RGNZ/MGPB

Improving the efficiency of in-situ uranium leaching via oxygen-enriched lixiviant injection

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2026.2.13

Preliminary communication

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Abstract
This paper explores the optimization of in-situ uranium leaching efficiency through the application of oxygen as an oxidizing agent in the lixiviant. With this objective in mind, geological characteristics of the target site were examined, followed by a series of laboratory and pilot-scale experiments. The resulting data were systematically processed and analyzed. The influence of sulfuric acid concentration on the degree of oxygen enrichment in the lixiviant was established. Laboratory tests on core samples from the uranium deposit revealed consistent relationships between uranium concentration in the pregnant solution, the oxidation states of iron (Fe^{2+} and Fe^{3+}) in lixiviant, and the level of oxygen saturation. Comparative results of uranium content in the pregnant solution over time were obtained for both the conventional and oxygen-enriched technologies. Laboratory results demonstrated a 23.0% increase in uranium concentration in the pregnant solution using an oxygen-enriched lixiviant over the control solution, indicating a potential reduction in recovery time and final metal production costs. Pilot-scale tests at a uranium mine confirmed the positive effect of oxygen-enriched lixiviant on iron oxidation and uranium concentration in the pregnant solution. All pumping wells within the test block showed increased or stabilized uranium concentration upon connecting a special injection system for oxidation in injection wells surrounding the pumping wells, and decreased uranium concentration after system disconnection.

Keywords:
in-situ leaching, oxidation, uranium concentration in solution, oxygen enrichment, ferrous and ferric iron

1. Introduction

According to expert forecasts, by 2030 leading uranium producers are expected to extract approximately 1.8 million tonnes of uranium, which would result in the depletion of 37% of the world's explored reserves. In other words, the reserves of primary uranium deposits are projected to decline by more than 1.5 times (**Li & Jia, 2024; Michel et al., 2022**).

With the gradual exhaustion of high-grade uranium ores, many mining enterprises have begun shifting toward the exploitation of low-grade deposits. CRU Group analysts predict that at many active uranium mining sites, the average uranium content is more than 1⁄3 below the global average, and at exploration-stage sites, it is more than 1⁄2. The involvement of such deposits in production requires substantial investment in infrastructure, particularly in remote and hard-to-access regions (**Youssef et al., 2024**). These factors will inevitably increase the production cost of final uranium products.

At present, 439 nuclear reactors are operating worldwide, and this number is expected to increase to 549 in the near future. This growth underscores the strategic importance of the uranium sector for global development and highlights the need to expand uranium resources and reserves. It also requires the efficient and comprehensive use of already explored deposits, considering the strategic importance of uranium as a raw material (**Togizov et al., 2024**). Various technological solutions exist within conventional mining methods to ensure efficient and comprehensive utilization of mineral reserves (**Bitimbayev et al., 2023; Almenov et al., 2025**). Particular attention should be given to the proposed solution, in which all processes at the enterprise are grouped: by degree of exploration, feasibility and economic efficiency. For each of them, certain coefficients were determined on the example of the operation of two specific combined technologies: the extraction of uranium ores and coal (**Dychkovskyi et al., 2018**). However, for low-grade uranium deposits, traditional mining is often economically unviable. In such cases, geotechnological methods particularly in-situ leaching (ISL) have proven to be more effective (**Begalinov et al., 2022; Yusupov et al., 2021b**), which is achieved through determining the change in the volume of miner-

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Received: 26 June 2025. Accepted: 4 November 2025.
Available online: 13 March 2026

als extracted from the ore body depending on the amount of reagent and the filtration rate, using the laws of physics, chemistry and computer modeling (**Vladyko et al., 2022**). In ISL operations, sulfuric acid is commonly used as the primary lixiviant (**Chen & Li, 2022**).

One of the main limitations in the development of ISL is the low dissolution rate of uranium, which is associated with its occurrence in refractory mineral forms and the low concentration of ferric iron (Fe^{3+}) in both ore and groundwater (**Yussupov et al., 2023; Kenzhetaev et al., 2022**). A typical industrial response to this challenge is to increase the concentration of sulfuric acid in the lixiviant. However, this approach not only raises production costs but is also constrained by the current shortage of sulfuric acid in the Republic of Kazakhstan. This shortage has forced National Atomic Company Kazatomprom JSK to revise production plans and initiate the construction of a new facility with an annual capacity of 800.000 metric tonnes of sulfuric acid.

