UDC 621.039 DOI: https://doi.org/10.15407/geotm2026.176.014

Anatolii Mukhachev[1,*], https://orcid.org/0000-0002-6025-3988
Dmytro Yelatontsev[1], https://orcid.org/0000-0003-1043-418X
Viktor Zhdanov[2], https://orcid.org/0009-0000-4828-9059
Viktor Yakovlyev[1], https://orcid.org/0009-0002-7729-4230
Grzegorz Wałowski[3], https://orcid.org/0000-0002-0866-4368

[1]*M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine*
[2]*Concern "YUZHRUDA", Dnipro, Ukraine*
[3]*Institute of Technology and Life Sciences - National Research Institute, Falenty, Poland*
**Corresponding author e-mail:* map45@ukr.net

ENVIRONMENTAL AND TECHNOLOGICAL ASPECTS OF URANIUM PRODUCTION IN UKRAINE

Abstract. The present article analyzes the development of uranium technology processes in Ukraine from 1949 to the present. The global experience of uranium production confirmed the high scientific and technical potential of the country's nuclear industry, showed the guidelines and criteria for its effective development, and defined the environmental requirements for production to protect the environment from harmful components of uranium ore. The analysis of the development of domestic technologies for uranium mining and processing of deposits of different mineralisations allowed us to conclude that it is expedient to further develop them to the level of uranium needs of the country's nuclear power industry. This task should be solved based on accumulated technological experience confirmed by the technical and economic indicators of uranium ore processing technology. The doctrine of creating a nuclear fuel cycle adopted by Ukraine envisages the production of uranium oxide concentrate, a product with a low degree of technological readiness, which prevents the country from entering the global uranium enrichment services market. It has been shown that uranium ore processing waste consists of sludge after uranium sorption, the yield of which can be 1.2 tons per 1 ton of ore. The increase in waste volume was caused by gypsum formation owing to the neutralisation of sulfuric acid with lime. The waste contains radium-226 and thorium-232 isotopes, which determine their radioactivity and disposal requirements. It has been established that uranium ore processing using nitric acid technology can reduce the yield of the solid phase containing radioactive isotopes from 120% to 30% by replacing sulfuric acid with nitric acid during ore leaching, thereby significantly reducing the environmental impact. An analysis of the efficiency of industrial technologies showed that they can be developed by reducing the cost of production and improving their quality in terms of critical impurities as well as by producing a product with a higher degree of technological sophistication, uranium hexafluoride. This makes it possible to preserve uranium-238 after its enrichment and use it as a new nuclear fuel in the uranium-plutonium cycle (MOX fuel).

Keywords: nuclear power, uranium ore, uranium hexafluoride, concentrate, industrial waste, radioactivity, tailings, extraction, leaching.

1. Introduction

Uranium production is a strategic factor in the development of nuclear energy, as it produces up to 11% of all electricity [1]. Nuclear fuel (NF) based on natural uranium isotopes (^{235}U, ^{238}U) remains the main fuel for commercial thermal neutron reactors of PWR, BWR, CANDU, and VVER types. The presence of these isotopes in the fission products of NF allows their reuse to obtain the artificial plutonium isotope ^{239}Pu, which is used in the production of MOX fuel for new-generation BN-type fast neutron reactors [2].

The main methods of uranium ore extraction (with a uranium content of up to 2%) are open-pit and mining. In situ uranium leaching (ISL) was used when the metal content was up to 0.07 wt. %. The production of natural uranium in the form of an oxide concentrate (U_3O_8) exceeds 50,000 tons per year [3]. The growth of uranium production is determined by the construction of new nuclear power plants in countries that not only have a shortage of hydrocarbon reserves but also seek to

Received: 15.09.2025 Accepted: 15.12.2025 Available online: 31.03.2026

reduce their dependence on them due to the limitation of the negative impact on climate change.

According to the Concept of the State Targeted Economic Program for the Development of the Nuclear Industrial Complex for the Period Until 2026, the country needs up to 2,400 tons of natural uranium to provide its nuclear power plants with nuclear fuel. Over the past 30 years, many decisions have been made by the President, the Government, and the Verkhovna Rada on this issue, but it has not been possible to combine uranium mining and processing with nuclear fuel production. The reasons for this are the lack of technology for the production of uranium hexafluoride (UF_6) and the small volume of uranium raw materials.

Simultaneously, its output practically did not even reach the design capacity of the processing plant, owing to restrictions on raw material extraction. The lack of profit due to the low volumes of uranium ore processing due to the depletion of reserves in old mines and the constant lack of investment in the development of new mines led to a crisis in the uranium industry. Ukraine has imported uranium from one supplier (the USA), exploring its own reserves of uranium raw materials for 100 years [4].

To assess the scientific and technical levels and prospects of the uranium industry, it is of practical interest to compare the structure and experience of the uranium industries of the world and Ukraine in terms of the development of technologies and environmental requirements for environmental protection [5]. The main product of the uranium industry is natural uranium concentrated in the form of nitrous oxide, which is a product of low technological readiness. Its prices in the world market and sales volumes are determined by the conditions regulated by large producers of uranium in the USA, the UK, and France [6].

The production of nuclear fuel is based on obtaining and enriching UF_6. Without UF_6 production, Ukraine cannot produce anything other than oxide concentrate, which must be sold on the world market to maintain uranium production. Simultaneously, the task of creating domestic production of nuclear fuel with the return of depleted uranium after enrichment of natural uranium with a content of ^{235}U – 0.3% remains unresolved. Having explored uranium reserves of up to 300 000 tons, Ukraine can independently provide its nuclear power plants with uranium, provided that HFC production is established in cooperation with the EU companies.

An analysis of the technological foundations of global uranium production [7–10] shows that the main method of uranium ore extraction remains mining, and the main (up to 90%) method of uranium extraction is sulfuric acid leaching using oxidants to convert U(IV) to U(VI). Along with uranium production, a related production of sulfuric acid is produced, which works on imported raw materials (native sulfur). In uranium production, sulfuric acid is completely processed with the formation of gypsum ($CaSO_4 \cdot 2H_2O$) and is not regenerated [11]. Simultaneously, radioactive residues are formed from the processing of uranium-containing ores with increased activity concentrations of daughter products of uranium-238 (radium-226, thorium-230, lead-210, and polonium-210). Gypsum, which is formed during acid neutralisation, increases the volume of technogenic waste by 20%, requiring the allocation of significant areas for permanent disposal [12]. This problem is relevant for Ukraine, as waste from uranium ore processing is located in agricultural areas far from the operating mines. This makes it costly to transport uranium ore enrichment residues by rail to mining sites as backfill and necessitates their storage in overloaded tailings facilities near the hydrometallurgical plant (HMP) [13].

