

Research into leaching of uranium from core samples in tubes using surfactants

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Abstract

Purpose. Improving the efficiency of borehole uranium recovery in difficult mining-and-geological conditions through the development of a new technology based on the intensification of geotechnological processes of in-situ uranium leaching, the selective effect of a new chemical reagents complex on a set of the mineralogical and particle-size distribution of the ore-bearing rocks of the productive horizon.

Methods. Sampling of core material from host rocks of the Syr Darya depression uranium deposit. The content of uranium, calcium, aluminum, iron, magnesium, and carbonate content in the samples has been revealed by the spectral analysis method. The quantitative and qualitative parameters and peculiarities of the host minerals have been determined by the method of X-ray phase analysis. By testing particle-size distribution, the fractional parameters of core samples have been determined. Specifications have been developed, as well as laboratory experiment have been conducted on uranium leaching from core material in a dynamic mode in tubes, with the addition of selected chemical reagents with different modes.

Findings. The aspects of borehole uranium recovery using sulfuric acid solutions as a solvent and the reasons that cause a decrease in geotechnological parameters in ores with low filtration characteristics have been determined. An effective method has been developed for intensifying borehole uranium recovery using superficially active substance (surfactants, SAS) in difficult mining-and-geological conditions, with an increased content of argillaceous and carbonate minerals, and low filtration host rocks properties. An efficient and economically feasible method for uranium leaching with sulfuric acid solutions with the addition of surfactants has been revealed and scientifically substantiated.

Originality. The scientific novelty is in the fact that the selected surfactants added to sulfuric acid solutions increases the uranium content in the productive solution and the degree of economically feasible uranium recovery with reduced sulfuric acid consumption and the ratio of liquid to solid (L:S).

Practical implications. The use of rational surfactants in uranium leaching makes it possible, in areas with low filtration characteristics, to reduce operating expenses for production by reducing the period of recovery, to increase the uranium content in the productive solution and the degree of recovery, as well as to reduce the consumption of sulfuric acid and sedimentation.

Keywords: borehole recovery, leaching, uranium, X-ray phase, tests on particle-size distribution, surfactants

1. Introduction

The technology of borehole uranium recovery provides for the useful component dissolution at the place of the ore body occurrence, followed by the removal of the formed compounds by a moving stream of solvent from the injection well to the pumping-out well [1]. In this case, leaching is the main operation of preparing uranium ore for recovery, since it determines the amount and cost of the final product [2]. The sulfuric acid, used as a reagent - solvent at the enterprises of Kazakhstan, is reasoned by the low cost, availability, the possibility of relatively complete conversion of uranium into solution [3], [4]. However, the high kinetics of the sulfuric acid interaction with feldspars and carbonate minerals of ore-bearing rocks in difficult mining-and-geological condi-

tions causes sedimentation in the form of a geochemical barrier that impedes the leaching process [5]-[7].

Hardly soluble sediments and displaced argillaceous particles in the productive horizon increase the hydraulic resistance and form impermeable geochemical barrier sections which overlap the solutions flow lines. As a rule, a decrease in the filtration characteristics of a productive horizon leads to a decrease in the uranium content in the productive solution, a decrease in the performance of production wells and injection capacity of injection wells, as a result of a decrease in the period of wells uninterrupted operation. As a result, the period of the technological blocks mining increases along with the consumption of sulfuric acid and other operating expenses. These blocks require frequent repair and restoration work, as

well as an additional increase in the host rocks permeability [8]. In some cases, cost-intensive, heavy complex treatments using drilling rigs do not give a positive result [9].

The authors of [10], [11] have achieved positive results in the intensification of sulfuric acid leaching of uranium during the iron oxidation (II) with nitrous acid, sodium nitrites and the use of lignosulphate as a complex-forming agent to increase the uranium content in productive solution and the degree of recovery. However, their use in borehole uranium recovery in ores with low filtration characteristics is not effective due to insufficient permeability into the productive horizon.

The authors of [12] propose a composition for decolmat-ing treatment of the near-filter zone in production wells in the case of borehole uranium leaching, containing hydro-chloric acid, ammonium hydrogen fluoride and surfactants. The decolmat-ing composition supplied through the wellhead provides an increase in the productive horizon permeability, an increase in wells performance, as well as an increase in the interrepair wells cycle. The result is provided by the high reactivity of fluorhydric acid with formation of chemical sediments and argillaceous particles. The additional use of surfactants provides an increase in efficiency due to a decrease in interfacial tensions and an increase in spreading in the near-filter zone. However, the use of this composition for the purpose of near-filter zone decolmatation in the wells does not increase the concentration of uranium in the productive solution, and does not affect the redox parameters of the solutions.

