УДК 621.039.7, 661.666 doi.org/10.31717/2311-8253.26.1.6

O. Yu. Dorman[1], K. V. Simeiko[1, 2]

[1] *Institute for Safety Problems of Nuclear Power Plants, NAS of Ukraine, 36a, Kirova St., Chornobyl, 07270, Ukraine*
[2] *Institute of Gas of the National Academy of Sciences of Ukraine, 39, Dehtiarivska St., Kyiv, 03113, Ukraine*

Identification of Ways to Improve the Methods for Crushing and Sorting Irradiated Graphite from Nuclear Facilities

Keywords:
nuclear energy,
decommissioning of nuclear power plants,
radioactive waste,
irradiated graphite,
artificial intelligence

The article is devoted to the problem of handling irradiated graphite (IG) from nuclear installations (NI). Reactor graphite (or nuclear-grade graphite) has been used as a neutron moderator or reflector in more than 100 nuclear reactors and is a structural and functional material in Generation IV nuclear power systems, in particular in high-temperature gas-cooled reactors (HTGR, HTR, VHTR) and molten salt reactors (MSR). Therefore, the problem of handling IG from nuclear power plants is a pressing scientific issue. For some possible options for the utilization of IG, in particular, incineration, burial, and treatment with ion exchange resins, the issue of crushing and sorting IG is relevant. Based on the analysis of the physical properties of graphite after long-term exposure to high temperatures and neutron irradiation, the authors propose ways to improve the methods of IG crushing and sorting using artificial intelligence (AI). The article describes a method for crushing IG using a ball mill with discharge through a grid and a developed algorithm for separating IG using AI, which includes processing and control cycles using neural networks. Future improvements in the use of a ball mill with discharge through a grid and the separation algorithm should be aimed at reducing energy consumption and adapting to remote control conditions.

Introduction

According to the General Safety Provisions for the Decommissioning of Nuclear Facilities (Order No. 440 of the State Nuclear Regulatory Inspectorate of Ukraine dated October 28, 2020 “On Approval of the General Safety Provisions for the Decommissioning of Nuclear Facilities”) [1], the term “decommissioning of a nuclear facility” is defined as the stage in the life cycle of a nuclear installation (NI) that begins after final shutdown of a NI and during which the site of the NI is completely or partially released from regulatory control. The relevance of improving methods for the management of radioactive waste (RW), including processing, conditioning, short- and long-term storage, as well as potential disposal methods, remains extremely high. Methods for short- and long-term storage also need improvement. The adopted strategy for RW management is aimed at containment and isolation from the environment and people for the period of its potential hazard. To this end, RW is collected and sorted according to its radiological characteristics [2].

Nuclear graphite is a high-purity polygranular graphite used as a neutron moderator or reflector in nuclear reactors and also as a structural material.

First- and second-generation graphite-moderated nuclear reactors (including military designs) were constructed in numerous countries, including the former USSR, the USA, the United Kingdom, Germany, France, Japan, Lithuania, China, etc. Reactor graphite has been used in more than 100 nuclear reactors as a neutron moderator or reflector and remains an important structural and functional material in Generation IV nuclear power systems, including high-temperature gas-cooled reactors (HTR, HTGR, VHTR) and molten salt reactors (MSR) [3]. At the Chornobyl Nuclear Power Plant alone, more than 5.4 thousand tons of irradiated graphite (IG), containing total activity of approximately 1.2×10^4 Ci and a thermal load of about 2×10^6 GJ will require dismantling in the near future, posing potential hazard to personnel and the environment [4]. When planning measures for the management of IG, it is necessary to consider the reactor type, the characteristics of the graphite, and specifics of its operation and storage [5].

The management of irradiated reactor graphite after the decommissioning of uranium-graphite reactors is a complex scientific problem and requires practical and technically feasible solutions.

State of the problem and analysis of literature data

The extensive use of graphite in nuclear reactors as a neutron moderator and reflector is due to its unique properties, including:

high thermal and corrosion resistance: allowing graphite to remain stable at very high temperatures;

high neutron-moderating efficiency and low neutron absorption: graphite effectively moderates fast neutrons, converting them into thermal neutrons necessary to sustain a chain reaction, while absorbing a minimal amount of them;

high mechanical strength and low thermal expansion coefficient: ensure the reliability and durability of the material;

high purity and low porosity: purity levels of up to 99.9% are achieved, which affects reactor performance [6, 7].