In Ukraine, uranium forms deposits with ore contents ranging from 0.04 to 1% of various mineralisations [14]. This raw material is difficult to enrich and is poor, which requires more efficient processing to ensure high uranium extraction, regeneration of chemical reagents, and the ability to comprehensively leach all useful components of the ore to obtain commercial products.

The achieved level of industrial technology requires the presence of ore with a uranium content of at least 0.1% for economically profitable processing. Processing ore from sandstone deposits with a uranium content of 0.03–0.07% requires a different technology than the mining method. In Kazakhstan alone, underground leaching technologies enable the extraction of up to 20% of the world’s uranium supply. They do not require mine construction. Ukraine was the first country to implement this technology at an industrial scale [15]. Uranium reserves in the sandstone deposits in Ukraine amount to up to 50,000 tons, making them promising for future extraction.

The global experience of processing off-balance ores using block and heap leaching methods makes it possible to produce off-balance uranium ores with a uranium content of 0.02–0.07%. The domestic experience of uranium ore processing is highlighted in [16]. One of the key technical achievements was the development of a process for enriching silicate uranium ores using radiometric indicators, which made it possible to isolate up to 30% of waste rock as an inert material. Autoclave leaching of ore made it possible to increase the uranium recovery from 91 to 93%. Simultaneously, the main disadvantages of sulfuric acid technology, such as a high yield of technological waste, irreversible loss of reagents, labouriousness of mining processes, and a low degree of raw material processing, remain concomitant factors in uranium production, reducing its efficiency.

According to the State Economic Program for the Management of Spent Nuclear Fuel of Domestic Nuclear Power Plants for the Period Until 2025, a strategy was adopted for the sale of uranium oxide concentrate to obtain UF_6 and nuclear fuel based on it, in cooperation with foreign companies. A critical analysis of the scientific and technical levels of known technologies for the processing of poor and complex uranium ores in developed countries has shown the need to obtain uranium oxide, uranium dioxide, and UF_6 instead of uranium oxide concentrates.

The purpose of this study is to analyse the scientific and technical level of global and Ukrainian uranium ore processing technology, study the possibility of increasing its efficiency and environmental safety, and the possibility of switching to UF_6 production to meet the needs of the country's nuclear power plants in nuclear fuel based on existing capacities.

2. Theoretical part

Characteristics of Ukraine's uranium production and its efficiency criteria

The first experience in processing uranium ores of Kryvbas (Pershotravneve, Zhovtorichenske, and Michurinske deposits) was obtained from 1949 to 1961. The initial product, a 40% uranium concentrate, was obtained in April 1949. Kryvbas ores contain 60–70% iron, and the first technology is blast furnace smelting to obtain pig iron and slag, which contains up to 0.8% uranium [17]. The slag was processed according to a previously described scheme using nitric and sulfuric acids or their mixtures. The use of nitric acid requires the utilisation of nitrate ions, which are implemented in the form of sodium nitrate production. Subsequently, blast furnace smelting was replaced by uranium leaching with nitric acid to obtain an iron-containing concentrate that was not contaminated with radionuclides for cast iron production. This is the world's first experience in the complex processing of uranium ore to produce pig iron, uranium concentrate, and sodium nitrate. The yield of the radioactive solid phase for disposal was less than 0.3 tons per 1 ton of ore.

The creation of a related enterprise for the production of nitric and sulfuric acids, ammonia, and ammonium carbonate made it possible to produce uranium with cheap reagents and to utilise them in the production of aluminum–ammonium alum and nitrogen fertilisers. All industrial technologies for processing carbonate and silicate ores, phosphorus concentrates, and "yellow cake" concentrate using nitric and sulfuric acids and obtaining fertilisers were tested. The uranium recovery exceeded 99%, and the quality of the nitrous oxide concentrate approached that of uranium dioxide [18]. This made it possible to recommend a concentrate for processing according to a more efficient refining scheme with the production of UF_6 for enrichment purposes. Nitric acid technology enables the transfer of toxic radionuclides into the solution and their concentration in the solid phase for disposal. The use of nitric acid makes it possible to carry out all processes in equipment made of corrosion-resistant steel, thereby reducing operating costs.

In parallel, the sulfuric acid scheme for processing uranium ores in Kryvbas has been operating since 1959. In industrial uranium processing, drilling and blasting [19], radiometric enrichment, self-grinding, sorption and desorption, extraction, and re-extraction were tested. The environmental problems of production, particularly the disposal of radioactive mine water, have been solved by chemical treatment.

Over the period 1959–2024, more than 60 million tons of uranium ore was processed in Ukraine. The resulting nitrous oxide concentrate met all requirements of the international ASTM standard. In general, scientific and technical achievements in uranium production provide a leading level for all the technical indicators. During industrial operations, reliable technological equipment and methods for automation and production control have been developed and implemented [20]. Both technologies (sulfuric and nitric acid) have proven to be effective in terms of a set of technical and economic indicators under a full load of design capacities and guaranteed sales of products for nuclear power production.

Under conditions of fierce competition in uranium production in the world market, in the absence of its own production of nuclear fuel but with the availability of its production capacities, the country must choose between two paths for the development of the industry:

1) Increase the production of uranium oxide concentrate to the design capacity of the HMP, which determines the level of profitability of the plant, with purchases from the State Reserve or sales in the world market (which can only be a temporary solution).

2) Maintain the volume of current production in the HMP at 50% of the projected production with subsidies.