The main objective when designing the field develop-ment, as well as the study of technical and economic feasibil-ity when selecting borehole mining technology involves the study of the composition, uranium content, shale volume factor and the host rocks granularity of the productive horizon. In addition, laboratory experiments should be made on uranium leaching from core material in a static and dynamic mode. The main purpose of modeling in-situ uranium leach-ing is to identify the patterns of the process, including the determination of various factors affecting the leaching result, as well as the selection of optimal geotechnological process parameters, which serve as initial data when planning mining.

2. Research methods

Research includes experiments on uranium leaching with sulfuric acid solutions using several samples with different acidity to determine the economically reasonable solvent concentration. In order to study the effectiveness of using the surfactants for the intensification of borehole uranium recovery, comparative experimental tests on uranium leaching from core material in tubes have been conducted. Laboratory experiments include studying the mineralogical composition of core samples, determining the particle-size distribution characteristics of the host rocks and uranium leaching from the core in the tubes under a dynamic mode using solutions with standard, high acidity, and also with the addition of specially selected surfactants as an intensifier of uranium leaching.

2.1. Particle-size distribution, spectral and X-ray phase studies

The studies are performed using the material of core samples from the Chu-Sarysu uranium province. The particle size distribution of the samples is studied using a sieving machine RETSCH AS200 basic. Table 1 shows the particle size distribution characteristics of the core sample.

Table 1. Parameters of the technological sample particle size distribution

Particle size distribution, %								Total %
> 2	> 1.6	> 1.4	> 1.0	> 0.8	> 0.5	> 0.35	< 0.35	
mm								%
11.05	2.24	1.38	3.15	1.93	6.35	15.46	57.33	100

The analysis of the particle size distribution (Table 1) indicates that more than 57% of the core sample consists of a fine-grained sand fraction, rock fragments and argillaceous-silt particles, which impede the solutions filtration and the uranium leaching process. The content of uranium, aluminum, calcium, iron, magnesium and carbonate content in the core sample is determined by the method of atomic emission spectroscopy with individually-coupled plasma using an iCAP 7400 spectrometer. The analysis of sample increment is presented in Table 2. Sample preparation involves selecting and weighing of material from the core sample, and then the formation of a technological sample for subsequent analysis and performing experimental tests on uranium leaching.

Table 2. Parameters of the sample increment spectral analysis

No. sample increment	U, %	CO ₂ , %	Al, %	Ca, %	Fe tot., %	Mg, %
1	0.0502	0.17	4.9640	1.2031	0.8031	0.3694
2	0.0568	0.18	4.5153	1.1953	0.8249	0.4780
3	0.0296	0.10	4.6824	0.8658	1.0250	0.3854
Average	0.0455	0.15	4.7205	1.0881	0.8843	0.4109

As can be seen from Table 2, the average CO₂ content of carbonates is 0.15% of the total sample mass, which indicates a low carbonate content of the ore-bearing rocks. The Al content of 4.5-4.9% in the technological sample evidences the presence of feldspars and argillaceous minerals.

An X-ray phase analysis of the technological sample material has been made using a DRON-3 diffractometer. The diffractogram of ore-bearing rocks sample is shown in Figure 1, and the X-ray phase analysis data are shown in Table 3.

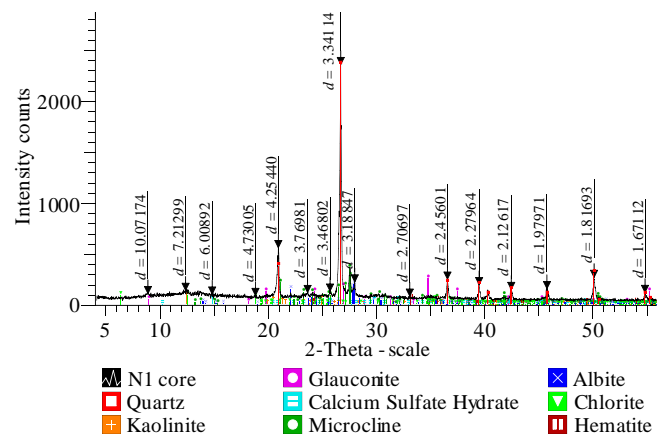


Figure 1. Diffractogram of the source core material sample

As can be seen from Table 3, the content of quartz is 58.6%, kaolinite 10.3%, glauconite 7.9%, microcline 6.4% and albite 4.1%. The calcium sulfate (7.5%) presented in the productive horizon will cause chemical colmatation. The increased fine fraction content in fine-grained sands of the productive horizon in practice complicates uranium leaching due to a decrease in the rocks filtration characteristics.

