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Rational Parameters for Uranium Concentration in Pregnant Leach Solution under *In Situ* Leaching Conditions

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ABSTRACT

The aim of this study is to develop and validate rational parameters for uranium concentration from pregnant leach solutions (PLS) with low uranium content during late-stage operation of technological blocks remote from the processing plant, with the objectives of improving processing efficiency, increasing labor productivity, and reducing operational costs. The study is motivated by the growing number of late-stage blocks at Kazakhstan uranium deposits characterized by low productivity and declining PLS uranium content. Pumping large volumes of low-grade PLS reduces processing efficiency and increases specific energy and labor consumption, thereby raising operational costs and the unit cost of the final product. Development of rational concentration parameters will increase the mean uranium content in the header pipeline, reduce specific costs at the sorption-desorption stage, and improve overall processing plant throughput. Application of the mobile concentration unit reduces the annual PLS volume directed from a single block to the processing plant to approximately 5,000 m³, representing a 5-6% reduction in total solution volume, with uranium concentration factors of 309 times. To determine process parameters, a series of laboratory sorption-desorption experiments were conducted using the selected sorbent. Based on the results obtained, a pilot concentration unit was designed, fabricated, and deployed on the geotechnological field, and pilot-scale tests were carried out at an operating mine site.

1. Introduction

Climate change consequences and the growing demand for electricity in developing countries have generated increased interest in the further development of nuclear energy. Projects for the development and commissioning of new small and large modular nuclear power plants with compact dimensions and a low carbon footprint can make a significant contribution to reducing CO₂ emissions worldwide. Uranium is the key element of sustainable nuclear energy development globally [1, 2]. The uranium mining industry of Kazakhstan, based on the highly efficient *in situ* leaching (ISL) technology, is well positioned to meet the increasing demand for uranium resources.

Uranium deposits in Kazakhstan are distributed across six provinces: Shu-Sarysu, Syrdarya, North Kazakhstan, Caspian, Balkhash, and Ili. The primary mining operations are concentrated in the first two

provinces, located in the Kyzylorda and Turkestan regions [3] (Fig. 1).

The ISL uranium mining technology involves dissolving uranium minerals *in situ*, lifting the uranium-bearing solutions to the surface, and subsequently processing the pregnant leach solution [4, 5]. The flowsheet for processing pregnant leach solutions (PLS) to a marketable uranium oxide concentrate (UOC) comprises several sequential stages. Sorption extraction of uranium from the PLS involves saturation of ion-exchange resin with uranium and formation of a barren solution, followed by further resin loading in sorption columns. Uranium is then eluted from the resin using nitrate solutions, yielding a marketable eluate in dedicated desorption columns. The barren liquor from sorption is fortified with sulfuric acid to create a leaching solution (LS) and then returned to the subsurface. Uranium is subsequently precipitated in precipitation reactors, forming a slurry and a precipitation mother liquor.

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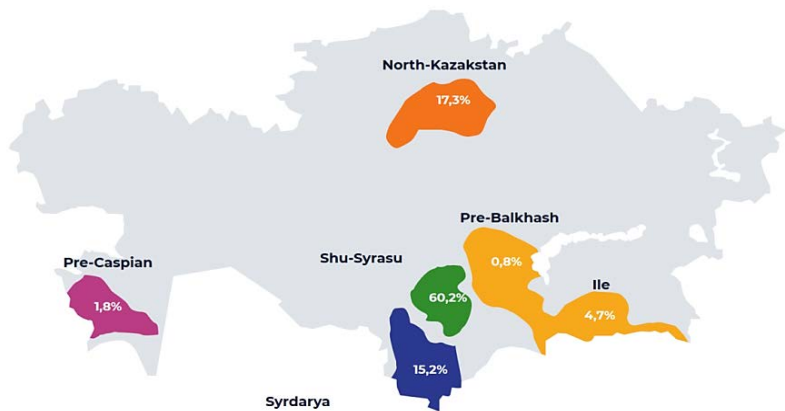


Fig. 1. Map of uranium deposit regions in Kazakhstan. Reproduced from [6], published under the CC BY 4.0 license.

The slurry is fed to a filter press where it is dried and processed to a marketable UOC ready for delivery to consumers. Figure 2 shows the typical flowsheet for processing uranium-bearing PLS as applied at most ISL uranium mining enterprises in the Republic of Kazakhstan.

According to field development plans, the extraction process is conventionally divided into three main stages. The first stage involves opening ore blocks with technological boreholes, completing them, and preparing the geotechnological field for production. The second stage comprises injecting

