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PROLONGING INTERREPAIR CYCLES OF IN-SITU LEACHING URANIUM WELLS USING A SPECIALIZED REAGENT

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All uranium production in the Republic of Kazakhstan is conducted using in-situ leaching (ISL) technology. One of the major challenges associated with this mining method is the reduction in the operational life of process wells due to clogging of well screens and the near-wellbore formation zone. Existing well-rehabilitation methods often fail to provide satisfactory results, as their effectiveness is frequently limited and the achieved improvements are typically short-lived.

The objective of this study was to develop a theoretical framework and evaluate the effectiveness of a specialized inhibitor-based reagent for extending the operating cycle of process wells.

Theoretical and laboratory investigations employing an inhibitor-dissolver reagent demonstrated enhanced dissolution of calcium-bearing deposits, thereby reducing the intensity of clogging within well screens and the near-wellbore zone. Relationships were established between calcium dissolution efficiency and inhibitor concentration in the leaching solution during uranium recovery, as well as between inhibitor dosage and the operating cycle of process wells. The preferential dissolution of calcium ions was achieved at an inhibitor concentration of 2%.

Pilot-scale field tests conducted at a uranium ISL operation demonstrated improved leaching performance owing to the extension of well operating cycles following inhibitor application. Compared with conventional technology, the proposed approach improved uranium production efficiency by up to 30% on average.

Keywords: in-situ uranium leaching, colmatation, specialized reagent, calcium ions, technological well, interrepair cycle.

АРНАЙЫ РЕАГЕНТТІ ПАЙДАЛАНА ОТЫРЫП, УРАНДЫ ЖЕРАСТЫ СІЛТЕЛЕУ КЕЗІНДЕ ҰҢҒЫМАЛАРДЫҢ ЖӨНДЕУ АРАЛЫҚ ЦИКЛІН ҰЛҒАЙТУ

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Қазақстан Республикасында уран өндірудің барлық көлемі жерасты ұңғымалық шаймалау технологиясы арқылы жүзеге асырылады. Бұл технологияның негізгі проблемаларының бірі-сүзгілердің және технологиялық ұңғымалардың сүзгі аймағының колматациясы нәтижесінде ұңғымалардың жөндеу аралық циклінің төмендеуі. Жөндеу және қалпына келтіру жұмыстарының қолданыстағы әдістері қажетті нәтиже бермейді, яғни кейбір жағдайларда - шамалы ғана болса, басқаларында - нәтижелер қысқа мерзімді.

Жұмыстың мақсаты - технологиялық ұңғымалардың жөндеу аралық цикліне ингибитор түріндегі арнайы реагенттің әсерін теориялық негіздеу және зерттеу болып табылады.

Еріткіш ингибиторын қолдана отырып жүргізілген теориялық және зертханалық зерттеулер кальций иондарының еру дәрежесінің жоғарылауын дәлелдеді, бұл сүзгілер мен сүзгі аймағының колматациясының түзілуін төмендетуге ықпал етеді. Кальций иондарының еру дәрежесінің уранды шаймалау сатысында шаймалау ерітіндісіне енгізілетін ингибитордың концентрациясына, сондай-ақ технологиялық ұңғымалардың жөндеу аралық циклінің өзгеруіне тәуелділігі анықталды. Кальций иондарының басым еруі ингибитордың 2% концентрациясында байқалды.

Уран кенішіндегі тәжірибелік-өнеркәсіптік жұмыстар ұңғымаларда жөндеу аралық жұмыс циклін 30% - ға дейн ұлғаю арқылы уранды жерасты ұңғымалық шаймалау тиімділігінің артқанын көрсетеді.

Түйін сөздер: уранның ұңғымаларын шаймалау, колматация, арнайы реагент, кальций иондары, технологиялық ұңғымалар, жөндеу аралық цикл.

УВЕЛИЧЕНИЕ МЕЖРЕМОТНОГО ЦИКЛА СКВАЖИН ПРИ ПОДЗЕМНОМ СКВАЖИННОМ ВЫЩЕЛАЧИВАНИИ УРАНА С ИСПОЛЬЗОВАНИЕМ СПЕЦИАЛЬНОГО РЕАГЕНТА

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Весь объем добычи урана в Республике Казахстан производится технологией подземного скважинного выщелачивания. Одним из основных проблем данной технологии является снижение межремонтного цикла работы скважин в результате кольматации фильтров и прифильтровой зоны технологических скважин. Существующие способы ремонтно-восстановительных работ не дают желаемых результатов, т.е. в одних случаях - не значительные, в других - результаты кратковременные.

