INFLUENCE OF CHEMICAL REAGENT COMPLEX ON INTENSIFICATION OF URANIUM WELL EXTRACTION

Purpose. To determine the effect of special chemical reagents in the composition of leaching solutions on geotechnological parameters during uranium well extraction. To study the possibility of applying this method to increase efficiency of well extraction of uranium ores by intensifying ecotechnological processes of underground uranium leaching. To ensure design capacity of producing blocks and the completeness of extracting metal from them, reduce and prevent sediment in porous medium, reduce specific consumption of sulfuric acid, electric power, labor and other production costs in the process of uranium well extraction. To study the possibility of applying this method to increase efficiency of well extraction of uranium ores by intensifying ecotechnological processes of underground uranium leaching. To ensure design capacity of producing blocks and the completeness of extracting metal from them, reduce and prevent sediment in porous medium, reduce specific consumption of sulfuric acid, electric power, labor and other production costs in the process of uranium well extraction.

Methodology. The research includes consistent literature review, laboratory and practical studies in real conditions. The samples studied in the laboratory by X-ray phase analysis of mineralogical characteristics of sedimentation were taken from Syrdarya depression. Chemical reagents were selected and tested in geotechnological wells during experimental extraction of uranium. The resulting geotechnological parameters of wells were compared to experimental data.

Findings. Values of pH parameters of leaching solutions were obtained within the range from 6.5 to 2.3; it was established that Eh values initially tend to increase sharply to 300–380 mV and then to decrease to 170 mV; uranium content in productive solution was consistently growing from 29 to 146 mg/l; the values of iron salts (Fe^{3+}, Fe^{2+}) concentration in the productive solution were determined in the case when they were affected by chemical multifunctional reagents.

Originality. The method for intensification of uranium well extraction has been developed and justified. It is based on a new complex of chemical reagents producing a selective effect on uraniumiferous minerals, which improves performance of producing blocks.

Practical value. Rationally selected oxidizer and chemical reagents, as well as the scheme of their feeding into the productive horizon allow intensifying solution of four-valent uranium in complex mining and geological conditions by underground leaching and improving performance of the producing block.

Keywords: well extraction, uranium ore, sedimentation, X-ray phase analysis, chemical reagents

Introduction. At present, various kinds of minerals are mined not only by conventional methods of mining [1, 2], but also – more and more widely – by geotechnological ones, especially well mining, which is used for the development of low quality and low-grade deposits [3, 4]. Geotechnological methods of mining are applicable when developing non-renewable energy sources, primarily gas and hydrate deposits containing mammoth volumes of compressed methane [5].

The technology of uranium well extraction involves pumping out productive solutions (PS) from the recovery wells of the producing block, sorptive extraction of uranium from solutions, lighting the master batch with subsequent fortification with concentrated sulfuric acid, feeding acidified leaching solution (LS) through injection wells into the ore body of the block [6]. The unquestionable advantage of such mining method – in comparison to conventional methods – is prevention of rock waste accumulation on the earth’s surface [7, 8]. The processing waste can be used as a component for solidifying mixtures to fill underground cavities [9]. At the same time, leaching is the main operation of preparing uranium ore for extraction, as it determines the quantity and cost of the final product. The use of sulfuric acid as a reagent solvent at enterprises of Kazakhstan is explained by its low cost, availability, the possibility of relatively complete transfer of uranium into the solution [10]. However, the high kinetics of sulfuric acid interaction with feldspar and carbonate minerals of ore-bearing rocks in difficult geological conditions causes sedimentation in the form of a geochemical barrier that impedes the leaching process.