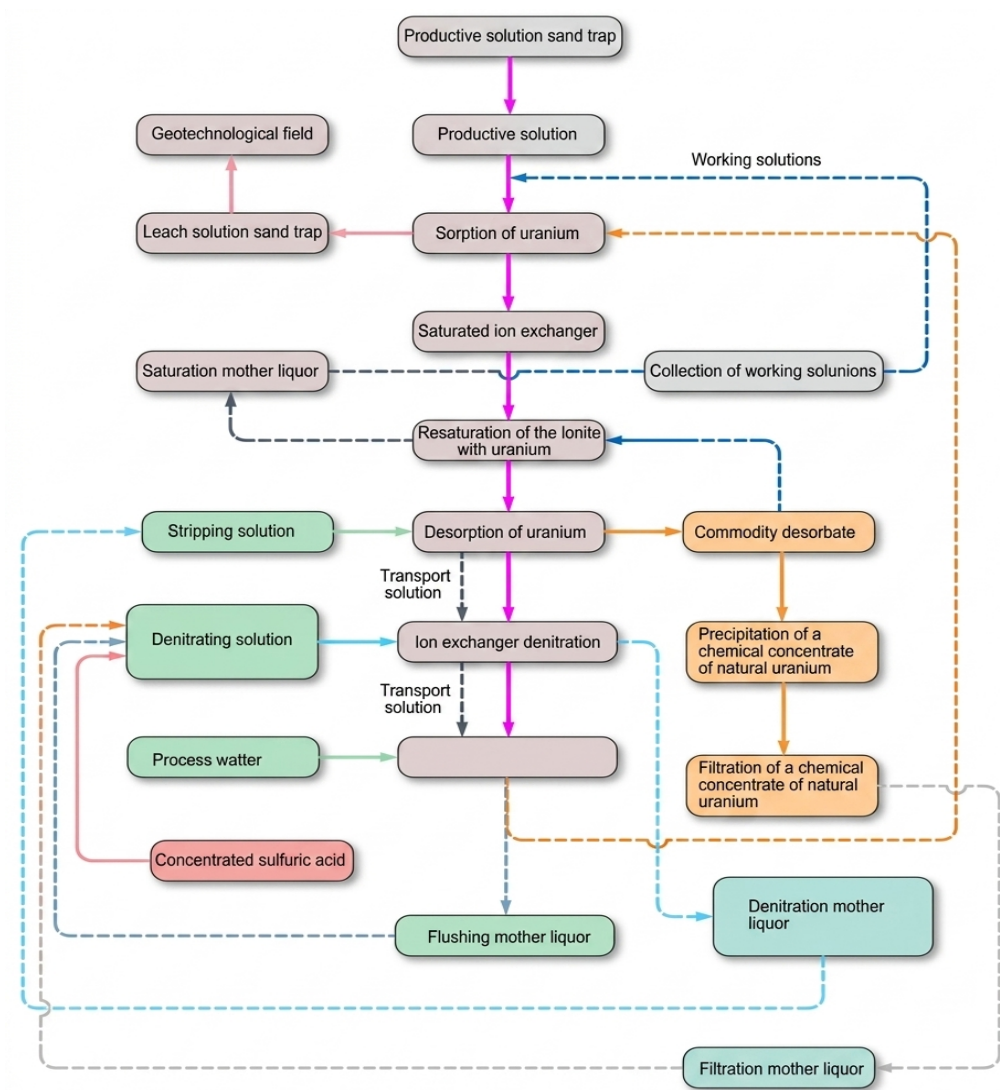


Fig. 2. Flowsheet for processing pregnant leach solutions. Reproduced from [11], published under the CC BY 4.0 license.

the sulfuric acid solution into the ore interval and actively extracting uranium from the subsurface. The third stage covers block completion, rinsing the productive horizon to remove contaminants, and subsequent reclamation [7, 8]. After the active extraction phase, uranium content in the PLS from depleted blocks rapidly declines to minimum levels due to reserve depletion, potentially falling below 0.02 g/L. Low uranium content in the PLS necessitates handling larger solution volumes and adversely affects processing efficiency by diluting uranium-rich solutions from new blocks with low-grade solutions from depleted blocks. The average throughput of a single block is approximately 100 m³/h of PLS; depending on the production plan, the daily volume of pumped PLS ranges from 10,000 to 30,000 m³. This increases costs and specific energy consumption, labor input, and reduces overall productivity and safety.

Authors in [9] propose a technology for concentrating uranium in solution using a specialized mobile unit for processing remote in-situ leaching uranium blocks. The unit comprises two sorption pressure columns, an additional dosing column installed upstream of the sorption columns, and a receiving column installed downstream. Incoming PLS from the production wells is filtered through ion-exchange resin in the sorption columns where uranium is sorbed, and the barren sorption solution is directed to the injection wells of the geotechnological field. Upon completion of the sorption cycle, the saturated resin is discharged from the sorption columns into the receiving column for subsequent loading into a transport tanker for further processing at the processing plant. Fresh regenerated resin is unloaded from the transport vessel into the dosing hopper and redistributed between the sorption columns, where the sorption cycle resumes.

This technology is particularly well-suited for remote deposits or ore bodies located far from the processing plant with relatively small uranium reserves of 2,000–5,000 t. However, the proposed technology lacks the capability for desorption on site and requires continuous loading, unloading, and transportation of ion-exchange resin to the processing plant upon completion of each sorption cycle.

In references [10], the authors examine the concentration of the product eluate using nanofiltration technology in the context of processing PLS from uranium ISL operations. The nanofiltration unit (NFU) consists of pipelines, pumping systems, and specialized acid-resistant membrane nano-filters. The primary working elements of the NFU are

acid-resistant membrane modules manufactured by Dow Chemical, through which the test solution is filtered under applied pressure. Maximum uranium content in the concentrate was achieved at an inlet pressure of 18×10^5 Pa, a concentrate output of 20%, a permeate output of 80%, and a recycle ratio of 233%. Uranium recovery into the concentrate was 98% at a permeate content of 0.006 g/L and a concentration factor of 3.8.

The technology proposed by those authors is sufficiently effective for purifying solution components and removing impurities, and for concentrating specific elements in solution. However, for large volumes of PLS with low uranium content, the application of nanofiltration technology is currently not sufficiently efficient.

The present study focuses on developing rational parameters for the local concentration of uranium in PLS on the geotechnological field under conditions of processing remote technological blocks using ion-exchange processes. A series of laboratory and pilot-scale experiments on sorption-desorption uranium concentration from low-grade PLS were conducted with the aim of increasing uranium content in the main manifold and reducing the volume of PLS pumped to the processing plant. A 5–10% reduction in pumped PLS volume will improve processing efficiency, reduce operational costs, and increase overall labor productivity.