Целью работы является теоретическое обоснование и изучение действия специального реагента в виде ингибитора на межремонтный цикл работы технологических скважин.

Проведенными теоретическими и лабораторными исследованиями с применением ингибитора-растворителя доказано повышение степени растворения ионов кальция, способствующий снижению образования кольматации фильтров и прифильтровой зоны. Установлены зависимости степени растворения ионов кальция от концентрации ингибитора, вводимого в выщелачивающий раствор на стадии выщелачивании урана, а также на изменение межремонтного цикла работы технологических скважин. Предпочтительное растворение ионов кальция достигается при концентрации ингибитора - 2%.

Опытно-промышленные работы на урановом руднике показали повышение эффективности подземного скважинного выщелачивания урана за счет увеличения межремонтного цикла работы скважин при применении ингибитора по сравнению с базовой технологией в среднем до 30%.

Ключевые слова: скважинное выщелачивание урана, кольматация, специальный реагент, ионы кальция, технологические скважины, межремонтный цикл.

Introduction. In-situ leaching (ISL) is the predominant and most efficient method for uranium extraction from sandstone-hosted and alluvial deposits characterized by high permeability of the host rocks. The process involves the injection of a sulfuric acid-based leaching solution into the productive horizon through injection wells [1, 2]. Uranium dissolution occurs through a series of chemical reactions, resulting in the formation of soluble uranyl sulfate complexes that are transported within the pregnant leach solution and subsequently recovered at the surface through production wells for further processing:

$$UO_2 + H_2SO_4 = UO_2SO_4 + H_2O$$

Owing to its high technological and economic efficiency, in-situ leaching has become the predominant method for uranium extraction in many countries worldwide. The Republic of Kazakhstan is currently the world's leading producer of uranium using ISL technology.

The majority of Kazakhstan's uranium resources are concentrated within the Syr-Darya uranium ore province, which comprises sandstone-hosted infiltration deposits. These deposits typically occur as stratiform ore bodies with thicknesses ranging from 20 to 30 m and exhibit sinuous ribbon-like geometries in plan view, extending from 1 to 10 km in length and 50 to 600 m in width. The morphology of the uranium mineralization is generally simpler than that of the individual ore-bearing and barren zones.

Development of uranium deposits within the Syr-Darya uranium ore province is primarily carried out using hexagonal and linear wellfield patterns. In these wellfields, the distance between production and injection wells typically ranges from 30 to 60 m, whereas the spacing between adjacent injection wells varies from 20 to 40 m. The average well depth is approximately 600–650 m. The average flow rates of production and injection wells are 4.8 and 2.4 m³/h, respectively. The sulfuric acid concentration in the leaching solution is maintained within the range of 6–12 g/L. KDF-118/90 frame-and-disc filters are installed across the entire thickness of the productive aquifer hosting the uranium mineralization.

Following the drilling of process wells, well development operations are carried out to remove clay particles, fine sand, and drilling debris from the well screen and the surrounding near-wellbore zone along the entire screened interval [3].

One of the major operational challenges in uranium ISL is the decline in well productivity over time, which results in unstable well performance and a shortened operating cycle between rehabilitation treatments.

In the present study, the maintenance cycle is defined as the period of operation of a process well from the completion of the previous rehabilitation treatment and the return of the well to normal operating conditions until the implementation of the subsequent rehabilitation intervention. The need for the next maintenance operation is determined by a decline in the injectivity of injection wells or the productivity of recovery wells below the threshold specified by operational regulations, resulting from the development of clogging processes within the well screen and the near-wellbore zone.

In the Syr-Darya uranium ore province, where sulfuric acid leaching is employed, the formation of poorly soluble mineral precipitates is a major factor contributing to well clogging. Gypsum is the predominant component of these deposits. Its formation results from the reaction of sulfuric acid with calcium-bearing minerals present in the host rocks, primarily calcite and dolomite:

$$CaCO_3 + H_2SO_4 + H_2O = CaSO_4 \cdot 2H_2O \downarrow + CO_2 \uparrow$$

$$Ca(Mg(CO_3)_2 + H_2SO_4 + 2H_2O = CaSO_4 \cdot 2H_2O \downarrow + MgSO_4 + 2CO_2 \uparrow$$

The gypsum precipitates formed as a result of these reactions are characterized by high mechanical strength and strong adhesion to mineral surfaces and therefore cannot be removed under normal hydraulic pressures or by the flow of injected leaching solution. The accumulation of gypsum on well screens and within the pore space of the near-wellbore zone reduces the injectivity of injection wells, decreases the productivity of process wells, and shortens the operating cycle between rehabilitation treatments. Additional factors contributing to well clogging include the accumulation of clay particles and suspended solids, the formation of corrosion products, and the migration of fine sand from the productive formation.