Accordingly, considerable attention is being directed toward the development of improved in-situ uranium leaching technologies.

Current approaches to intensifying uranium leaching involve physical, physico-chemical and chemical methods (**Yanjing et al., 2023; Rakishev et al., 2022; Pękala, 2017**), as well as the sequential leaching of ore bodies at different depths using boreholes of various diameters and special designs (**Khomenko et al., 2023**). While extensive theoretical, laboratory and pilot-scale tests has been carried out, many of these techniques remain expensive, technically complex for industrial application and often environmentally burdensome (**Chen & Li, 2022; Elmardi Suleiman Khayal & Bashier Elagab, 2022; Oryngozha et al., 2020**).

Both research findings and practical experience indicate that the intensity of uranium leaching is strongly influenced by the concentration of dissolved oxygen in the lixiviant. Oxygen content can be increased either by aeration or by direct injection of liquid oxygen (**Cramer et al., 2023; Banos & Scott, 2020; Zeng et al., 2013**). However, oxygen transitions to a liquid phase only under cryogenic conditions or elevated pressure. Although lower lixiviant temperatures improve oxygen solubility, they negatively affect the leaching kinetics. Conversely, increasing hydraulic pressure fivefold from 60 meters has been shown to raise dissolved oxygen concentrations by 70% and uranium content by a factor of seven. As a result, some uranium producers have experimented with in-situ oxygen dissolution methods. For example, at the Uchkuduk deposit, compressed air was injected into the formation using a compressor system. As the oxygen-enriched lixiviant reached pumping wells, uranium concentrations in the pregnant solution increased from 10.0 mg/L (under baseline conditions) to 35.0 mg/L. In another test block, oxygen saturation was achieved through pressure differentials and vacuum induction, doubling uranium content in the solution.

2. Materials and Methods

To improve oxygen enrichment, this study proposes the use of a specialized injector that intensively mixes air with the lixiviant and enhances oxygen transfer by increasing internal solution pressure (see **Figure 1**). The injector consists of a short pipe with a constriction at the center and an opening for air intake.

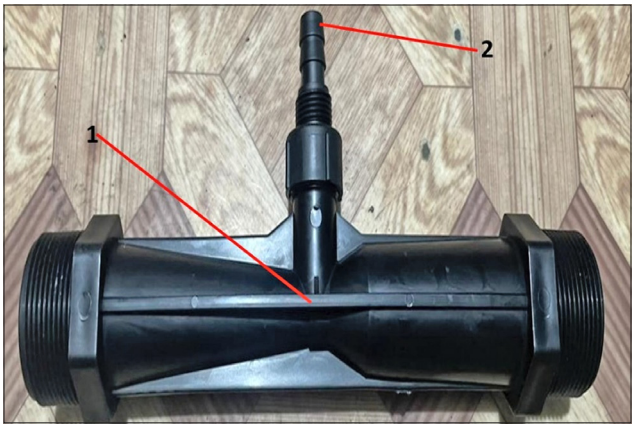

Figure 1. Specialized injector (Venturi tube): 1 –constricted section for pressure drop; 2 – opening for air suction.

As the solution passes through the narrowed section of the injector tube, a pressure drop occurs, causing air to be drawn in. When the solution enters the expanded section, the pressure rises, which promotes the effective dissolution of oxygen from the air into the solution. The advantages of using the specialized injector include low capital and operational expenditures, ease of integration into the lixiviant pipeline, and environmental safety.

To validate the proposed technology, laboratory experiments were conducted using core material from the study site. The Central area of the Mynkuduk deposit was selected as the research object. An analysis of historical leaching data (**Ortalyk Mining Enterprise, 2021**), indicates that, after reaching the maximum uranium concentration in the pregnant solution during the acidification stage with elevated sulfuric acid concentrations of 30.0–50.0 g/L, a distinct and abrupt decline in uranium concentration is observed upon transitioning to the active leaching stage, where the acid concentration decreases to 8.0–10.0 g/L (see **Figure 5**).

The ore body at the study site is predominantly composed of uraninite and coffinite, accounting for approximately 85% and 15%, respectively (**Ortalyk Mining Enterprise, 2021**). It is well known that uranium in uraninite is poorly soluble in sulfuric acid, which necessitates the addition of oxidizing agents to the lixiviant.

