Mining of Mineral Deposits
Volume 19 (2025), Issue 1, 37-46

https://doi.org/10.33271/mining19.01.037

Study of rational solution parameters during in-situ uranium leaching

Shukhrat Alikulov [1], Javokhir Toshov [2], Ravil Mussin [3], Mukhammedrakhym Rabatuly [3*], Bauyrzhan Tolovkhan [3], Zhanbota Bogzhanova [3], Ayauzhan Gabitova [3]

[1] *Navoi State University of Mining and Technologies, Navoi, Uzbekistan*
[2] *Tashkent State Technical University, Tashkent, Uzbekistan*
[3] *Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan*

**Corresponding author: e-mail mukhammedrakhym@gmail.com*

Abstract

Purpose. The research aims to study and optimize the in-situ leaching (ISL) process for uranium mining using surface-active substances (surfactants) to improve the efficiency of uranium extraction from low-permeability ores.

Methods. As part of the research, samples of low-permeability ores are taken and previously analyzed for porosity and filtration anisotropy coefficient, which is important for assessing their filtration properties. To study the effect of surfactants such as polyacrylamide, sulfanol and Mesh Drainage Liquid Filter (MDLF) compounds, solutions with different concentrations of these substances are prepared. Also, to determine the most effective surfactant concentrations, additional studies are conducted to optimize the leaching conditions, taking into account the effects of various factors such as temperature and pH of the solution. All the obtained results are mathematically analyzed to identify the optimal conditions, which helps to increase the efficiency of the uranium leaching process and improve the experimental results.

Findings. In the course of the research conducted on the selection of surfactants for uranium leaching from low-permeability ores, the following results have been obtained. Sulfanol, as one of the surfactants used, shows the best results, significantly increasing the filtration coefficient from 0.5 to 2.0 m/day. This confirms its high efficiency in improving the ore horizon permeability and in accelerating the leaching process.

Originality. The scientific novelty of the research is in the development of methods for optimal use of surface-active substances to improve the efficiency of the in-situ uranium leaching process from low-permeability ores. Studies have been conducted to determine the influence of various surfactants on the filtration properties of ores, as well as their in-fluence on accelerating the leaching process.

Practical implications. The practical significance of the research is in the possibility of using the obtained data to optimize the in-situ uranium leaching process at real deposits with low-permeability of ore horizons. The developed recommendations on the selection of surfactants, such as sulfanol and polyacrylamide, as well as their optimal concentrations, can be directly applied to improve leaching efficiency, increase filtration coefficient, and reduce seam treatment time.

Keywords: *in-situ leaching, colmatation, sulfanol, polyacrylamide, porosity, anisotropy, filtration coefficient*

1. Introduction

Mining engineering plays a critical role in supplying essential raw materials for energy production, industrial development, and infrastructure. However, the industry faces numerous challenges related to geomechanical stability, gas-dynamic phenomena, and the safety of underground operations. Recent activities have focused on improving mine support systems in zones of elevated rock pressure [1]-[3], assessing the impact of the coal surface layer on gas-dynamic events within seams [4], [5], and analyzing the influence of rock shear processes on methane accumulation at longwall faces [6]-[9]. In response to these challenges, there is growing interest in the application of geotechnological methods that enable resource extraction with minimal disturbance to the rock mass and surrounding environment.

The in-situ leaching (ISL) method is one of the most effective approaches for uranium mining from low-grade ores and deposits with unfavorable mining-geological conditions [10], [11]. Today, the world's natural uranium reserves are estimated at 6.14 million tons, with 28% concentrated in Australia, 15% in Kazakhstan and 9% in Canada. Uzbekistan, with 132 thousand tons of proven reserves (about 2% of the world's reserves) ranks 11th in the world by this index. Since 1994, uranium mining in the republic has been conducted entirely by in-situ leaching method through geotechnological borehole systems [12]-[15].

In in-situ leaching, the most important factor is the production horizon permeability, which can be natural or created artificially by using special methods (hydraulic fracturing, destruction by blasting, etc.). In addition, the

Received: 15 November 2024. Accepted: 7 February 2025. Available online: 30 March 2025

Mining of Mineral Deposits. ISSN 2415-3443 (Online) | ISSN 2415-3435 (Print)

presence of partial or complete natural water cut of ores, confinement of ore mineralization to pores and fractures that provide permeability of ore, etc. are important for in-situ leaching (ISL) method [16]-[20].

The ISL method is widely used in the world for uranium mining and there are a number of depleted uranium deposits, where the studied ISL method has improved the efficiency of mining uranium deposits with difficult mining-geological conditions [21]-[23]. For mined-out and newly mined areas, the ISL method gives a full characterization of the structure, integrated approach to solving the issue, innovative application of the technical-technological aspect of the selected technology [24].

Interest in in-situ leaching method has been steadily growing in recent years [25]-[29]. In-situ leaching makes it possible to profitably exploit low-grade ores lost during stope mining, as well as deposits with difficult geological-hydrogeological conditions [30], [31]. Leaching at the site of ore occurrence is conducted either with preliminary crushing of ore bodies, or from stratified deposits composed of loose water-saturated sediments. Approximately 90-95% of uranium mined by in-situ leaching method occurs in stratified deposits [32], [33].

In-situ uranium leaching (ISL) has a number of significant advantages over traditional uranium ore mining and processing methods [34], [35]. The method eliminates such labor-intensive and costly operations as excavation, transportation, crushing and milling of ore, as well as the construction and operation of off-balance ore dumps and tailings dams [36], [37]. In addition, the use of ISL helps to reduce the time required to bring deposits into operation and the volumes of capital construction, simplify the hardware design of processes and improve working conditions by minimizing manual operations and reducing the risk of environmental pollution [38]. Experience of operating industrial in-situ leaching sites shows the following key advantages:

– reduction of specific capital costs and construction time by 3-5 times compared to traditional mining methods;

– 2-3 times increase in labor productivity;

– reduction of uranium mining costs by 15-25%.

Currently, more than 22 uranium deposits in Uzbekistan are successfully mined using in-situ leaching method. Among them, the most significant are South and North Bukinai, Uchkuduk, Ketmenchi, Sabyrsai, Sugraly and in-situ leaching site 102. These deposits are characterized by difficult mining-geological conditions, but the ISL technology has proven its effectiveness and economic feasibility in their mining.

Over the past decades, many mathematical models have been developed in theory and practice to improve the efficiency of in-situ leaching process. They are used to calculate and optimize the filtration rate of leaching solutions [39], pressure distribution in the production horizon [40], and the kinetics of transfer of useful component into pregnant solution [41]. These models provide the ability to predict the system behavior when changing process parameters and to develop optimal deposit mining modes.

Optimization of in-situ leaching parameters, such as filtration rate, leaching solution consumption and technological well network, plays a key role in intensifying the transfer of a useful component into the pregnant solution. Conducting research in this area contributes to improving the ISL efficiency, especially in mining of complex deposits, and forms a scientific basis for designing innovative uranium mining technologies.

2. Research background

The research focuses on selecting leaching solutions for mining uranium from low-permeability ores. We have therefore explored various reagents for mining deep, low-permeability uranium deposits using the ISL method. One of the solutions to the scientific-technical problem is to develop new technologies that ensure the completeness of metal extraction from the subsurface and control the hydrodynamic regimes of leaching solutions. Involvement of a low-permeability ore horizon in mining is expedient, thus increasing metal concentration in solutions, reducing the time of processing and specific consumption of reagent, and increasing the production capacity of the enterprise [42]-[44].