Therefore, various rehabilitation measures are required to restore well productivity, with the selection of the treatment method depending on the dominant type of clogging, as summarized in Table 1 [4, 5].

Table 1 - Classification of colmatation types and methods for restoring well productivity in the Syr-Darya province

Type of colmatation	The main colmatating compounds	The method of well rehabilitation
Mechanical colmatation	Sand, clay particles, mechanical suspensions, drilling sludge.	Mechanical cleaning (flushing, air-lift leveling up, removal of sand plugs).
Chemical colmatation	Mainly gypsum, as well as aluminite, carbonate and hydroxide compounds.	Chemical treatment (acid and reagent substances for dissolving colmatants)

At uranium deposits of the Syr-Darya uranium ore province, well rehabilitation is predominantly performed using either mechanical or chemical treatment methods. The duration of the well operating cycle is largely determined by the selected rehabilitation approach. Figure 1 presents the operating cycles of 12 wells subjected to mechanical rehabilitation and 9 wells treated using chemical rehabilitation methods at the study site.

As shown in Figure 1, the operating cycle of wells following mechanical rehabilitation ranged from 8 to 32 days, with an average value of 20 days. After the implementation of chemical rehabilitation methods, the operating cycle increased to 15-34 days, with an average duration of 23 days.

To extend the operating cycle of wells in the Syr-Darya uranium ore province, various reagents have been investigated for well treatment. Acid-based treatments have been shown to increase the permeability of host rocks and contribute to enhanced productivity. For example, treatment with a solution containing 100 g/L sulfuric acid increased the injectivity of injection wells from 0.2-0.5 m³/h to 4.5 m³/h, representing an improvement of more than ninefold. In addition,

15-20% hydrochloric acid (HCl) solutions are widely used for well rehabilitation.

Clogging deposits containing aluminite exhibit high solubility in acidic solutions. Sodium polyphosphates are also employed as effective dissolving agents at concentrations ranging from 30 to 100 g/L. Furthermore, technical sodium tripolyphosphate solutions are commonly used for the treatment of the near-wellbore zone of wells [6, 7].

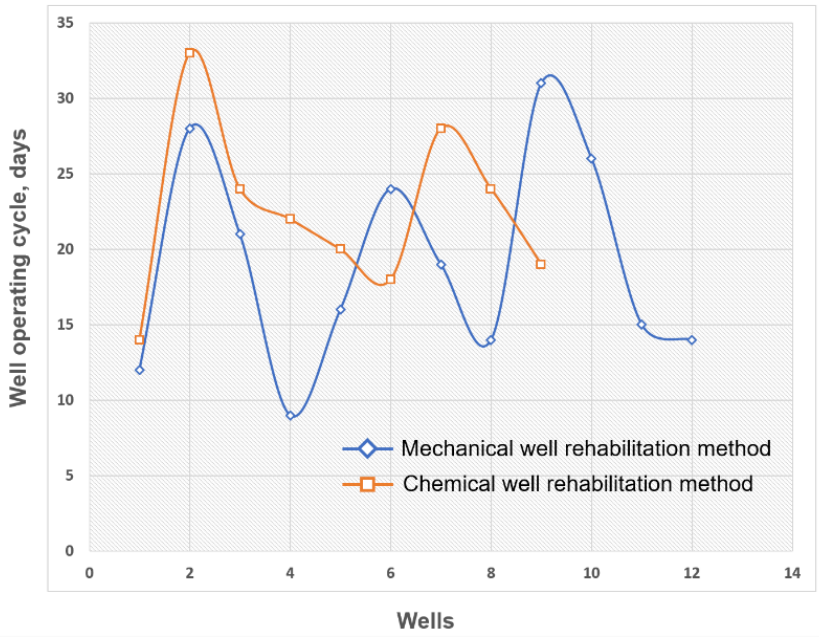


Fig.1. Comparison of well operating cycles after mechanical and chemical rehabilitation

However, these rehabilitation methods have not consistently produced satisfactory results. In some cases, the increase in well productivity was limited, whereas in others the observed improvements were only temporary.