Field identification of the core material classified it as gray sand. Data analysis over recent years shows that the average concentration of ferrous iron (Fe^{2+}) in the solution is around 1.3 g/L, while ferric iron (Fe^{3+}) is approximately 0.15 g/L, resulting in a Fe^{3+}/Fe^{2+} ratio of 0.115

(**Ortalyk Mining Enterprise, 2021**). The low concentration of ferric iron also reduces the leaching intensity and similarly necessitates the introduction of oxidants into the lixiviant.

The combined effect of these factors results in a marked decrease in uranium concentration in the pregnant solution.

The research methods consist of analyzing and synthesizing scientific and technical information (**Ortalyk Mining Enterprise, 2021; Vershina LLP, 2010**), as well as practical experience in underground in-situ uranium leaching. They also include laboratory and pilot-scale tests, along with statistical processing and analysis of the results.

Laboratory tests were conducted using a custom-built experimental setup consisting of vessels for the lixiviant, intermediate and pregnant solutions, a core sample from the deposit, and a device for oxygen enrichment of the solution.

The first stage involved determining the influence of sulfuric acid concentration on the degree of oxygen enrichment in the lixiviant. Four vessels were prepared with acid concentrations of 5.0; 8.0; 10.0 and 12.0 g/L. A total of 8 measurements of dissolved oxygen were taken at varying acid concentrations.

Upon determining the optimal concentration of sulfuric acid, subsequent experiments were conducted to examine the relationship between key leaching parameters such as uranium content, the concentrations of ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron, and the degree of oxygen enrichment in the lixiviant. The results obtained using the oxygen-enriched lixiviant were compared with those obtained using the standard (non-enriched) solution.

Oxygen concentration in the lixiviant was measured after passage through the specialized injector. The lixiviant was collected in a sealed vessel designed with a port in the lid for introducing the solution–air mixture, and an electrode was placed at the bottom to measure dissolved oxygen content. Each leaching cycle lasted 7 hours for each core sample. One sample of the initial lixiviant and seven sequential samples of the pregnant solution were taken hourly, totaling eight samples per test. Oxygen concentration was measured using an oximeter, while uranium and iron species were analyzed at the mine's laboratory. The uranium content in the core material used for testing was 0.035%.

For pilot-scale testing, a test block was selected comprising 3 pumping wells and 13 injection wells. Specialized injectors for oxygen enrichment were installed at the injection wells via a bypass line connected to the lixiviant distribution network (see **Figure 2**).

The pilot-scale testing was conducted from late February through November. To obtain comparative data, the operation of the specialized injectors was periodically halted, thereby interrupting the oxygen enrichment of the lixiviant. Uranium concentrations in the pregnant solution were measured in three pumping wells (48-5-04), (48-5-05) and (48-5-06), which were surrounded by injection wells equipped with oxygen injectors. Sampling was carried out in accordance with the operational schedule and supplemented with additional measurements between scheduled dates. It should be noted that, following the installation of oxygen enrichment systems, the average sulfuric acid concentration in the lixiviant was gradually reduced from 12.0 g/L in March to 3.0 g/L by September.

Figure 2. Specialized injectors installed on the lixiviant line via a bypass connection: 1 – main pipeline; 2 – injection well pipeline; 3 – specialized injectors.

3. Results and Discussion

During the laboratory experiments, the initial concentration of dissolved oxygen in the baseline lixiviant was 5.2 mg/L. The results of the laboratory tests assessing the effect of sulfuric acid concentration on the degree of oxygen enrichment in the lixiviant after passage through the specialized injector are illustrated graphically in **Figure 3**.

As shown in **Figure 3**, at a sulfuric acid concentration of 5.0 g/L, the degree of oxygen enrichment in the lixiviant after passing through the specialized injector was 8.4 mg/L in the first test and 8.6 mg/L in the second. Under laboratory conditions, the maximum observed concentration of dissolved oxygen of 9.2 mg/L was achieved when the sulfuric acid concentration was 10.0 g/L. It is important to note that increasing the sulfuric acid concentration from 5 g/L to 10 g/L resulted in an average increase in oxygen enrichment of 8.2%, based on the results of two experimental tests. A further increase in the sulfuric acid concentration to 12 g/L resulted in a decrease of oxygen enrichment of the solution. This finding suggests that sulfuric acid concentration has a significant effect on the degree of oxygen enrichment in the lixiviant, and that its optimal concentration is 10 g/l.