Since 1942, more than 100 designs of graphite-moderated reactors have been developed. Most uranium-graphite reactors have been decommissioned or are subject to decommissioning [8].

The International Atomic Energy Agency (IAEA) has initiated several consultations and technical meetings on the disposal of IG. The conclusion of the first IAEA technical meeting on the life cycle of graphite moderators at the University of Bath (UK) [9] highlighted the need to create an international database on the properties of nuclear graphite in order to preserve knowledge for the development of future graphite-moderated reactors and their subsequent decommissioning and disposal. The Electric Power Research Institute (EPRI, USA) has created a "graphite reactor decommissioning network" and published a series of review articles [10–16] on this topic. Other publications [16–23] cover options for graphite disposal, including considerations of the socio-economic aspects of this issue.

Given the numerous ongoing research programs, the IAEA proposed a network aimed at promoting the practical application of knowledge related to IG to facilitate current and future decommissioning/disposal programs. This led to the creation of the Global Project on Approaches to the Treatment of Irradiated Graphite (GRAPA) network [24].

The technologies for removing IG components from reactors (mainly the moderator and reflector) depend on the design of the NI. Dismantling such components may involve the extraction of individual components or the crushing of IG. For some possible options for IG management, including incineration, disposal, and treatment using ion-exchange resins, the issue of crushing and sorting IG is relevant.

Research objectives: based on the use of open neural network libraries, propose improvements to crushing methods and develop an algorithm for IG segregation.

Description of research methods: computer vision neural networks based on free open source libraries such as OpenCV, TensorFlow, and Keras were applied. Visualization of IG fragments was performed using free generative artificial intelligence (AI) Adobe Firefly.

Computer vision is a technology that enables computers and other devices interpret and analyze visual information from the environment. In industry, computer vision is used for process automation, quality control, security, and other operational tasks.

Key industrial applications of computer vision include:

quality control: computer vision systems can automatically detect defects with high inspection accuracy and speed;

object identification: using cameras and image processing algorithms to identify different components or products on conveyor lines;

process automation: computer vision can be integrated into robotic systems to perform tasks such as packaging, assembly, or object manipulation;

security: video surveillance systems with computer vision elements can be used to monitor safety in production, detect dangerous situations, or unauthorized access;

data analysis: images and videos can be stored and analyzed to get useful data on what's going on, which helps with decision-making;

issues to consider when implementing computer vision: in the real world, complex scenes with many objects are common, and lighting can significantly affect image quality.

The visualization of IG debris was performed using the free generative AI Adobe Firefly.

The effect of operation on the strength of reactor graphite

The strength of reactor graphite initially increases with low neutron fluence, but subsequently decreases. Closer to the surface of the block, the graphite swells, its porosity increases, and the concentration and energy of neutrons are significantly higher there. The strength of the IG decreases due to changes in the crystal lattice and high temperatures. The greatest changes occur in the surface layer. Uneven swelling creates internal stresses, which leads to changes in the shape of the blocks and the formation of longitudinal cracks [25].

Separation of the graphite block into parts with subsequent sorting

The choice of crushing method depends on the initial size of the graphite pieces, the requirements for the final fraction, and the presence of radioactive contamination (for reactor graphite). A typical ball mill (BM) design with grid discharge (Fig. 1) can be used for this purpose, which is a drum with balls that crush the material.

The ball mill with central discharge (Fig. 1) consists of a cylindrical drum (1) with end covers (2, 14)

The drum and covers are lined on the inside with steel plates (8, 10). The end covers have hollow trunnions (3, 13), with support the drum on the main bearings (6, 11). The rotation of the drum is driven byan electric motor through the ring gear (9), which is fixed on the drum. The drum or combined type feeder (5) is attached to the loading trunnion. The hollow trunnions are equipped with removable loading and discharge funnels (4, 12). Small mills have hatches (7, 15) for inserting lining into the drums. In large mills, this operation is performed through the discharge trunnion. The discharge trunnion has a slightly larger diameter than the loading trunnion, which causes the pulp mirror to tilt towards the discharge side of the mill. Steel or cast iron balls of various diameters (typically 40–150 mm) are loaded into the drum. The volume of the balls is approximately half the volume of the mill. When the drum rotates, the balls slide, roll or fall and crush the grains of the mineral. The ore is crushed mainly by the impact of the crushing bodies and partly by abrasion and crushing. The feed material is loaded into the mill through the feed trunnion, and the crushed product is discharged from the mill through the discharge trunnion [26, 27]. The initial data for calculating the experimental parameters of the BM are given in the table.