To meet the needs of nuclear power plants, the degree of uranium processing into UF_6 must be increased, which will open the world market for enrichment services. The tablet production of enriched uranium can be established only in cooperation with foreign high-tech companies (from the USA, UK, and France). This will allow us to begin producing nuclear power from an assembly plant. At the same time, the price of uranium to meet the needs of nuclear power plants can be accepted, based on the strategic position of nuclear energy, at the level of the cost of its production, since the main profit will be obtained during the production of electricity and heat

The development of uranium production requires innovative technical solutions and significant capital investments to ensure stable raw-material production and more efficient HMP operations. Achieving high efficiency with current uranium technology at existing capacities is possible by deepening the processing of raw materials into UO_2 tablets and solving environmental problems during the disposal of technogenic waste. Under the current conditions, a domestic uranium raw material base must be developed for the design capacity of HMP to ensure stable operation.

The lack of an objective possibility of selling Ukrainian uranium concentrate on world markets by 2030 (the time of the forecast price reaching $130 per 1 kg) suggests the only option: to establish uranium production in a limited volume and purchase concentrate for the State Reserve (following the example of the USA and the PRC), and to create a system of preferential financing of the plant to attract investments for the period of creating the final technology redistribution, with the receipt of UF_6 and UO_2 tablets through international cooperation.

The criteria for the efficiency of uranium production activities are as follows:

- The quality of the manufactured products meets the requirements of the ASTM standards.
- The level of technology that allows for the comprehensive processing of raw materials with the removal of all by-products and the disposal of reagents.
- Minimal loss of valuable components and reagents
- Technical efficiency, high specific productivity, and reliability of technological equipment
- Environmental safety;
- Competitive product costs and availability of balance sheet profits
- Financial sustainability of production.

To develop uranium production at the HMP in accordance with sustainable development criteria, it is necessary to directly obtain nuclear-pure uranium dioxide instead of uranium oxide concentrate and uranium tetrafluoride (UF_4) as raw materials for UF_6 in the available areas. The UF_4 production technology is similar to previously developed Ukrainian technologies for the production of zirconium and hafnium tetrafluorides, which have proven their high efficiency in comparison with foreign competitors [21].

The domestic production of UF_6 based on the fluorination of uranium tetrafluoride with elemental fluorine can be achieved by purchasing equipment and technologies from developed countries or by producing UF_6 from its tetrafluoride at the free capacities of companies that produce this product in series. A reduction in uranium cost can be achieved by using and developing domestic and global experience in mining and the complex processing of raw materials by increasing uranium extraction, technical characteristics, and specific productivity of equipment.

Environmental aspects of uranium production and waste management

The methods for mining and processing uranium ores have different environmental effects. The mine-mining method has been used in Ukraine since 1949. In 1959, a new method for mining uranium without lifting it to the surface was developed: ISL mining [22]. The depth of uranium mines can reach 1.3 km, which requires safe conditions for their operation [23]. This requires the placement of primary processes for uranium ore extraction and enrichment in underground horizons in compliance with industrial safety standards, primarily protecting personnel from radon-222, which is released during ore crushing. The appearance of fractions with a uranium content of <0.07% in the uranium ore extraction process requires processing outside the main technology by block and heap leaching methods using sulfuric acid. These processes make it possible to obtain solid waste that can be used to backfill the spent horizons instead of moving them to the tailings. The removal of radioactive radon gas through a ventilation system makes it possible to reduce its concentration in the working area to meet the sanitary standards. The dilution of ores with a uranium content of <0.3% with poorer ore to a concentration of 0.1% is a mandatory process in the industry. Although this increases metal recovery, it also results in increased solid waste after leaching and faster filling of tailing ponds.

The uranium content of the ore after heap leaching was reduced to less than 0.02% [24]. Uranium residues must be recovered from the heap leaching waste and stored separately from the sludge after the main leaching process. The presence of uranium and thorium decay products (^{226}Ra, ^{210}Po, and ^{210}Pb) in the ore determines the need for the isolation of the solid phase after uranium extraction, which requires the creation of expensive and dangerous tailings facilities in agricultural areas.

The negative impact of uranium mining waste on the environment, primarily on the alienation of agricultural lands for an unlimited period, requires more advanced methods of uranium ore processing than the standard sulfuric acid scheme [25]. Sulfuric acid did not transfer Ra into the solution. It remains in the form of sulfate in the solid phase and contaminates it.

The partial replacement of the mining method of uranium ore extraction with the ISL method makes it possible to produce poorer ores with uranium contents of up to 0.03–0.07% at depths of 40–600 m [26]. Their processing allows all radioactive elements, except uranium and thorium, to remain on the ground and does not raise the waste rock to the surface. The uranium solution was extracted using submersible pumps in the form of a dissolved compound (uranyl sulfate) and was processed to obtain a nitro-oxide concentrate. The cost of this extraction method does not exceed $60 per 1 kg of uranium, which is 2–3 times lower than that of uranium extracted using the mine method. The environmental advantages of the ISL method have led to an increase in uranium extraction by up to 20% worldwide.

Ores from the Pershotravneve, Zhovtorichenske, and Michurinske deposits were processed from 1949 to 1970 using a nitric acid scheme at the Prydniprovskyi Chemical Plant in Kamianske [27]. Since 1991, ores from Kryvbas have been processed using only the sulfuric acid scheme. A comparative analysis of the advantages and disadvantages of various uranium technologies used in industrial practices is of practical interest. The results of the analysis are presented in Tables 1 and 2.

A comparison of the indicators of both schemes shows that the nitric acid scheme is much more technological and less energy intensive. After 1991, the nitric acid scheme was discontinued, and uranium silicate ore was processed only by the sulfate acid scheme and carbonate ore by the carbonate scheme using the Ukrainian AMP anion exchanger. Over 75 years of uranium production, technological equipment for all stages, from ore processing to the production of uranium tetrafluoride, have been created and successfully tested. The main technological advantages of the nitric acid scheme are outlined in a previous study [27].