Poorly soluble sediments and dislocated clay particles in the productive horizon increase hydraulic resistance and form impermeable areas of the geochemical barrier that overlap the flow lines of solutions. As a rule, decrease in the filtration characteristics of the productive horizon leads to decrease in the uranium content in the PS, reduction in the productivity and injectivity of wells as a result of a decreased period of uninterrupted well operation [11]. Hence, the period of adjusting producing blocks grows, while the consumption of sulfuric acid and other operating costs increases. These blocks need frequent repair and restoration and an additional enhancement of the host rocks permeability [12]. In some cases, conducting costly, difficult and complex handling using drilling installations does not yield a positive result. Difficult geological conditions of uranium occurrence such as: deep occurrence, clay content (> 20 %) and carbonate content (> 1.5 – 2 %) of the host rocks, filtration heterogeneity of the productive horizon, etc. are characteristic for deposits, confined to the Syrdarya depression.

Literature review. State-of-the-art research focused on improvement of well extraction of uranium ores comprises a wide range of scientific problems. The authors of [13] analyze a set of issues related to application of geotechnological 3D modelling for increasing efficiency of uranium underground leaching. To optimize the patterns of drilling in the ore intervals, it is proposed to use mathematical models describing predictive scenarios of adjusting blocks with probable variants of geotechnological processes development for the purpose of analysis and adopting the most efficient and acceptable flowback option. Despite the logical structural scheme of geotechnological modelling, the work is based on standard computing parameters of distribution of pressures, filtration rates and convective...
The authors of [14] describe a number of measures to improve underground leaching of uranium by developing the process of the formation hydraulic fracturing using surface-active agents (SAA). The method is based on increasing permeability of the productive horizon by creating excessive pressure in it and adding SAA. The study revealed that all SAA solutions reduce surface tension of the solution by 79–86 % [15]. Pumping mud through the technological well into the formation results in distribution of pressures and creation of additional fracturing of matrix rock, which increases geological parameters of producing blocks. However, such method for intensifying uranium underground leaching is applicable only to uranium deposits whose orebody comprises hard or solid rocks. The principal ore-bearing rocks of uranium deposits in Kazakhstan Republic mined by underground leaching systems consist of sands with clay veins where the solution is filtered through capillars and pores.

In [16], the author analyzes the results of experimental research into intensification of uranium leaching with addition of ammonium bifluoride in conditions of sulfuric acid leaching of uranium. The method is based on feeding sulfuric acid solution with addition of ammonium bifluoride into the near-filtering zone of the well, which results in exchange reaction with formation of hydrofluoric acid. The material presented in this work is important for considering ammonium bifluoride as an efficient solvent of sediments in conditions of uranium ores well extraction. However, the method of cyclic operations in the well involving the solvent feeding and disposal of the productive horizon reduces the index of the well utilization and increases the period of producing blocks operation, which eventually increases the cost of the final product.

The author of [17] focuses on intensification of uranium underground leaching using oxidizer (hydrogen peroxide) added to the leaching solution. Using hydrogen peroxide is explained by its availability and strong oxidizing effect. However, using this solvent in formation seepage deposits of Kazakhstan Republic is not feasible because of the depth of uranium orebody occurrence and high pressure of the formation waters. When hydrogen peroxide is solved in the leaching solution, the resulting water complex is not stable and its disintegration causes gas emission.

**Methods.** To study mineralogical characteristics of sediments impeding the process of uranium well extraction in laboratory conditions, we have selected samples of colmatants from the deposit in the Syrdarya depression. X-ray phase analysis was used to determine peculiarities of sediments formation and their qualitative and quantitative parameters which are presented in Table 1. Quantitative and qualitative parameters of the main sedimentation are shown in Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Name of the component</th>
<th>Chemical formula</th>
<th>Amount, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankerite</td>
<td>Ca (Mg Fe Mn) (CO₃)₂</td>
<td>10–50</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Ca Mg Fe (CO₃)₂</td>
<td>10–50</td>
</tr>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
<td>2–30</td>
</tr>
<tr>
<td>Aluminum phosphate</td>
<td>Al (PO₄)</td>
<td>2–15</td>
</tr>
<tr>
<td>Iron oxide</td>
<td>Fe₂O₃</td>
<td>2–15</td>
</tr>
<tr>
<td>Magnesium sulfate</td>
<td>MgS</td>
<td>2–25</td>
</tr>
<tr>
<td>Calcium aluminum hydroxide</td>
<td>CaAl₂(OH)₃ (H₂O)₂</td>
<td>1–30</td>
</tr>
</tbody>
</table>