Load factor ψ represents the percentage of drum volume and is used in formula (2). For the initial stage of the studyψ was set to 3%. Using the data below, the number of balls was calculated for illustration purposes.

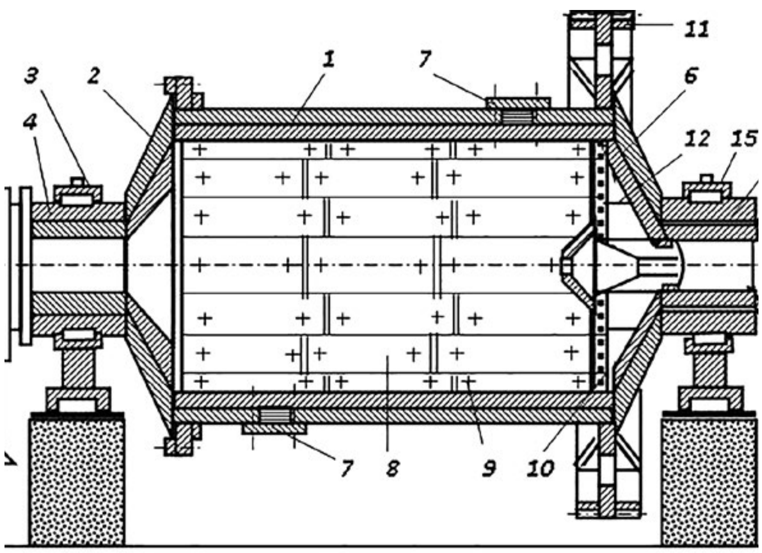

Fig. 1. BM with discharge through a grate: 1 — drum, 2, 6 — end covers, 3, 15 — bearings, 4 — loading trunnion, 5 — feeder, 7 — hatches, 8 — armored plates, 9 — bolts, 10 — grate, 11 — crown gear, 12 — lifters, 13 — throat, 14 — discharge trunnion

Proposed data for calculating the experimental parameters of the BM

Drum diameter, d, m	Mill drum length, L, m	Recommended ball diameter, $d\kappa$, mm	Selected ball diameter, mm	Drum volume m^3	Load factor ψ, 3% kg	Selected quantity, pcs
1	1.45	25	30	1.13	109.61	856
1	1.5	28	30	1.17	113.49	886
1	1.6	33	40	1.25	119	404
1	1.65	36	40	1.29	125.13	417
1	1.7	39	40	1.33	126.616	430
1	1.75	42	40	1.37	130.424	443
1	2.05	58	60	1.61	149.73	152
1	2.1	61	60	1.64	152.52	155
1	2.15	64	60	1.68	156.24	159

The following data show the characteristics of balls for BM provided by the manufacturer. Various formulas, mainly empirical, used by BM manufacturers were applied to calculate the dimensions of the balls and the drum for the experimental setup, which is smalled and may be adjusted during testing. The 3% load is the initial value, subject to refinement during the experiment.

Ball diameter, mm .... Mass of 1 cubic meter of metal balls, *t*
30..4.85
40..4.76
50..4.7
60..4.65
80..4.6
100......................................4.56
125......................................4.52

Ball diameter, mm ....Weight of 1 ball, kg
25..0.064
30..0.128
35..0.199
40..0.294
45..0.413
50..0.58
55..0.761
60..0.98
65..1.291
80..2.35
120 ....8.03

$$d_k = \frac{(L-d)}{18}, \tag{1}$$

The diameter of the grinding balls required for IG crushing was estimated using the empirical relation (Formula 1), where d_k *is* the ball diameter (mm), L is the length of the mill drum (m), and d is the drum diameter (m).

The maximum effective rotation speed N_{max} is determined by the following formula:

$$N_{\max} = 42,3\psi\sqrt{D}, \tag{2}$$

where ψ is the drum filling coefficient, D is the internal diameter of the drum (m), and N_{max} is the number of revolutions per minute [28].