Table 3. Parameters of X-ray phase analysis of the technological sample material

Mineral	Formula	Concentration, %
Quartz	SiO ₂	58.6
Kaolinite	Al ₂ (Si ₂ O ₅)(OH) ₄	10.3
Glauconite	(K, Ca, Na) _{0.8} (Al, Fe, Mg) ₂ (Si, Al) ₄ O ₁₀ (OH) ₂ nH ₂ O	7.9
Calcium Sulfate Hydrate	Ca(SO ₄)(H ₂ O) _{0.5}	7.5
Microcline	(K, Na)AlSi ₃ O ₈	6.4
Albite	(Na, Ca)(Al, Si) ₄ O ₈	4.1
Chlorite	(Mg, Fe) ₅ Al(Si ₃ Al)O ₁₀ (OH) ₈	2.8
Hematite	Fe ₂ O ₃	2.4

This leads to an increase in operating expenses for the maintenance of geotechnological wells in the corresponding technological specification range leaching solution injection – productive solution pumping-out, as well as to a decrease in the operational efficiency of wells due to idle time for repair and restoration work [13].

2.2. Selecting of chemical reagents for intensifying uranium leaching

The following intensifiers are selected as reagents for in-situ borehole leaching of uranium:

- sulfamic acid (amidosulfonic acid, amidosulfuric acid) – NH₂SO₂OH, crystalline product of white-gray color. The choice of sulfamic acid is reasoned by its active interaction with metals, their oxides, hydroxides and carbonates. According to the results of exchange chemical reactions, sulfamic acid forms a strong complex with Fe²⁺ ions, reduces their activity in solution, as a result of which the Fe³⁺/Fe²⁺ ratio and the Eh value of the solution increase, which intensifies the uranium leaching process;

- lignosulfonates are anionic surfactants. In water, they are usually in a colloidal state (degree of hydration is 30-35%). The use of ammonium lignosulfonate for increasing the productive horizon permeability is conditioned by its ability to reduce the surface tension of solutions, as well as to create stable emulsions and foams. Lignosulfonate reduces the viscosity of argillaceous solutions, contributing to a more efficient dispersion of argillaceous formations, significantly increasing the productive horizon porosity [14], [15].

2.3. Procedures of conducting experiments on uranium leaching in the tubes

Laboratory experiments on uranium leaching from core samples in a dynamic mode make it possible to obtain information on the process of uranium leaching and to select the effective modes of leaching solution acidity. Filtration of the leaching solution through ore material sample is performed using the setup shown in Figure 2. Filtration is conducted at a constant drop of head between the inlet and outlet in the tubes and at a constant consumption of solution. In accordance with the procedures, the prepared leaching solution is filtered through the core material in the tube and collected in an appropriate collection tank for further analysis and determination of the filtration coefficient, as well as uranium recovery and specific sulfuric acid consumption.

The leaching solution is prepared on the basis of stratum water to obtain conditions as close as possible to real ones. In the first two experiments, the acidity of the initial solutions is standard and increased.

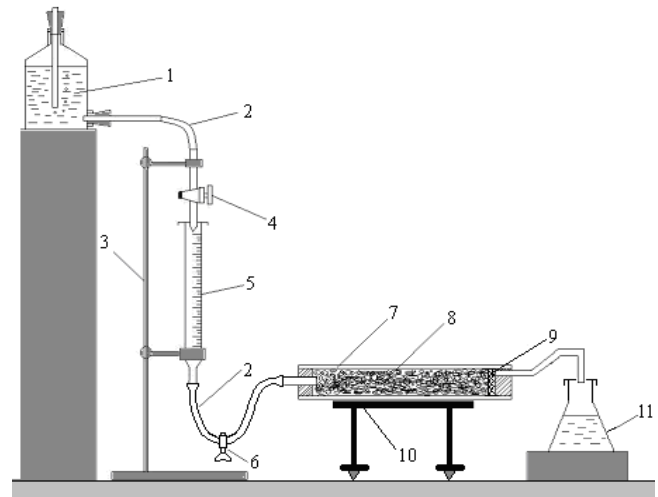


Figure 2. The scheme of a laboratory setup for dynamic leaching of uranium from core sample material: 1 – Mariotte's bottle with leaching solution; 2 – a flexible hose made of acid-resistant rubber or silicone; 3 – stand rod; 4 – adjusting valve; 5 – measuring burette; 6 – screw chuck; 7 – tube; 8 – core material; 9 – porous filter; 10 – support table with adjustable height of legs; 11 – flask with productive solution

To compare the effectiveness of the surfactants effect on the leaching results, it is decided in the third experiment to prepare a solution with standard acidity and add the selected chemical reagents. Parameters of the leaching solutions acidity modes according to the corresponding experiments are shown in Table 4.