Extensive operational experience has shown that the most effective approach to controlling clogging is to prevent the formation of deposits before they occur. Therefore, the present study proposes the use of an inhibitor-dissolver reagent capable of dissolving clogging deposits during the uranium leaching process. The effectiveness of such reagents is attributed to physicochemical mechanisms that influence nucleation, crystal growth, and mineral precipitation. Depending on their chemical composition, inhibitors suppress crystallization and scale formation through different mechanisms of interaction.

The action of scale inhibitors is primarily based on several key mechanisms. These reagents inhibit scale formation by increasing the supersaturation threshold required for precipitation, modifying crystal growth and morphology through adsorption onto crystal surfaces, and dispersing fine particles to prevent their aggregation and deposition within the system [8].

To the best of the authors' knowledge, the application of inhibitor-dissolver reagents for mitigating well clogging during uranium in-situ leaching has not yet been reported in the literature and has not been implemented in industrial practice. Furthermore, a number of environmentally friendly ("green") reagents with high ecological safety have recently been developed, including carboxyl carbon quantum dots [9, 10].

Materials and Methods. The concentration of dissolved calcium ions is one of the key factors controlling gypsum precipitation during uranium in-situ leaching. As the concentration of free calcium ions in the leaching solution increases, the likelihood and intensity of calcium sulfate precipitation also increase, thereby promoting clogging of well screens and the surrounding near-wellbore formation.

$$Ca^{2+} + SO_4^{2-} + 2H_2O = CaSO_4 \cdot 2H_2O \downarrow$$

Consequently, a decrease in the concentration of free calcium ions in the leaching solution reduces the degree of gypsum supersaturation and promotes the dissolution of previously formed mineral deposits. Given the critical role of calcium ions in gypsum scale formation, an inhibitor-dissolver reagent containing a polyacrylsulfonated polymer, hydroxyethylidene diphosphonic acid (HEDP), and water was investigated in the present study.

The inhibitor-dissolver reagent developed for mitigating clogging in the Syr-Darya uranium ore province consists of a 10% organic phosphonate solution with a density of 1.01-1.10 g/cm³ and a pH ranging from 0 to 5. Due to its acidic nature, the reagent is classified as a Class IV hazardous substance.

To evaluate the applicability of the proposed inhibitor-dissolver reagent for uranium in-situ leaching, theoretical investigations, laboratory experiments, and pilot-scale field tests were conducted.

Laboratory experiments were performed to determine the dissolution efficiency of carbonate minerals as a function of inhibitor concentration and to assess the potential of the reagent for preventing clogging within well screens and the surrounding near-wellbore zone. Five experimental samples with a volume of 1000 mL each were prepared using 99.99 g of core material collected from process wells within the Syrdarya uranium ore province.

During the laboratory work model leaching solutions were prepared. The first sample contained 1000 mL of sulfuric acid solution with a concentration of 2.5 wt. % without the addition of the inhibitor-solvent. The second, third, fourth, and fifth samples were filled with 1000 mL of the same 2.5 wt.% sulfuric acid solution supplemented inhibitor-solvent with the colmatants presipitates at concentrations of 1%, 2%, 3%, and 4%, respectively. For each inhibitor concentration (0, 1, 2, 3 and 4%), a single laboratory experiment was conducted. Therefore, statistical analysis of the results was not performed, and the obtained data should be considered as comparative experimental results demonstrating trends in inhibitor performance.

The concentration of calcium ions (Ca^{2+}) in the liquid phase was determined by complexometric titration using a Trilon B (EDTA) solution. After equilibrium had been established in the solution-rock system, a 10 mL aliquot was withdrawn using a graduated pipette and transferred to a 250 mL conical flask. Subsequently, 40 mL of distilled water measured with a graduated cylinder, 2.5 mL of a 20 wt.% sodium hydroxide solution, and 10-15 mg of a murexide-sodium chloride indicator mixture were added. Titration was carried out using a 25 mL burette with a standard 0.05 N Trilon B solution until the endpoint was reached, as indicated by a change in the indicator color. The volume of titrant consumed was recorded from the burette scale, after which the calcium ion concentration was calculated and expressed in g/L.

