh, aspirantov i studentov* [Isotopes: technologies, materials

and applications: book of abstracts from the VII International scientific conference of young scientists, graduate students and students], Tomsk, October 25—28, 2021. Tomsk, TPU Publ., 2021. P. 149.

19. *Baza dannykh po reaktornomu grafitu AES AO "Rosenergoatom"* [Database on reactor graphite of NPP operated by Rosenergoatom. TF, 2019.

20. *Obosnovaniye bezopasnosti pri provedenii lokal'nogo remonta po VRKH reaktornoy ustanovki energobloka No. 1 Leningradskoy AES v 2018 godu* [Safety assessment for local repairs proposed to restore the resource characteristics of the reactor power unit No. 1 of the Leningrad NPP in 2018]. Report 323.122. From JSC NIKIET, NRC Kurchatov Institute. Moscow, 2018.

21. Narkunas E., Smaizys A., Poskas P. Analysis of Nitrogen Impurity Impact on 14 C Generation in Rbmk-1500 Reactor Graphite / EPRI International Decommissioning and Radioactive Waste Management Workshop, 6—7 October 2009, Hamburg, Germany.

22. Virgil'ev Yu. S. Primesi v reaktornom grafite i yego rabotosposobnost' [Impurities in the Reactor Graphite and its Serviceability]. *Atomnaya energiya — Atomic energy,* 1998, vol. 84, iss. 1, pp. 7—15 (regarding data on unit No. 1 of the Leningrad NPP).

23. Virgil'ev Yu. S. Primesi v reaktornom grafite i yego rabotosposobnost' [Impurities in the Reactor Graphite and its Serviceability]. *Atomnaya energiya — Atomic energy,* 1998, vol. 84, iss. 1, pp. 7—15 (regarding data on unit No. 2 of the Leningrad NPP).

24. Bulanenko V. I., Frolov V. V., Nikolaev A. G. Radiatsionnyye kharakteristiki grafita snyatykh s ekspluatatsii uran-grafitovykh reaktorov [Radiation characteristics of graphite from decommissioned uranium-graphite reactors]. *Atomnaya energiya — Atomic energy,* 1996, vol. 81, no. 4, pp. 304—306.

25. Bushuev A. V., Kozhin A. F., Petrova E. V., Zubarev V. N., Aleeva T. B., Girke N. A. *Radioaktivnyy reaktornyy grafit* [Radioactive reactor graphite]. Moscow, National Research Nuclear University MEPhI Publ., 2015. 148 p.

26. Plukiene R. et al. Modelling of Impurity Activation in the RBMK Reactor Graphite Using MCNPX. *Progress in Nuclear Science and Technology,* 2011, vol. 2, pp. 421—426. DOI: 10.15669/pnst.2.421.

27. Ancius D. et al. Evaluation of the activity of irradiated graphite in the Ignalina Nuclear Power Plant RBMK-1500 reactor. *Nukleonika,* 2005, vol. 50, no. 3, pp. 113—120.

28. Plukiene R. et al. Investigation of impurities of RBMK graphite by different methods. *Radiocarbon,* 2018, vol. 60, no. 6, pp. 1861—1870. DOI: 10.1017/RDC.2018.93.

29. Narkunas E. et al. Estimation of the inventory of 14 C and other key radionuclides in irradiated RBMK-1500 graphite based on limited measurements and full 3D core modeling. *Radiocarbon,* 2018, vol. 60, no. 6, pp. 1849—1859. DOI: 10.1017/RDC.2018.122.

30. *SP 2.6.1.2612-10. Sanitarnyye pravila i normativy. Osnovnyye sanitarnyye pravila obespecheniya radiatsionnoy bezopasnosti* [SP 2.6.1.2612-10. Sanitary rules and regulations Basic sanitary rules for radiation safety] (OSPORB-99/2010).

31. *Obosnovaniye bezopasnosti ekspluatatsii energobloka No. 2 Leningradskoy AES na moshchnosti posle vypolneniya lokal'nogo remonta po VRKH reaktornoy ustanovki v 2016 godu* [Report on the safety assessment supporting power operation of power unit No. 2 at Leningrad NPP upon completing its local repairs to restore the recourse characteristics of the reactor installation in 2016]. Report 321.073. Approved by the First Deputy Director — General Designer of JSC NIKIET. Moscow, 2016.