When extraction and injection wells are operated in the process of deposit mining using the ISL method, as a rule, there is a decrease in their flow rates. The main reason for such a negative technological factor is the process of colmatation of the pore rock volume in the near-filter zone of boreholes, as well as “clogging” of the perforation of the filters themselves. The main, if not the most important condition for reducing geotechnological well flow rates is colmatation of filters and near-filter zones of the production horizon rocks, which causes an increase in hydraulic resistances during the supply and pumping-out of process solutions [45]-[47].

During the mechanical colmatation process, the water intake openings of filters and pore sections of solution-conducting channels are blocked by fine sandy-clay particles contained both in drilling mud fluid during well construction and during their operation as a result of suffosion development. Thus, when using high-clay solutions with a density of 1.15-1.18 g/cm^3 in the drilling process to strengthen the walls of geotechnological wells, constructed on hydrogenic deposits, represented by interstratified loose, mostly weakly bound sandy-clay varieties, this leads to a decrease in their flow rates by dozens of times. In the process of claying of the production seam rocks in the near-filter zone, a clay crust up to 5-7 mm thick is created on the well wall, the permeability of which is 4-5 orders of magnitude lower than the permeability of the rocks.

Swelling of clay particles of drilling mud fluid filling the pore volume of the production seam near-filter zone reduces the flow section of effective pore channels, which also increases the hydraulic resistance of the driving liquid phase. With increasing contact time of clay drilling mud fluid with solid phase, the resulting clay crust compacts under the action of adsorption processes and molecular interaction forces, which leads to certain costs (construction pumping) for its removal [48]. Based on the kinetic mechanism of formation of such low-permeability clay screens, the contact time of drilling mud fluid with the production seam rocks should be minimized.

Along with mechanical colmatation of filter perforations and pore volume of rocks in the near-filter zone of the production seam, there are also chemical colmatation processes, caused by the changes in the chemical composition of supplied and pumped-out solutions when they interact with groundwater, as well as by the changes in the hydrodynamic fluid filtration parameters.

For example, reduction of hydraulic head in the zone of extraction (discharge) wells leads to a disturbance of the gas and salt solubility balance, causing them to be released from the liquid phase in the form of gel-like salt substances and in the form of gas dispersed insoluble bubbles.

Colmatation is the process of reducing the filtration properties of technological well filters and near-filter zones of the ore-bearing horizon due to deposition of substances dissolved in working solutions, mechanical movement of ore-bearing horizon particles, as well as due to outgassing [49], [50]. The following forms of colmatation are known:

– chemical, associated with the formation of chemical sediments in the pores;

– gas, caused by the formation of carbon dioxide and hydrogen sulfide in the ore-bearing horizon as a result of interaction of acid with carbonate rock components;

– ion exchange, related to the change in pore size in the presence of organic matter and clay minerals in permeable rocks under the action of pH change and mineralization of filtering solutions;

– mechanical, caused by clogging of rock pore channels with mechanical suspended solids and particles contained in filtering solutions.

Anisotropic in terms of filtration are rocks, the filtration coefficients of which in the stratification direction (K_{fx}) and transverse direction (K_{fx}) are different. The ratio K_{fz} / K_{fx} is commonly referred to as the filtration anisotropy coefficient.

Porosity is the ratio of a rock cavity volume to its total volume (% η). There are:

– total porosity (η_t) – the ratio of the volume all pores to rock volume;

– active porosity (η_a) – the ratio of the volume of pores open for filtration to the total volume of the rock.

The intensification of leaching processes using surfactants in solutions is the ability to reduce surface and interfacial tension due to adsorption and orientation of molecules on the interphase surface. This enhances the wettability of the ore during leaching and improves its chemical interaction with the reagent. Results of laboratory tests of some surfactants are given in the papers.

The research conducted aimed at selecting surfactants for mining uranium deposits with low permeability of ore-bearing horizons. Based on the results of natural emulsion decomposition tests on solution concentration, it is necessary to select surfactant for uranium leaching from low-permeability ores. When using leaching solutions, it is recommended to use OP-10, sulfanol, MDLF-1, MDLF-2, MDLF-3, and polyacrylamide (PAA).

In order to select chemical surfactant reagents, sediment dissolution tests were previously performed under laboratory conditions. Research results confirmed the effectiveness of chemical reagents in combination in terms of the dissolving capacity of the main carbonate and secondary sediment formation. To intensify the process of in-situ uranium leaching with the use of surfactant reagents will increase the rate of mining of technological blocks and reduce cost of final products. Description of the selected chemical reagents is given below.

PAA polyacrylamide solution (produced by JSC Navoiazot) (Fig. 1.) The following types of polyacrylamides are distinguished: non-ionic, anionic and cationic, which are used for water purification, water treatment and in mining industry. Polyacrylamides are used to process gold, uranium, iron, aluminum, etc. The general formula $(\text{-}CH_2CHCONH_2\text{-})_n$ represents the general structure of polyacrylamide, which consists of a repeating link based on an acrylamide group.

OP-10 solution. The auxiliary substances OP-7 and OP-10 are products of treatment of a mixture of mono- and dialkylphenols with ethylene oxide. They are used as wetting and emulsifying surfactants in oil-production, oil-refining, chemical, textile and other industries; one of the advantages is that they can be easily subjected to biological treatment in wastewater. Chemical formula: $O(CH_2\text{-}CH_2\text{-}O)_n\ CH_2\text{-}CH_2\text{-}OH$. n = 7-9 (for substance OP-7) and n = 10-12 (for substance OP-10). It is well soluble in water, completely decomposes, and is used to reduce the viscosity of leaching solutions (Fig. 2).

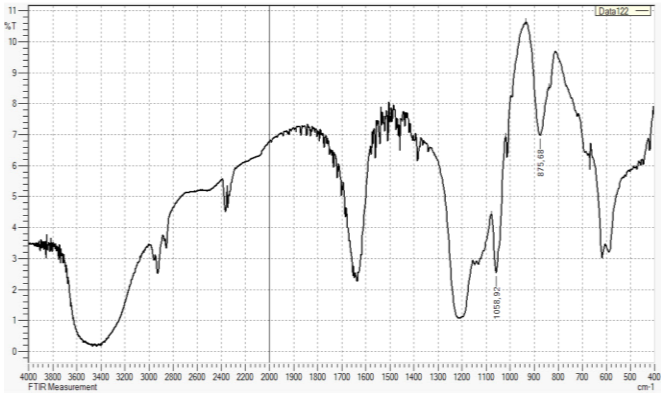

Figure 1. IR spectrum of leaching solution using polyacrylamide

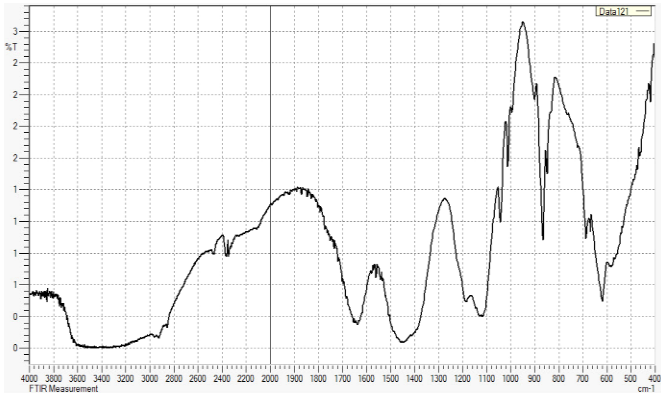

Figure 2. IR spectrum of leaching solution using OP-10

Aqueous solutions become turbid in the presence of NaCl. It is well soluble in water; solubility in water is greatly reduced in the presence of 70% sulfuric acid; reduces surface tension of water, creates persistent emulsions and foams. The product is non-toxic. In uranium mining enterprises, it is successfully used in acid leaching of uranium. It improves filtration characteristics, dissolves and loosens sediments in the well and increases the permeability of the bottomhole zone of the seam, thus increasing the well flow rate. Figure 3 shows the IR spectrum of the obtained leaching solutions using sulfanol.

