Journal homepage: https://mining-journal.com.ua/en

MINING JOURNAL
of Kryvyi Rih National University

Vol. 59, No. 1, 2025

Received: 20.12.2024; Revised: 18.04.2025; Accepted: 30.06.2025

UDC 622.234.42:622.235

DOI: 10.31721/2306-5435-2025-1-33-41

Borys Andreev
Doctor of Techhnical Sciences, Professor
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0000-0002-9243-816X

Yevhen Bryzhevskyi*
Postgraduate Student
Kryvyi Rih National University
50027, 11 Vitalii Matusevich Str., Kryvyi Rih, Ukraine
https://orcid.org/0009-0000-4542-5887

Overview of technologies and prospects for underground uranium mining

Abstract. The relevance of research into underground uranium mining is underpinned by the growing demand for a stable supply of nuclear raw materials for atomic energy, which is regarded as a key factor in ensuring energy security amid the ongoing global energy crisis. Given the scarcity of high-grade ores and the necessity to exploit low-grade deposits, particular attention is drawn to the implementation of advanced leaching technologies directly within underground ore blocks. The objective of this study was to investigate and assess the efficiency of underground block leaching for uranium, considering the geological conditions of Ukrainian deposits, and to evaluate its prospects for enhancing the economic performance of mining enterprises. The research employed methods including analysis of the geological and structural features of ore deposits, simulation of leaching processes, and techno-economic assessment of block leaching under the specific conditions of Ukrainian uranium-bearing formations. A comparative analysis was conducted between conventional uranium mining techniques and advanced underground leaching technologies. The principal findings demonstrated that underground block leaching significantly reduces the costs associated with mining and processing of low-grade uranium ores, minimises environmental impact, and enhances the profitability of mining operations. Furthermore, the study confirmed that the geological and hydrogeological conditions of Ukraine's uranium deposits are favourable for the implementation of this technology. The application of block leaching facilitates the expansion of the raw material base by incorporating low-grade and substandard ores that were previously not considered for industrial exploitation. The practical value of the study lies in its potential to enhance the economic efficiency of mining enterprises, reduce mining and processing costs, and mitigate the adverse effects on the environment. The implementation of underground block leaching will contribute to the sustainable development of Ukraine's uranium industry

Keywords: underground block leaching; mining-chemical technology; uranium deposits; low-grade ores; nuclear energy

Suggested Citation:
Andreev, B., & Bryzhevskyi, Ye. (2025). Overview of technologies and prospects for underground uranium mining. *Mining Journal of Kryvyi Rih National University*, 59(1), 33-41. doi: 10.31721/2306-5435-2025-1-33-41.

*Corresponding author

Introduction

Ensuring a stable supply of uranium raw materials is a strategically critical objective for nuclear energy. As nuclear power remains one of the world's primary electricity sources, the demand for high-quality nuclear fuel continues to grow. However, conventional uranium mining techniques such as open-pit and underground mining pose substantial economic and environmental challenges. The depletion of high-grade uranium ores necessitates the exploration of more efficient and environmentally friendly mining methods. Underground block leaching is one such method enabling the utilisation of low-grade and sub-standard ores while minimising environmental impact and reducing mining costs.

Modern underground leaching technologies, particularly of the block type, enable the efficient exploitation of low-grade deposits, a factor highly relevant to the Ukrainian uranium industry (IAEA, 2019). L. Guihe & Y. Jia (2024) further highlighted that *in-situ* leaching is the most efficient uranium recovery method. This approach not only significantly lowers ore processing costs but also ensures minimal environmental impact compared with conventional mining techniques. They additionally emphasise the necessity of detailed hydrogeological assessment prior to implementation to mitigate lixiviant loss.

R. Jin *et al.* (2023) analysed the formation patterns of uranium deposits in large sedimentary basins, concluding that hydrogeological conditions, rock porosity, and mineralogical composition of the ore body are the principal determinants of underground leaching effectiveness. The authors emphasised that in low-permeability formations, leaching parameters should be adapted to optimise the process efficiency. Y. Zhou *et al.* (2020) investigated the recovery of uranium from sandstone deposits by underground acid leaching, demonstrating that sulphuric acid concentrations of 3-5% significantly enhance uranium yield, and that dissolution kinetics depends on mineral composition and permeability. M. Donskyi *et al.* (2023), in their analysis of geological features of Ukraine's uranium deposits, found that many of the deposits contain albitites that are well suited for underground leaching. However, the authors emphasised the imperative of rigorous hydrogeological monitoring to prevent lixiviant migration into groundwater.

V. Verkhovtsev *et al.* (2023a) assessed the environmental risks associated with underground uranium leaching in Ukraine, identifying potential lixiviant migration into aquifers and the necessity of controlling chemical reactions within leaching blocks, and recommending real-time monitoring systems. In a separate study, V. Verkhovtsev *et al.* (2023b) evaluated recent technological advances in uranium ore processing in Ukraine, asserting that combining leaching with downstream hydrometallurgical treatment can significantly increase uranium yields while reducing losses of valuable components.