32. *Federal'nyj zakon ot 11 iyulya 2011 goda No. 190-FZ "Ob obrashchenii s radioaktivnymi othodami i o vnesenii izmenenij v otdel'nye zakonodatel'nye akty Rossijskoj Federacii"* [Federal Law of July 11, 2011 No. 190-FZ "On the Management of Radioactive Waste and on Amendments to Certain Legislative Acts of the Russian Federation"].

33. *Tarify na zakhoroneniye radioaktivnykh otkhodov na period s 2023 po 2027 gody* [Radioactive waste disposal tariffs valid from 2023 to 2027]. NO RAO Rosatom — URL: https://www.norao.ru/about/tarify/ (accessed on: 15.07.2024).

34. Pavliuk A. O., Kotlyarevsky S. G., Kan R. I., Volkova A. G., Zakcharova E. V., Ilyukhina M. A., Gorshkov V. B., Dorofeev A. N., Zinnurov B. S., Komarov E. A. Podhody k kharakterizacii grafitovykh blokov UGR po beta-izluchayushchim radionuklidam ^{14}C i ^{36}Cl. Aprobaciya na reaktorakh tipa RBMK-1000 [Approaches to the Characterization of Graphite UGR Blocks Based on Beta-emitting ^{14}C and ^{36}Cl Radionuclides. Testing at RBMK-1000-type Reactors]. *Radioaktivnye otkhody — Radioactive Waste,* 2021, no. 2 (15), pp. 21—32. DOI: 10.25283/2587-9707-2021-2-21-32.

35. *Poslereaktornyye issledovaniya v goryachikh kamerakh obraztsov (kernov) grafita, vzyatykh iz kladki energobloka No. 2 Leningradskoy AES v 2018 godu* [Post-reactor hot cell studies of graphite samples (cores) taken from the stack of power unit No. 2 at Leningrad NPP in 2018]. Report, inventory No. 110.9-15vn-19. 78 p.

36. NGR-01-90. *Normy rascheta na prochnost' tipovykh uzlov i detaley iz grafita uran-grafitovykh kanal'nykh reaktorov* [Strength calculation standards for typical graphite-based units and components from uranium-graphite pressure-tube reactors].

37. Dollezhal N. A., Emelyanov I. Ya. *Kanal'nyy yadernyy energeticheskiy reaktor* [Pressure-tube nuclear power reactor]. Moscow, Atomizdat Publ., 1980. 208 p.

Information about the authors

Selkin Sergey Sergeevich, leading specialist, JSC "All-Russian Research Institute for Nuclear Power Plants Operation" (25, building 1, Ferganskaya st., Moscow, 109507, Russia), e-mail: SSSelkin@vniiaes.ru.

Sharov Dmitriy Alexandrovich, PhD in Physical-Mathematical Sciences, Deputy head of JSC VNIIAES (NTP), head of the department of radiation safety, radioactive waste and spent nuclear fuel, decommissioning, JSC "All-Russian Research Institute for Nuclear Power Plants Operation" (25, building 1, Ferganskaya st., Moscow, 109507, Russia), e-mail: DASharov@vniiaes.ru.

Plekhanov Ruslan Vladimirovich, department head, JSC "All-Russian Research Institute for Nuclear Power Plants Operation" (25, building 1, Ferganskaya st., Moscow, 109507, Russia), e-mail: RVPlehanov@vniiaes.ru.

Zinakov Dmitry Leonidovich, leading specialist, JSC "All-Russian Research Institute for Nuclear Power Plants Operation" (25, building 1, Ferganskaya st., Moscow, 109507, Russia), e-mail: DLZinakov@vniiaes.ru.

Bibliographic description

Selkin S. S., Sharov D. A., Plekhanov R. V., Zinakov D. L. Computational study of radiation characteristics inherent in the reactor graphite from RBMK-1000 units. *Radioactive Waste,* 2024, no. 4 (29), pp. 31—41. DOI: 10.25283/2587-9707-2024-4-31-41. (In Russian).