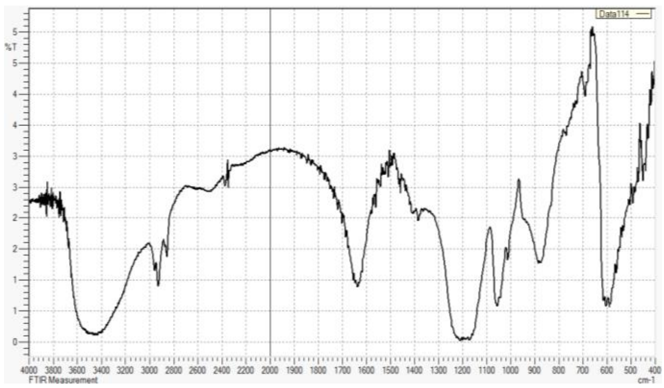

Figure 3. IR spectrum of leaching solution using sulfanol

Sulfanol solution is loose granular powder of yellow to light brown color, odorless or with a slight odor of kerosene; content of sodium salts of alkylbenzene sulfonic acids – not less than 80%, sodium sulfate – not more than 15%.

Sulfanols have a very characteristic absorption due to symmetric and antisymmetric SO_2 group vibrations. These bands are very intense and easily identified. In the spectra of solid compounds, they split to form a group of strong bands with close frequencies. Typically, solids absorb 10-20 cm lower than substances in solution. The low-frequency band shifts slightly less than the high-frequency band due to a change in aggregation state or hydrogen bond formation. In the spectra of sulfonic acids and their salts, the frequencies of symmetric and antisymmetric valence vibrations of the SO_2 group are in the range of 1260-1150 cm for antisymmetric and 1080-1010 cm for symmetric vibrations. The difference in frequencies between salts and the acids themselves is very small. In sulfochlorides and covalent sulfonates and sulfates, there is an increase in the frequency of valence vibrations of SO_2 groups. Thus, methane-sulphonyl chloride has bands in the range of 1370-1175 cm, and p-toluene sulphonyl chloride has bands in the range of 1366-1166 cm. Covalent sulfonates absorb in the ranges of 1420-1330 and 1200-1145 cm, while covalent sulfates absorb in the ranges of 1440-1350 and 1230-1150 cm.

MDLF-1 solution. The main characteristics of MDLF-1 solution make it possible to use it as a reagent (oxidizing agent) in the field of metallurgy to extract metals.

MDLF-2 and MDLF-3 solutions. Polycarboxylates are linear polymers with high molecular mass ($Mr \leq 100000$) and multiple carboxylate groups. They are acrylic acid polymers or acrylic acid and maleic acid copolymers. The polymer is used as a sodium salt.

However, the complex physical-chemical phenomena formed in the production seam during the reagent solution supply have a direct impact on well productivity through the resulting processes of seam pore volume colmatation and filter perforations. From here it follows that in the calculation formulas used in estimating the hydrodynamic regime parameters, it is necessary to take into account the factor of change in well productivity, depending on the values of filtration parameters of solutions. However, some aspects related to increasing the efficiency of deposit mining using the in-situ leaching method have not yet been solved. Thus, a technological regulation of measures and methods to prevent mechanical colmatation of seams, caused mainly by a decrease in the intake capacity of production horizons due to the penetration of suspended solids contained in injected solutions, has been developed.

Even at the first stages of operation of in-situ uranium leaching sites composed of loose water cut sediments, the phenomenon of a decrease in intake capacity of injection wells during their operation has been identified. In some sites, the reduction in intake capacity was so significant that even under conditions of its periodic restoration by pumping, drilling of additional injection wells was needed to ensure normal operation. For example, in the in-situ leaching site 2, the average intake capacity of injection wells decreased from 1.2 m^3/hour in 2019-2020 to 0.26 m^3/hour. To date, more than 50 additional wells have been drilled within the production site area to intensify the injection process. At the same time, it has been found that the main cause of well flow rate reduction is pore space colmatation with gases, sediments and suspended solids.

During the mechanical colmatation process, the water intake openings of filters and pore sections of solution-conducting channels are blocked with fine sandy-clay particles contained both in drilling mud fluid during well construction and during their operation as a result of suffosion development. Thus, when using high-clay solutions with a density of 1.15-1.18 g/cm^3 in the drilling process to strengthen the walls of geotechnological wells, constructed on hydrogenic deposits, represented by interstratified loose, mostly weakly bound sandy-clay varieties, this leads to a decrease in their flow rates by dozens of times. In the process of claying of the production seam rocks in the near-filter zone, a clay crust up to 5-7 mm thick is created on the well wall, the permeability of which is 4-5 orders of magnitude lower than the permeability of the rocks.

Swelling of clay particles of drilling mud fluid filling the pore volume of the production seam near-filter zone reduces the flow section of effective pore channels, which also increases the hydraulic resistance of the driving liquid phase. With increasing contact time of clay drilling mud fluid with solid phase, the resulting clay crust compacts under the action of adsorption processes and molecular interaction forces, which leads to certain costs (construction pumping) for its removal. Based on the kinetic mechanism of formation of such low-permeability clay screens, the contact time of drilling mud fluid with the production seam rocks should be minimized.

Along with mechanical colmatation of filter perforations and pore volume of rocks in the near-filter zone of the production seam, there are also chemical colmatation processes, caused by the changes in the chemical composition of supplied and pumped-out solutions when they interact with groundwater, as well as by the changes in the hydrodynamic fluid filtration parameters.

For example, reduction of hydraulic head in the zone of extraction (discharge) wells leads to a disturbance of the gas and salt solubility balance, causing them to be released from the liquid phase in the form of gel-like salt substances and in the form of gas dispersed insoluble bubbles.

Carbon dioxide balance is disturbed in the front line of the supplied acidic solutions:

$$2HCO^{3-} \rightarrow CO_3^{2-} + CO_2\uparrow + H_2O. \quad (1)$$

Calcium and magnesium cations previously dissolved as a result of carbon dioxide balance disturbance precipitate out, filling (colmatating) the pore volume of the production seam rocks in the form of gel-like (gelatinous) hard-soluble sediments – $CaCO_3$, $MgCO_3$. At the same time, the perforations of the filters of injection and discharge wells become "clogged" with such salt substances, thereby causing a decrease in their flow rates.

In filters of discharge wells, when water intake openings become clogged, the values of hydraulic resistances increase. If the flow rates are maintained at a constant level, the values of hydraulic heads in wells and on their external surface decrease, which also provides an increase in salt precipitation intensity and, accordingly, an increase in filtration resistances of filters.