O.A. Lysenko & A.Kh. Bakarzhyiev (2019) reviewed the Ukrainian uranium sector's current state and prospects, concluding that while most deposits show leaching potential, but further research is needed to evaluate its effectiveness across diverse geological settings. Additionally, the authors recommended refining regulatory frameworks to stimulate sector development. Similarly, the World Nuclear Association's (2023) report highlighted the pre-eminence of underground leaching among uranium mining techniques, underscoring its capacity to mitigate environmental impact and lower mining costs compared with conventional underground mining methods.

Despite considerable progress in underground leaching research, unresolved issues remain concerning the long-term hydrogeological impact of this technology and associated environmental risks. Furthermore, the optimisation of leaching parameters for diverse uranium ore types, particularly under Ukrainian geological conditions, remains understudied. Consequently, this study aimed to evaluate the effectiveness of underground leaching for Ukrainian uranium deposits, considering their specific geological-structural and hydrogeological characteristics, and to determine optimal process parameters.

Materials and Methods

This study was underpinned by a comprehensive analysis of scientific and technical literature, reports by international organisations, statistical datasets, and the findings of prior research in the field of uranium ore mining and processing, with a particular focus on underground block leaching (UBL) technologies.

The State Enterprise "Eastern Mining and Processing Plant" (SE "SkhidGZK"), Ukraine's primary and Europe's largest uranium producer, was selected as a key case study for this research. The enterprise exploits deposits characterised by complex mining and geological conditions and relatively low uranium content (0.02-0.06%), often composed of albitite ores. Its operational experience and deposit characteristics provide a valuable contextual basis for assessing the broader applicability of UBL in Ukraine. To evaluate the effectiveness of the UBL technologies for uranium ores, international best practices were reviewed. These included: the application of leaching techniques in geologically challenging deposits in Australia; technologies adapted to ore bodies hosted in dense hard-rocks in Canada; automated leaching monitoring systems employed in Kazakhstan; and techno-economic considerations presented at a French symposium on block leaching. The comparative analysis encompassed technological flowsheets, process parameters, economic performance indicators, and environmental implications.

A wide range of sources was systematised, including peer-reviewed scientific publications, doctoral theses, technical reports, and documentation from international agencies such as the IAEA (2019), UNECE (2019), NEA (2022), and World Nuclear Association (2023). A critical examination of existing scientific methodologies and their relevance to the research topic was undertaken. Conventional uranium mining techniques (underground and open-pit) were contrasted with the UBL method using techno-economic and environmental criteria. Analytical assessments were performed to evaluate geological, hydrogeological, technological, and economic prerequisites for effective implementation of UBL in Ukrainian uranium deposits.

The methodological framework for this study incorporated key scientific research methods, analysis and synthesis. Analysis was applied to meticulously examine various aspects of the UBL technology, geological characteristics of the deposits, economic factors, and environmental consequences. Synthesis facilitated the integration of the obtained data to form a comprehensive understanding of the method's advantages, its limitations and prospects for its implementation in Ukraine. For instance, the mineralogical composition of the ores (uranite, pitchblende, coffinite, brannerite) and the host rocks (albitites) was analysed to assess their suitability for sulphuric acid leaching. A comparative analytical method was also used to evaluate conventional uranium ore mining technologies compared with the UBL method, particularly in terms of production cost, mining efficiency, environmental impact, and occupational safety. Ukraine's experience was contrasted with leading international practices from Australia, Canada, Kazakhstan, and France. Finally, a system-based approach enabled the assessment of the implementation of UBL as an integrated system, considering the interrelationship of geological, technological, economic, and environmental factors.

While this study did not encompass original numerical simulations, it was underpinned by an extensive review of previously published leaching process models. These models aided in understanding the dynamics of chemical reactions between leaching solutions and the ore body, and the influence of hydrogeological conditions on process efficiency. Being analytical in nature, this study did not incorporate original fieldwork or laboratory experiments conducted by the authors. Instead, the research focused on in-depth interpretation of available geological-structural data on Ukrainian uranium deposits, particularly those within albitite formations. Previous laboratory and pilot-scale leaching trials were also studied, including investigations into diffusion and filtration dynamics within ore bodies. Supplementary relevant data were sourced from academic articles, technical reports, and institutional databases.

Primary research materials included monographs and academic articles by Ukrainian, Canadian, Chinese, and Kazakh scientists, doctoral theses, and data on the geological structure, mineralogical composition (including uraninite, pitchblende, coffinite, and brannerite within albitite rocks), and hydrogeological conditions of Ukrainian uranium deposits. Information on properties of leaching solutions and their interactions with ores was also used. The study of co-leaching of uranium and radium allowed for the consideration of the impact of accompanying processes on overall recovery efficiency (Bai *et al.*, 2023). This study analysed the key indicators such as uranium content in ores (e.g. % U_3O_8), uranium recovery rates, leaching rates, ore permeability and porosity, filtration coefficients, and process duration. Economic indicators, including production cost, capital and operational expenditures, profitability, and cost reduction potential were also examined. Attention was paid to environmental indicators, including the mitigation of negative environmental impact, waste minimisation, as well as to physical and mechanical properties of ores and host rocks, operational safety.