2. Research methods

Experimental work was carried out using commercially available sorbents applicable under in-situ leaching conditions. Standard qualification tests were performed to verify conformance of the sorbent sample with the norms established at natural uranium mining enterprises in accordance with ST NAK 20-2022 «Requirements for ion-exchange resins for enterprises of Kazatomprom JSC» (ST NAK 20-2022). Table 1 presents the principal technical characteristics of the selected ion-exchange resin grade.

As shown in Table 1, the selected resin grade Biolite 200 U meets the requirements of the Kazatomprom JSC standard and demonstrates the highest equilibrium exchange capacity (EEC). This indicator is one of the main characteristics of the choice of Biolite 200 U ionite. Table 2 presents the results of physicochemical property testing of the selected resin.

As shown in Table 2, Biolite 200 U exhibits sufficiently high physicochemical properties and a uniform particle size distribution. Its physical and phys-

Table 1. Physical properties and equilibrium exchange capacity (EEC) of the sorbent for uranium

No.	Resin name	Moisture content, %	Specific volume (swollen in distilled water), cm³/g	Bulk density, g/cm³	Swelling coefficient	Uniformity coefficient	EEC, %	EEC, g/L
1	Biolite 200 U	49.86	2.86	0.68	1.38	1.26	3.17	11.82
2	Norm ST NAK 20-2022	30-65	2.5-4.0	0.4-0.8	1.0-2.0	1.0-1.6	–	–

Table 2. Physicochemical properties of the sorbent

No.	Resin name	Mechanical strength at 114 rpm, %	Mechanical strength at 200 rpm, %	Mechanical strength at 230 rpm, %	Chemical stability and mechanical strength under variable working media, %
1	Biolite 200 U	100.0	100.0	100.0	99.0

icochemical characteristics fully comply with the norms established by ST NAK 20-2022.

To establish rational parameters for uranium concentration in PLS using ion-exchange processes, laboratory experiments on uranium concentration from low-grade PLS were required. This allows determination of effective parameters for the sorption-desorption uranium concentration process and the design characteristics of the process equipment [12]. For this purpose, a laboratory apparatus was developed for conducting experiments on sorption loading of uranium from PLS and desorption recovery of concentrated uranium using ion-exchange sorbents in dynamic mode. Laboratory experiments allow determination of the parameters of resin saturation with uranium and characterization of the desorption of concentrated uranium from ion-exchange sorbents in dynamic mode [13]. Fig. 3 shows the schematic of the laboratory setup for uranium concentration in PLS in dynamic mode.

Laboratory experiments on uranium concentration in dynamic mode were conducted on an apparatus comprising a sorption column, stand, peristaltic pump, feed solution reservoir, and a graduated cylinder for collecting barren solutions. Acid- and alkali-resistant filters that do not allow resin particles larger than 0.25 mm to pass through and provide low filtration resistance were installed at the top and bottom of the column. Table 3 presents the chemical composition of the model solution used for the laboratory uranium concentration experiments.

The experiment duration (contact time) for sorption with pH 3.1 solution was 72 h, and 207 h with the pH 2.1 solution. All experiments were conducted at a solution temperature of 25 °C. The sorption concentration process was continued until uranium content in the barren sorption solution equilibrated with that in the feed solution.

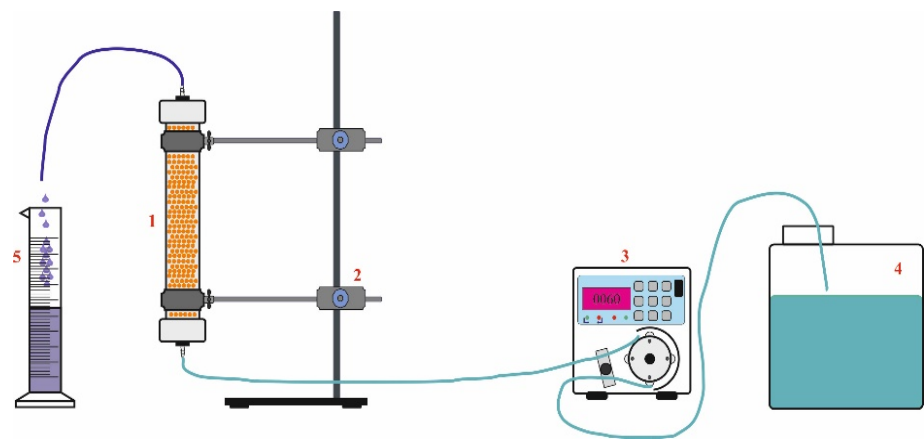


Fig. 3. Schematic of the sorption concentration laboratory apparatus: 1 – sorption column with ion-exchange resin; 2 – stand; 3 – peristaltic pump; 4 – feed PLS reservoir; 5 – graduated cylinder for collecting barren solutions.

Table 3. Chemical composition of the model solution for sorption experiments

Parameter	PLS at pH 2.1, g/L	Parameter	PLS at pH 3.1, g/L
U, g/L	0.02	U, g/L	0.02
NO ₃ [−] , g/L	0.5	NO ₃ [−] , g/L	0.5
SO ₄ ^{2−} , g/L	8.93	SO ₄ ^{2−} , g/L	8.93
Cl [−] , g/L	0.159	Cl [−] , g/L	0.159
Fe ³⁺ , g/L	0.307	Fe ³⁺ , g/L	0.307
pH	2.1	pH	3.0–3.1

2.1. Uranium Sorption

The experimental methodology involved determining the saturation parameters of the selected ion-exchange sorbent with uranium in a specialized column from PLS supplied by a peristaltic pump from a reservoir. In the feed PLS, the concentrations of U, Fe³⁺, Fe²⁺, SiO₂, NO₃[−], SO₄^{2−}, and pH were determined. The column was filled with distilled water and loaded with swollen ion-exchange resin. The resin bed was compacted by tapping the column. Sorption was carried out by filtering the feed PLS through the resin bed. The solution flow rate was calculated using Eq. (1) [14]:

$$V_p = \frac{q}{\beta \ln(C_{PLS}/C_{LS})}, \quad (1)$$

where: V_p – solution flow rate during sorption in dynamic mode; q – sorbent volume, L; β – kinetic sorption coefficient; C_{PLS} – PLS concentration, g/L; C_{LS} – LS specified discharge concentration at column outlet, g/L.