Studies of sedimentary formations when mining the Syrdarya group of deposits show the sedimentation of many components including calcium, iron, magnesium, and calcium and magnesium carbonate hydroxides, sand, and clay. The predominance of carbonate sedimentation (from 10 to 50 %) is due to the high content of carbonate rock-forming minerals in the productive horizon. The presence of quartz, aluminum, and magnesium in the range of 2–30 % indicates dissolution and transfer of feldspar and clay minerals by a solvent flow. The deposition of many components proves the diversity of the processes taking place in the ore-bearing rocks during the sulfuric acid leaching of uranium and complex sedimentation [18].

A complex of multifunctional chemical reagents was selected to intensify the processes occurring during well extraction of uranium in complex mining and geological conditions based on the study of the nature of chemical sedimentation and analysis of the main rock-forming minerals of the productive horizon. The effectiveness of a complex of chemical reagents is determined by its composition and is selected depending on geological features of the productive horizon and quantitative and qualitative characteristics of the formed sediments. The chemical reagents included in the complex have the dissolving ability of the primary carbonate and secondary sedimentation, contribute to active clay release and the creation of additional flows in the porous space of the formation, and also have a high oxidizing ability of Fe²⁺ to Fe³⁺ at high pH values to prevent repeated sedimentation. Intensification of well extraction of uranium using a complex of chemical reagents will allow increasing the rate of mining producing blocks and reducing the cost of the final product.

The study on the effectiveness of impact of the chemical reagent complex was carried out on a geotechnological field of a uranium deposit in the Syrdarya depression during experimental work. The experiments were conducted in geotechnological wells with low time between overhaul (TBO) values and insufficient production by PS, as well as in wells with low uranium content in the productive solution (PS). During semi-industrial tests, specifically selected chemical reagents were fed to the productive horizon through the well collars of selected technological wells with simultaneous injection of leaching solution (LS) into them, until the calculated spreading radius of the solutions from the well filter was achieved. Further, after the injection of the required amount of chemical reagents and LS, compressor pumping was conducted in the production wells and they were put into service. The injection wells were in operation under the pressure of LS. The selection of chemical reagents was carried out according to the characteristics corresponding to the task set for each agent in the complex geological conditions of the sulfuric acid leaching of uranium. The effectiveness of the impact of a chemical reagent on intensification of well extraction of uranium was determined by the results of monitoring and analysis of geotechnological parameters before and after the experimental work. The equipment and the outline of supplying chemical reagents to the productive horizon is shown in Fig. 1.

Equipment for preparing and supplying chemical reagent solutions consists of a tank and a pump made of corrosion-resistant material, because they are in contact with LS fortified with sulfuric acid. The LS simultaneously injected into the wells ensured the distribution of chemical solutions in the productive horizon within the effective spreading radius limited at the top and the bottom by impermeable rocks. Spreading and dosing of solutions was carried out and regulated by a pumping unit and stop valves (Fig. 1).

The intensity of mining opened reserves of producing blocks depends on the PS productivity as well as the content of uranium in the solution, taking into account the utilization rate of the wells. In this regard, monitoring of geotechnological parameters of wells before and after conducting experimental work included daily measurements of average
Gradual intensification of uranium well extraction process and an increase in the duration of the well non-interrupted operation is due to the gradual destruction of the geochemical barrier under the synergistic effect of chemical reagents in a porous medium. The synergistic effect of chemical reagent complex allows increasing the rate of mining a producing block and reducing the specific consumption of sulfuric acid for uranium leaching in difficult geological conditions.