An increase in carbon content of the production horizon rocks intensifies the colmatation process. In the practice of in-situ uranium leaching from ores through boreholes, rock colmatation processes with iron-bearing sediments are also observed. This process occurs when ferrous iron is present in groundwater and rocks. When dissolved oxygen (oxidizing agent) is present in the fed solutions, the iron changes from ferrous to ferric oxide:

$$Fe(HCO_3)_3 \rightarrow Fe(OH)_2 + 2CO_2; \quad (2)$$

$$4Fe(OH)_2 + O_2 + 2H_2O = 4Fe(OH)_3. \quad (3)$$

The precipitated iron oxide, having the structure of a gelatinous substance, is deposited on the filter surface, fills the perforation openings of the filter column and the pore volume of near-filter zone rocks in the production seam. The most active clogging of filters with iron-bearing sediments occurs during the mining of non-pressure ore aquifers using in-situ uranium leaching through boreholes, especially under the condition of a decrease in the dynamic level in the well below the upper zone of the filter column area, when creating a contact of perforations (water-intake openings) with atmosphere. The intensity of such sedimentation increases in the process of non-uniform hydrodynamic regime of operation of extraction wells. The use of an airlift or injector as a solution-lifting means also increases the oxygen supply intensity to the pumped solutions.

The first studies of colmatation phenomena in relation to the conditions of uranium in-situ leaching date back to 1965-1969. These studies have revealed (and operating practice data has confirmed) a significant development of two forms of colmatation at the initial stage of mining (the stage of the leached stratum saturation with acid solution): chemical and gas, which, however, at subsequent stages of mining do not have a decisive influence on the overall reduction in the filtration parameters of the production horizon. Unlike the types discussed above, colmatation of filters and near-filter zones of injection wells with suspended solids contained in leaching solutions occurs continuously from the beginning of mining until its completion, increasing over time, and is irreversible. A decrease in the filtration properties of leached stratum due to clogging of pore channels with suspended solid particles causes an increase in dynamic level in the injection well and pressure gradients in the area directly adjacent to it. This circumstance, in turn, contributes to the development of suffosion.

3. Materials and methods

Laboratory research was conducted on the basis of the approved program of JSC Navoi Mining and Metallurgical Company, together with scientific staff of Navoi State University of Mining and Technologies. Increasing the flow rate of extraction wells in the process of in-situ leaching depends on the permeability of rocks, and in order to improve the efficiency of rock filtration, it is necessary to use surfactants. The surfactant reagent helps to reduce the viscosity of leaching solutions, thereby improving their flow capacity, increasing uranium recovery from the ore seam, cleaning the fractures from filtrate and improving well productivity. The use of surfactants is increasing every year. Their use gives not only technological effect, but also cost savings with its relative availability in Navoi Region, as they are produced by JSC Navoiazot Company. The use of surfactants was studied on the filtration column, as well as on cores on the KFOM unit.

To perform laboratory research on determining the parameters and influence of surfactants on rock filtration, a research methodology has been developed and conducted at the laboratory base of Navoi State University of Mining and Technologies. This methodology allows modeling of filtration-leaching processes in porous media and taking into account real geotechnological parameters such as permeability, bulk density and chemical composition of the ore horizon.

The research on studying the influence of surfactants on the filtration coefficient was conducted using low-permeability core material (monolith). The Ketmenchi Uranium Deposit site with low ore permeability was selected and exploration drilling of one well was conducted to study the lithological composition of the earth' crust.

Geological exploration wells were drilled 100 m deep and 14 core samples were taken. Chemical and mineralogical compositions of core samples were determined. Geometric parameters of core samples, taken from the ore horizon, are 40 cm in length and 90 mm in diameter. Core material from the in-situ leaching site was visually examined and sampled for mineralogical analysis. It was then crushed to particle sizes of less than 2 mm and tested. The material was mixed by rolling and sampled to study the granulometric and chemical composition of the ores.

After delivery of core samples to the Central Research Laboratory of JSC Navoi Mining and Metallurgical Company, moisture content was determined using geotechnological research methods. Central Research Laboratory is a scientific division of Navoi Mining and Metallurgical Company, the largest uranium and gold mining-processing enterprise in Uzbekistan. Moisture content was determined by gravimetric method by drying core samples to constant weight at a temperature of 105°C. The main lithologic-filtration types of rocks and ores were identified by combining core samples with identical substance and granulometric composition.

Laboratory research was conducted to obtain geotechnological parameters of the leaching process for designing an experimental-industrial complex for metal mining using this method. The research is based on the methodology of studying liquid filtration in porous medium, known from the practice of laboratory research. Uranium leaching tests were performed in agitation and percolation modes. In the agitation mode (static for in-situ leaching conditions), the technological parameters of ore leaching with sulfuric acid solutions and using surfactants were mainly determined. Experiments were conducted when mixing pulp with mechanical stirrers and at given parameters - leaching solution temperature, pulp density, sulfuric acid concentration, experiment time, etc.

In the percolation mode (dynamic conditions for in-situ leaching process) experiments were performed on models representing a modern model close to the in-situ leaching process conditions (Fig. 4).

Figure4. Photofixation of uranium leaching process in statics

To date, this methodology has been widely used for leaching of metals from loose sandy deposits with some modifications taking into account the characteristics of the chemical process. Laboratory geotechnical tests were performed on core samples. Samples were taken at maximum core yield and represented a geologic section of the production aquifer of the deposit. During the leaching process, the following parameters were controlled: volume of solution passed through the model per unit time, pH and their oxidation-reduction potential, as well as uranium and bicarbonate ions content in solutions were determined. The results of the experiment are shown in Figure 5.

Figure 5. Photofixation of research process for determining acidity in leaching solutions without the use of surfactants

The technological and hydrodynamic parameters of ores in static and dynamic leaching conditions were studied on a group sample material formed from 14 core samples.

The laboratory experiments provided data on the influence of various factors on filtration and technological properties of rocks, including the use of surfactants, composition of leaching solutions and process parameters. The results obtained made it possible to identify optimal conditions for efficient uranium extraction from the ore horizon, as well as to assess the influence of key parameters on the leaching kinetics and permeability of the porous medium. The following section presents the research results that can be a basis for subsequent development of recommendations for designing the experimental-industrial complex. Research on geotechnological factors influencing the processes of colmatation of filters and near-filter zone of technological wells was conducted using the experimental block at the Tohumbet deposit.

To conduct research to identify the dependence of water permeability reduction in the production horizon rocks on filtration parameters and chemical composition of leaching solutions at the Tohumbet deposit, a block was selected, the natural (geological) parameters of which corresponded to the average for the deposit.

4. Results and discussion

Determination of moisture content of core samples and their bulk density is an important step in the assessment of lithologic-filtration properties of the production horizon. These parameters are key to understanding the filtration processes of leaching solutions through a porous media and, consequently, in optimizing in-situ leaching technology. The results of moisture content and bulk density measurements are summarized in Table 1.

Table 1. Results of determining the moisture content of core samples using geotechnological research methodology

No. of core samples	Moisture content, %	Bulk density, g/cm^3
1	14	1.18
2	15	1.19
3	17	2.22
4	20	2.47
5	20	2.57

The data in the table show that the moisture content of the samples varies from 14 to 20%, while the bulk density increases with increasing moisture content and reaches a maximum value of 2.57 g/cm^3 at 20% moisture content.