According to the methodology, the filtration rate was regulated by the peristaltic pump. Solution samples after sorption were taken every 3 h for uranium content analysis. The experiment continued until uranium content in the inlet and outlet solutions equalized. After sorption, the sorbent was unloaded from the column, washed to remove residual acidity, and analyzed for E_{max} . Concentration data points obtained from outlet solution analysis were plotted to produce a breakthrough curve $C = f(t)$. The kinetic sorption coefficient β was determined from the breakthrough curve using Eq. (2) [14]:

$$\beta = \frac{\Delta t_{C_1 \rightarrow C_2}}{K_{pxln}(C_2/C_1)}, \quad (2)$$

where: $\Delta t_{C_1 \rightarrow C_2}$ – time during which the concentration changes from the beginning of breakthrough to

the concentration before the end of breakthrough; C_1 – uranium concentration at the beginning of breakthrough on the sorption curve; C_2 – uranium concentration before the end of breakthrough on the sorption curve; K_C – concentration factor, determined from Eq. (3) [14]:

$$K_C = E_{max}/C_{is}, \quad (3)$$

where: E_{max} – saturation of the resin with uranium in dynamic mode, g/L; C_{is} – uranium concentration in the initial model solution, g/L.

2.2. Uranium Desorption

The parameters of desorption recovery of concentrated uranium from ion-exchange resins were studied using the same laboratory apparatus with stripping solutions. The experimental methodology involved determining the desorption parameters of concentrated uranium from the selected ion-exchange resin as a function of sulfuric acid concentration in the stripping solution. The stripping solution was fed at a constant rate to the bottom of the column at a rate of 1 bed volume per hour [15, 16, 17]. This rate ensures attainment of equilibrium concentrations of the stripped element in the reaction medium. Aliquot samples of the outlet solution were collected and analyzed for uranium content every hour. Desorption was terminated when the uranium concentration in a sample decreased to minimum values [18, 19]. Desorption curves were plotted from the analytical results. The kinetic desorption coefficient was determined from Eq. (4):

$$\beta = \frac{\Delta t_{des}}{K_{pxln}(C_{max}/C_{fin})}, \quad (4)$$

where: Δt_{des} – time during which the concentration of the stripped element decreases from C_{max} to C_{fin} ; K_p – distribution coefficient of the eluate, determined from Eq. (5):

$$K_p = \frac{E_{sat}}{C_{max}}, \quad (5)$$

where: E_{sat} – uranium content in the saturated sorbent, g/L; C_{max} – maximum uranium content obtained in the eluate, g/L.

The design of industrial columns for uranium sorption concentration is performed using the data obtained, from which the constructive dimensions of the sorption columns (diameter, total height, number of columns) are determined. The total height of the sorbent bed is calculated from Eq. (6):

$$H_c = \Delta h + h_{rs} \quad (6)$$

where: Δh – height of the working sorbent bed; h_{rs} – reserve sorbent bed height = $0.15 \times \Delta h$. The working sorbent bed height is determined from Eq. (7):

$$\Delta h = W_{Lx} \beta_{xln} (C_{PLS}/C), \quad (7)$$

where: W_L – linear solution velocity, m/h; β – kinetic sorption coefficient, h; C_{PLS} – PLS concentration, g/L; C_{LS} – LS specified discharge concentration at column outlet, g/L. The linear solution velocity is determined from Eq. (8):

$$W_L = V/S \quad (8)$$

where: V – solution throughput, m³/h; S – column cross-sectional area.

The results of the laboratory experiments on sorption concentration of uranium from low-grade PLS, followed by desorption recovery of concentrated uranium, will allow determination of the effective parameters of the uranium concentration process and the dimensions of the process equipment.

3. Results and discussion

Based on the results of sorption concentration of uranium from low-grade PLS on the selected ion-exchange resin, uranium sorption concentration curves were plotted. Figure 4 shows the uranium sorption breakthrough curves.

After completion of the laboratory sorption experiments, the sorbent was removed from the columns, washed of residual acidity, and E_{max} was measured [20, 21]. Table 4 presents the uranium concentration parameters from PLS in dynamic mode at various pH values.

Table 4. Uranium sorption parameters in dynamic mode

Parameter	pH 3.1	pH 2.1
E_{max} , g/L	6.18	26.42
K_k	309	1321
β	0.043	0.037

As shown in Fig. 4 and Table 4, the uranium sorption concentration parameters from low-grade PLS demonstrate that the selected ion-exchange resin can be loaded with up to 26 g/L uranium when working with model solutions. Uranium loading is significantly more efficient at pH 2.1 compared to pH 3.1, since at higher pH values loading is substantially reduced due to a considerable portion of the resin capacity being occupied by iron via sorption of anionic iron complexes. The high iron content in the sorbent during uranium sorption from pH 3.1 solutions is attributable to competitive sorption of anionic aqua-complexes of trivalent iron of composition $[\text{Fe}(\text{H}_2\text{O})_4(\text{OH})_2]\text{SO}_4$. The iron (Fe^{3+}) content in