Pilot-scale field studies were carried out to assess the effect of the inhibitor-dissolver reagent on the operating cycle of process wells under production conditions. The study is based on the analysis of operational data from eight wells and has an observational field-scale character. No statistical significance testing was performed; therefore, the results should be interpreted as a comparative assessment of changes in operational performance indicators before and after reagent application.

Results and Discussion. Analysis of the geological conditions of the study area showed that the carbonate content of the deposit reaches up to 1.7%, whereas in most uranium deposits of the Republic of Kazakhstan it does not exceed 0.5%. The elevated concentration of carbonate minerals enhances the release of calcium ions into the leaching solution, thereby increasing the potential for gypsum precipitation and clogging. As shown in Table 2, the inhibitor-dissolver reagent contains 1-hydroxyethylidene-1,1-diphosphonic acid (HEDP) as its principal active component [11, 12].

Table 2 - Composition of the antiscaling reagent used

No.	Components	Density	pH Range
1	Polyacrylate-sulfonated polymers	1.05–1.15 g/cm^3	1–14
2	1-Hydroxyethylidene-1, 1-diphosphonic acid (HEDP)	1,43–1,45 g/cm^3	0–12
3	Water	1.0 g/cm^3	6.5–8.5

1-Hydroxyethylidene-1,1-diphosphonic acid (HEDP) is an organophosphonate compound with the molecular formula $C_2H_8O_7P_2$. The molecule contains two phosphonic acid groups and one hydroxyl group attached to a central carbon atom, providing multiple oxygen donor sites for metal-ion coordination.

Under acidic conditions, the phosphonic acid groups partially dissociate and form anionic species capable of chelating calcium ions. Consequently, stable soluble calcium-HEDP complexes are formed:

$$Ca^{2+} + HEDP^{4-} \rightleftarrows [CaHEDP]^{2-}$$

The stability constant of the calcium-HEDP complex is sufficiently high to promote effective sequestration of calcium ions even at the low pH values characteristic of sulfuric acid uranium leaching.

The reduction in the concentration of free calcium ions shifts the gypsum dissolution equilibrium toward dissolution of the solid phase, thereby enhancing the removal of calcium-bearing deposits:

$$CaSO_4 \cdot 2H_2O \rightleftarrows Ca^{2+} + SO_4^{2-} + 2H_2O$$

The calcium ions released during gypsum dissolution are subsequently sequestered by HEDP, which promotes the progressive dissolution of existing gypsum scale while simultaneously inhibiting its re-precipitation.

Polyacrylsulfonated polymers are anionic high-molecular-weight compounds containing carboxylate and sulfonate functional groups along the polymer backbone. These functional groups impart strong dispersing properties and inhibit particle aggregation, thereby reducing the accumulation of mineral precipitates within well screens and the near-wellbore zone. A schematic representation of the polymer structure is presented below:

$$[-CH_2 - CH(COOH) -]_m [-CH_2 - CH(SO_3H) -]_n$$

Under acidic conditions, the polymer undergoes partial dissociation, generating carboxylate (-COO^-) and sulfonate (-SO_3^-) functional groups. These negatively charged groups interact with calcium ions and adsorb onto the surface of gypsum crystals, disrupting crystal growth and promoting the formation of surface calcium-polymer complexes:

$$2RCOO^- + Ca^{2+} \leftrightarrow (RCOO)_2Ca$$

$$2RSO_3^- + Ca^{2+} \leftrightarrow (RSO_3)_2Ca$$

As a result of these interactions, the active growth sites of salt-precipitate crystals are blocked, reducing crystal growth rates and preventing gypsum re-precipitation. In addition, the polymer chains generate electrostatic repulsion between particles, thereby inhibiting gypsum particle aggregation and their retention within the pore space.

The effectiveness of the proposed inhibitor-dissolver composition is based on the synergistic action of two complementary mechanisms. HEDP forms stable soluble complexes with calcium ions and promotes the dissolution of gypsum deposits, whereas polyacrylsulfonated polymers suppress crystal nucleation and growth. Together, these processes reduce scale formation and prevent the re-precipitation of calcium-bearing mineral deposits.

Based on these considerations, laboratory experiments were conducted to evaluate the effect of inhibitor concentration on the dissolution efficiency of calcium-bearing minerals.

The results of the ion analysis of the five experimental solutions are presented in Figure 2.