This study primarily relied on the consolidation and interpretation of findings, methodologies, and approaches presented in existing scholarly literature. Conclusions and recommendations are supported by numerous academic and technical publications. Data were extracted from authoritative information sources and the official websites of international organisations such as the UNECE (2019), NEA (2022), IAEA (2023), and World Nuclear Association (2025), providing up-to-date statistics, analytical insights, and overviews of uranium industry technologies. This methodological approach ensured a robust and reproducible assessment of the UBL technology and its prospects for deployment in Ukraine.

Results and Discussion

The characteristics of uranium deposits in Ukraine, coupled with the accumulated exploitation experience and global uranium mining practices highlight the promising potential of a mining-chemical technology: leaching uranium from stockpiled ores within underground stope blocks (IAEA, 2022). NEA (2022) reports the average global uranium content in industrial ores at approximately 0.22% U_3O_8. Ukrainian deposits, as noted by O.A. Lysenko & A.Kh. Bakarzhyiev (2019), often exhibit significantly lower uranium grades, typically 0.02-0.06%. This necessitates that the Ukrainian uranium industry specifically adapt its mining technologies to these low-grade ores. Given the current production costs for natural uranium concentrate in Ukraine and the prevailing market price, the profitability of mining and processing operations remains critically low. This creates a difficult situation: current mining and processing methods are highly capital- and labour-intensive, yet they are applied to ores that are predominantly low- or sub-economic grade. Conventional underground mining and subsequent hydrometallurgical processing at centralised plants remain in use in 2025 and are only economically viable for high-grade ore bodies. Therefore, enhancing profitability requires the implementation of novel, cost-effective technologies for mining and processing low- or sub-economic grade ores. A particularly promising approach is the mining-chemical technology of underground leaching from monolithic hard-rock ores, which involves creating artificial permeability within the ore massif. V.I. Lyashenko *et al*. (2024) indicate that UBL technology retains competitiveness even under conditions of low uranium content.

Compared to conventional hard-rock mining techniques, mining-chemical technologies offer several advantages: the elimination of expensive, labour-intensive and hazardous ore handling operations, the 70-75% reduction in the volume of ore haulage to the surface, the prevention of underground void formation, decreased dependence on rail transport for ore transportation and reduced tailings management costs. The NEA (2022) and the World Nuclear Association (2025) report similar advantages at uranium deposits in Australia, where underground leaching minimised damage to surface ecosystems while ensuring highly efficient recovery of valuable components. Mining-chemical technologies for uranium recovery enable the exploitation of previously sub-economic or sub-standard ore reserves. Preliminary estimates suggest that bringing such ores in production could expand the raw material base of Ukrainian uranium mines by a factor of 1.4-1.6. According to V. Verkhovtsev *et al*. (2023b), UBL offers several advantages including reduced transportation costs, diminished environmental impact, enhanced profitability, and the incorporation of sub-standard ores into production.

Y. Yang *et al*. (2023) demonstrated that the utilisation of CO_2 and O_2 in underground leaching processes can reduce greenhouse gas emissions, thereby mitigating the environmental impact of UBL. Canadian researchers R. Jin *et al*. (2023) underscored the criticality of assessing hydrogeological conditions for the successful implementation of UBL. The study by E.C. Reinisch & B.G. Henderson (2023) on Canadian UBL experience in dense hard-rocks highlighted that leaching efficiency depends on the permeability achieved through prior blasting. Additionally, ore body morphology plays a crucial role in UBL performance. L. Meng *et al*. (2024) note that hydrogeological assessment and leaching potential evaluation must become mandatory components of the planning phase. Operational practices from Australia and Canada suggest that combined approaches may be feasible for Ukrainian uranium mines wherein conventional mining methods are applied to balance reserves, and UBL is reserved for sub-economic, sub-standard and isolated ore deposits.

The deposits currently exploited by the SE "SkhidGZK" – Vatutinske, Michurinske, Tsentralne, and Novokonstantynivske – are located within Precambrian formations of the Ukrainian Shield, overlain by 30-50 m thick Cenozoic loose sediments. Uranium-bearing bodies are associated with metasomatically altered albitites. These albitites, being as dense as the surrounding metamorphic rocks, formed impermeable monoliths during ore genesis, thus presenting conditions conducive to UBL. Their high density, low permeability, and comprehensively studied post-ore fracturing are advantageous for the implementation of this technology. Within the mentioned deposits, blocks prepared for leaching may be conceptually likened to sealed vessels filled with porous, permeable ore. Solution leakage is limited, particularly if blocks are situated beyond fractured zones. The uranium minerals present include uraninite, pitchblende, coffinite, and brannerite. Of these, the first three dissolve readily in sulphuric acid solutions when an oxidant is present. While brannerite typically demonstrates resistance to leaching, it does not occur in its pristine state in Ukrainian deposits; rather, it manifests as decomposed fine aggregates of uranium oxides and silicates with titanium and iron oxides. Consequently, ores containing brannerite exibit leaching characteristics comparable with those containing uraninite and pitchblende.