Therefore, further investigations aimed at assessing the effect of oxygen enrichment in the lixiviant on leaching performance were conducted using a sulfuric acid

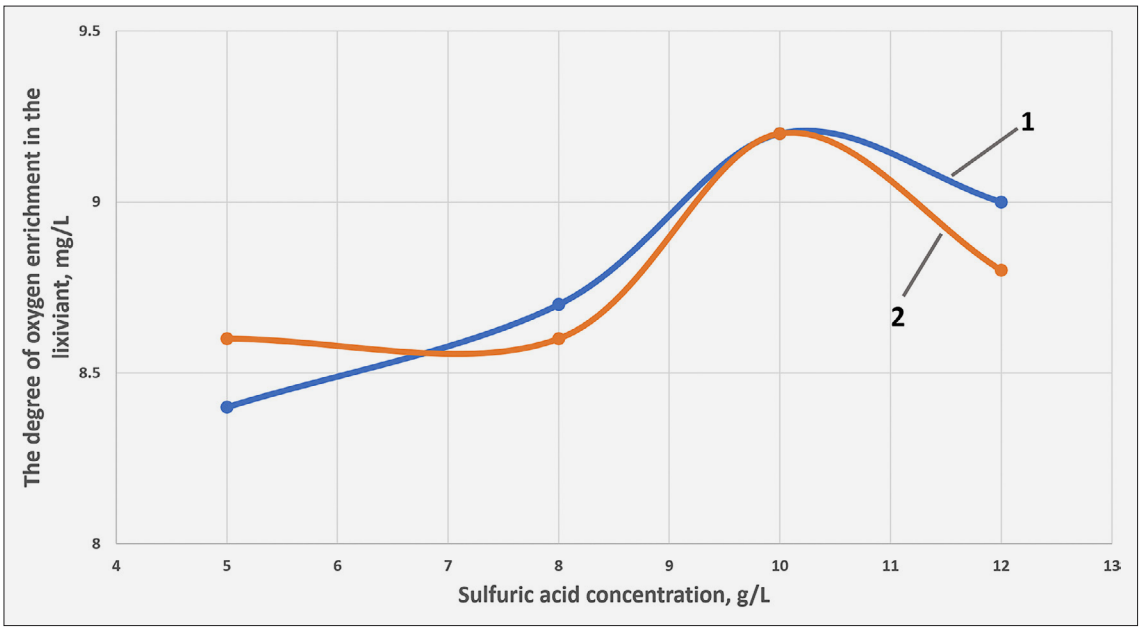

Figure 3. Dependence of oxygen enrichment in the lixiviant on sulfuric acid concentration:
1 – oxygen enrichment, mg/L (Test 1); 2 – oxygen enrichment, mg/L (Test 2).