Table 1 – Technological indicators of acid processes for uranium ore processing

Process	Indicator	
	Sulfate acid scheme	Nitric acid scheme
Grinding	-0.074 mm	-0.15 mm
Leaching	Autoclave under pressure	Stirring
Thickening	1650 g/cm^3	>1750 g/cm^3
Sorption apparatus	Volumetric mixing patch	Patch with floating resin layer
Ion exchange sorption	AMP	AMP
Neutralizing agent	$Ca(OH)_2$	Na_2CO_3
Phase separation	Decantation at the tailings pond	Vacuum thickeners, disc vacuum filters, disc vacuum filters
Using dam water in the cycle	Ore pulping	Tailings transport to storage
Disposal of reagents	Plaster for burial	Sodium nitrate for fertilizer
Specific yield of solid phase	1.2 t/t	0.3 t/t
Concentrate of radioactive elements	Solid phase	Salt phase
Solid phase disposal	100% for burial	Up to 70% as an inert building material

Table 2 – Technical and economic indicators of acid uranium ore processing schemes

Article	Indicator	
	Sulfate acid scheme	Nitric acid scheme
Electricity consumption for grinding	Fine grinding (-0.074 mm)	Coarse grinding (-0.15 mm)
Reagent consumption per 1 ton of uranium, kg:		
H_2SO_4	60–100	-
MnO_2	0.04	-
HNO_3	15	0.75
Ion exchanger consumption, g/t	25	20
Uranium recovery, %	93	99.5
Reagent utilization, %	0	80–85
Solid phase yield for disposal, %	120	30
Tailings storage facility filling period, years	25	75
Finished product	U_3O_8	UO_2

A study of uranium ore processing technology using the Pershotravneve deposit as an example was conducted according to the scheme shown in Figure 1. The results of industrial testing of the scheme are presented in [27].

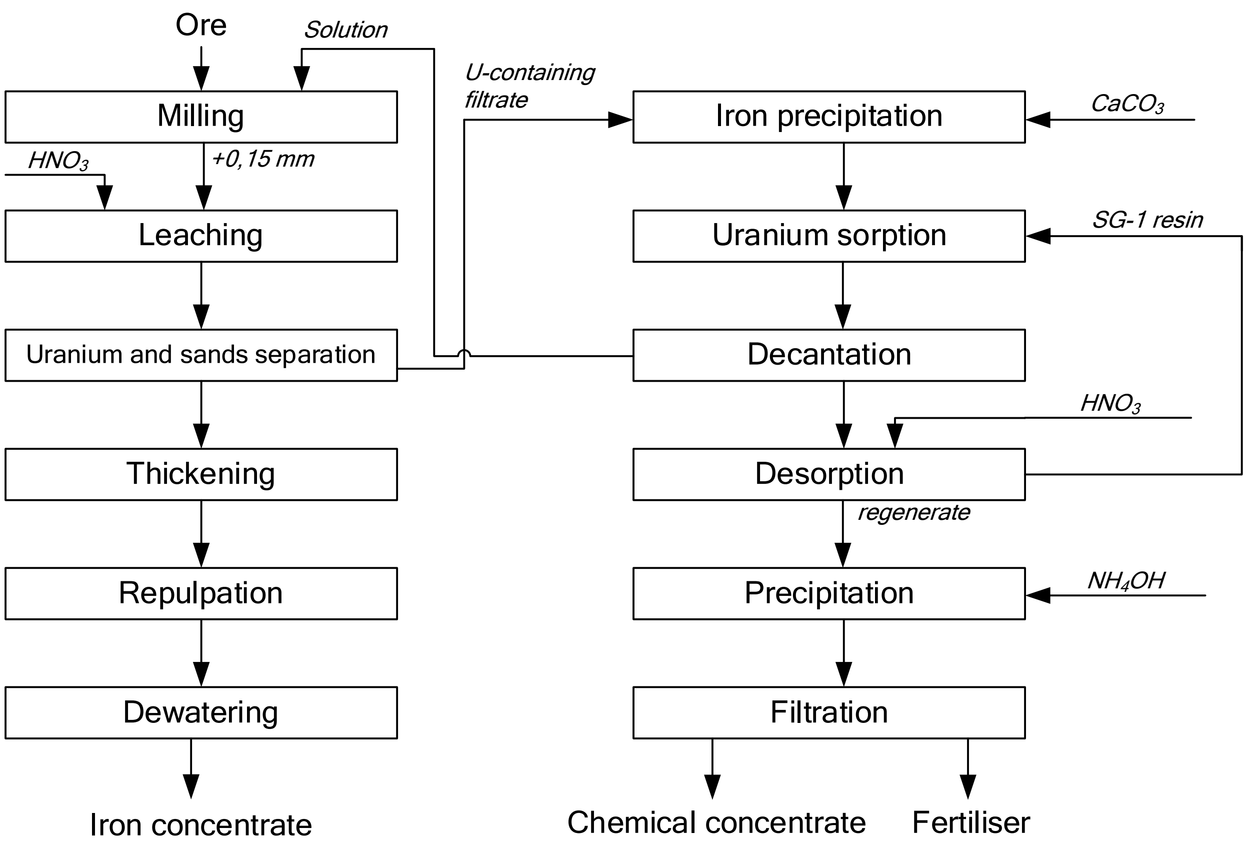

Figure 1 – Schematic diagram of ore processing at the Pershotravneve deposit

The results of the radiochemical analysis of the iron-ore sands are presented in Tables 3 and 4.

Table 3 – Radioisotope composition of sands

Acidity, g/dm³	Component	
	U, %	^{226}Ra, Bq/g
7.8	0.005	0.094
25.0	0.006	1.0

Table 4 – Chemical composition of iron-bearing sands

Component	Content, %
U	0.006
FeO	16.0
Fe_2O_3	68.1
Al_2O_3	0.61
MnO	0.04
S	0.07
V_2O_5	0.345
P_2O_5	0.082
SiO_2	9.1
CaO	0.178
MgO	1.43
H_2O	15.0

The sands are the iron ore concentrate (IOC), with an iron content of over 70%. The iron ore sands were washed with water at hydromodule S:L = 1:1 and treated with nitric acid at S:L = 1:0.9 at a temperature of 80 °C for 2 h. Isotope content ^{226}Ra before processing was 0.87 Bq/h, and after processing, it was 0.07 Bq/g, indicating that the activity of the sands after treatment was noticeably reduced. This made it possible to use IOC in blast furnace smelting to obtain pig iron and slag, thereby reducing the solid phase output for disposal to 0.3 t per 1 t of ore. The degree of iron extraction from the IOC was 85%.