**Results.** Redox reactions and filtration processes occurring in the formation largely determine the efficiency of well extraction of uranium mining technology, the completeness of metals extraction into the solution, the specific consumption of chemical reagents, energy consumption and overall technical, economic and environmental indicators of production [19]. According to the obtained results, Fig. 2 shows the graph describing the dynamics of uranium concentration changes over time depending on the pH level in the PS.

As can be seen from Fig. 2, the initial pH values of the solution were at a high level of 6.55, which indicates the dilution of productive solutions by formation waters, because of the creation of a geochemical barrier in the formation impeding the leaching solution flow lines. Low values of uranium content in PS confirm the assumptions of the solvent blocking by colmatage. After feeding solutions of multifunctional chemical reagents into the productive horizon, a noticeable decrease and fluctuation in the solution pH values occur within the level of 2.33–5.54 caused by the interaction of multifunctional chemical reagents in the formation. Fluctuations in the pH level in the solution are caused by the influence of the LS front movement in the porous space of the productive horizon. The first pH decrease is caused by the approach of LS containing chemicals delivered to the formation through the well collar, the second decrease is caused by the LS front effect from injection wells. The two-stage increase in the uranium content in the PS is due to the restoration of filtration characteristics and the flow line of the productive horizon. Subsequent well testing shows a gradual increase and stabilization of the previous (pre-experimental) pH value of 6.21, which confirms the termination of the interaction of the chemical reagent complex in the productive horizon and restoration of geochemical barrier and clogging of the formation.

Dynamics of uranium content change over time depending on the Eh level in the PS during the period from the first to the fourth month of the well parameters monitoring testifies that Eh values were stable at the level of 300–308 mV, while the increase in uranium content in PS is caused by transition of uranium soluble minerals into the solution. During the fifth month of monitoring, there is an increase in Eh level to 380 mV due to the approach of LS front from the injection

### Table 2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before treatment</th>
<th>After treatment</th>
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<tbody>
<tr>
<td></td>
<td>Month</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Cu, mg/l</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>Q, m³/h</td>
<td>8.0</td>
<td>7.8</td>
</tr>
<tr>
<td>pH</td>
<td>6.6</td>
<td>6.4</td>
</tr>
<tr>
<td>Fe³⁺, mg/l</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>Fe²⁺, mg/l</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>SO²⁻, g/l</td>
<td>8.38</td>
<td>7.42</td>
</tr>
<tr>
<td>eH</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

Data from monitoring of geotechnological parameters of wells before and after conducting experimental research.
The results of experimental research into uranium well extraction intensification using a chemical complex of multifunctional reagents indicate the effectiveness of the method. Gradual intensification of the uranium leaching process and the increase in the uranium content in solutions is due to the gradual destruction of the geochemical barrier, the restoration of the initial permeability of the productive horizon under the synergistic effect of chemical reagents. The use of a chemical reagent complex with a synergistic effect allows increasing the rate of mining producing blocks and reducing the specific consumption of sulfuric acid for uranium leaching in difficult geological conditions.

Intensification of uranium well extraction in complex mining and geological conditions should be carried out using an effective complex of chemical reagents depending on the composition of ore-bearing rocks. The supply of effective concentrations of chemical reagents to the leaching solution in combination with traditional methods of well regeneration intensifies uranium leaching process.

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Влияние комплекса химических реагентов на интенсификацию свердловинного видобутку урана

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Мета. Встановити вплив спеціальних хімічних реагентів, що подаються у складі вилуговувальних розчинів, на геотехнологічні параметри при свердловинному видобутку урану. Вивчити можливість застосування методу для підвищення ефективності середовищової розробки уранових руд, що заснований на інтенсифікації геотехнологічних процесів підземного вилуговування урану. Забезпечити проектну продуктивність експлуатаційних блоків та повноту вилучення металу з них, зменшити й попередити утворення осаду в порістій середовищі, знити питомі витрати сірчаної кислоти, електроенергії, трудових затрат та інших виробничих витрат у процесі свердловинного видобутку урану.