This indicates the dependence of bulk density on the degree of water saturation of cores, which is important for understanding the porous medium permeability. High values of moisture content and bulk density in samples No. 4 and No. 5 may be related to the peculiarities of the lithological composition of ore, containing finer-grained or clayey inclusions. This is confirmed by further mineralogical research results.

The data obtained allow us to identify the main lithological-filtration types of rocks, which are characterized by a combination of high moisture content and density. These types require special consideration when designing an in-situ leaching scheme, as their low permeability may limit the filtration of leaching solutions.

Interval testing of core samples from wells. From April 2021 to September 2021, groups of core samples were analyzed at the Central Research Laboratory of Navoi Mining and Metallurgical Company. Complex interval-based testing was performed on core material from well No.3, the results of which are summarized in Table 2.

Table 2. Core material testing

No.	Interval, m	Uranium content, c.u.	Content of CO_2, %	Concentration of Fe^{+3}, g/l	Eh, mV
1	147	6.5	2.20	0.025	460
2	149	5.9	0.88	0.025	470
3	151	5.8	1.20	0.077	480
4	156	3.6	0.44	0.19	400

In the studied interval of 147-156 m, the uranium content in the ore layer varied within 3.5-6.5 c.u. (Fig. 6). Carbonate mineral content varied within 0.23-2.20%.

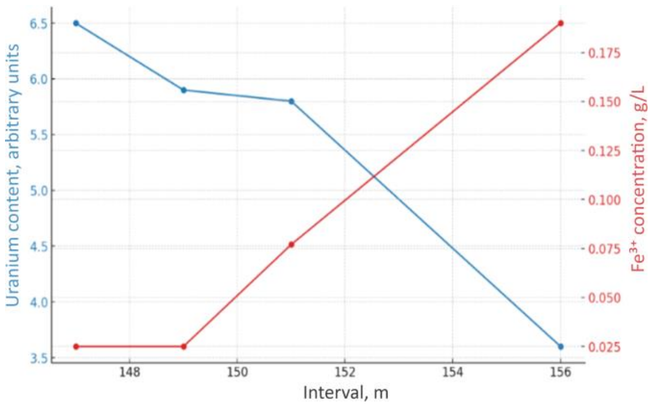

Figure 6. Results of core material testing (uranium and Fe^{3+} concentration) for horizon intervals

The acid content of the rocks averaged 37 kg of sulfuric acid per 1 ton of ore over the interval, and ranged from 20 to 66 kg per 1 ton of ore for individual samples. The acid content of rocks is usually dependent on their carbonate mineral content. However, this pattern is not always observed for the studied ores. At an excess acidity of 35-45 g/l of sulfuric acid, the dissolution of uranium minerals was easy and practically applicable. But in the 156 m interval, the uranium extraction for incompletely extracted samples No. 4 was about 36-64%. Whether this is the case for all samples or only in a single case will be determined by complex technological testing of core samples from other wells.

For most samples, the trivalent iron content is lower than that of divalent iron. The trivalent iron ion content in the solutions after leaching was higher, and the average value of oxidation-reduction capacity of rocks mined using in-situ uranium leaching through boreholes was 38 mV over the studied interval. The largest deviations from the average value are +7 and -13 mV.

Co-extraction of metals from in-situ leaching solutions is an important process that allows for the simultaneous recovery of valuable components and optimization of resource utilization. As part of the analysis performed, in-situ leaching solutions were examined to determine the content of various metals, as well as their concentrations in the extracted medium.

Figure 7 shows the results of the analysis of metal content in in-situ leaching solutions. It can be seen that the metal concentrations are not evenly distributed, and among them the rare-earth elements are distinguished, occurring in minimal amounts, but greater than 5%. The maximum concentration was observed for uranium, making it the dominant element in the solutions. Second in importance is iron (Fe), the concentration of which reaches its maximum. These elements have the highest proportion among all tested components, which emphasizes their importance for further extraction during the leaching process. The distribution graph shows rare-earth elements such as Ce, Sm, Dy, Ho, Er and Tm, the concentrations of which do not exceed 6%.

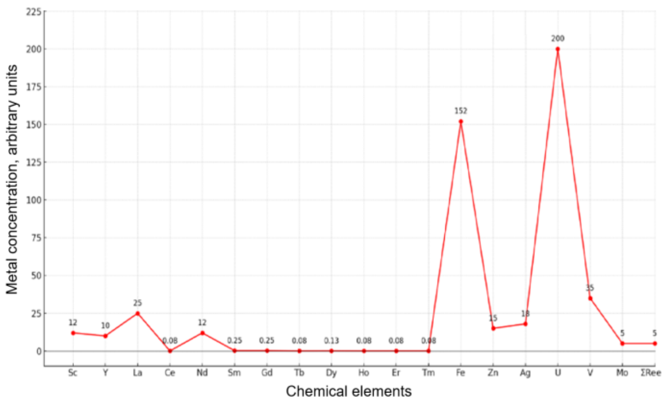

Figure 7. Metal concentrations for chemical elements

The total value of rare-earth elements (ΣRЗЭ) is only 5 c.u., which indicates their low content in solutions and possible economic inexpediency of their extraction under current conditions. Average concentration values are observed for elements such as zinc (Zn) – 15 c.u., silver (Ag) – 18 c.u., and vanadium (V) – 35 c.u.

Thus, the analysis of metal distribution in in-situ leaching solutions makes it possible to identify uranium and iron as the most promising elements for extraction, given their high concentrations. Rare-earth elements, on the other hand, require a separate approach to assess the economic feasibility of their extraction.

According to the presented data, it can be seen that the chemical composition of core material samples is characterrized by the content of such elements as aluminum, carbon, sulfur, silver, arsenic and lead. Moreover, among the elements, aluminum (Al) is characterized by the maximum amount, the content of which varies from 4.8 to 7.3%.

Separate analyses were also performed on uncrushed well samples. The results of the chemical analysis also showed that the sample contained an estimated amount of gold. The results of the analysis are shown in the following graphs (Fig. 8).