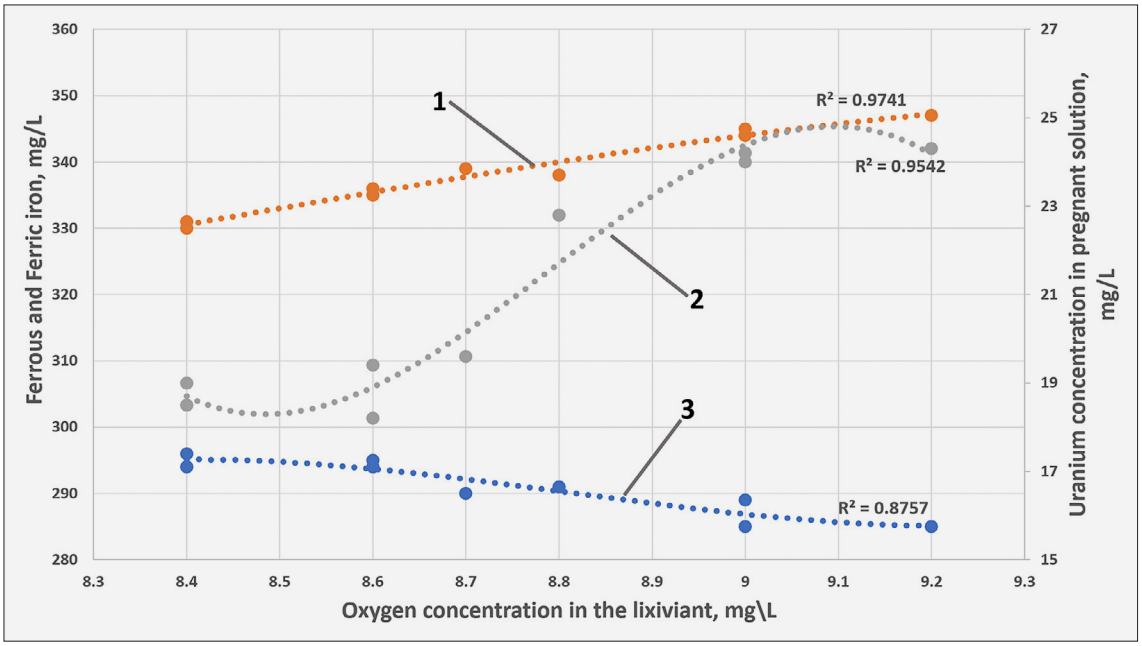

Figure 4. Polynomial regression curves based on dissolved oxygen concentration in the lixiviant:
1 – ferric iron concentration; 2 – uranium concentration; 3 – ferrous iron concentration.

concentration of 10 g/L. The results of this study are illustrated graphically in **Figure 4**.

As shown in **Figure 4**, increasing the degree of oxygen enrichment in the lixiviant from 8.4 mg/L to 9.2 mg/L led to a decrease in ferrous iron concentration from 296 mg/L to 285 mg/L, while the ferric iron concentration increased from 331 mg/L to 347 mg/L. Overall, oxygen enrichment of the lixiviant resulted in an increase in the ferric-to-ferrous iron concentration ratio from 1.12 to 1.22. As the dissolved oxygen concentration in the lixiviant increased from 8.4 mg/L to 9.2 mg/L, and as Fe^{2+} was oxidized to Fe^{3+}, uranium concentration in the pregnant solution increased by 5.8 mg/L.

To compare uranium concentration in the pregnant solution during leaching with and without oxygen enrichment, laboratory experiments were conducted using core material over a period of 7 hours. Comparative plots were generated to illustrate the change in uranium concentration in the pregnant solution during leaching with and without oxygen enrichment (see **Figure 5**).

As shown in **Figure 5**, uranium concentrations in the sixth and seventh samples of the pregnant solution

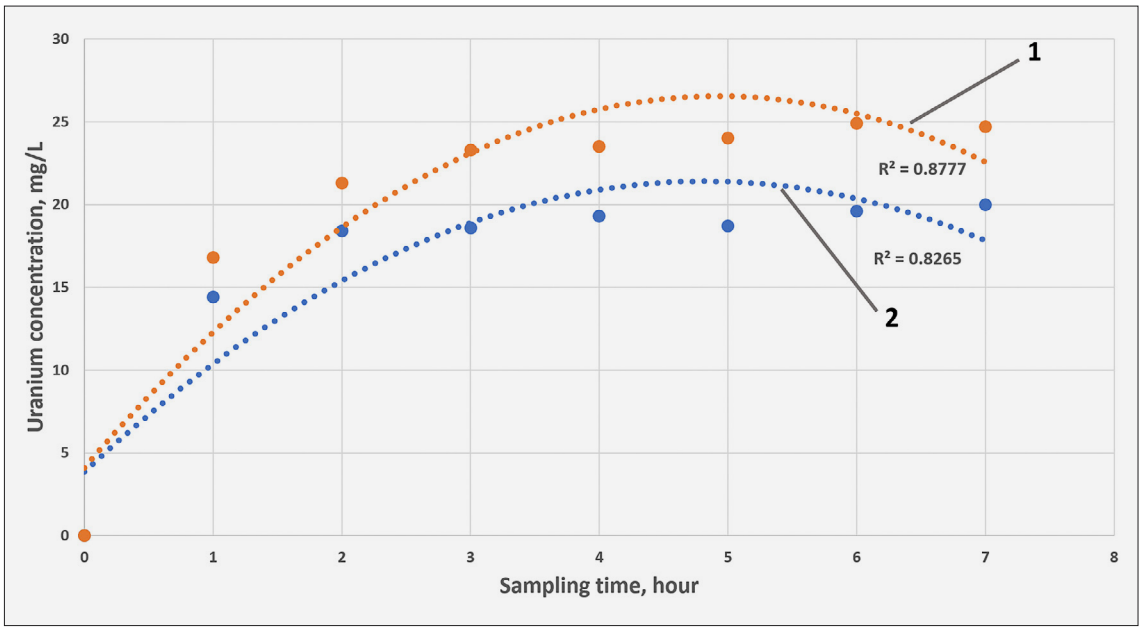

Figure 5. Polynomial regression curves showing uranium concentration in the pregnant solution: 1 – with oxygen-enriched lixiviant, mg/L; 2 – without oxygen enrichment, mg/L.