Table 4. Parameters of selecting the leaching solutions acidity

Procedures of leaching	Water washing		
	Experiment 1	Experiment 2	Experiment 3
Ratio of L:S	Sulfuric acid concentration in leaching solution		
0-0.2	20	25	20 + 2 g/l sulfamic acid + 0.5 g/l lignosulfonates
0.2-0.8	15	20	15 + 2 g/l sulfamic acid + 0.5 g/l lignosulfonates
0.8-1.5	10	15	10 + 1 g/l sulfamic acid + 0.25 g/l lignosulfonates
1.5-2.0	5	10	5 + 1 g/l sulfamic acid + 0.25 g/l lignosulfonates
2.0-2.5	3	5	3
2.5-4.0	0	0	0

The developed acidity mode of the solutions provides for preparing a leaching solution for each experiment at the corresponding L:S values. The first experiment involves preparing the solutions with standard acidity, adopted in the mining of fields by the borehole method, and gradually decreasing sulfuric acid from 20-15-10-5-3 g/l at L:S ranges of 0-0.2; 0.2-0.8; 0.8-1.5; 1.5-2.0; 2.0-2.5; 2.5-4.0. The second experiment involves preparing the solutions with acidity higher than standard, used in special conditions with high ore filtration characteristics. The acidity changes in the following sequence: 25-20-15-10-5 g/l of sulfuric acid in the range

0-0.2; 0.2-0.8; 0.8-1.5; 1.5-2.0; 2.0-2.5; 2.5-4.0 of L:S. To determine the effectiveness of selected chemical reagents in the intensification of borehole uranium recovery, it is decided to use solutions of standard acidity with the addition of sulfamic acid 2.0 and lignosulfonates 0.5 g/l. The procedures of the third experiment provide for preparing solutions with a standard acidity of 20-15-10-5-3 g/l and the addition of sulfamic acid 2 g/l and lignosulfonates 0.5 g/l at the initial stage of the experiment. In all experiments, with an excess of L:S > 2.5, the leaching solutions are supplied with zero acidity.

To study the effect of the oxidizing agent on uranium leaching in the tubes, the filtrate is regularly collected at the outlet into measuring vessels for further measurements and analysis. The volume of the solution in the sample, the concentration of uranium in the solution, L:S, pH, the uranium content in the productive solution and the degree of recovery, specific consumption of sulfuric acid per kg of uranium and ore mass are measured in the obtained samples. The concentration of uranium in the solution is determination by titration MVI No. 36-2019 No. KZ06.01.00050-2019 dated July 11, 2019. Using experiments on uranium leaching in the tubes, the following geotechnological parameters of the experiment are determined by means of a calculation:

- filtration coefficient of ore K ;
- average concentration of uranium in productive solutions C_{av} ;
- maximum degree of uranium recovery ε from ore;
- L:S value f of the process (mass (volume) of the working solution per unit mass of core material in the tube);
- specific consumption of sulfuric acid per unit mass of uranium recovered and unit mass of ore in the tube.

Coefficient of ore filtration K_f , calculated from Formula (1), is associated with the fluid Q consumption and the drop of head:

$$K_f = \frac{\Delta V \cdot L}{\Delta t \cdot \Delta H \cdot S}, \quad (1)$$

where:

- ΔV – volume of filtered solution;
- L – tube length;
- Δt – sample measurement time;
- ΔH – hydrostatic head drop;
- S – tube cross-sectional area.

The dynamics of changes in the uranium content in the solution with respect to L:S, shows that the initial values of the maximum uranium concentration are achieved in the output solution with the corresponding filtered solution volume. The average uranium content in productive solutions is determined by the following Formula (2):

$$C_{av}^U = \frac{\sum_{i=1}^n C_i^U \cdot \Delta V_i}{\sum_{i=1}^n \Delta V_i}, \quad (2)$$

where:

- n – number of samples for selected measurement;
 - C_i^U – uranium content in i -th sample;
 - ΔV_i – solution volume in i -th sample.
- Summation is performed for all samples n .

Degree of uranium recovery (ε) from ore (recovery by solution) is calculated as the ratio of the total uranium mass in the output solutions to its initial mass in the ore (Formula (3)):

$$\varepsilon = \frac{\sum_{i=1}^n C_i^U \cdot \Delta V_i}{M_p \cdot C_{core}^U}, \quad (3)$$

where:

- C_i^U – uranium content in the output solution in i -th sample;
- ΔV_i – solution volume in i -th sample;
- M_p – ore mass in the initial sample;
- C_{core}^U – uranium content in the initial core sample.

The value of L:S with a specified degree of recovery ε is determined by the ratio (4):

$$f_\varepsilon = \frac{\sum_{i=1}^n \Delta V_i}{M_p}, \quad (4)$$

where:

- ΔV_i – solution volume in i -th sample;
- M_p – ore mass in the initial sample.