The nitric acid solutions were neutralised with soda, followed by preliminary precipitation and separation of calcium, magnesium carbonates, and radioactive elements. The filtrate containing sodium nitrate was used for the production of sodium nitrate, which reduced the cost of uranium. The consumption of acid per 1 ton of uranium was 160 kg.

Nitric acid technology has proven to be effective for processing uranium raw materials because of its comprehensive processing. During industrial operations, three types of products are obtained: uranium, IOC, and sodium nitrate. The latter did not contain radioactive elements and its yield was 0.184 t/t. Sodium nitrate is more effective than ammonia in acidic soils in arid regions. Nitrate ions (NO_3^-) quickly enter plants, and Na^+ ions partially replace potassium in plants and increase crop yields. The sales of sodium nitrate reached 20%.

The technology of processing uranium ores by the sulfuric acid method produces solid waste containing 0.005–0.02% uranium and radionuclides of the uranium series: isotopes ^{226}Ra, ^{210}Po, and ^{210}Pb. The mineralogical composition of these wastes is practically identical to that of the ore, as shown in the carbonate and quartzite ore examples in Table 5.

Table 5 – Chemical composition of technogenic waste from uranium mining

Component	Content, %	
	Carbonate ore	Quartzite ore
SiO_2	50.0±0.5	58.5±0.5
F_2O_3	4.8±0.1	4.9±0.1
Al_2O_3	13.0±0.5	14.0±0.5
CaO	7.0±0.5	7.0±0.2
MgO	4.0±0.5	3.7±0.3
MnO	0.2	0.28
P_2O_5	0.08	0.07
S	0.3	0.35
V_2O_5	0.58	0.02
TiO_2	0.55	0.7

The radioactivity of both types of wastes requires additional decontamination and processing. During the leaching process, up to 93% of the uranium passed into the solution. Up to 7% of uranium and all radioactive isotopes remain in the solid phase and are stored in tailings facilities [28].

During uranium ore processing using the sulfuric acid scheme, up to 60 million tons of waste are accumulated and stored in contact with the atmosphere. Given the significance of territories that withdraw from agricultural use, there is a need for reclamation. Possible solutions to this problem are considered in [29].

Improvement of uranium refining processes

The development of uranium production in Ukraine has progressed from obtaining a 40% concentrate to nuclear-grade uranium dioxide concentrate [28, 30]. This makes it possible to recommend a concentrate for direct fluorination with hydrofluoric acid and elemental fluorine, with the production of uranium tetrafluoride and hexafluoride, respectively. The replacement of the settling-filtration scheme for uranium ore processing with a sorption-free filtration scheme in 1961 made it possible to obtain a uranium oxide concentrate that served as the main raw material for the production of uranium hexafluoride, with the production of enriched uranium tablets within the framework of a single technological cycle of the USSR.

The first sorption process involved the extraction of uranium from dilute sulfuric acid slurries on the SG-1 cation exchanger in the patch with air mixing. The disadvantages of this process are dilution of the system, low selectivity, low capacity of the cation exchanger, and increased consumption.

In the sulfuric acid variant, iron impurity removal during uranium sorption was performed by chalk treatment of pulp to a pH of 3. This made it possible to reduce the iron content from 9.3 g/dm^3 to 5 g/dm^3 and obtain a purer uranium concentrate with respect to the impurities. However, the precipitation of iron in the form of hydroxides leads to uranium capture and a decrease in its recovery.

In the nitric acid version, the nitrate ion concentration did not exceed 120 g/dm^3, which increased steam consumption for nitrate production. With such dilution, uranium was in solution in the form of the UO_2^{2+} cation, which was sorbed by the SG-1 cation exchanger. No chalk treatments were performed.

The technological shortcomings of uranium sorption on the SG-1 cation exchanger necessitated the use of an AMP anion exchanger. Therefore, the nitrate ion concentration was increased to 400–450 g/dm³. Under these conditions, uranium forms a complex compound $Na_2[UO_2(NO_3)_4]$, which is a complex anion. Impurities remained in the solution during sorption. Converting uranium to its anionic form made it possible to increase the capacity of the sorbent to 30–35 mg/g and its selectivity.

The sorption of a uranium complex on an AMP anion exchanger can be described by the following equation:

$$2R(NO_3)_2 + [UO_2(NO_3)_4]^{2-} \leftrightarrow R_2[UO_2(NO_3)_4] + 2NO_3^-.$$

The capacity of the anion exchanger for aluminum was less than 2 mg/g and that for iron was less than 6 mg/g. The temperature of the sorption process was maintained below 50 °C. The sorption process was conducted in a patch version in the counterflow of the sorbent and pulp. Desorption was performed using 2% HNO_3 solution according to the following reaction:

$$R_2[UO_2(NO_3)_4] + HNO_3 \leftrightarrow 2RNO_3 + UO_2(NO_3)_2.$$

An increase in the nitrate ion concentration was achieved by introducing the mother liquor after the crystallisation of sodium nitrate with a concentration of NO_3^- up to 500 g/dm³ into the head of the process. Increasing the total concentration of NO_3^- to 400–450 g/dm³ made it possible to reduce the acidity from 25 to 4 g/dm³, which maintained a high degree of transition of radioactive elements into the solution and ensured the possibility of their isolation into a separate concentrate for disposal. Uranium recovery during leaching was greater than 98%. Before the sorption process, the density of the pulp reached 1750 g/dm³, which reduced the water and steam consumption. The difference in the specific gravities of the liquid and solid phases made it possible to carry out the uranium sorption process in a floating layer and reduce resin consumption due to abrasion.

The transition from dilute media with a density of 1050 to 1750 g/dm³ made it possible to reduce the watering of the system, increase the concentration of uranium in technological solutions, increase the working capacity of the sorbent, and reduce electricity consumption. The development of technology for the sorption extraction of uranium has made it possible to reduce its content in tailings to 0.001% and 1 mg/dm^3 in the raffinate. The creation of our own production of ion-exchange resins made it possible to provide the country's uranium industry with these resins. The need to increase the selectivity and working capacity of sorbents has led to the creation of a new class of sorbents, namely, solid extractants (TVEX), which combine an organic matrix with extractants such as TBP, POR, and DEHPA, thereby increasing their capacity to 100 mg/g, reducing their consumption, and improving the quality of uranium compounds in terms of impurity content [31]. The creation of a line of pulsed columns with a distribution nozzle made it possible to intensify uranium concentration processes and replace energy-intensive bulky patches with energy-efficient column apparatuses, as well as to reduce the simultaneous loading of the sorbent and its loss.

