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INVESTIGATION OF THE POSSIBILITY OF SEPARATE BIO-LEACHING OF URANIUM AND VANADIUM FROM BLACK SHALE RAW MATERIALS

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Abstract. This study presents the results of experiments aimed at developing an effective method for the selective leaching of uranium and vanadium from black-shale mineralization. The relevance of the research is associated with the complex mineral composition of black-shale deposits, the presence of organic matter, and the low solubility of uranium- and vanadium-bearing phases, which limit the efficiency of conventional in-situ leaching technologies. The study evaluates an improved well-based bioleaching approach that combines preliminary bio-oxidation by Acidithiobacillus Ferrooxidans with the use of perforated pipes equipped with heating and aeration systems to maintain optimal reaction conditions during the winter period. A series of experiments was conducted to assess the influence of temperature, sulfuric acid concentration, and biological oxidation on metal dissolution. The maintenance of elevated temperatures within the perforated pipes promoted the activation of oxidation processes in the deeper zones of black-shale deposits. Experimental findings demonstrated that achieving 96% uranium recovery in the productive solution requires maintaining a temperature of 20 °C and a sulfuric acid concentration of 2.5% following preliminary bio-treatment of the ore. Subsequent vanadium leaching was performed using 10% sulfuric acid at 30 °C, resulting in a recovery rate of 83.6%. The results confirm the high efficiency of the combined bio-oxidation and thermal-aeration approach, indicating its potential for year-round application in In-Situ processing of black-shale deposits. The proposed technology enhances both the selectivity and overall recovery of uranium and vanadium compared to baseline methods, thereby offering promising prospects for industrial implementation and improved resource utilization.

Key words: black shale ore, leaching, hydrometallurgy, oxidation processes, extraction

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ҚАРА ТАҚТАТАС ШИКІЗАТЫНАН УРАН МЕН ВАНАДИЙДІ БӨЛЕК БИОШАЙМАЛАУ МҮМКІНДІГІН ЗЕРТТЕУ

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Аннотация. Бұл зерттеуде қара тақтатас шикізатынан уран мен ванадийді селективті шаймалаудың тиімді әдісін әзірлеуге бағытталған эксперименттердің нәтижелері ұсынылады. Жұмыстың өзектілігі қара тақтатас кендердің күрделі минералдық құрамымен, органикалық заттардың болуымен және уран мен ванадий минералдарының төмен ерігіштігімен байланысты, бұл дәстүрлі ұңғымалық шаймалау технологияларының тиімділігін шектейді. Зерттеуде биототықтыруды Acidithiobacillus Ferrooxidans дақылымен және жылыту және аэрация жүйесімен жабдықталған перфорацияланған құбырлармен біріктіретін жақсартылған ұңғымалы биошаймалау жүйесі бағаланады. Бұл жүйе қысқы кезеңде оңтайлы реакциялық жағдайларды сақтауға мүмкіндік береді. Температураның, күкірт қышқылының концентрациясының және биологиялық тотығудың металдардың ерігіштік үдерістеріне әсерін зерттеу үшін бірқатар тәжірибелер жүргізілді. Перфорацияланған құбырлардың ішіндегі температураны көтеру қара тақтатас қойнауындағы тотығу үдерістерінің белсенділігін арттырды. Тәжірибелік деректер алдын ала биологиялық өңдеуден кейін 20 °С температурада және 2,5 % күкірт қышқылы ерітіндісінде уранның 96 % өнімді ерітіндіге өтуі қамтамасыз етілетінін көрсетті. Кейінгі ванадийді шаймалау 10 %-дық күкірт қышқылын және 30 °С температурасын қолдану арқылы жүргізіліп, 83,6 % алыну деңгейіне қол жеткізілді. Алынған нәтижелер био-тотықтыру мен термо-аэрациялық әсерді үйлестірудің жоғары тиімділігін дәлелдейді, бұл технологияны қара тақтатас кендерді жыл бойы In-Situ әдісімен өңдеуде қолдануға мүмкіндік береді. Ұсынылған тәсіл уран мен ванадийді алудың селективтілігін және жалпы деңгейін арттырып, өнеркәсіптік енгізуге және минералдық ресурстарды ұтымды пайдалануға кең мүмкіндіктер ашады.