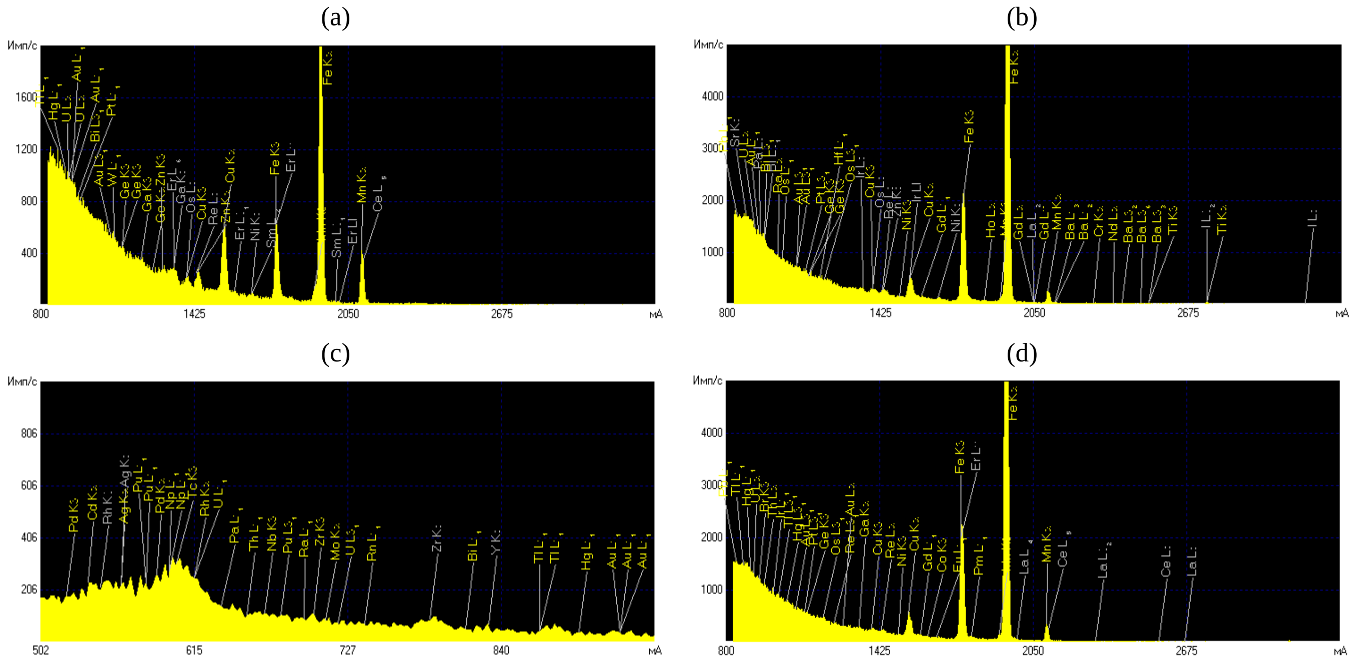

Figure 8. Results of core testing analysis: (a) from core samples No. 1; (b) from core samples No. 2; (c) from core samples No. 3; (d) from core samples No. 4

The graphs show that in the range from 800 to 2050 nanometers, the decomposition spectrum shows expressed fluctuations of the main peaks of uranium-U, iron-Fe, copper-Cu, manganese-Mn, and zinc-Zn. Also, in the decomposition spectrum, there are fluctuations of rare-earth elements such as osmium-Os, rhenium-Re, neodymium-Nd, actinium-Ac, scandium-Sc, cesium-Ce, bismuth-Bi and others.

It is worth noting that the decomposition spectra show spectral lines of mercury (Hg) and implicit fluctuations of gold, as well as other metals. The formation of uranium ores by chemical composition produces sulfide minerals with which mercury is formed, as these minerals are genetically related to mercury by chemical nature. Mercury, in turn, forms compounds with gold during an amalgamation reaction.

For successful implementation of uranium in-situ leaching technology using surface-active substances (surfactants) at industrial sites, it is necessary to scale the experiments conducted in laboratory conditions to real geological-hydrogeological conditions of industrial deposits. This is an important step, as the surfactant behavior, surfactant action efficacy, and overall leaching results can change significantly when moving from laboratory to industrial conditions. Incorporating pilot projects, modeling conditions, use of new technologies and monitoring systems will not only improve leaching efficiency, but also make it more predictable and environmentally safe in real sites.

5. Conclusions

Research conducted to improve the uranium in-situ leaching (ISL) technology has confirmed the high efficiency of surface-active substances (surfactants) to increase the ore horizon permeability and accelerate leaching processes. Among the studied reagents, sulfanol has shown the best results, providing an increase in the filtration coefficient from 0.5 to 2.0 m/day. This indicates its significant contribution to the improvement of seam filtration properties and leaching process intensification. Other surfactants such as OP-10, MDLF-1, MDLF-2 and polyacrylamide also have shown positive effects, but their effectiveness is less evident. For example, OP-10 has increased the filtration coefficient to 1.5 m/day, polyacrylamide – to 1.0 m/day, MDLF-1 – to 0.8 m/day, while MDLF-2 has shown the least increase, reaching 0.6 m/day. An important problem identified during long-term use of some surfactants, such as MDLF-1, is the occurrence of mechanical colmatation of seams, which negatively influences the leaching process efficiency at later stages. This emphasizes the need for careful selection of reagents, taking into account the geological conditions of the deposit, ore characteristics and process parameters such as solution viscosity and filtration rate.

Practical application of the methods at real deposits has made it possible to reduce the level of seam colmatation by 25-30%, which contributes to an increase in production efficiency and reduction of production losses. To further improve the efficiency of in-situ uranium leaching, it is recommended to focus research on adapting methodologies to different geological conditions, as well as on developing automated systems for process monitoring and control.

In conclusion, the use of modern technologies and reagents, such as sulfanol, provides not only increased economic profitability, but also environmental safety of mining, which makes in-situ uranium leaching a promising method for deposit mining.

Author contributions

Conceptualization: RM; Data curation: MR; Formal analysis: JT, BT; Investigation: MR, BT; Methodology: JT; Project administration: MR; Resources: MR; Software: AG; Validation: MR; Visualization: ZB; Writing – original draft: SA, JT, RM, MR, BT; Writing – review & editing: JT, MR, BT, ZB, AG. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

References

[1] Demin, V., Kalinin, A., Baimuldin, M., Tomilov, A., Smagulova, A., Mutovina, N., Shokarev, D., Aliev, S., Akpanbayeva, A., & Demina, T. (2024). Developing a technology for driving mine workings with combined support and friction anchors in ore mines. *Applied Sciences*, *14*(22), 10344. https://doi.org/10.3390/app142210344

[2] Kononenko, M., & Khomenko, O. (2010). Technology of support of workings near to extraction chambers. *New Techniques and Technologies in Mining*, 193-197. https://doi.org/10.1201/b11329-31

[3] Demin, V., Khalikova, E., Rabatuly, M., Amanzholov, Zh., & Zhumabekova, A. (2024). Research into mine working fastening technology in the zones of increased rock pressure behind the longwall face to ensure safe mining operations. *Mining of Mineral Deposits*, *18*(1), 27-36. https://doi.org/10.33271/mining18.01.027

[4] Maussymbayeva, A.D., Yurov, V.M., Portnov, V.S., Rabatuly, M., & Rakhimova, G.M. (2024). Assessment of the influence of the surface layer of coals on gas-dynamic phenomena in the coal seam. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *2*, 5-11. https://doi.org/10.33271/nvngu/2024-2/005

[5] Bondarenko, V.I., Kharin, Ye.N., Antoshchenko, N.I., & Gasyuk, R.L. (2013). Basic scientific positions of forecast of the dynamics of methane release when mining the gas bearing coal seams. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *5*, 24-30.

[6] Maussymbayeva, A.D., Portnov, V.S., Imanbaeva, S.B., Rabatuly, M., & Rakhimova, G.M. (2024). Influence of rock shear processes on the methane content of longwall faces. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *4*, 11-17. https://doi.org/10.33271/nvngu/2024-4/011

[7] Wang, Z., Ren, T., & Cheng, Y. (2017). Numerical investigations of methane flow characteristics on a longwall face Part I: Methane emission and base model results. *Journal of Natural Gas Science and Engineering*, *43*, 242-253. https://doi.org/10.1016/j.jngse.2017.03.029

[8] Bondarenko, V., Symanovych, G., & Koval, O. (2012). The mechanism of over-coal thin-layered massif deformation of weak rocks in a longwall. *Geomechanical Processes During Underground Mining*, 41-44. https://doi.org/10.1201/b13157-8

[9] Ostrogórski, P., Skotniczny, P., & Pucka, M. (2022). Measurements of the methane concentration along the longwall excavations and longwall. *Archives of Mining Sciences*, *67*(1). https://doi.org/10.24425/ams.2022.140861