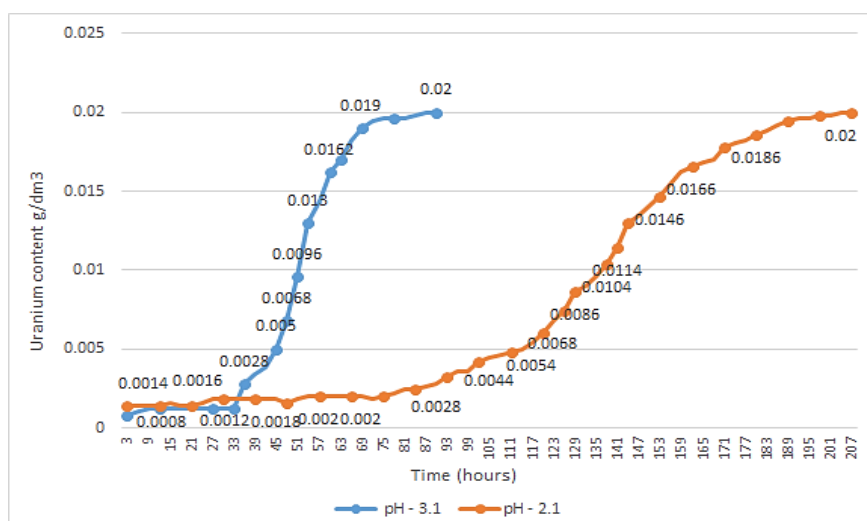


Fig. 4. Uranium sorption breakthrough curves on Biolite 200U resin at various pH values.

the saturated ion exchanger was 12.04 g/L, while the uranium content was 6.18 g/L, which indicates competition. Accordingly, as shown in Fig. 4, at pH 3.1, the uranium content in the barren sorption solutions reaches the feed concentration within 60 h, indicating attainment of the full dynamic exchange capacity. At pH 2.1 in the feed solution, competitive sorption of anionic iron complexes does not occur; consequently, the time to reach full dynamic exchange capacity increases to 200 h, while the most efficient resin loading is achieved. In this case, the iron (Fe^{3+}) content in the saturated ion exchanger was only 0.96 g/L, while the uranium content was 26.42 g/L.

Desorption recovery of concentrated uranium from the ion-exchange resin was carried out using a sulfuric acid stripping solution at the optimal concentration of 150 g/L, ensuring a uranium desorption degree of 98.8%. The desorption process parameters under dynamic conditions were determined in the laboratory by constructing uranium desorption curves from saturated resin. Figure 5 presents the uranium desorption kinetic curves at various pH values.

Desorption was carried out until complete extraction of uranium from the ion-exchange sorbents and reduction of uranium content in the resin to minimum values. Table 5 presents the main calculated desorption parameters obtained under laboratory conditions.

Table 5. Main indicators and parameters of uranium desorption

Sorbent pH	$\Delta t_{\text{des}}, \text{h}$	K_p	Average uranium concentration in eluate, g/L
3.1	6	3.09	1.03
2.1	8	2.97	3.20

As shown in Fig. 5 and Table 5, the average uranium concentration in the concentrated solution reached 1.03 and 3.20 g/L, respectively. The mean uranium content in the obtained eluate is significantly higher upon desorption of the sorbent loaded to 26.4 g/L, which was achieved after sorption from pH 2.1 solutions. The data indicate that the weakly loaded resin obtained from pH 3.1 solutions does not yield high mean uranium concentrations in the eluate. The most effective desorption concentration of uranium from the ion-exchange resin is achieved at a sulfuric acid concentration of 150 g/L in the stripping solution, owing to the significantly higher resin loading (26.4 g/L) achieved at pH 2.1.

Completion of technological blocks requires maintaining a balance of PLS/injection solution volumes and sorption-desorption cycles of process solutions. This allows achieving maximum process efficiency while maintaining safe working conditions. The solution flow diagram for the sorption-desorption concentration cycle on the mobile unit at an initial PLS uranium content of 0.02 g/L is shown in Fig. 6.

As shown in Fig. 6, the solution flow diagram for uranium concentration is intended for calculating equipment requirements, pipeline routing, and consumables. The process scheme consists of a sorption-desorption uranium concentration node with withdrawal of the barren sorption solution into the injection solution pipeline, and a stripping solution preparation node with withdrawal of the concentrated uranium solution into the PLS pipeline. The incoming low-grade PLS from the production wells of the depleted block enters the sorption-desorption columns, where uranium is sorbed onto the ion-exchange resin; the barren sorption solution is directed to the injection wells of the same block. After saturation of the ion-exchange resin, the PLS

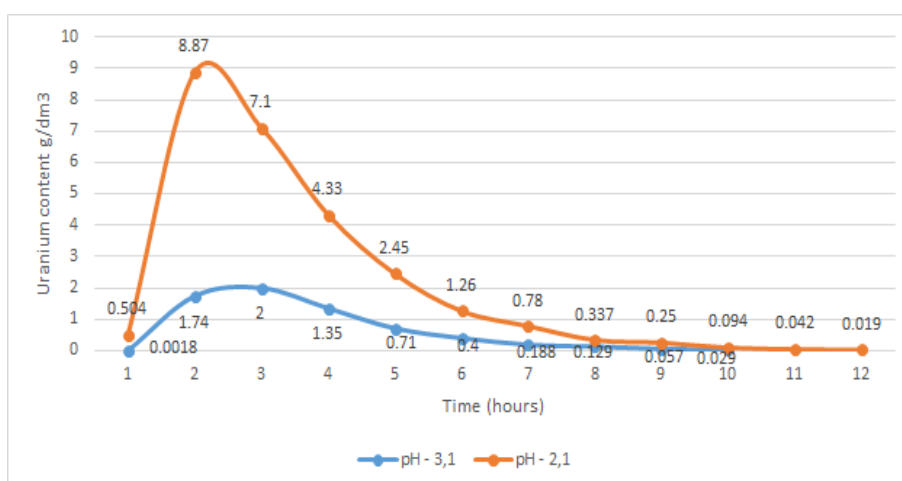


Fig. 5. Uranium desorption kinetic curves at various pH values.