The specific consumption of sulfuric acid per kilogram of uranium P_k is calculated as the ratio of the total mass consumed for the experiment to the mass of uranium recovered during the experiment according to Formula (5):

$$P_k = \frac{\sum_{i=1}^n (C_0^k - C_i^k) \cdot \Delta V_i}{\sum_{i=1}^n C_i^U \cdot \Delta V_i}, \quad (5)$$

where:

- C_0^k – initial acid concentration in the working solution;
- C_i^k – acid concentration in i -th sample (residual);
- ΔV_i – solution volume in i -th sample;
- C_i^U – uranium content in the output solution in i -th sample;
- M_p – ore mass in the initial sample.

The specific reagent consumption per unit of processed ore mass (ore acidity) is determined by Formula (6):

$$P_k = \frac{\sum_{i=1}^n (C_0^k - C_i^k) \cdot \Delta V_i}{M_p}, \quad (6)$$

where:

- C_0^k – initial acid concentration in the working solution;
- C_i^k – acid concentration in i -th sample (residual);
- ΔV_i – solution volume in i -th sample;
- M_p – ore mass in the initial sample.

3. Results and discussion

When the experimental tests are performed and the geotechnological parameters are calculated, preliminary conclusions can be made about the effectiveness of the adopted leaching mode for borehole uranium recovery. Research into leaching of uranium in tubes provides information on the effect of the of sulfuric acid and surfactant concentration, as well as the velocity of solutions movement on the geotechnological parameters of uranium leaching. Based on the obtained results of laboratory experiments, the data are analysed and graphs of uranium content changes in the solution, the filtration coefficient, the degree of uranium recovery, the specific consumption of sulfuric acid, the consumption of sulfuric acid per unit of ore mass in relation to L:S are plotted.

Studies of uranium leaching processes involves measuring the values of the uranium content in solution, and depending on the individual stages speed, the rate of uranium transition into

solution is determined. The duration of a separate stage and dissolution of uranium minerals depends on the host rocks composition. Figure 3 shows the plotted graph of the uranium content in the productive solution depending on the ratio of L:S.

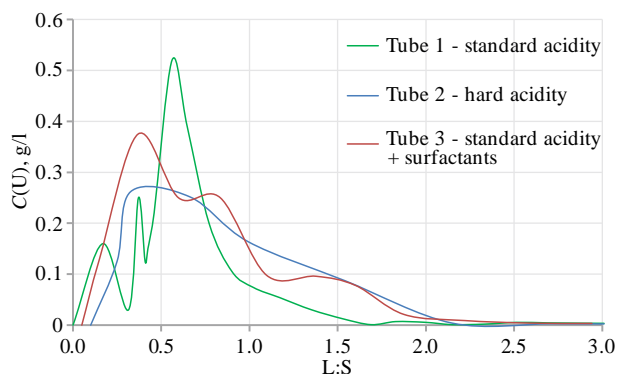


Figure 3. Uranium content in the solution depending on the ratio of L:S

As can be seen from Figure 3, in the first experiment, the uranium content at standard acidity reaches its maximum values of 520 mg/l at L:S of 0.6, followed by a sharp decrease to 80 mg/l at L:S of 0.9. The data indicate that a decrease in acidity in the leaching solution from 15 to 10 mg/l in the L:S range of 0.8-1.5 reduces the dissolving ability of solutions and reduces the uranium content in the productive solution. The second experiment evidences that the uranium content reaches its maximum values of 262 mg/l at previous L:S values of 0.375, with a gradual decrease in the uranium content in the productive solution to 80 mg/l at L:S values of 1.6. The data indicate an intensive crossing of the solubility threshold and the achievement of active uranium leaching at an earlier stage due to the higher leaching solution acidity. The low uranium content in the productive solution is possibly caused by sedimentation in the sample and repeated deposition of uranium minerals followed by repeated dissolution. In the third experiment, the uranium content in the productive solution reaches values of 375 mg/l with L:S values similar to experiment 2 of 0.380 and a subsequent gradual decrease in the uranium content in the productive solution to 80 mg/l with L:S of 1.6. This indicates the high efficiency of the dissolving ability of leaching solution with the addition of surfactants at low L:S values and preventing sedimentation in the pore space.

The filtration characteristics of ores during the processes of the solvent interaction with uranium minerals, and further transportation to the unloading zones is one of the key parameters and is determined by the ore filtration coefficient [16], [17]. Figure 4 shows a graph of the change in the filtration coefficient (K_f) depending on L:S.

As can be seen from Figure 4, the filtration velocity of solutions in the first experiment sharply decreases to the minimum values of 0.1 m/day at the L:S range of 0.2-0.4, after which it gradually increases to 0.6 at L:S of 1.5. In the second experiment, the average filtration velocity of solutions is slightly lower. The first two experiments data indicate that high acidity in the leaching solution at the initial stage reduces the filtration characteristics, and the subsequent decrease in acidity reduces the colmatation effects. The average filtration velocity in the third experiment slightly exceeds the previous results at the L:S range of 0.2-0.6, perhaps this is caused by the action of surfactants and the prevention of sedimentation at high leaching solution acidity.