Experimental studies with different rotation speeds and ball sizes will allow determination of the optimal drum filling coefficient KM and the mode that will be more gentle for low irradiated graphite (LIG) and more effective for the destruction of highly irradiated graphite (HIG). Moderately IG is classified as LIG, and it is not separated.

Preliminary measurements and analysis of radioactivity in the reactor area, as well as the possible application of a contrast agent that adheres to active graphite surfaces and can be detected by cameras, may support the use of computer vision in cyclic IG crushing and segregation. This will automate the process and limit the need for human intervention. The BM, traditionally used for grinding solid materials, is proposed as a means of dosed destruction, dividing the blocks into parts with potentially high and low levels of irradiation. During the processing cycle, various (combined) effects occur: impact, friction, pressure, depending on the speed of rotation and filling of the drum.

The use of a BM with periodic unloading through a grate will enables removal of fine fractions from the grinding zone, preventing them from being ground into dust, which should be classified as hazardous waste. Very fine particles may be removed using liquid or air, which also provides cooling of the graphite. The discharge of crushed graphite can be carried out through a hatch or a spigot, where metal balls will be retained or returned to the drum with the help of an electromagnet, since graphite has diamagnetic properties, unlike iron for balls, which is ferromagnetic.

The crushed IG must be evaluated, sorted, separated from marked fragments, with additional processing if necessary. Appropriate selection of ball size and material, as well as mill operating parameters, increases the likelihood of primarily affecting the weaker and more porous areas of the blocks.

Sorting methods include mechanical processes such as extraction and fractionation by radioactivity level. It is important to note that physical separation does not always allow for complete separation of different fractions. It is important to note that complete separation of fractions using only physical methods is a difficult task. Partial mixing of crushed LIG with HIG is possible. To improve recognition accuracy, it is proposed to use several video cameras, with repeated control of recognized debris in each processing cycle. Equipment error must be minimized. It is expected that the size of LIG fragments will exceed the size of HIG fragments. This is the main criterion for sorting IG. The objective is to minimize the mass of unclassified graphite.

$$Mg = Mhig + Mlig + Mns, \quad Mns \rightarrow \min, \tag{3}$$

where Mns is the mass of fragments, kg, that could not be separated (they will have sufficiently large areas of painted and unpainted fragments), Mg is the mass of all graphite, Mhig and Mlig are the masses of HIG and LIG that will be obtained during separation.

$$Mcalc <= Mhig <= Mcalc + Mperm. \tag{4}$$

With appropriate material accounting approach, it is possible to introduce preliminary weighing of graphite and make a quantitative assessment of the yield of HIG Mcalc. Mhig >= Mcalc. In this case, the size of the LIG fragments is equal to the size of the KM grid holes. On the other hand, Mhig <= Mcalc + Mperm, where Mperm is the maximum permissible deviation. It is also necessary to minimize energy consumption and excessive grinding.

The proposed irradiated-graphite (IG) separation algorithm is shown schematically in Fig. 2.

According to the algorithm, IG blocks are loaded into the BM and processed for a specified time. Fine fractions — primarily HIG particles — are discharged through the grate. The remaining graphite is assessed to determine whether additional processing cycles are required.

IG samples emit α-, β-, and γ-radiation. Therefore, initial dosimetric monitoring should be performed to