The next significant step towards improving uranium quality could be the transfer of extraction equipment from box-type apparatuses with a volume of 15 m^3 to centrifugal extractors. This made it possible to reduce the volume of the extractant loaded by an order of magnitude owing to better process kinetics with the imposition of a centrifugal field, and to reduce the costs of fire prevention measures. Centrifugal extractors EC-250, EC-125, and EC-400 have undergone successful industrial tests using complex technologies for purifying zirconium and hafnium from impurities [32]. This makes it possible to significantly reduce capital and operating costs, save production space, and reduce production costs. The development and implementation of the extractant back-irrigation method in industrial practice has made it possible to increase its capacity to 110 mg/g and reduce the content of impurities in the product to 10^{-3}%.

Selective processing of ammonium uranyl carbonate (AUC) crystals made it possible to isolate a light, contaminated fraction and process it according to an autonomous scheme with deeper purification of uranium. Improvements in the solid-phase uranium re-extraction process have made it possible to increase the crystal size and obtain a concentrate with a bulk density of 2.8 g/cm^3. The calcination of AUC crystals in a reducing atmosphere of ammonia and hydrogen reduced the U(VI) content to 4% and made it possible to obtain nuclear-pure uranium dioxide suitable for obtaining UF_4, the starting compound for obtaining UF_6 [30]. Selling uranium oxide concentrates in the world market or using it as a toll raw material for producing nuclear fuel under cooperation leads to the loss of up to 85% of uranium-238 after its enrichment with the uranium-235 isotope.

Sulfuric acid scheme of uranium production and ways to increase its efficiency

The technology for processing poor uranium ores in Ukraine has been described in detail in [28]. This differs from world experience in that uranium is leached in titanium autoclaves, which increases the metal recovery to 93%. The final product was a uranium oxide concentrate that met the international ASTM C967 standard.

The features of sulfuric acid technology are as follows:

1. Low uranium production.
2. Significant loss of reagents.
3. The solid-phase yield for disposal increases by up to 20%.
4. The dilution of ores with rock to form off-balance ores requires additional acid processing to extract uranium.
5. Lack of return of technogenic tailings to production of hardening binder.
6. The need to allocate agricultural land to new tailings facilities is another issue.
7. Insufficient use of additional methods for leaching uranium from off-balance ores.
8. Increased extractant consumption.
9. Discharge of mineralised mine water in the environment.

10. There is a lack of effective gas purification systems for capturing nitrogen oxides.
11. Use of energy-intensive technological equipment for leaching, sorption, and extraction

To increase the technical and economic efficiency of uranium production, the following technological problems must be solved:

1. Increasing the degree of uranium extraction.
2. The degree of dissolution of ores can be reduced by increasing the efficiency of enrichment processes.
3. Increasing the efficiency of uranium sorption using more effective sorbents and technological equipment.
4. Improvement of extraction processes and use of new highly efficient equipment, regeneration of extractants with improved uranium quality, and reduction of extractant losses.
5. Obtaining large crystals of AUC to increase the bulk weight of the nitrous oxide concentrate by 20–30%.
6. Reconstruction of the furnace compartment to increase productivity and concentrate quality.
7. Processing of mine water to obtain technical water.
8. Processing nitrogen oxides via catalytic decomposition.
9. Creation of a chalk calcination plant to produce calcium oxide and ammonium carbonate for uranium production.
10. Use of "yellow cake" concentrate, domestic or imported, as an additional uranium raw material.
11. Creation of installations to produce tetrafluoride, hexafluoride, and enriched uranium dioxide tablets.

Reconstruction of existing facilities and modernisation of technological equipment based on domestic and international experience [33–35] will make it possible to improve the quality of the concentrate to uranium dioxide, which is suitable for obtaining uranium hexafluoride, reducing the energy intensity of production, reducing the output of the solid phase for disposal, and reducing the cost of production to a profitable level.

3. Conclusions

1. The use of nitric acid technology for processing uranium ores can reduce the yield of solid waste to 0.3 tons per 1 ton of ore, whereas the current sulfuric acid technology increases the yield of the solid phase to 1.2 tons per 1 ton of ore.

2. The presence of radioactive isotope radium-226 in the solid phase necessitates its storage in specialised tailings facilities, which are expensive and result in irreversible loss of agricultural land. Nitric acid technology for processing uranium ores makes it possible to reduce the burden on the environment by increasing the tailings life of storage facilities by four times and utilising nitric acid in the production of mineral fertilisers.

3. The use of nitric acid media in uranium technology makes it possible to increase the recovery to 99.5%, increase the quality of the uranium oxide concentrate, and offer it for direct fluorination to UF_6.

4. The use of more effective sorbents, such as TVEX, and a new type of centrifugal extractor, makes it possible to reduce the energy consumption and cost of uranium concentrate redistribution.

5. The domestic production of zirconium and hafnium tetrafluorides makes it possible to organise the production of UF_4 using Ukrainian technology.