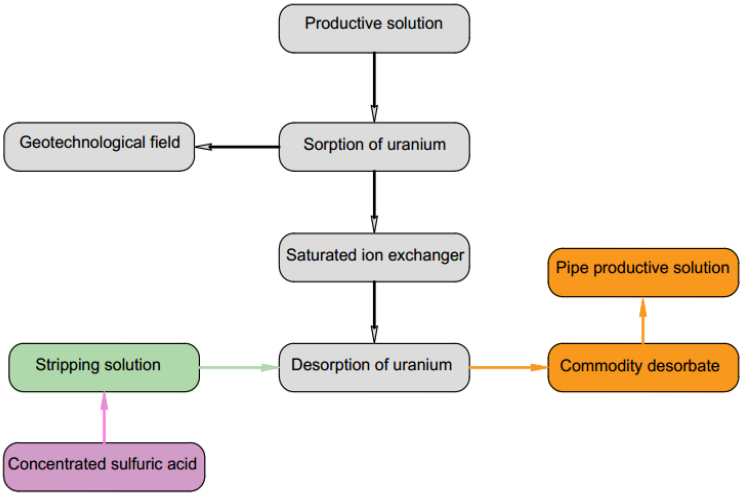


Fig. 6. Solution flow diagram for uranium concentration.

is redirected to the main pipeline to the processing plant, and the desorption process is initiated using the leaching solution with addition of sulfuric acid. The concentrated uranium solution from the columns is then directed into the PLS pipeline, significantly increasing its uranium content. Depending on the resin mass, volume of incoming PLS, injectivity of the injection wells, and uranium content in the PLS, the concentration cycle time may vary over a wide range. The saturated concentrated uranium solution entering the PLS pipeline increases uranium content in the main manifold, thereby reducing specific power consumption and improving the productivity of the processing complex.

The choice of technology for concentrating uranium in a productive solution was due to the presence of significant advantages and minor disadvantages compared to known analogues. The table 6 provides

comparative data on the advantages and disadvantages of the proposed and known concentration methods.

As can be seen from Table 6, the advantages of the technology in question, such as mobility and the ability to concentrate low-content uranium in PS, cover the disadvantage in the need for main pipelines.

Conducting pilot-scale tests on the geotechnological field required fabrication of the uranium concentration unit and thorough preparation of pipeline systems, instrumentation and control, ventilation, and emergency protection systems. Figure 7 shows the process scheme of the mobile uranium concentration unit installed on the geotechnological field at the natural uranium mining enterprise, designed based on calculated parameters.

As shown in Fig. 7, the uranium concentration node from PLS consists of four sorption-desorption

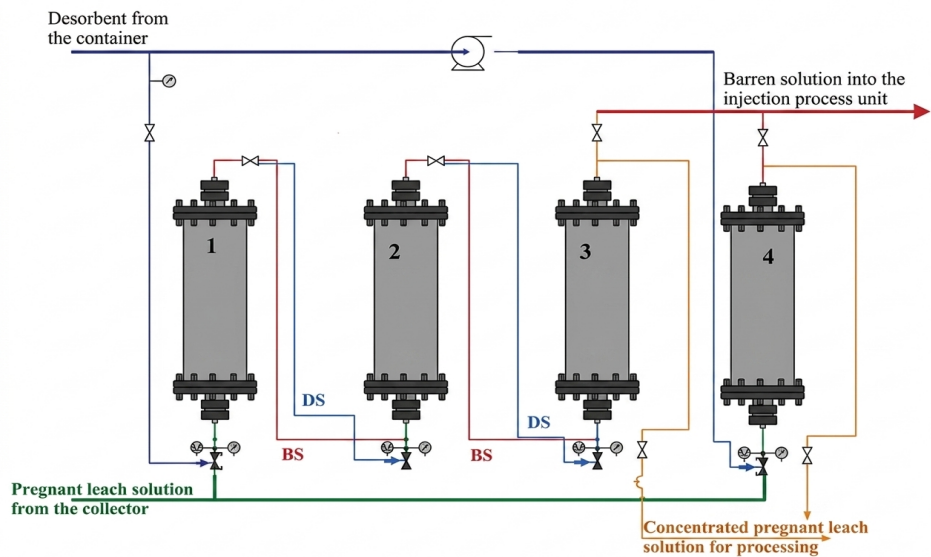


Fig. 7. Process scheme of the uranium concentration node.

Table 6. Comparative characteristics of different approaches to local uranium concentration

The concept	Advantages	Disadvantages
The proposed concept is a productive solution concentration unit	• More complete and effective use of the capacitive properties of ionite, the possibility of achieving the values of the temperature and depth of regeneration; • The possibility of using it for processing high and low-concentration solutions; • The possibility of mounting and dismantling the concentration unit, which allows for relocation to new production sites	• The need for a main pipeline for the transportation of concentrated raw materials for processing; • The need for periodic cleaning of the sorbent from mechanical dispersed particles
A mobile installation for mining separated blocks of deposits	• There is no need to create the necessary infrastructure for the transportation of PS to the main processing complex; • The possibility of assembly and disassembly, which allows for relocation to new production sites	• The complex process of loading and unloading saturated and regenerated sorbent and the process of reloading • sorbent in columns; • The need to transport the sorbent in specialized vehicles (acid trucks); • Large dimensions of tank, column and intermediate equipmen
Nanofiltration technology	• Minimal amount of storage capacity and no column equipment; • No need to use ion exchange sorbents	• The need for pre-cleaning of solutions before entering the membrane plant; • The effective life span of the membranes is short compared to ion-exchange sorbents; • Low concentration of uranium