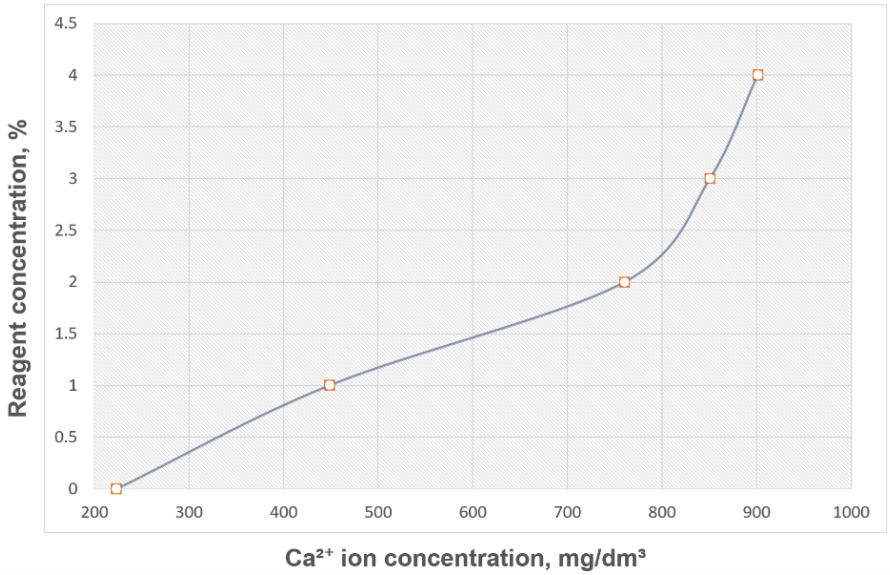


Fig. 2. Results of calcium ion analysis in experimental solutions

As shown in Figure 2, the control sample without the inhibitor-dissolver reagent exhibited a calcium ion concentration of 223.2 mg/dm^3 in the liquid phase. This value indicates a limited degree of calcium transfer into solution, suggesting that only a small proportion of calcium was present in ionic form, while the majority remained in the solid phase as sparingly soluble compounds. Under such conditions, calcium-bearing mineral precipitates are more likely to form within well screens and the near-wellbore zone of process wells, resulting in reduced hydraulic conductivity and a shortened well operating cycle.

The addition of the inhibitor-dissolver reagent at a concentration of 1.0% resulted in a substantial change in calcium behavior. The concentration of dissolved calcium increased to 450 mg/dm^3, which is more than twice that observed in the control sample. This result indicates enhanced dissolution of calcium-bearing compounds under the action of the inhibitor.

A further increase in inhibitor concentration to 2%, 3%, and 4% resulted in an even greater increase in dissolved calcium concentration. Specifically, the concentration of calcium in solution increased by 240%, 280%, and 300%, respectively, relative to the control sample without inhibitor addition. These results demonstrate a clear relationship between inhibitor concentration and calcium dissolution efficiency.

The observed results demonstrate that the inhibitor promotes the transfer of calcium into the solution phase in a stable dissolved form, thereby reducing the likelihood of secondary precipitation. As a consequence, compounds responsible for clogging remain stabilized in the liquid phase rather than forming solid deposits. This substantially decreases the potential for their accumulation within the pore space and on well screens.

Therefore, the application of the inhibitor-dissolver reagent enhances the dissolution of clogging deposits and contributes to the preservation of the hydraulic properties of the near-wellbore zone. Under the operating conditions of the Syr-Darya uranium ore province, this effect reduces the intensity of well clogging and represents one of the key factors contributing to the extension of well operating cycles and the improvement of overall uranium ISL performance.

Thus, an inhibitor concentration of 2% may be considered the preferred concentration. Under these conditions, the concentration of dissolved calcium increased from 223.2 mg/dm^3 in the control sample to 760.3 mg/dm^3, indicating a substantial enhancement in the dissolution of calcium-bearing compounds.

A further increase in reagent concentration led to only a marginal rise in dissolved calcium concentration, reaching approximately 280% and 300% at reagent concentrations of 3% and 4%, respectively. This finding indicates that the maximum practical effectiveness of the reagent had been achieved, with the major dissolution processes already completed. Additional inhibitor addition had only a minor effect on the dissolution kinetics and the transfer of calcium into the solution phase.

To verify the results of the theoretical and laboratory investigations and to compare well operating cycles before and after the introduction of a 2% inhibitor into the leaching solution, pilot-scale field tests were conducted on eight wells (Nos. 1–4, 6–7, and 9–10) that had previously undergone mechanical rehabilitation (Figure 1).