[10] Lian, G., An, Y., Sun, J., Yang, B., & Shen, Z. (2024). Effects and driving mechanisms of bioremediation on groundwater after the neutral in situ leaching of uranium. *Science of the Total Environment*, *946*, 174406. https://doi.org/10.1016/j.scitotenv.2024.174406

[11] Wang, B., Luo, Y., Liu, J.H., Li, X., Zheng, Z.H., Chen, Q.Q., & Fan, Q.R. (2022). Ion migration in in-situ leaching (ISL) of uranium: Field trial and reactive transport modelling. *Journal of Hydrology*, *615*, 128634. https://doi.org/10.1016/j.jhydrol.2022.128634

[12] Kitchen, H.J., Vallance, S.R., Kennedy, J.L., Tapia-Ruiz, N., Carassiti, L., Harrison, A., & Gregory, D.H. (2014). Modern microwave methods in solid-state inorganic materials chemistry: From fundamentals to manufacturing. *Chemical Reviews*, *114*(2), 1170-1206. https://doi.org/10.1021/cr4002353

[13] Mukherjee, S., Goswami, S., & Zakaulla, S. (2023). Geological relationship between hydrocarbon and uranium: Review on two different sources of energy and the Indian scenario. *Geoenergy Science and Engineering*, *221*, 111255. https://doi.org/10.1016/j.petrol.2022.111255

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

[15] Yang, H., Liu, Y., Chen, Z., Waterhouse, G. I., Ma, S., & Wang, X. (2022). Emerging technologies for uranium extraction from seawater. *Science China. Chemistry*, *65*(12), 2335-2337. https://doi.org/10.1007/s11426-022-1358-1

[16] Tsoy, B.V., Myrzakhmetov, S.S., Bekbotaeva, A.A., & Yusupov, Kh.A. (2022). New geophysical logging techniques for practical problem solving at complex hydrogenetic uranium deposits. *Gornyi Zhurnal*, *7*, 27-31. https://doi.org/10.17580/gzh.2022.07.04

[17] Stupnik, N.I., Fedko, M.B., Kolosov, V.A., & Pismennyy, S.V. (2014). Development of recommendations for choosing excavation support types and junctions for uranium mines of state-owned enterprise Skhidhzk. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *5*, 21-25.

[18] Yousufi, A., Ahmadi, H., Bekbotayeva, A., Arshamov, Y., Baisalova, A., Omarova, G., & Pekkan, E. (2023). Integration of remote sensing and field data in ophiolite investigations: A case study of Logar ophiolite complex, SE Afghanistan. *Minerals*, *13*(2), 234. https://doi.org/10.3390/min13020234

[19] Mendygaliyev, A., Arshamov, Y., Selezneva, V., Yazikov, E., & Bekbotayeva, A. (2021). Prospects for application of multi-spectral earth sensing data in forecasting and searching for reservoir-infiltration uranium deposits. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *2*(446), 90-97. https://doi.org/10.32014/2021.2518-170x.39

[20] Alikulov, S., Babayev, S., Alimov, M., Yuldoshev, A., & Sharopov, K. (2023). Research on the choice of the composition of the leaching solution during the extraction of gold by the method of underground leaching from used uranium wells. *E3S Web of Conferences*, *414*, 01004. https://doi.org/10.1051/e3sconf/202341701004

[21] Lyashenko, V.I., Dudar, T.V., Stus, V.P., & Shapovalov, V.A. (2024). Justification of efficiency and subsoil protection during underground development of ore deposits using traditional technologies in combination with metals leaching. *Mineral Resources of Ukraine*, *2*, 69-77. https://doi.org/10.31996/mru.2024.2.69-77

[22] Qiu, W., Yang, Y., Song, J., Que, W., Liu, Z., Weng, H., & Wu, J. (2025). A deep-learning-based multiobjective optimization for the design of in-situ uranium leaching system under multiple uncertainties. *Journal of Hydrology*, *651*, 132576. https://doi.org/10.1016/j.jhydrol.2024.132576

[23] Liu, Y., He, Y., Chen, J., Cheng, N., & Wang, H. (2024). Progress on enhancing seepage-leaching mass-transfer research for in-situ leaching mining of low-permeability uranium-bearing sandstone: A review. *Journal of Radioanalytical and Nuclear Chemistry*, *333*(9), 4485-4502. https://doi.org/10.1007/s10967-024-09585-5

[24] Abney, C.W., Mayes, R.T., Saito, T., & Dai, S. (2017). Materials for the recovery of uranium from seawater. *Chemical Reviews*, *117*(23), 13935-14013. https://doi.org/10.1021/acs.chemrev.7b00355

[25] Yusupov, K.A., Rysbekov, K.B., Aben, K.K., & Bakhmagambetova, G.B. (2021). Increasing gold leaching efficiency with change of solution rheological properties. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *3*, 14-18. https://doi.org/10.33271/nvngu/2021-3/014

[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. https://doi.org/10.28991/CEJ-2024-010-10-014

[27] Zhang, L., Wen, B., Chen, L., Chen, H., & Wu, K. (2024). Variations in pore structures and permeabilities of ion adsorption rare earth ores during simulated in-situ leaching: Effect of newly formed clay particles and their swelling. *Hydrometallurgy*, *228*, 106357. https://doi.org/10.1016/j.hydromet.2024.106357

[28] Khomenko, O., Rudakov, D., Lkhagva, T., Sala, D., Buketov, V., & Dychkovskyi, R. (2023). Managing the horizon-oriented in-situ leaching for the uranium deposits of Mongolia. *Rudarsko Geolosko Naftni Zbornik*, *38*(5), 49-60. https://doi.org/10.17794/rgn.2023.5.5

[29] Vladyko, O., Maltsev, D., Sala, D., Cichoń, D., Buketov, V., & Dychkovskyi, R. (2022). Simulation of leaching processes of polymetallic ores using the similarity theorem. *Rudarsko-Geolosko-Naftni Zbornik*, *37*(5), 169-180. https://doi.org/10.17794/rgn.2022.5.14

[30] Rysbekov, K.B., Kyrgizbayeva, D.M., Miletenko, N.A., & Kuandykov, T.A. (2024). Integrated monitoring of the area of Zhilandy deposits. *Eurasian Mining*, *41*(1), 3-6. https://doi.org/10.17580/em.2024.01.01

[31] Rakishev, B.R., Bondarenko, V.I., Matayev, M.M., & Kenzhetayev, Z.S. (2019). Influence of chemical reagent complex on intensification of uranium well extraction. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, *6*, 25-30. https://doi.org/10.29202/nvngu/2019-6/4

[32] Yuan, Y., Yang, Y., Ma, X., Meng, Q., Wang, L., Zhao, S., & Zhu, G. (2018). Molecularly imprinted porous aromatic frameworks and their composite components for selective extraction of uranium ions. *Advanced Materials*, *30*(12), 1706507. https://doi.org/10.1002/adma.201706507

[33] Bektay, E., Turysbekova, G., Shiderin, B., & Bektayev, M. (2024). Industrial application of bacterial iron oxidation in in-situ leaching technologies for uranium. *Engineering Journal of Satbayev University*, *146(*5), 25-31. https://doi.org/10.51301/ejsu.2024.i5.04

[34] Chen, J., Zhao, Y., Song, Q., Zhou, Z., & Yang, S. (2018). Exploration and mining evaluation system and price prediction of uranium resources. *Mining of Mineral Deposits*, *12*(1), 85-94. https://doi.org/10.15407/mining12.01.085