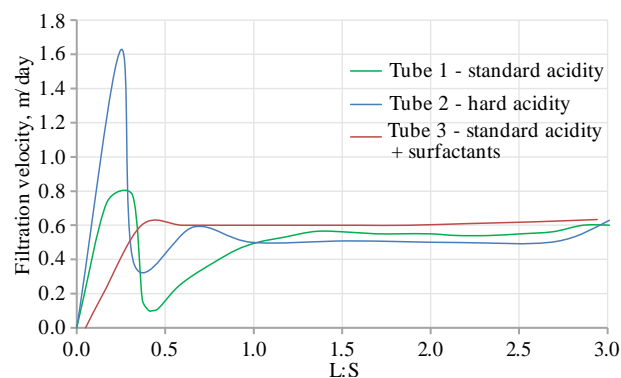


Figure 4. Dynamics of the change in the filtration coefficient depending on the L:S

The filtration velocity in all experiments is approximately the same, and varies in the range of 0.4-0.6 m/day. These values are satisfactory and correspond to the maximum real conditions of uranium leaching.

To determine the effectiveness of the surfactants effect on uranium leaching and to compare the parameters under conditions of standard and hard acidity of solutions, the data are calculated and graphs of uranium extraction are plotted. The values of the degree of uranium recovery are the most informative and indicative in terms of the process efficiency of uranium minerals conversion into solution, taking into account the total mass reflection of uranium in the output solutions and the time of the process. Figure 5 shows the graphs of changes in uranium recovery depending on L:S according to experiments.

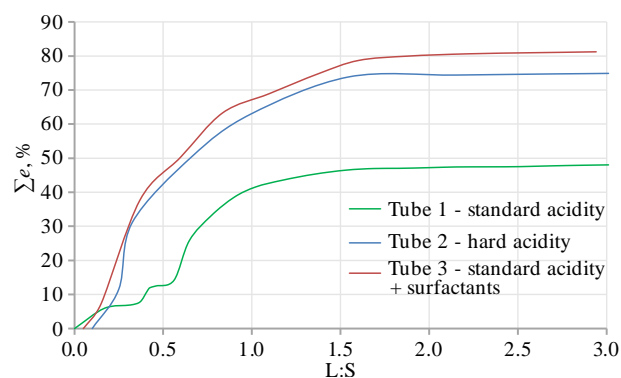


Figure 5. Degree of uranium recovery depending on the L:S

As can be seen from Figure 5, the comparative values of uranium recovery according to the experiments, the maximum values of uranium recovery of 80% are achieved in the third experiment, when using the solutions with standard acidity and when adding surfactants. A sharp increase occurs from 0 to 65% in the L:S range of 0-0.8, with the maximum leaching solution acidity, which is conditioned by an increase in the dissolving ability of uranium minerals, the prevention of sedimentation and increased filtration characteristics [18], [19]. The curve of the degree of uranium recovery in the second experiment reaches 74%, which indicates the intensive uranium recovery using solutions with a hard acidity mode. The degree of uranium recovery in the first experiment achieves only 48% at standard acidity, which indicates the insufficient dissolving ability of the solutions and their low filtration characteristics. Despite the high uranium content in the productive solution at the L:S range of 0-0.8, low filtration characteristics do not allow increasing the recovery.

To select the effective and economically reasonable mode of solutions acidity, the necessity of adding the surfactants during the intensification of uranium leaching, the specific consumption parameters of the sulfuric acid per kilogram of recovered uranium are determined. Figure 6 shows the graphs of changes in the sulfuric acid specific consumption per kilogram of uranium depending on the L:S in the experiments.