columns filled with ion-exchange resin, three of which are connected in series with one in standby, calculated to operate during the desorption cycle of the first three. The series connection of sorption-desorption columns is related to the requirement to prevent uranium breakthrough into the injection solution and achieve maximum resin saturation with uranium. The volume of ion-exchange resin is calculated for uranium sorption from PLS at a throughput of up to 100 m³/h at a uranium content of up to 0.02 g/L. The uranium sorption process was conducted until uranium appeared in the barren sorption solution of the last column in the chain, indicating saturation of the ion-exchange resin and signaling that further operation would reduce uranium extraction efficiency. Average resin loading with uranium across three columns was 40.4 g/L, with uranium distributed among columns as follows: Column 1 – 41.6 g/L; Column 2 – 41.3 g/L; Column 3 – 38.3 g/L.

As shown in Figure 8, the maximum uranium content during desorption reached 21.3 g/L at the initial stage, after which it sharply declined to minimum values of 0.153 g/L. The stripping solution volume was 102 m³. The liquid-to-solid ratio (L:S) was 8 vol/cycle. The mean uranium content in the eluate was 4.64 g/L, i.e., the concentration factor from 0.015

to 4.64 g/L of PLS was 309 times. Uranium recovery from the resin into the eluate was 98.17%. The concentrated uranium solution entering the main manifold and PLS pipeline increased the mean uranium content in the PLS from 0.03 to 0.1 g/L. As a result of pilot-scale tests conducted under actual field conditions at the ISL uranium mine, the optimal throughput of the uranium concentration unit was established at 90–100 m³/h. The pilot-scale test results are consistent with laboratory data and confirm the validity of the chosen strategy for addressing issues of block completion and uranium concentration.

During field testing of the unit, a full cycle of uranium sorption and desorption was performed in trial mode at a reduced pregnant leach solution (PLS) flow rate (30 m³/h) at the geotechnical site. Saturating the entire resin volume with uranium took approximately 30 days of operation, during which the uranium concentration in the solution fluctuated. The desorption cycle lasted 8 h; by the time desorption was completed, the sorption process in the backup column had not yet finished. Overall, the pilot test demonstrated high efficiency and made it possible to identify certain design flaws. In particular, the positions of the solution overflow sensors were revised to ensure precise balance when trans-

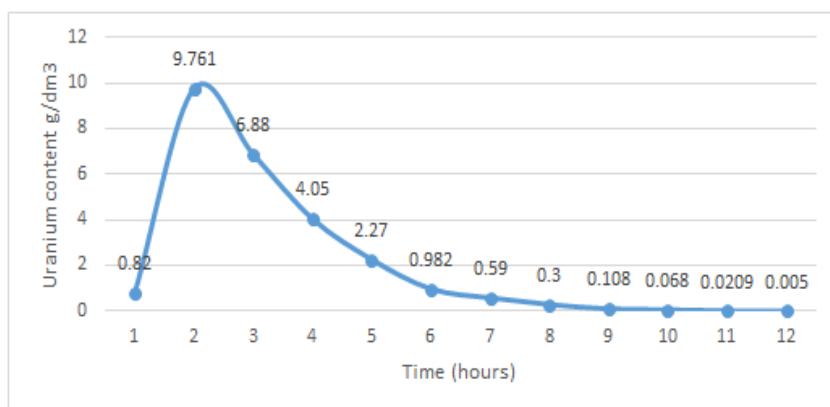


Fig. 8. Uranium content during desorption concentration.

ferring solution between columns. After the sensor positions were adjusted, the unit was restarted, reaching a PLS flow rate of 80-100 m³/h and reducing the resin saturation (sorption) time to 7 days. During repeat testing, the desorption process again lasted 8 hours.

4. Conclusion

In situ uranium leaching at the block completion stage requires significant expenditure on equipment maintenance, labor, electricity, increased sorption section capacity, and rising unit costs. The completion stage can span a considerable period of 6 to 36 months, causing serious financial losses and increasing the unit cost of the final product.

The laboratory experiments enabled development of rational parameters for sorption-desorption uranium concentration from low-grade PLS: selection of the most effective ion-exchange resin grade, calculation of effective process equipment parameters, and determination of the sulfuric acid concentration in the stripping solution. Based on the results obtained, the optimum sorbent Biolite 200 U was selected, with a feed solution pH of 2.1 and a sulfuric acid concentration in the stripping solution of 150 g/L, at which maximum sorption-desorption uranium concentration is achieved. Sorption-desorption apparatus were designed, the geometric dimensions of sorption and desorption columns for the pilot mobile concentrator were calculated, and solution distribution and withdrawal nodes were selected.

Based on the data obtained, a mobile unit for uranium concentration from low-grade PLS was fabricated. The mobile uranium concentration unit, representing a modular containerized unit comprising three 40-foot sea containers, was manufactured and delivered to the ISL uranium mine site.

Pilot-scale tests demonstrated high efficiency of

uranium concentration from PLS at a technological block remote from the processing plant. Average resin loading with uranium across three columns was 40.4 g/L, while the mean uranium content in the eluate was 4.64 g/L, representing a concentration factor of 309 times (from 0.015 to 4.64 g/L of PLS). This increased uranium content in the main manifold from 0.03 to 0.1 g/L. Application of local uranium concentration units deployed on the geotechnological field makes it possible to avoid these expenditures and improve the efficiency of PLS processing, while reducing operational costs and increasing labor productivity at mature mining operations. With an Equipment capacity of 75 m³/h and an average uranium content of 4.64 g/dm³, an additional 594 kg of uranium was obtained in one sorption-desorption cycle with desorbate.