[35] Monnet, A., Gabriel, S., & Percebois, J. (2017). Long-term availability of global uranium resources. *Resources Policy*, *53*, 394-407. https://doi.org/10.1016/j.resourpol.2017.07.008

[36] Jia, M., Luo, B., Lu, F., Yang, Y., Chen, M., Zhang, C., & Xu, Q. (2024). Improved FMM for well locations optimization in in-situ leaching areas of sandstone uranium mines. *Nuclear Engineering and Technology*, *56*, 3750-3757. https://doi.org/10.1016/j.net.2024.04.023

[37] Nurpeisova, A., Shevko, V., Aitkulov, D., & Kushakova, L. (2023). Optimization of the electrothermal production of ferrosilicon from the leaching tailings of the oxidized copper ore of Almaly. *Engineering Journal of Satbayev University*, *145*(1), 19-24. https://doi.org/10.51301/ejsu.2023.i1.03

[38] Li, G., & Yao, J. (2024). A review of in situ leaching (ISL) for uranium mining. *Mining*, *4*(1), 120-148. https://doi.org/10.3390/mining4010009

[39] Sanakulov, K.S., Fuzaylov, O.U., & Kenbaeva, Zh.A. (2020). Microwave processing of sulphide gold concentrates. *Gornyy Vestnik Uzbekistana*, *1*, 53-56.

[40] Chen, M., Yang, Y., Liu, W., Wang, C., & Johannessen, B. (2018). An in-situ synchrotron XAS study on the evolution of aqueous arsenic species in acid pressure leaching. *Hydrometallurgy*, *175*, 11-19. https://doi.org/10.1016/j.hydromet.2017.10.016

[41] Khawassek, Y.M., Taha, M.H., & Eliwa, A.A. (2016). Kinetics of leaching process using sulfuric acid for Sella uranium ore material, South Eastern Desert, Egypt. *International Journal of Nuclear Energy Science and Engineering*, *6*, 62-73. https://doi.org/10.14355/ijnese.2016.06.006

[42] Rakishev, B., Kenzhetaev, Z., Mataev, M., & Togizov, K. (2022). Improving the efficiency of downhole uranium production using oxygen as an oxidizer. *Minerals*, *12*(8), 1005. https://doi.org/10.3390/min12081005

[43] Kuandykov, T.A., Karmanov, T.D., Kuldeyev, E.I., Yelemessov, K.K., & Kaliev, B.Z. (2022). New technology of uncover the ore horizon by the method of in-situ leaching for uranium mining. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Science*, *3*, 142-154. https://doi.org/10.32014/2022.2518-170X.186

[44] 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. https://doi.org/10.33271/mining15.04.001

[45] Myrzakhmetov, B.A., Kuandykov, T.A., Mauletbekova, B.K., Balgayev, D.Y., & Nurkas, J.B. (2024). Multifunctional valve for the arrangement of submersible downhole pumps in downhole oil production. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *2*(464), 156-168. https://doi.org/10.32014/2024.2518-170x.400

[46] Nazirova, A., Abdoldina, F., Aymahanov, M., Umirova, G., & Muhamedyev, R. (2016). An automated system for gravimetric monitoring of oil and gas deposits. *Digital Transformation and Global Society*, 585-595. https://doi.org/10.1007/978-3-319-49700-6_58

[47] Shakiyeva, T.V., Sassykova, L.R., Dzhatkambayeva, U.N., Khamlenko, A.A., Zhakirova, N.K., Batyrbayeva, A.A., Azhigulova, R.N., Kubekova, S.N., Zhaxibayeva, Z.M., Kozhaisakova, M.A., Sendilvelan, S., & Bhaskar, K. (2021). Optimization of the oxidative cracking of fuel oil on catalysts obtained from Kazakhstan raw materials. *Rasayan Journal of Chemistry*, *14*(2), 1056-1071. https://doi.org/10.31788/RJC.2021.1426152

[48] Rabatuly, M., Myrzathan, S.A., Toshov, J.B., Nasimov, J., & Khamzaev, A. (2026). Views on drilling effectiveness and sampling estimation for solid ore minerals. *Complex Use of Mineral Resources*, *336*(1), 5-14. https://doi.org/10.31643/2026/6445.01

[49] Sanakulov, K., Alikulov, S., Alimov, M., Yuldoshev, A., & Sharopov, K. (2024). Research of the movement of solutions in waterless dry horizons. *E3S Web of Conferences*, *525*, 01001. https://doi.org/10.1051/e3sconf/202452501001

[50] Xie, Y., Wu, Y., Liu, X., Hao, M., Chen, Z., Waterhouse, G.I., & Ma, S. (2023). Rational design of cooperative chelating sites on covalent organic frameworks for highly selective uranium extraction from seawater. *Cell Reports Physical Science*, *4*(1), 101220. https://doi.org/10.1016/j.xcrp.2022.101220

Дослідження раціональних параметрів розчинів при підземному вилуговуванні урану

Ш. Алікулов, Ж. Тошов, Р. Мусін, М. Рабатули, Б. Толовхан, Ж. Богжанова, А. Габітова

Мета. Дослідження та оптимізація процесу підземного вилуговування урану із застосуванням поверхнево-активних речовин (ПАР) для підвищення ефективності вилучення зі слабопроникних руд.

Методика. В рамках дослідження були відібрані зразки слабопроникних руд, які попередньо аналізувалися на пористість та коефіцієнт фільтраційної анізотропії, що є важливим для оцінки їх фільтраційних властивостей. Для вивчення ефекту таких ПАР як поліакриламід, сульфанол та сполуки сітчастих дренажних рідинних фільтрів (СДРФ), були підготовлені розчини з різними концентраціями цих речовин. Також для встановлення найбільш ефективних концентрацій ПАР проводилися додаткові дослідження, спрямовані на оптимізацію умов вилуговування з урахуванням впливу різних факторів, зокрема, температури та pH розчинів. Усі отримані результати піддавалися математичному аналізу для виявлення оптимальних умов, що дозволяло підвищити ефективність процесу вилуговування урану й поліпшити результати експериментів.

Результати. У ході проведених досліджень щодо вибору ПАР для вилуговування урану зі слабопроникних руд були отримані наступні результати. Сульфанол, як один із використаних ПАР, показав найкращі результати, значно збільшивши коефіцієнт фільтрації, який підвищився з 0.5 до 2.0 м/добу. Це підтверджує його високу ефективність у покращенні проникності рудного горизонту та прискоренні процесу вилуговування.

Наукова новизна полягає у розробці методів оптимального використання ПАР для покращення ефективності підземного вилуговування урану зі слабопроникних руд. Проведені дослідження, що визначають вплив різних ПАР на фільтраційні властивості руд, а також їх вплив на прискорення процесу вилуговування.

Практична значимість полягає у можливості використання отриманих даних для оптимізації процесу підземного вилуговування урану на реальних родовищах із низькою проникністю рудних горизонтів. Розроблені рекомендації щодо вибору поверхнево-активних речовин, таких як сульфанол і поліакриламід, а також їх оптимальних концентрацій, можуть бути безпосередньо застосовані для підвищення ефективності вилуговування, збільшення коефіцієнта фільтрації та скорочення часу обробки пластів.

Ключові слова: *підземне вилуговування, кольматація, сульфанол, поліакриламід, пористість, анізотропія, коефіцієнт фільтрації*

Publisher's note