Thus, Ukraine possesses a sufficient resource base for UBL, as the mineralogical composition and properties of ores across all deposits are favourable for this technology's application. This technology is particularly suited for the development of individual ore bodies within deposits that consist of low-grade and sub-economic uranium ores, individual fragments of deposits with losses within fractured zones that cannot be mined by other technologies, and small deposits at shallow depths. A detailed analysis of the geological structure, mineral composition, and mining-geological conditions of uranium deposit formation in sodium metasomatites indicates that, based on a combination of characteristics, they are favourable for UBL.

The solubility of uranium compounds in sulphuric acid solutions is primarily determined by the form in which uranium is present within the ore. Like other elements in the Earth's crust, uranium may occur either as discrete mineral phases or as isomorphic impurities within the crystal lattices of other minerals. Typically, uranium incorporated as an isomorphic impurity exhibits its poor solubility, whereas uranium occurring in its own distinct mineralogical forms dissolves readily in sulphuric acid solutions. From this perspective, ores from albitite-hosted uranium deposits are deemed highly amenable to leaching, as uranium in these formations is predominantly occurs as discrete minerals such as uraninite, pitchblende, brannerite, coffinite, and various uranium hydroxides. Of particular importance to the dissolution process is the oxidation state of uranium in these compounds. Minerals containing uranium in the hexavalent state exhibit significantly greater solubility in sulphuric acid solutions. The chemical equation for this reaction is as follows:

$$UO_{3(s)} + 2H^{+}_{(aq)} \rightarrow UO^{2+}_{2(aq)} + H_2. \quad (1)$$

Tetravalent uranium minerals, prevalent in the ores of albitite-hosted deposits, exhibit slow reactivity with sulphuric acid solutions. However, under practical block leaching conditions, the dissolution process is significantly accelerated by the presence of trivalent iron ions in the productive solutions. These ions are released into solution from iron-bearing dark-coloured minerals such as chlorite, biotite, phlogopite. The reaction can be represented by the following equation:

$$UO_{2(s)} + 2Fe^{3+}_{(aq)} \rightarrow UO^{2+}_{2(aq)} + 2Fe^{2+}_{(aq)}. \quad (2)$$

Thus, uranium contained in albitite-hosted ores – composed predominantly of uraninite, pitchblende, and brannerite (minerals in which uranium is present in the tetravalent state) – readily dissolves under block leaching conditions. This is facilitated by the presence of ferric iron ions, which are leached by sulphuric acid from the host rocks. During underground mining operations that incorporate drilling and blasting, seismic shockwaves are generated within the rock massif. Stress release tends to occur preferentially along pre-weakened tectonic zones that commonly host ore mineralisation. This process induces the opening of microfractures where ore mineralisation is concentrated, thereby enabling productive leaching solutions to access the ore minerals. Given that ore blasting during the preparation of block leaching rooms is typically performed without a compensatory space, the seismic energy from blasting exerts a more pronounced impact on the ore material, significantly increasing the extent of microfracture development. Thus, the combination of ore genetic features and the specific block leaching preparation method results in the formation of an artificially permeable zone within the leaching block. In this zone, the bulk of ore minerals are exposed to acidic solutions through an interconnected network of fractures and microfractures.

The physical and mechanical properties of uranium ores and their transformation under following sulphuric acid exposure are of critical importance for the leaching process. The presence of clay minerals in the input ore, or their intensive formation due to acid exposure severely mitigate permeability and filtration characteristics, potentially leading to the cessation of block leaching operations. However, P. Goyal *et al*. (2024) highlight that the application of modern chemical reagents can significantly enhance the dissolution rate and completeness of uranium recovery, thereby boosting the economic efficiency of the process. A detrimental factor for block leaching is ore compaction, defined as the tendency of loosened ore to self-compress and reduce permeability due to physicochemical interactions with oxygen and acidic solutions.

The ores and host rocks of the deposits exploited by the SE "SkhidGZK" are composed of considerably strong albitites with natural bulk densities of 2,650-2,660 kg/m^3 and loosened densities of 1,660 kg/m^3. Due to the minimal carbonate content and complete absence of clays, these ores are not prone to compaction. The porosity of blasted ore reaches up to 37%, which supports high permeability, and the leached ore massif maintains stable filtration characteristics throughout the block leaching process. From both a technological and environmental perspective, the success of block leaching operations is critically dependent on inundation of the deposit and permeability of host rocks. High inundation leads to dilution of productive solutions, thereby increasing acid consumption and diminishing economic viability. Furthermore, excessive permeability in host rocks can result in solution losses, uranium migration, and aquifer contamination by sulphates and other leachate components.