6. The establishment of UF_6 production will allow the country to enter the global market for enrichment services and save lunch uranium for the organisation of a closed nuclear power plant. The lack of domestic fluoride redistribution in uranium technology leads to losses of up to 85% of uranium-238 during the sale of uranium oxide concentrates.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Shannak, S. D., Cochrane, L. and Bobarykina, D. (2025), "Global uranium market dynamics: analysis and future implications", *International Journal of Sustainable Energy*, vol. 44, no. 1, 2457376. https://doi.org/10.1080/14786451.2025.2457376
2. Babenko, V. A., Jenkovszky, L. L., and Pavlovych, V. N. (2007), "Nuclear power industry: Tendencies in the world and Ukraine", *Physics of Particles and Nuclei*, vol. 38, pp. 795–826. https://doi.org/10.1134/S1063779607060056
3. Wang, T., Wu, Z., Xiong, W., Pan, X., Ye, X. and Liu, X. (2025), "The Impact of Uranium Resource Constraints on China's Nuclear Power Development", *Energies*, vol. 18, no. 6, 1507. https://doi.org/10.3390/en18061507
4. Puhalskiy V.N., Sinchuk V.V. and Basarab N.N. (2017), "Production and processing of uranium ore in Ukraine", *Geo-Technical Mechanics*, vol. 133, pp. 27–33.
5. Yıldız, T. D. and Tombal-Kara, T. D. (2024), "Challenges and recovery opportunities in waste management during the mining and enrichment processes of ores containing uranium and thorium–a review", *Gospodarka Surowcami Mineralnymi-Mineral Resources Management,* vol. 40, no. 1, pp. 25–62. https://doi.org/10.24425/gsm.2024.149305
6. NEA (2023), "Uranium 2022: Resources, Production and Demand", available at: https://www.oecd-nea.org/jcms/pl_79960/uranium-2022-resources-production-and-demand (Accessed 1 April 2025).
7. Li, T., Cui, Z., Sun, J., Li, Q., Liu, X. and Li, G. (2025), "Oxygen nanobubbles as an innovative oxidant for sustainable sulfuric acid leaching of uranium", *Journal of Cleaner Production*, vol. 501, 145352. https://doi.org/10.1016/j.jclepro.2025.145352
8. Woods, P.H. (2016) "Uranium mining (open cut and underground) and milling," in Hore-Lacy, I. (ed.), *Uranium for Nuclear Power: Resources, Mining and Transformation to Fuel*, Elsevier, Amsterdam, Netherlands, pp. 125–156. https://doi.org/10.1016/B978-0-08-100307-7.00006-5
9. International Atomic Energy Agency (2016), "In situ leach uranium mining: An overview of operations", *IAEA TECDOC Series* [Preprint], available at: https://www.iaea.org/publications/10974/in-situ-leach-uranium-mining-an-overview-of-operations (Accessed 1 April 2025).
10. International Atomic Energy Agency (2025), "Recovery of uranium from phosphate ores", *IAEA TECDOC Series [Preprint],* available at: https://doi.org/10.61092/iaea.2at3-fndo (Accessed 1 April 2025).
11. Lyashenko, V., Khomenko, O., Chekushina, T., Dudar, T. and Topolnij, F. (2021), "Evaluation of efficiency and environmental safety of leaching metals from ore: ways of development and prospects", *Technology audit and production reserves*, no. 3(3/59), pp. 19–26. https://doi.org/10.15587/2706-5448.2021.235288
12. Lyashenko, V. I. and Kovalenko, G. D. (2011), "Protection of the natural environment during mining and processing of uranium ores in Ukraine", *Ecology and Industry*, no. 4, pp. 29–35.
13. Lyashenko, V. I., Dyatchin, V. Z. and Tarkhin, Y. N. (2010), "Scientific and technical bases of life safety improvement in the uranium mining region" *Naukovyi Visnyk NHU*, vol. 2, pp. 7–14.
14. Cuney, M., Emetz, A., Mercadier, J., Mykchaylov, V., Shunko, V. and Yuslenko, A. (2012), "Uranium deposits associated with Na-metasomatism from central Ukraine: A review of some of the major deposits and genetic constraints", *Ore Geology Reviews,* vol. 44, pp. 82–106. https://doi.org/10.1016/j.oregeorev.2011.09.007
15. Khomenko, O., Tsendzhav, L., Kononenko, M. and Zhanchiv, B. (2017), "Nuclear fuel energy of Ukraine: production, science, education", *Mining of mineral deposits*, vol. 11, pp. 86–95. https://doi.org/10.15407/mining11.04.086
16. Mukhachev, A.P., Yelatontsev, D.O. and Nefedov, V.G. (2021), "Industrial technology of processing carbonaceous uranium ore in Ukraine", *Geo-Technical Mechanics*, vol. 158, pp. 84–102. https://doi.org/10.15407/geotm2021.158.084

17. Mukhachev, A.P., Nefedov, V.G. and Yelatontsev, D.O. (2022), "Physicochemical foundations of the pioneering technology for the carbonaceous uranium ore processing", *IOP Conf. Series: Earth and Environmental Science*, vol. 970, 012027. https://doi.org/10.1088/1755-1315/970/1/012027

18. Yelatontsev, D.O., Mukhachev, A.P., Kharytonova, O.A. and Nefedov, V.G. (2021), "Development and commercialization of economic scheme of uranium extraction from iron ore of Pervomayskoye deposit", *Bulletin of NAGN*, vol. 1, no. 14, pp. 6–15.

19. Lyashenko, V.I., Nebogin, V.Z. and Shkarin, V.V. (2016), "Improving the efficiency of blasting operations in the mines of Ukraine", *Surveying and subsoil use*, no. 3, pp. 14–21.

20. Mukhachev, A.P., Yelatontsev, D.A. and Kharytonova, O.A. (2022), "Physical and chemical foundations of the extraction refining of natural uranium", *Problems of Atomic Science and Technology*, vol. 137, no. 1, pp. 106–110. https://doi.org/10.46813/2022-137-106

21. Mukhachev, A.P., Yelatontsev, D.O. and Shevchenko, V.H. (2023), "Resource-saving and environmental protection in nuclear-grade zirconium and hafnium production", *Geo-Technical Mechanics*, vol. 164, pp. 135–149. https://doi.org/10.15407/geotm2023.164.135

22. Khomenko, O., Rudakov, D., Lkhagva, T., Sala, D., Buketov, V. and Dychkovskyi, R. (2023), "Managing the horizon-oriented in-situ leaching for the uranium deposits of Mongolia", *Rudarsko-geološko-naftni zbornik*, vol. 38, no. 5, pp. 49–60. https://doi.org/10.17794/rgn.2023.5.5

23. Palamarchuk, T., Prokhorets, L. and Amelin, V. (2024), "Analysis of technological developments for the maintenance of ore and uranium mines of Ukraine", *Geo-Technical Mechanics*, vol. 168, pp. 35–48. https://doi.org/10.15407/geotm2024.168.035

24. Stupnik, M., Kalinichenko, O., Kalinichenko, N., Yakovleva, S. and Pochtarev, A. (2025), "Environmentally sound technologies of ore drawing with waste rock disposal in underground mines", *IOP Conference Series: Earth and Environmental Science,* vol. 1457, no. 1, 012008. https://doi.org/10.1088/1755-1315/1457/1/012008