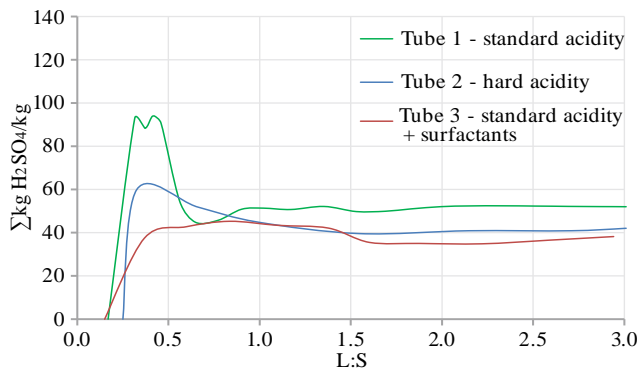


Figure 6. Specific consumption of the sulfuric acid depending on the L:S

As can be seen from Figure 6, the sulfuric acid specific consumption for uranium leaching in the first experiment, at standard acidity of leaching solution, reaches a maximum value of 93 kg/kgU at the L:S range of 0.2-0.8, after which sharply decreases to 50 kg/kgU. The average values of the sulfuric acid specific consumption in the first experiment are 60 kg/kgU. A sharp increase in the sulfuric acid specific consumption is caused by a high acidity in the working solutions and the low degree of uranium recovery in the corresponding period of L:S, due to low filtration characteristics. The maximum values of the sulfuric acid specific consumption in the second experiment, with a hard acidity of leaching solution, reach 60 kg/kgU, and the average values of the entire experiment are 45 kg/kgU. The decreased values of the specific consumption in the second experiment when comparing with the first experiment is caused by the more intensive uranium recovery of in the corresponding period of L:S, due to the higher leaching solution acidity. The curve of the sulfuric acid specific consumption in the third experiment, at standard acidity with the addition of surfactants, is smoothed and does not have sharp jumps and peaks, on average it is 40 kg/kgU. The low sulfuric acid consumption is ensured by high recovery factors conditioned by the dissolving ability of the surfactant, which in turn, in practice, leads to savings in sulfuric acid and other operating expenses for production.

To select the optimal acid concentration and the need to add a surfactant, the parameters of the sulfuric acid specific consumption per unit of ore mass are taken into account, that is, the acid consumption of rocks. Figure 7 shows the graphs of the sulfuric acid specific consumption per unit of ore mass, depending on L:S.

As can be seen from Figure 7, the sulfuric acid consumption per unit of ore mass depending to L:S is as follows: in the second experiment with solutions of hard acidity the maximum consumption is 13 kg/ore mass, in the third experiment is 11.5 kg/ore mass, and in the first experiment is 10 kg/ore mass at L:S of 1.0. The sulfuric acid high consumption in the second experiment is conditioned by the increased leaching solution acidity and the sufficient filtration characteristics of the ore for the solutions circulation.

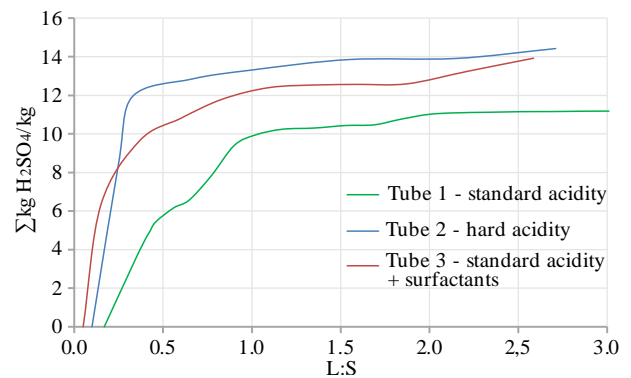


Figure 7. Sulfuric acid specific consumption per unit of ore mass, depending on L:S

The average values in the third experiment, when comparing with the first and second experiments, indicate that the sulfuric acid consumption with the addition of a surfactant for treating a unit of the ore mass is lower than with a hard acidity, but higher than with a standard acidity. This is conditioned by increased filtration characteristics and the intensity of the solution circulation processes. Low values of the sulfuric acid consumption per unit of ore mass in the first experiment, with a standard leaching solution acidity, indicate the presence of residual acidity in the productive solution that has not reacted [20], [21].

4. Conclusions

The tests performed on particle-size distribution of core samples indicate the prevalence of > 57% of the total mass of the fine-grained fraction in the host rocks, which complicates uranium leaching and leads to formation of mechanical colmatation in the productive horizon. X-ray phase studies of core material samples show the presence of argillaceous minerals of more than 14% of the total mass, contributing to chemical and mechanical colmatation of wells and near-filter zone. The results evidence a complex structure of the productive horizon, heterogeneity and low filtration characteristics. The experience of exposing and mining the blocks with a complex structure and low filtration characteristics of the host rocks indicates a complex preparatory work and a long stage of operation due to low circulation rates of solutions, insufficient operational efficiency of wells. This causes additional expenses for sulfuric acid, repair and restoration work, electrical energy, and increases operating expenses for production.

In laboratory conditions, it has been revealed that by adding small volumes of surfactants to the leaching solution, it is possible to intensify the uranium recovery up to 80% without increasing the sulfuric acid specific consumption, and also to increase the filtration velocity of solutions. The decreased values of the sulfuric acid specific consumption per unit of uranium recovered of 40 kg/kgU indicates the economic feasibility of adding surfactants at the initial stage of uranium leaching in difficult mining-and-geological conditions and areas with a high content of argillaceous minerals.

High leaching solution acidity leads to an increase in the concentration of uranium in the productive solution, and an increase in the rate of leaching. However, in practice, an increase in the sulfuric acid concentration in the leaching solution leads to an increase in its specific consumption, an additional occurrence of the colmatation effect.

The addition of surfactants during leaching contributes to an increase in the intensity of uranium recovery and a decrease in the sulfuric acid specific consumption, as well as to a decrease in the colmatation effect and operating expenses.