The changes in well operating cycles are presented in Table 3.

Table 3 -Variation in the interrepair cycle of wells

Number of wells	1	2	3	4	6	7	9	10
Interrepair cycle, days	18	34	26	13	30	24	36	34

As shown by the data presented in Table 3, the addition of the inhibitor-dissolver reagent to the leaching solution resulted in changes in the operating cycle of process wells. In the wells that had previously undergone mechanical rehabilitation, the operating cycle following inhibitor application increased and ranged from 13 to 36 days, with an average value of 27 days.

For comparison, the average operating cycle of these wells prior to inhibitor application was 21 days. Therefore, the use of the inhibitor-dissolver reagent increased the average operating cycle by approximately 30%, indicating improved well stability and reduced clogging of well screens and the surrounding near-wellbore zone.

Comparative data on well operating cycles before and after inhibitor application are presented in Figure 3.

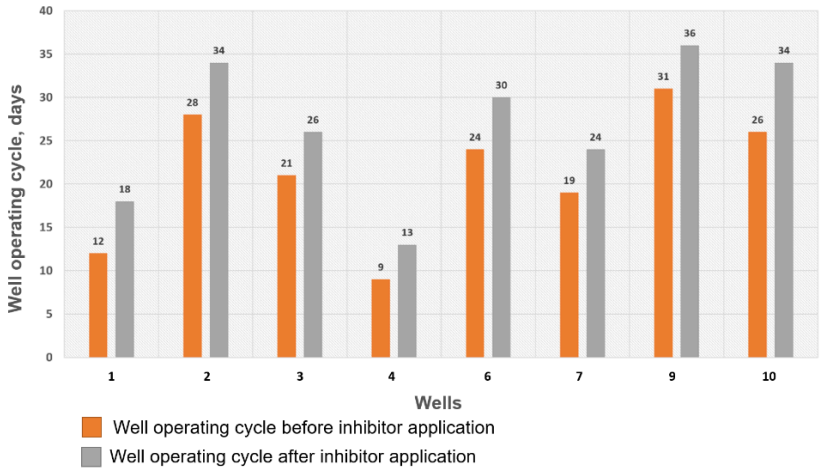


Fig. 3 - Comparison of well operating cycles before and after inhibitor application

For comparison, the average operating cycle of the studied wells before inhibitor application was 21 days. The introduction of the inhibitor-dissolver reagent increased the average operating cycle by approximately 30%, demonstrating enhanced well performance and reduced clogging of well screens and the adjacent near-wellbore formation zone.

Comparison with previously reported studies [13, 14] indicates that treatment of process wells with 50 kg of ammonium bifluoride per well, as well as a combined rehabilitation method involving chemical and mechanical treatment, extended the operating cycle of wells to 12-18 days. Nevertheless, the application of ammonium bifluoride is associated with significant operational limitations, as it is a hazardous chemical requiring additional expenditures and strict safety measures for storage, transportation, and reagent injection into the leaching solution circuit.

Conclusion. The laboratory studies demonstrated that the application of the inhibitor-dissolver reagent promotes the dissolution of calcium-bearing compounds comprising the clogging deposits formed during uranium in-situ leaching. The obtained results indicate an increased transfer of calcium into the liquid phase and a reduced likelihood of its re-precipitation under the investigated conditions. Therefore, the reagent can be considered a promising approach for mitigating clogging processes in well screens and the near-wellbore zone of process wells.

It was established that the dissolution efficiency of calcium-bearing deposits depends on the concentration of the inhibitor-dissolver reagent. Within the investigated reagent concentration range of 1-4%, a concentration of 2% was considered the preferred option.

The results of the pilot-scale field tests indicate the practical applicability of the inhibitor-dissolver reagent under the investigated production conditions. During the testing period, the use of the reagent increased the average operating cycle of process wells by 28% compared with wells operated under similar conditions without reagent application. These findings suggest that the reagent may contribute to improved operational stability of wellfields and mitigation of clogging-related effects on well performance under the investigated conditions.

Overall, the obtained results indicate that the use of the inhibitor-dissolver reagent may be a promising approach for preventing and mitigating calcium-related clogging during uranium in-situ leaching. However, due to the observational pilot-scale nature of the study and the absence of a parallel control group, the observed effects should be interpreted with caution. Additional controlled and long-term field studies are required to confirm the effectiveness of the proposed approach and to establish causal relationships between reagent application and changes in well operating performance.

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