25. Lyashenko, V. and Andreev, B. (2024), "Increasing the efficiency and environmental safety of combined geotechnologies for leaching metals from and off-balance ores", *Norwegian Journal of development of the International Science*, no, 144, pp. 123–139. https://doi.org/10.5281/zenodo.14169157

26. Stupnik, M., Kalinichenko, V., Fedko, M., Pysmennyi, S., Kalinichenko, O. and Pochtarev, A. (2022), "Methodology enhancement for determining parameters of room systems when mining uranium ore in the SE" SkhidGZK" underground mines, Ukraine", *Mining of Mineral Deposits*, vol. 16, no. 2, pp. 33–41. http://dx.doi.org/10.33271/mining16.02.033

27. Korovin, Yu.F. (2011), "Solving environmental and resource-saving problems in uranium production", *Zbírnik naukovikh prats' Natsíonal'nogo gírnichogo uníversitetu*, no. 36, pp. 183–189.

28. Chernov, A.P. (2001), *Dobycha i pererabotka uranovykh rud v Ukraine* [Mining and processing of uranium ores in Ukraine], ADEF-Ukraina, Kyiv, Ukraine.

29. Sorokin, O.G., Sinchuk, V.V., Bezrodnyy, S.O. and Koshik, I.I. (2014), *Optimization of technological processes in the extraction and enrichment of uranium ores in Ukraine,* [Online], available at: http://www-pub.iaea.org/MTCD/Publications/PDF/TE-1739_CD/PDF/Session_4.pdf (Accessed 1 April 2025).

30. Mukhachev, A.P., Yelatontsev, D.A. and Kharytonova, O.A. (2022), "Physical and chemical foundations of the technology for obtaining uranium oxides", *Problems of Atomic Science and Technology*, vol. 138, no. 2, pp. 62–67. https://doi.org/10.46813/2022-138-062

31. Korovin, V., Shestak, Y., Pogorelov, Y. and Cortina, J.L. (2008), "Solid Polymeric Extractants (TVEX): Synthesis, Extraction Characterization and Applications for Metal Extraction Processes", in Aguilar, M. and Cortina, J.L. (eds.), *Solvent Extraction and Liquid Membranes*, CRC Press, Boca Raton, USA, pp. 279–318. https://doi.org/10.1201/9781420014112.ch8

32. Korovin, Yu.F. (2014), "Waste-free technology of nuclear-pure zirconium", *Zbírnik naukovikh prats' Natsíonal'nogo gírnichogo uníversitetu*, no. 44, pp. 152–161.

33. Stupnik, M., Kalinichenko, V., Kalinichenko, O., Shepel, O. and Pilchyk, V. (2024), "Environmentally friendly technologies of integrated open pit-underground mining", *Mining Revue*, vol. 30, pp. 25–31. https://doi.org/10.2478/minrv-2024-0037

34. Wang, Z., Song, H., Chen, Y., Song, J., Hou, M., Li, Q. and Yu, H. (2024), "Uranium resource of Europe: Development status, metallogenic provinces and geodynamic setting", *Energy Strategy Reviews*, vol. 54, 101467. https://doi.org/10.1016/j.esr.2024.101467

35. Kiegiel, K., Chmielewska-Śmietanko, D., Herdzik-Koniecko, I., Miśkiewicz, A., Smoliński, T., Rogowski, M., Ntang, A., Rotich, N.K., Madaj, K. and Chmielewski, A.G. (2025), "The Future of Nuclear Energy: Key Chemical Aspects of Systems for Developing Generation III+, Generation IV and Small Modular Reactors", *Energies*, vol. 18, no. 3, 622. https://doi.org/10.3390/en18030622

ЕКОЛОГІЧНІ ТА ТЕХНОЛОГІЧНІ АСПЕКТИ ВИРОБНИЦТВА УРАНУ В УКРАЇНІ

Мухачев А.П., Єлатонцев Д.О., Жданов В.М., Яковлєв В.М., Валовський Г.

Анотація. У статті наведено аналіз розвитку процесів уранової технології в Україні, починаючи з 1949 р. до теперішнього часу. Світовий досвід уранового виробництва підтвердив високий науково-технічний потенціал атомної промисловості країни, показав орієнтири і критерії її ефективного розвитку, визначив екологічні вимоги до виробництва щодо захисту навколишнього середовища від шкідливих компонентів уранової руди. Аналіз розвитку вітчизняних технологій видобутку і переробки урану родовищ різної мінералізації дав змогу зробити висновок про доцільність їх подальшого розвитку до рівня потреб ядерної енергетики країни в урані. Це завдання має вирішуватися на основі накопиченого технологічного досвіду, підтвердженого техніко-економічними показниками технології переробки уранових руд. Прийнята Україною доктрина створення ядерно-паливного циклу передбачає випуск концентрату закису-окису урану – продукту невисокого ступеня технологічної готовності, що перешкоджає виходу країни на світовий ринок послуг з його збагачення. Показано, що відходами переробки уранових руд є шлами після сорбції урану, вихід яких може становити 1,2 т на 1 т руди. Збільшення об'єму відходів спричиняється утворенням гіпсу внаслідок нейтралізації сірчаної кислоти вапном. Відходи містять ізотопи радій-226 і торій-232, які визначають їхню радіоактивність і необхідність захоронення. Встановлено, що переробка уранової руди за азотнокислотною технологією дозволяє знизити з 120 % до 30 % вихід твердої фази, яка містить радіоактивні ізотопи за рахунок заміни сірчаної кислоти на азотну при вилуговуванні руди, що істотно знижує екологічне навантаження на навколишнє середовище. Аналіз ефективності промислових технологій показав, що вони можуть розвиватися завдяки зниженню собівартості продукції та підвищенню її якості за вмістом критичних домішок, а також завдяки отриманню продукту вищого ступеня технологічної досконалості – гексафториду урану. Це дає змогу зберегти уран-238 після його збагачення і використовувати його як новий вид ядерного палива в уран-плутонієвому циклі (МОХ-паливо).

Ключові слова: ядерна енергетика, уранова руда, гексафторид урану, концентрат, техногенні відходи, радіоактивність, хвостосховище, екстракція, вилуговування.