reached high values under both oxygen-enriched and non-enriched leaching conditions. Laboratory test results demonstrated that leaching with an oxygen-enriched lixiviant yielded uranium concentrations that were, on average of 4.21 mg/L, higher than the concentrations yielded by the baseline (non-enriched lixiviants) technology.

Taking into account the distance between the injection and pumping wells, as well as the filtration coefficient of the formation, positive results from the pilot-scale field trials were observed within 20–30 days after the specialized injector was put into operation. Before solution enrichment with oxygen, the uranium concentration in the productive solution from pumping well 3 (48-5-06) showed a decrease from 113 mg/L to 38 mg/L during the period from February 27, 2024 to March 28, 2024. Following the activation of the injector and the introduction of oxygen-enriched lixiviant, the uranium concentration increased by 10.0 mg/L, or more than 13%. During the course of the pilot operation, a minimal decline in uranium concentration was observed. This was attributed to a reduction in the volume of lixiviant injected into wells 48-4-5, 48-5-10, and 48-5-11, falling below the operational target due to clogging of the well filters. As a result, air intake into the injectors ceased, and oxygen enrichment of the lixiviant was interrupted. After well redevelopment and the restoration of injection flow rates, uranium concentrations in the pregnant solution began to rise again.

In pumping wells 1 and 2, a steady decline in uranium concentration in the pregnant solution was observed over the three months preceding oxygen enrichment of the lixiviant. For example, in pumping well 1, uranium concentration decreased by 10.0 mg/L during the first month, by 20.0 mg/L in the second, and by 30.0 mg/L in the third. After the activation of the specialized injectors and the initiation of oxygen enrichment, uranium concentrations in the pregnant solutions of the experimental wells increased from 108 mg/L to 111 mg/L (well 1), and from 94 mg/L to 98 mg/L (well 2). The difference in uranium content between laboratory and pilot-scale operations can be explained as follows. Laboratory work was carried out using core material over a period of 7 hours, while in pilot industrial operations, the leaching solution passes from the injection well to the pumping well over a period of 15 days. Accordingly, the uranium content in pilot industrial operations will be higher.

As part of the pilot-scale trials, the operation of the specialized injectors was temporarily suspended for comparative analysis. The injectors were turned off between March 20 and May 20, 2024, and again between June 12 and August 1, 2024. It was found that a sharp decline in uranium concentration in the pregnant solution occurred within 20–30 days following the deactivation of the injectors. For example, between May 20 and the end of the month, uranium concentration in the pregnant solution from pumping wells 2 (48-5-05) and 3 (48-5-06) decreased from 97.0 mg/L to 81.0 mg/L and from 86.0 mg/L to 75.0 mg/L, respectively, corresponding to reductions of 16.5% and 12.8%. After reactivating the injectors on June 1, an increase of 3 mg/L was recorded in well 3 (48-5-06), while concentrations in wells 1 and 2 remained stable, indicating no further decline.

As a result, after disconnecting of the special injectors and the termination of oxidation (June 12, 2024 – July 2024), the uranium concentration in the productive solutions exhibited a decline: in well 2 (48-5-05), from 80 mg/L to 62 mg/L (a reduction of 22.5%), and in well 3