Challenges associated with controlling the permeability of the ore massif and preventing the leakage of productive solutions underscore the need for advanced monitoring systems. B. Yang *et al*. (2023) highlight that uranium adsorption by sandstones beyond the leaching zone can compromise environmental safety, thereby requiring enhanced hydrogeological monitoring during block leaching operations. As demonstrated in the study by B. Tsoy *et al*. (2021) on the application of this technology in Kazakhstan and Canada, the integration of automated monitoring systems can lead to significant improvements in both the efficiency and safety of leaching processes.

The uranium-bearing crystalline host rocks in uranium deposits consist of albitites, albitic-microcline rocks, granites, migmatites, and gneisses. Their mineralogical composition is primarily feldspars (90%), quartz (up to 30%), and mafic minerals (e.g., aegirine, chlorite, phlogopite, riebeckite, epidote, biotite), which may account for 15-20%. These formations are naturally water- and acid-resistant, rendering natural leaching unfeasible. Consequently, artificial permeability zones with filtration coefficients of several metres per day should be generated by blasting. M. Stupnik *et al*. (2020) confirmed that the stress-strain state induced by blasting at the SE "SkhidGZK" deposits enhance microfracture development, thereby improving artificial permeability for block leaching.

The substantial filtration coefficient gradient at the interface between the rock massif and an artificially permeable zone prevents productive solutions from filtration into undisturbed crystalline rocks. Only diffusion processes occur across this boundary. Laboratory and pilot-scale studies demonstrated that the maximum depth of diffusion penetration for productive solutions into undisturbed host rock at albitite deposits does not exceed 0.2 m. These findings confirmed that the natural geological and hydrogeological conditions of Ukrainian uranium deposits provide reliable containment of leaching solutions within artificially created permeable zones, ensuring minimal dilution and loss while protecting aquifers from contamination.

In their report at the 1970 São Paulo symposium, M. Harel & P. Suqier (1970) addressed the technical and economic aspects of block leaching. They provided a comparison with conventional mining methods and described the specific techniques for the preliminary destruction of the ore massif. The blasted ore was stockpiled with an average uranium content of 0.102 conventional units. The amount of ore in the stockpile was 2,540 t, and the uranium recovery rate was 82.5%. The method of leaching from a preliminary destructed ore mass in underground blocks proved to be promising based on its techno-economic indicators. Subsequently, a significant portion of the uranium at one of the mines was planned to be recovered using this method. Extensive experimental research on block leaching of uranium ores was also undertaken by Canadian scientists. X. Luo *et al.* (2022) demonstrated that leaching can be successfully applied to steeply dipping ore bodies, while B. Tsoy *et al.* (2021) noted that shallow-dipping bodies may lead to suboptimal solution distribution in blasted ore. Infiltration leaching processes are characterised by a rapid increase in uranium content in the initial stages of spraying, followed by a decline after reaching a peak. During the final stage, uranium concentrations remain low and stable for a prolonged period. Theoretically, this behaviour is attributed to the molecular diffusion of uranium from dispersed mineral phases to the surface of solid ore fragments or the ore massif – a conclusion corroborated by empirical results from block leaching operations, Figure 1.

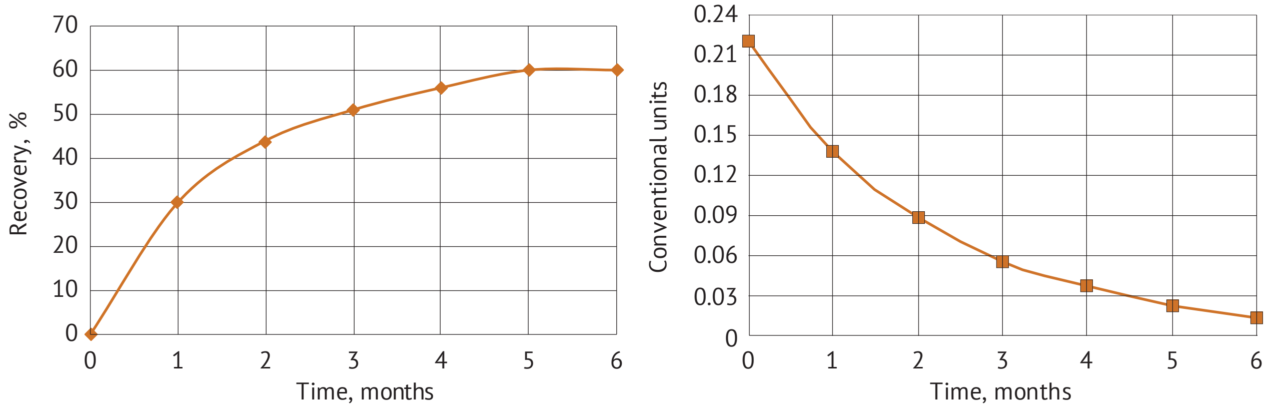

Figure 1. *Variation in uranium leaching indicators as a function of process duration*
Source: *P.M. Kucha (2013)*