Author Contributions

Manarbek Kylyshkanov – Conceptualization, Methodology, Software, Validation, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Project Administration, Funding Acquisition. **Zhiger Kenzhetaev** – Conceptualization, Validation, Formal Analysis, Investigation, Writing – Review & Editing, Supervision. **Bagdat Altaibayev** – Methodology, Software, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization. **Mariya Petrovna** – Conceptualization, Validation, Resources. **Aleksey Leksin** – Formal Analysis, Resources, Writing – Original Draft, Writing – Review & Editing.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Рациональные параметры концентрирования урана в продуктивном растворе в условиях подземного выщелачивания

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АННОТАЦИЯ

Целью настоящей работы являются разработка и апробация рациональных параметров концентрирования урана из продуктивного раствора (ПР) с низким содержанием полезного компонента на этапе доработки отдаленных от перерабатывающего комплекса технологических блоков, а также повышение эффективности переработки продуктивных растворов, увеличение производительности труда и снижение эксплуатационных затрат. Актуальность работы обусловлена тем, что на урановых месторождениях Казахстана увеличивается количество технологических блоков на этапе доработки с низкой продуктивностью и сниженным содержанием урана в ПР. При перекачке большого количества ПР с низким содержанием урана эффективность переработки снижается и увеличиваются удельные расходы, электроэнергии и трудозатрат. В связи с чем повышаются эксплуатационные расходы на переработку и себестоимость конечной продукции. Разработка рациональных параметров концентрирования урана в ПР позволят повысить среднее содержание в магистральном трубопроводе, сократить удельные расходы на этапе сорбционно-десорбционной переработки и повысят производительность труда перерабатывающего комплекса. При применении мобильной установки концентрирования годовой объем ПР с блока, направляемого на переработку, составит ~5000 м³. Снижение общего объема раствора, направляемого на переработку, составит приблизительно 5-6%. Степень концентрирования урана может составлять до 309 раз. С целью определения технологических параметров мобильной установки проведена серия лабораторных опытов по сорбционно-десорбционному

концентрированию урана в ПР с применением выбранного сорбента для разработки эффективных параметров процесса. На основании полученных данных разработана и изготовлена экспериментальная установка по концентрированию урана на геотехнологическом поле и проведены опытно-промышленные испытания на действующем месторождении.

Разработка рациональных параметров концентрирования урана в ПР на отдаленных от перерабатывающего комплекса участках весьма важная и актуальная задача для изучения.

Ключевые слова: сорбция, десорбция, концентрирование, установка, ионообменная смола

Жерасты шаймалау жағдайында өндірістік ерітіндідегі уранның мөлшерін көбейтудің ұтымды параметрлері

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АНДАТПА

Осы жұмыстың мақсаты – қайта өңдеу кешенінен алшақ орналасқан технологиялық блоктарды соңғы игеру кезеңінде пайдалы компонент мөлшері төмен өндірістік ерітінділерден уранның мөлшерін көбейтудің ұтымды параметрлерін әзірлеу және тәжірибелік түрде апробациялау болып табылады. Бұл өндірістік ерітінділерді өңдеу тиімділігін арттыруға, еңбек өнімділігін жоғарылатуға және өңдеу кезіндегі пайдалану шығындарын төмендетуге бағытталған. Зерттеудің өзектілігі Қазақстандағы уран кен орындарында соңғы игеру кезеңіндегі технологиялық блоктардың санының артуымен байланысты. Мұндай блоктарда өндірістік ерітіндідегі уран мөлшері төмендеп, жалпы өнімділік азаяды. Құрамында ураны аз үлкен көлемдегі ерітінділерді тасымалдау кезінде қайта өңдеу тиімділігі төмендеп, электр энергиясы мен еңбек ресурстарының меншікті шығындары артады. Соның нәтижесінде өндірістік процестердің пайдалану шығындары көбейіп, соңғы өнімнің өзіндік құны өседі. Өндірістік ерітіндідегі уранның мөлшерін көбейтудің ұтымды параметрлерін анықтау магистральдық құбыр желісіндегі уранның орташа мөлшерін арттыруға, сорбция-десорбция кезеңіндегі меншікті шығындарды қысқартуға және қайта өңдеу кешенінің еңбек өнімділігін арттыруға мүмкіндік береді. Мобильді қондырғыны қолдану кезінде бір технологиялық блоктан қайта өңдеуге бағытталатын өндірістік ерітінді көлемі жылына шамамен 5000 м³ құрайды. Қайта өңдеуге жіберілетін ерітіндінің жалпы көлемін қысқарту шамамен 5-6% болады. Уранның мөлшерін көбейту дәрежесі 309 есе аралығында болуы мүмкін. Мобильді қондырғының технологиялық параметрлерін анықтау мақсатында таңдалған сорбентті қолдана отырып, өндірістік ерітіндідегі уранның мөлшерін арттыру бойынша сорбция-десорбция процестеріне зертханалық тәжірибелер жүргізілді. Алынған нәтижелер негізінде геотехнологиялық алаң жағдайында уранның мөлшерін көбейтуге арналған тәжірибелік қондырғы әзірленіп, дайындалды және жұмыс істеп тұрған кен орнында тәжірибелік-өнеркәсіптік сынақтар өткізілді.

Қайта өңдеу кешенінен алшақ орналасқан учаскелерде өндірістік ерітіндідегі уранның мөлшерін көбейту параметрлерін анықтау қазіргі уақытта маңызды әрі өзекті ғылыми-техникалық міндеттердің бірі болып табылады.

Түйін сөздер: сорбция, десорбция, уран мөлшері, қондырғы, ионоалмасу смоласы