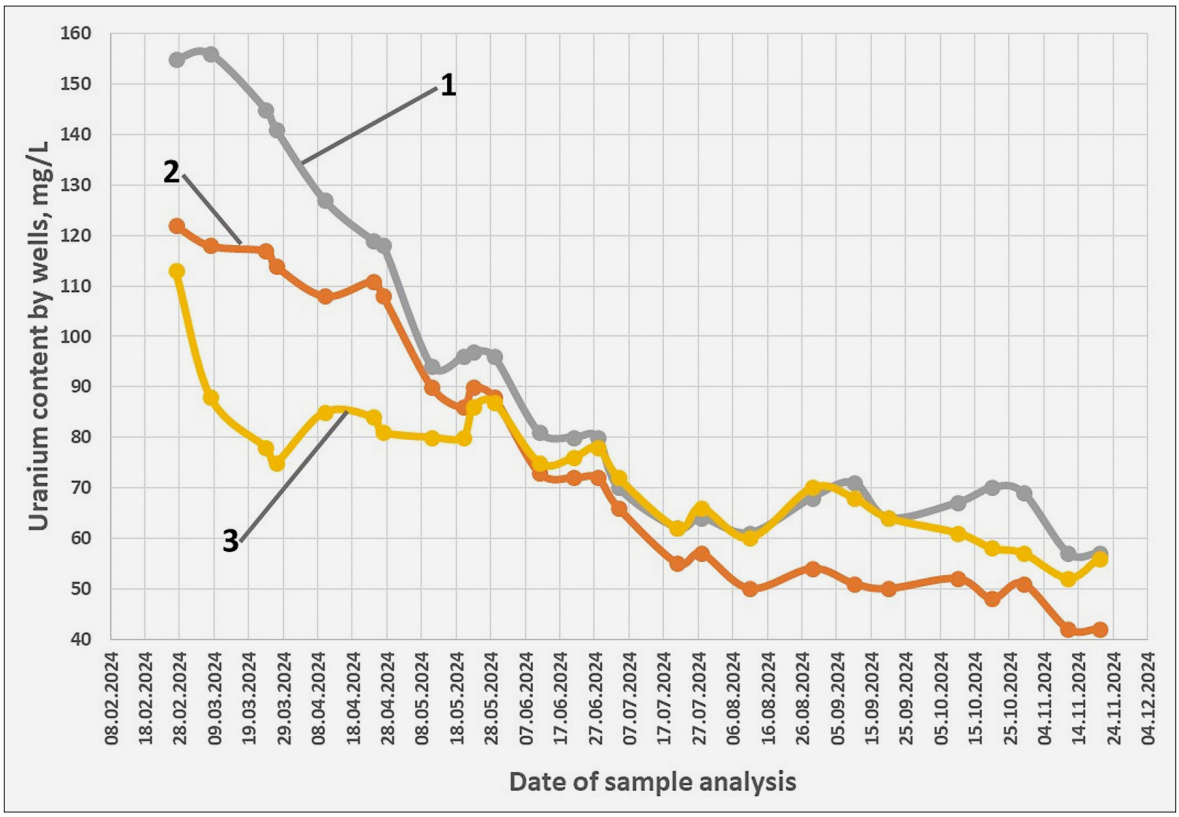

Figure 6. Changes in uranium concentration in the pregnant solution associated with activation and deactivation of the specialized injector at the pilot test block: 1 – uranium concentration in well 48-5-05, mg/L; 2 – uranium concentration in well 48-5-04, mg/L; 3 – uranium concentration in well 48-5-06, mg/L

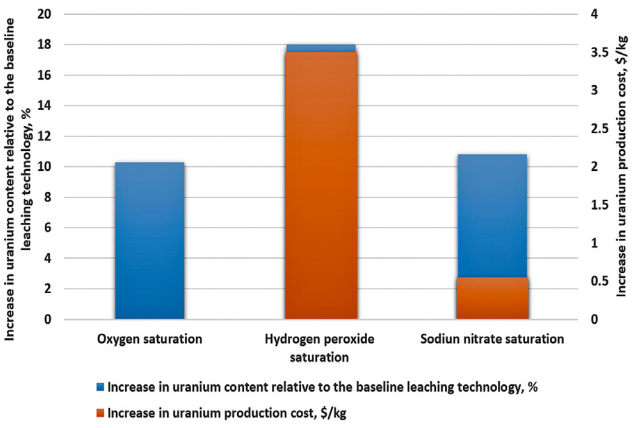

Figure 7. Comparison of selected indicators for different reagents

(48-5-06), from 75 mg/L to 65 mg/L (a reduction of 13.3%). Once the injectors were brought back online between August 1 and August 14, 2024, uranium concentrations in the pregnant solutions of pumping wells 1 (48-5-04), 2 (48-5-05), and 3 (48-5-06) increased from 50.0 mg/L to 54.0 mg/L, from 60.0 mg/L to 68.0 mg/L, and from 60.0 mg/L to 70.0 mg/L, respectively, corresponding to relative increases of 8.0%, 13.3% and 16.7%.