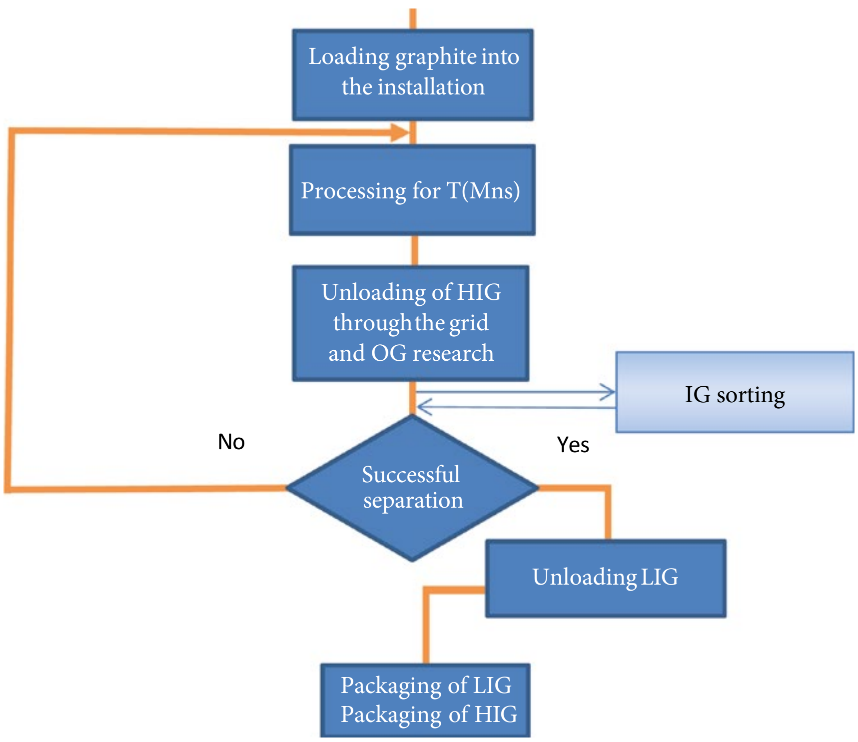

Fig. 2. IG separation algorithm diagram

Fig. 3. IG after processing (generated using Adobe Firefly — free generative AI)

characterize activity levels. Subsequently, video cameras positioned at a safe distance (2–3 m) can acquire images for automated processing. Based on these data, it is possible to estimate the amount of debris and the probable amount of incompletely separated graphite.

An example visualization of IG debris is shown in Fig. 3, generated using a generative-AI tool. Visual analysis of sequential images shows improved graphite separation: the number of red-colored fragments decreases with each subsequent stage. The quality of processing can be evaluated using a neural network (classification or clustering) after unloading or directly inside the BM after it has stopped by means of photo recording. Machine learning methods can be applied to such images.

Processing optimization based on photographs

Based on the images provided, the following recommendations for further processing can be made:

Case 1: Continue processing at time τ_1 and speed N_1.

Cases 2 and 3: Continue processing at $\tau_2 < \tau_1$ and $\tau_3 < \tau_2$, and corresponding speeds N_2 and N_3.

Case 4: Processing may be stopped and the LIG discharged if the estimated mass of the HIG reaches Mcalc within acceptable deviation.

In general, fragments could be sorted according to the degree of coloration during intermediate stages of separation. Although this approach could improve the process quality, it would increase complexity of its implementation and require additional automated lines. Therefore, at this stage, a more acceptable option is to process all fragments to the desired degree of separation.

Conclusions

1. The proposed method of IG crushing has a number of significant advantages. It is relatively simple to implement and may guarantee a high safety level of process. In addition, it can be extensively automated facilitating implementation and subsequent operation.

2. Separation of IG into different categories (low, medium, and high) can significantly reduce the volume of high-level waste requiring decontaminated or disposed.

3. Graphite is chemically stable under normal conditions, and the proposed method does not alter its chemical composition through aggressive substances, thereby avoiding additional hazards. Graphite is insoluble in water and does not release hazardous compounds. This method minimizes generation of gaseous emissions, active aerosols, and secondary waste. The rate of radionuclides leaching from graphite blocks is low and comparable to the rate of leaching from vitrified radioactive waste. After separation, established treatment methods may be applied.

4. An algorithm for separating IG using special equipment has been developed, which includes processing and control cycles using neural networks and has a high level of safety.

5. Future refinement of the BM-based crushing method and the AI-supported separation algorithm should focus on reducing energy consumption and enhancing compatibility with remote-control conditions.