Методика. Включає послідовне проведення літературного пошуку, лабораторних і практичних робіт в реальних умовах. Відбір проб та вивчення в лабораторних умовах рентгенографічним методом мінералогічних характеристик осадкоутворення з родовищ Сирдар’їнської депресії. Підбір хімічних реагентів та опробування на геотехнологічних свердловинах при проведенні експериментальних робіт в умовах свердловинового видобутку урану. Збір вихідних результатів геотехнологічних параметрів свердловин з наступним проведенням порівняльного аналізу з експериментальними даними.

Результати. Отримані значення параметрів pH вилуговувальних розчинів у діапазоні від 6,5 до 2,3; виявлено по- мітне підвищення з наступним зниженням значень pH від 300–380 до 170 мВт; встановлено стабільне збільшення вмісту урану в продуктивному розчині з 29 до 146 мг/л; виділено концентрацію солей заліза (Fe2+, Fe3+) у продуктивному розчині з діапазону pH від 4 до 12 мг/л.

Наукова новизна. Розроблений та обґрунтований метод інтенсифікації свердловинного видобутку урану, застосований на осадкоутворенні нового комплексу хімічних реагентів селективного впливу на уранові мінерали, що забезпечує підвищення продуктивності експлуатаційних блоків.

Практична значимість. Рационально підібрани окислюючі та комплексні реагенти, а також розроблена схема їх подачі в продуктивний горизонт, дозволяють інтенсифікувати розчинення чотирьохвалентного урану в складних гідро-геохімічних умовах глиняних підземних вилуговувань та підвищувати продуктивність експлуатаційного блоку.

Ключові слова: свердловинний видобуток, уранова руда, осадкоутворення, рентгенографічний аналіз, хімічні реагенти.
Цель. Установить влияние специальных химических реагентов, подаваемых в составе выщелачивающих растворов, на геотехнологические параметры при скважинной добыче урана. Выявить возможность применения метода для повышения эффективности скважинной разработки урановых руд, основанной на интенсификации геотехнологических процессов подземного выщелачивания урана. Обеспечить проектную производительность эксплуатационных блоков и полноту извлечения металла из них, уменьшить и предупредить образование осадков в пористой среде, снизить удельные расходы серной кислоты, электроэнергии, трудовых затрат и других производственных расходов в процессе скважинной добычи урана.

Методика. Включает последовательное проведение литературного поиска, лабораторных и практических работ в реальных условиях. Отбор проб и их изучение в лабораторных условиях рентгенофазовым методом на примере месторождений Сырдарьинской депрессии. Подбор химических реагентов и опробование на геотехнологических скважинах при проведении экспериментальных работ в условиях скважинной добычи урана. Сбор выходных результатов геотехнологических параметров скважин с последующим проведением сравнительного анализа с экспериментальными данными.

Результаты. Получены значения параметров рН выщелачивающих растворов в диапазоне от 6,5 до 2,3; явлено заметное повышение с последующим понижением значений Eh от 300–380 до 170 мВт; установлено стабильное увеличение содержания урана в продуктивном растворе с 29 до 146 мг/л; определены значения концентрации солей железа (Fe^{3+}, Fe^{2+}) в продуктивном растворе под действием химических реагентов многофункционального назначения.

Научная новизна. Разработан и обоснован метод интенсификации скважинной добычи урана, основанный на применении нового комплекса химических реагентов селективного воздействия на ураносодержащие минералы. Практическая значимость. Рационально подобранные окислитель и химические реагенты, а также разработанная схема их подачи в продуктивный горизонт, позволяют интенсифицировать растворение четырехвалентного урана в сложных горно-геологических условиях путем подземного выщелачивания и повысить производительность эксплуатационного блока.

Ключевые слова: скважинная добыча, урановые руды, осадкообразование, рентгенофазовый анализ, химические реагенты

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