After the subsequent shutdown of the injectors on August 15, a decline in uranium concentrations was again observed: from 54.0 mg/L to 50.0 mg/L in well 1, from 68 mg/L to 64 mg/L in well 2, and from 70 mg/L to 64 mg/L in well 3.

The dynamics of uranium concentration in the pregnant solution associated with the activation and deactivation of the specialized injectors are presented in **Figure 6**.

The evaluation of the proposed technology was performed through a comparative analysis of selected results from previous studies employing various reagents (see **Figure 7**).

The comparative analysis indicates that the use of hydrogen peroxide (**Yusupov et al., 2021a**) and sodium nitrite (**Bashilova & Baibatsha, 2022**) results in an increase in uranium recovery of 7.3% and 0.5%, respectively, relative to atmospheric oxygen. However, this improvement is accompanied by higher production costs: the cost of 1 kg of uranium rises by $3.25 when using hydrogen peroxide and by $0.55 when using sodium nitrite, whereas no additional cost is associated with the use of atmospheric oxygen. It should also be noted that the application of hydrogen peroxide and sodium nitrite necessitates stricter safety measures.

4. Conclusions

Laboratory and pilot-scale studies have demonstrated the positive effect of oxygen-enriched solutions on the

efficiency of in-situ uranium leaching. The increased saturation of the solution with oxygen from air is achieved through the use of a special injector. However, increasing the dissolved oxygen content in the solution promoted the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), which in turn enhanced uranium concentration in the pregnant solution.

All three pumping wells in the test block showed either an increase in uranium concentration or a cessation of its decline following the activation of oxygen injectors in the surrounding injection wells. Conversely, uranium concentrations consistently decreased after the injectors were turned off.

On average, the increase in uranium concentration in the pregnant solution amounted to 10.3%, indicating that the implementation of oxygen enrichment technology can reduce the leaching cycle duration and lower operational costs for uranium recovery within the technological block.

A comparison of the results of the proposed technology with previous studies employing various reagents has demonstrated a low production cost of the final product.

As a result of these findings, the oxygen enrichment method using a specialized injector has been adopted by the uranium production enterprise for large-scale implementation.

Funding

This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26198685).

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SAŽETAK

Povećanje učinkovitosti terenskoga izluživanja uranija injektiranjem oksidiranoga lužnatog sredstva

U radu se istražuje mogućnost optimizacije učinkovitosti terenskoga izluživanja uranija primjenom kisika kao oksidacijskoga sredstva u lužnatome mediju. S tim ciljem analizirana su geološka obilježja ležišta, nakon čega je provedena serija laboratorijskih i poluindustrijskih istraživanja. Dobiveni podatci sustavno su obrađeni i analizirani. Utvrđen je utjecaj koncentracije sumporne kiseline na stupanj oksidacije lužnatoga sredstva. Laboratorijska istraživanja jezgrinih uzoraka iz ležišta uranija pokazala su konzistentne odnose između koncentracije uranija u bogatoj otopini (*pregnant solution*), oksidacijskih stanja željeza (Fe^{2+} i Fe^{3+}) u lužnatome mediju te razine zasićenosti kisikom. Dobiveni su usporedni rezultati promjene koncentracije uranija u otopini tijekom vremena za konvencionalnu tehnologiju i tehnologiju s oksidiranim lužnatim sredstvom. Laboratorijski rezultati pokazali su povećanje koncentracije uranija za 23,0 % u otopini pri uporabi oksidiranoga lužnatog sredstva u odnosu na kontrolno sredstvo, što upućuje na mogućnost skraćenja vremena izluživanja i smanjenja konačnih troškova proizvodnje metala. Poluindustrijska istraživanja provedena u rudniku uranija potvrdila su pozitivan učinak oksidiranoga lužnatog sredstva na oksidaciju željeza te na povećanje koncentracije uranija u otopini. Sve crpne bušotine unutar istraživanoga bloka pokazale su povećanje ili stabilizaciju koncentracije uranija nakon spajanja posebnoga sustava za oksidaciju u injekcijskim bušotinama koje okružuju crpne bušotine, dok je nakon isključenja sustava koncentracija uranija pala.

Ključne riječi:
terensko izluživanje, oksidacija, koncentracija uranija u otopini, oksidirano lužno sredstvo, dvovalentno i trovalentno željezo

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All authors have read and agreed to the published version of the manuscript.