References

1. On the approval of the general safety provisions for the decommissioning of nuclear installations. Order of the State Inspection of Nuclear Regulation of Ukraine dated October 28, 2020, No. 440. Available at: https://zakon.rada.gov.ua/laws/show/z1311-20#Text. (in Ukr.)
2. Classification of radioactive waste. General safety guide. IAEA Safety Standard No. GSG-1. Vienna: IAEA, 2014, 75 p. (in Rus.)
3. Komir A. I., Odeychuk N. P., Nikolaenko A. A., Tkachenko V. I., Derevyanko V. A., Krivchenko O. V., Shepelev A. G. (2016). Grafit kak konstruktsionnyy material yadernykh energeticheskikh sistem IV pokoleniya [Graphite as a structural material for Generation IV nuclear energy systems]. *Problems of Atomic Science and Technology*, vol. 1 (101), pp. 51–55. (in Rus.)
4. Azarov S. Y., Babych E. V. (2001). [Possible options for the disposal of spent reactor graphite during the decommissioning of the Chornobyl Nuclear Power Plant units]. *Naukovi ta tekhnichni aspekty mizhnarodnoho spivrobitnytstva v Chornobyli. Zbirnyk naukovykh statei* [Scientific and technical aspects of international scientific research in Chornobyl. Collection of scientific articles]. Vol. 3. Kyiv: Vyshcha shkola, pp. 219–231. (in Rus.)
5. Nosovskyi A. V. (2007). [Handling of irradiated graphite during decommissioning of nuclear power plant units]. *Naukovi visti NTUU "KPI"* [Scientific news of NTUU "KPI"], vol. 3 (53), pp. 12–19. (in Ukr.)
6. Marsden B. J. (2001). Nuclear graphite for high temperature reactors. *Proceedings of the Technical committee meeting on gas turbine power conversion systems for modular HTGRs (Palo Alto, CA, USA, November 14–16, 2000)*, pp. 177–192.
7. Schmitt R. (2021). 6.5.9 Synthetic graphite in nuclear applications. In: *Industrial Carbon and Graphite Materials, Volume I: Raw Materials, Production and Applications, I.* doi.org/10.1002/9783527674046.ch6_5_9.
8. IAEA (2006). *Characterization, treatment and conditioning of radioactive graphite from decommissioning of nuclear reactors*. IAEA-TECDOC-1521. Vienna: IAEA, 80 p.
9. IAEA (1996). Graphite moderator life cycle behavior. *Proceedings of a Specialists Meeting (Bath, United Kingdom, September 24–27, 1995).* IAEA-TECDOC-901. 352 p.
10. Bradbury D., Wickham A. J. (2006). *Graphite decommissioning* (EPRI Report No. 1013091). Palo Alto, CA: Electric Power Research Institute, 156 p.
11. Bradbury D., Wickham A. J. (2007). *Graphite dust deflagration* (EPRI Reports 1014797 and Supplement 1015460). Palo Alto, CA: Electric Power Research Institute, 128 p.
12. Bradbury D., Wickham A. J. (2008). *Graphite leaching* (EPRI Report 1016772). Palo Alto, CA: Electric Power Research Institute.
13. Bradbury D., Mason B. (2008). *Program on technology innovation: Graphite waste separation* (EPRI Report 1016098). Palo Alto, CA: Electric Power Research Institute.
14. Wickham A. J. (2010). *Carbon-14 in irradiated graphite waste* (EPRI Report 1021109). Palo Alto, CA: Electric Power Research Institute.
15. Bradbury D., Goodwin J. (2010). *Innovative graphite removal technology for graphite-moderated reactor decommissioning: Nibble and vacuum* (EPRI Report 1021110). Palo Alto, CA: Electric Power Research Institute.
16. Wickham, A. J. (2012). *Behavior of Cl-36 and tritium in irradiated graphite wastes* (EPRI Report 1025312). Palo Alto, CA: Electric Power Research Institute.
17. Marsden B. J., Wickham, A. J. (1998). Graphite disposal options — a comparison of the approaches proposed by UK and Russian reactor operators. In: *Proceedings of the International Conference on Nuclear Decommissioning*, vol. 9, pp. 145–153.
18. Neighbour G. B., Wickham A. J., Hacker P. J. (2000). Determining the future for irradiated graphite disposal. *Nuclear Energy,* vol. 39, pp. 179–186.
19. Ojovan M. I., Wickham A. J. (2014). Treatment of irradiated graphite to meet acceptance criteria for waste disposal: Problem and solutions. *Materials Research Society Symposium Proceedings,* vol. 1665.
20. Ojovan, M. I., & Wickham, A. J. (2016). Radiation effects in graphite. In: *Proceedings of the Joint ICTP-IAEA Workshop on Radiation Effects in Nuclear Waste Forms and their Consequences for Storage and Disposal (International Centre for Theoretical Physics, Trieste, Italy).* Available at: http://indico.ictp.it/event/7633.
21. Metcalfe M. P., Wareing A. (2013). *Deliverable D-1.7.2: Collation of data and information from other work packages* (Report of the CARBOWASTE Project, European Union).
22. CAST Project (2018). *EU Project on Carbon-14 Source Term (CAST).* European Union. Available at: https://www.projectcast.eu/publications/reports.
23. Wickham A., Steinmetz H.-J., O'Sullivan P., Ojovan M. I.