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Дослідження вилуговування урану з ядерних проб в трубках із застосуванням поверхнево-активних речовин

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Мета. Підвищення ефективності свердловинного видобутку урану у складних гірничо-геологічних умовах за рахунок розробки нової технології, заснованої на інтенсифікації геотехнологічних процесів підземного вилуговування урану, селективного впливу нового комплексу хімічних реагентів на сукупність мінералогічного і гранулометричного складу рудовмісних порід продуктивного горизонту.

Методика. Відбір проб ядерного матеріалу вміщуючих порід родовища урану Сирдар'їнської депресії. Методом спектрального аналізу встановлено вміст урану, кальцію, алюмінію, заліза, магнію та карбонатність у пробах. Рентгенофазовим методом визначені кількісно-якісні параметри й особливості вміщуючих мінералів. Проведено гранулометричні дослідження і встановлені фракційні параметри ядерних проб. Розроблено регламенти та проведені лабораторні досліди щодо вилуговування урану з ядерного матеріалу в динамічному режимі в трубках, з додаванням обраних хімічних реагентів з різними режимами.

Результати. Визначено особливості свердловинного видобутку урану із застосуванням розчинів сірчаної кислоти як розчинника, а також встановлено причини, які викликають зниження геотехнологічних параметрів у рудах з низькими фільтраційними характеристиками. Розроблено ефективний метод інтенсифікації свердловини видобутку урану із застосуванням поверхнево-активних речовин (ПАР) у складних гірничо-геологічних умовах, з підвищенням вмістом глинистих і карбонатних мінералів, низькими фільтраційними характеристиками вміщуючих порід. Встановлено й науково обґрунтовано ефективний та економічно доцільний метод вилуговування урану розчинами сірчаної кислоти з додаванням ПАР.

Наукова новизна. Встановлено, що додавання обраних ПАР у сірчано-кислотні розчини підвищує вміст урану у продуктивному розчині та ступінь вилучення урану при зниженні витрат сірчаної кислоти і відношення рідкого до твердого (Р:Т).

Практична значимість. Застосування раціональних ПАР при вилуговуванні урану дозволяє на ділянках з низькими фільтраційними характеристиками зменшити експлуатаційні витрати на видобуток за рахунок скорочення періоду відпрацювання, підвищити вміст урану у продуктивному розчині та ступінь вилучення, знизити витрати сірчаної кислоти й утворення відкладень.

Ключові слова: свердловинний видобуток, вилуговування, уран, рентгенофазовий, гранулометричні дослідження, поверхнево-активні речовини

Исследования выщелачивания урана из керновых проб в трубках с применением поверхностно-активных веществ

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Цель. Повышение эффективности скважинной добычи урана в сложных горно-геологических условиях за счет разработки новой технологии, основанной на интенсификации геотехнологических процессов подземного выщелачивания урана, селективного воздействия нового комплекса химических реагентов на совокупность минералогического и гранулометрического состава рудовмещающих пород продуктивного горизонта.

Методика. Отбор проб кернового материала вмещающих пород месторождения урана Сырдарьинской депрессии. Методом спектрального анализа установлены содержание урана, кальция, алюминия, железа, магния, а также карбонатность в пробах. Рентгенофазовым методом определены количественно-качественные параметры и особенности вмещающих минералов. Проведены гранулометрические исследования и установлены фракционные параметры керновых проб. Разработаны регламенты и проведены лабораторные опыты по выщелачиванию урана из кернового материала в динамическом режиме в трубках, с добавлением выбранных химических реагентов с различными режимами.

Результаты. Определены особенности скважинной добычи урана с применением растворов серной кислоты в качестве растворителя, а также установлены причины, которые вызывают снижение геотехнологических параметров в рудах с низкими фильтрационными характеристиками. Разработан эффективный метод интенсификации скважинной добычи урана с применением поверхностно-активных веществ (ПАВ) в сложных горно-геологических условиях, с повышенным содержанием глинистых и карбонатных минералов, низкими фильтрационными характеристиками вмещающих пород. Установлен и научно обоснован эффективный и экономически целесообразный метод выщелачивания урана растворами серной кислоты с добавлением ПАВ.

Научная новизна заключается в том, что добавление выбранных ПАВ в сернокислотные растворы повышает содержание урана в продуктивном растворе и степень извлечение урана при сниженном расходе серной кислоты и отношения жидкого к твердому (Ж/Т).

Практическая значимость. Применение рациональных ПАВ при выщелачивании урана позволяет на участках с низкими фильтрационными характеристиками снизить эксплуатационные расходы на добычу за счет сокращения периода отработки, повысить содержание урана в продуктивном растворе и степень извлечения, снизить расход серной кислоты и осадкообразования.

Ключевые слова: скважинная добыча, выщелачивание, уран, рентгенофазовый, гранулометрические исследования, поверхностно-активные вещества

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