Under conditions of lixiviant application to blasted ore, uranium minerals in a readily soluble state dissolve first. This is followed by the leaching of uranium from minerals remaining on the surfaces of rock fragments, and finally from impregnated zones. These specific characteristics of uranium leaching from stockpiled ore masses in blocks were successfully used to manage and optimise the underground leaching process, thereby enhancing its efficiency. The analysis of accumulated experience from enterprises engaged in block leaching revealed several technical, economic, and social advantages of this method. Primarily, it allows for the expansion of the raw material base of mining enterprises through the inclusion of low-grade uranium deposits, including significant reserves of sub-economic and sub-standard ores. It also contributes to labour productivity per unit of final product, improves working conditions and occupational safety, and mitigates the environmental impact.

These advantages of block leaching contribute to lower production costs, improved profitability of enterprises, and enhanced competitiveness of the final product. According to the IAEA (2023), the implementation of combined approaches for the extraction of balance and sub-standard ores will facilitate process optimisation and cost reduction. The economic efficiency of UBL is a key factor in its implementation. Research indicates that this method can reduce uranium production costs and improve operational profitability. The analysis by K. Yussupov *et al.* (2024), which examined the economic parameters of uranium deposits in Ukraine, confirms the feasibility of applying block leaching to low-grade deposits. The cost-benefit evaluation revealed that the cost of uranium obtained from underground leaching is 30% lower than that from conventional underground mining. Moreover, the use of advanced reagents can mitigate the consumption of chemical agents and enhance metal recovery, positively impacting the financial performance of enterprises.

The economic analysis indicates that achieving total uranium recovery from solutions at a level of 75-80% compared with that obtained via conventional underground mining is sufficient to ensure competitiveness. When advantages of block leaching – specifically, reduced losses, the inclusion of low-grade and sub-standard ores in development, and lower mine preparation costs – are considered, an acceptable overall recovery rate may be as low as 65-72%

or less. The review of experience and outcomes from mining-chemical uranium recovery technologies revealed three main directions for the effective use of leaching from stockpiled ores in blocks. The first is the recovery of balance reserves and existing sub-economic ores left after mining the deposit when their extraction by conventional means is unprofitable. The second is a combined mining-chemical scheme for uranium deposit development that integrates conventional methods for mining balance reserves with chemical recovery of sub-economic, sub-standard ores and individual ore bodies. The third is utilising block leaching as a principal method for developing both balance and sub-standard ores.

Under the specific conditions of Ukrainian uranium deposits, the second technological approach is entirely feasible. This would allow for uranium recovery from *in-situ* stockpiled ores, if not entirely, then from a significant proportion of balance reserves in run-of-mine, sub-economic and even off-balance ores. This would contribute to securing a stable uranium supply for nuclear energy needs, enhance the industry's competitiveness, and support sustainable economic development. UNECE (2019) underscores the necessity to modernise uranium resource utilisation strategies, including the implementation of UBL to ensure sustainable development of the industry in Ukraine.

Conclusions

The UBL technology for uranium ores presents a promising trajectory for the development of the mining industry, as it combines economic efficiency with a mitigated environmental impact. The findings of this study confirmed that the geological and hydrogeological conditions of Ukrainian deposits are conductive for the implementation of this technology. This allows for a substantial reduction in both extraction and processing costs, as well as the minimisation of environmental pollution. To sustain the competitiveness of the technology, the total uranium recovery rate from solutions of 75-80% is typically required. Nevertheless, considering the comprehensive benefits of UBL (reduced material losses, the capacity to exploit low-grade and sub-standard ores, and lower mine preparation costs), an acceptable total recovery rate can make 65-72% or even less, while retaining economic viability.

A primary economic benefit of UBL is the significant reduction in operational expenditure. Research demonstrates that uranium produced via underground leaching incurs production costs that are approximately 30% lower than those of conventional underground mining. This substantial cost saving directly enhances the profitability and competitiveness of enterprises operating in the uranium sector, particularly those processing low-grade ores. UBL also optimises the mining process by reducing the volume of ore that needs to be brought to the surface by 70-75%. This considerable decrease obviates several costly, labour-intensive, and hazardous operations associated with conventional ore handling, including ore drawing, haulage, and surface handling. Consequently, this also mitigates expenditures on rail transport to processing facilities and on the long-term maintenance of tailings facilities.

Future research should focus on the development and justification of specific geological-technological models tailored to Ukrainian deposits. These models should aim to practically achieve and optimise key performance indicators for UBL identified in this analysis, which include a potential 30% reduction in production costs, a 1.4-1.6-fold expansion of the mineral resource base, and uranium recovery rates of 65-80%. Based on these findings, the implementation of underground block leaching will enhance the efficiency of Ukraine's uranium mining industry and guarantees a stable supply of nuclear raw materials for the energy sector.