(2017). Updating irradiated graphite disposal: Project 'GRAPA' and the international decommissioning network. *Journal of Environmental Radioactivity*, vol. 171, pp. 34–40.
24. Kirby W. (2011). Brookhaven Graphite Research Reactor (BGRR) D and D Project — 11243. *Proceedings of the Waste Management Symposium 2011 (Phoenix, AZ, February 27 — March 3, 2011),* 6 p. Available at: https://archivedproceedings.econference.io/wmsym/2011/papers/11243.pdf.
25. Voievodin V. M., Hrybanov Yu. O., Hurin V. A., Hurin I. V., Huida V. V. (2015). [Carbon-graphite materials in nuclear energy (Review)]. *Problems of Atomic Science and Technology,* Vol. 2 (96), pp. 52-64. (in Rus.)
26. Smyrnov V. O., Biletskyi V. S. (2012). *Pidhotovchi protsesy zbahachennia korysnykh kopalyn [Preparatory processes for mineral enrichment]* (Study guide). Donetsk: Skhidnyi Vydavnychyi Dim [Donetsk: Eastern Publishing House]. 284 p. (in Ukr.)
27. Sokur M. I., Kiianovskyi M. V., Vorobiov O. M., Sokur L. M., Sokur I. M. (2014). *Dezintehratsiia mineralnykh resursiv [Disintegration of mineral resources].* Kremenchuk: Publishing House of Private Enterprise Shcherbatykh O. V., 304 p. (in Ukr.)
28. Smyrnov V. M., Biletskyi V. S., Sokur M. I. (2019). [Theoretical foundations of calculating the productivity of drum mills]. *Zbahachennia korysnykh kopalyn [Mineral Enrichment],* vol. 73 (114), pp. 58–66. (in Ukr.)

О. Ю. Дорман[1], К. В. Сімейко[1, 2]

[1] Інститут проблем безпеки АЕС НАН України, вул. Кірова, 36а, Чорнобиль, 07270, Україна
[2] Інститут газу НАН України, вул. Дегтярівська, 39, Київ, 03113, Україна

Визначення шляхів удосконалення методів подрібнення та сортування опроміненого графіту ядерних установок

Стаття присвячена проблемі поводження з опроміненим графітом (ОГ) ядерних енергоустановок. Реакторний графіт (або графіт ядерної чистоти) використовувався як сповільнювач чи відбивач нейтронів у більш ніж 100 ядерних реакторах та є конструкційним і функціональним матеріалом у ядерних енергетичних системах IV покоління, зокрема у високотемпературних газоохолоджувальних (HTR, HTGR, VHTR) і рідко-сольових реакторах (MSR). Тому проблема поводження з ОГ ядерних енергоустановок є актуальною науковою проблемою.

Для деяких можливих варіантів утилізації ОГ, зокрема, спалювання, захоронення, обробки іонізуючими смолами актуальним є питання подрібнення та сортування ОГ. На основі аналізу фізичних властивостей графіту після тривалої дії високих температур та нейтронного опромінення авторами пропонуються шляхи вдосконалення методів подрібнення та сортування ОГ з використанням штучного інтелекту (ШІ). Описано метод дроблення ОГ з використанням кульового млина з розвантаженням через решітку та розроблений алгоритм розділення ОГ з використанням ШІ, що включає цикли обробки та контролю з допомогою нейронних мереж. Майбутнє вдосконалення використання кульового млина з розвантаженням через решітку та алгоритму розділення має бути направлено на зменшення енергетичних витрат та адаптації до умов дистанційного керування.

Ключові слова: атомна енергетика, зняття з експлуатації АЕС, радіоактивні відходи, опромінений графіт, штучний інтелект.

Надійшла / Received 09.09.2025
Рекомендована до друку / Accepted 03.11.2025