Acknowledgements

None.

Funding

None.

Conflict of Interest

None.

References

[1] Bai, Z., Zhao, X., Zhang, J., Wu, F., & Tang, Q. (2023). Optimisation of uranium-radium co-leaching from uranium ore. *Journal of Radioanalytical and Nuclear Chemistry*, 332, 1841-1845. doi: 10.1007/s10967-023-08892-7.

[2] Donskyi, M.O., Syomka, V.O., Sukach, V.V., Ivanov, B.N., Bondarenko, S.M., & Belskyi, V.M. (2023). The features of distribution of uranium of albitites of the Novokostiantynivka and the Partyzanske deposits. *Geochemistry and Ore Formation*, 44, 14-32. doi: 10.15407/gof.2023.44.014.

[3] Goyal, P., Sengupta, A., Srivastava, A., Mukherjee, S., Rout, V.V., & Mohapatra, P.K. (2024). *In-situ*-generated fluoride-assisted rapid dissolution of uranium oxides by ionic liquids. *Inorganic Chemistry*, 63(8), 3275-3284. doi: 10.1021/acs.inorgchem.3c04075.

[4] Guihe, L., & Jia, Y. (2024). A review of *in situ* leaching (ISL) for uranium mining. *Mining*, 4(1), 120-148. doi: 10.3390/mining4010009.

[5] Harel, M., & Suqier, P. (1970). *Report of France at the international symposium on uranium extraction from uranium ores and other sources No. M 154/4*. Retrieved from https://inis.iaea.org/records/en147-9nm12.

[6] IAEA. (2019). *Uranium production cycle selected papers 2012-2015*. Retrieved from https://surl.lt/pqceiz.

[7] IAEA. (2022). *Recent developments in uranium exploration, production, and environmental issues*. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/te_1463_web.pdf.

[8] IAEA. (2023). *Advances in uranium ore processing and recovery from non-conventional resources*. Retrieved from https://www.iaea.org/publications/3542/advances-in-uranium-ore-processing-and-recovery-from-non-conventional-resources.

[9] Jin, R., Yu, R., & Miao, P. (2023). Basin uranium mineralization law. In *Geological background of sandstone-type uranium deposits in Ordos Basin, Northwest China* (pp. 325-356). Singapore: Springer. doi: 10.1007/978-981-19-6028-4_5.

[10] Kucha, P.M. (2013). *Substantiation of technology and parameters of underground mining operations during block leaching of uranium from rock ores*. (Doctoral thesis, Kryvyi Rih National University, Kryvyi Rih, Ukraine).

[11] Luo, X., Zhang, Y., Zhou, H., He, K., Zhang, B., Zhang, D., & Xiao, W. (2022). Pore structure characterization and seepage analysis of ionic rare earth orebodies based on computed tomography images. *International Journal of Mining Science and Technology*, 32(2), 411-421. doi: 10.1016/j.ijmst.2022.02.006.

[12] Lyashenko, V.I., Dudar, T.V., Stus, V.P., & Shapovalov, V.A. (2024). Improvement of combined technologies for underground block leaching of metals from off-balance and substandard ores. *Environmental Safety and Natural Resources*, 52(4), 5-27. doi: 10.32347/2411-4049.2024.4.5-27.

[13] Lysenko, O.A., & Bakarzhyiev, A.Kh. (2019). State and prospects of the uranium raw material base of Ukraine. *Mineral Resources of Ukraine*, 1, 11-17. doi: 10.31996/mru.2019.1.11-17.

[14] Meng, L., Ning, H., Jiang, W., Sheng, Y., Wang, W., & Tang, C. (2024). Comprehensive study on hydrogeological conditions and suitability evaluation of *in situ* leaching for sandstone-hosted uranium deposit in Erlian Basin. *Water*, 16(19), article number 2785. doi: 10.3390/w16192785.

[15] NEA. (2022). *Uranium 2021: Resources, production, and demand*. *Paris: OECD Publishing*.

[16] Reinisch, E.C., & Henderson, B.G. (2023). Spatio-temporal analysis and volumetric characterization of interferometric synthetic aperture radar-observed deformation signatures related to underground and *in situ* leach mining. *Journal of Applied Remote Sensing*, 17(4), article number 044511. doi: 10.1117/1.JRS.17.044511.

[17] Stupnik, M., Kalinichenko, V., Fedko, M., Kalinichenko, O., & Hryshchenko, M. (2020). The study of the stress-strain state of the massif in mining uranium at "VOSTGOK" deposits. *E3S Web of Conferences*, 166, article number 03006. doi: 10.1051/e3sconf/202016603005.

[18] Tsoy, B., Myrzakhmetov, S., Yazikov, E., Bekbotayeva, A., & Bashilova, Y. (2021). Application of radio-wave geointoscopy method to study the nature of spreading the solutions in the process of uranium underground leaching. *Mining of Mineral Deposits*, 15(4), 1-7. doi: 10.33271/mining15.04.001.

[19] UNECE. (2019). *Redesigning the uranium resource pathway*. Geneva: United Nations.

[20] Verkhovtsev, V., Musich, O.G., Fomin, Y.O., & Demikhov, Y.M. (2023a). Bacterial leaching of balanced ores of albitite deposits of the Ukrainian Shield. *Mineralogical Journal*, 45(1), 72-82. doi: 10.15407/mineraljournal.45.01.072.

[21] Verkhovtsev, V., Sushchuk, K., Tyshchenko, Y., Meshcheryakov, S., & Koliabina, I. (2023b). Control of the environmental impact of uranium underground well mining (on the example of Mykhailivka polygenic deposit of the Ukrainian Shield). *Visnyk of Taras Shevchenko National University of Kyiv. Geology*, 101, 81-87. doi: 10.17721/1728-2713.101.12.

[22] World Nuclear Association. (2023). *In-situ leach (ISL) mining of uranium*. Retrieved from https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.

[23] World Nuclear Association. (2025). *Uranium mining overview*. Retrieved from https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.

[24] Yang, B., Cui, D., Meng, T., Lian, G., & Guo, H. (2023). Characteristics and influencing factors of uranium adsorption by sandstones outside an acid *in situ* leaching uranium mining area. *Environmental Earth Sciences*, 82, article number 532. doi: 10.1007/s12665-023-11230-5.

[25] Yang, Y., Zuo, J., Qiu, W., Wu, J., Que, W., Zhou, G., Liu, Z., & Wu, J. (2023). Assessment of the greenhouse gas footprint and environmental impact of CO_2 and O_2 *in situ* uranium leaching. *Acta Geologica Sinica (English Edition)*, 97(3), 986-994. doi: 10.1111/1755-6724.15058.

[26] Yussupov, K., Aben, E., Myrzakhmetov, S., Akhmetkanov, D., & Sarybayev, N. (2024). Increasing the efficiency of underground block leaching of metal. *Civil Engineering Journal*, 10(10), 3339-3349. doi: 10.28991/CEJ-2024-010-10-014.

[27] Zhou, Y., Li, G., Xu, L., Liu, J., Sun, Z., & Shi, W. (2020). Uranium recovery from sandstone-type uranium deposit by acid *in situ* leaching. *Hydrometallurgy*, 191, article number 105209. doi: 10.1016/j.hydromet.2019.105209.

Борис Андрєєв
Доктор технічних наук, професор
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0000-0002-9243-816X

Євген Брижевський
Аспірант
Криворізький національний університет
50027, вул. Віталія Матусевича, 11, м. Кривий Ріг, Україна
https://orcid.org/0009-0000-4542-5887

Огляд технологій та перспективи підземного видобутку уранової сировини

Анотація. Актуальність дослідження підземного видобутку урану зумовлена зростанням потреби у стабільному постачанні ядерної сировини для атомної енергетики, яка розглядається, як один із ключових факторів енергетичної безпеки в умовах глобальної енергетичної кризи. Враховуючи обмеженість високоякісних руд та необхідність розробки низькосортних покладів, особливу увагу привертає впровадження сучасних технологій вилуговування урану безпосередньо в підземних блоках. Метою роботи було дослідження та оцінка ефективності блочного підземного вилуговування урану з урахуванням геологічних умов родовищ України, а також визначення перспектив застосування цього методу для підвищення економічної ефективності гірничодобувних підприємств. У процесі дослідження використано методи аналізу геолого-структурних особливостей родовищ, моделювання процесів вилуговування, а також техніко-економічне оцінювання застосування блочного вилуговування в умовах українських родовищ. Застосовано порівняльний аналіз традиційних методів видобутку урану та новітніх технологій підземного вилуговування. Основні результати показали, що блочне підземне вилуговування дозволяє суттєво знизити витрати на видобуток та переробку низькосортних уранових руд, мінімізувати екологічний вплив на довкілля та підвищити рентабельність підприємств. Дослідження підтвердили, що геологічні та гідрогеологічні умови уранових родовищ в Україні є сприятливими для впровадження цієї технології. Застосування блочного вилуговування дозволяє розширити сировинну базу за рахунок залучення бідних та некондиційних руд, які раніше не розглядалися для промислової розробки. Практична цінність роботи полягає у можливості підвищення економічної ефективності гірничодобувних підприємств, зниженні витрат на видобуток та переробку руд, а також зменшенні негативного впливу на навколишнє середовище. Запровадження підземного блочного вилуговування сприятиме сталому розвитку уранової промисловості України

Ключові слова: блочне підземне вилуговування; гірничо-хімічна технологія; уранові родовища; низькосортні руди; ядерна енергетика