Түйін сөздер: қара тақтатас кені, шаймалау, гидрометаллургия, тотығу процестері, бөліп алу

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ИССЛЕДОВАНИЕ ВОЗМОЖНОСТИ РАЗДЕЛЬНОГО БИО-ВЫЩЕЛАЧИВАНИЯ УРАНА И ВАНАДИЯ ИЗ ЧЕРНОСЛАНЦЕВОГО СЫРЬЯ

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Аннотация. В представленной работе исследована возможность создания эффективной технологии селективного выщелачивания урана и ванадия из черносланцевого сырья. Актуальность исследования обусловлена сложной минералогией черносланцевых месторождений, высоким содержанием органического вещества и низкой растворимостью урано- и ванадийсодержащих минералов, что значительно снижает эффективность традиционных методов скважинного выщелачивания. В исследовании рассматривается усовершенствованный вариант технологии биовыщелачивания, включающий предварительное биоокисление сырья культурой Acidithiobacillus ferrooxidans с использованием перфорированных труб, оснащённых системой нагрева и аэрации. Такая конструкция обеспечивает поддержание оптимальных температурных условий в зимний период, что повышает скорость микробиологических процессов. Проведена серия экспериментов по изучению влияния температуры, концентрации серной кислоты и биологического окисления на степень растворения урана и ванадия. Поддержание повышенной температуры внутри перфорированных

труб способствовало активному протеканию окислительных процессов в глубинных зонах черносланцевых залежей. Экспериментальные результаты показали, что извлечение 96 % урана в продуктивный раствор достигается при температуре 20 °C и концентрации серной кислоты 2,5 %, если сырьё предварительно подвергнуто биологической обработке. Последующее выщелачивание ванадия 10%-ной серной кислотой при 30 °C обеспечило извлечение 83,6 % металла. Полученные данные подтверждают высокую эффективность сочетания биоокисления и термо-аэрационного воздействия, демонстрируя перспективность метода для круглогодичного применения при in situ переработке черносланцевых залежей. Представленный подход повышает селективность и общий коэффициент извлечения урана и ванадия, открывая возможности для промышленного внедрения технологии и более рационального использования минерального сырья.

Ключевые слова: черносланцевая руда, выщелачивание, гидрометаллургия, окислительные процессы, извлечение

Introduction. The experience of world studies of black shale samples of mineral raw materials shows the presence of a fairly diverse composition of metals. However, the most characteristic association of V-Mo-U-Ni-Zn is relatively universal for many samples of black shale ores, with scattered mineralization and fine-grained rocks. Vanadium is most often associated with silicates, which also leads to limited opportunities for its enrichment (flotation, etc.). Methods for extracting uranium and vanadium range from conventional hydrometallurgy, bioleaching and in-situ leaching (In-Situ), combinations with roasting, microwave, etc., autoclaving or other ancillary operations are possible. The final choice of technology depends on the specific object, its characteristics, while there are no single, universal solutions (Vind et al, 2021).

Laboratory tests on the leaching of uranium, vanadium and rare-earth metals, taking into account the mineralogical characteristics of the main and residual components, show that non-extractable uranium mainly consists of micron-sized granules of resin bluff encased in quartz and other insoluble minerals, while the cause of inefficient extraction of vanadium are phyllosilicates, which have different, but generally poor solubility at room temperature (Radwany et al, 2022). An additional reason is the retention of small amounts of fine-grained vanadium hydroxide and tar blanket, autigenic quartz and vanadium phyllosilicates (Drexler et al, 2023). Comparison with data from studies of samples of other uranium- and vanadium-containing resources suggests that the different solubility of vanadium-phyllosilicate ore minerals can also reduce extraction from more common types of ore deposits, such as black shales or coal, especially in heap leaching of low-grade ores with large grain size (Barton et al, 2023).

The results show that uranium leaching tests in production wells are close to the results of simulation of the kinetic reaction model, but differ significantly from the results of simulation of the thermodynamic equilibrium model (Wang et al, 2022). Therefore, the kinetic reaction model may better reflect the uranium leaching extraction process than the thermodynamic equilibrium model. At the same time, comparing the simulation results of the thermodynamic equilibrium model and the reaction kinetics model, it can be seen that the first simulation leads to an increase in the leaching area, an increase in the amount of leached uranium minerals and a reduction in the time of complete leaching of uranium minerals. In addition, when predicting the degree of uranium mining and uranium concentration during leaching in an ore-bearing aquifer, the prediction result of the thermodynamic equilibrium model is too high, and the time required for mining is too short, which leads to an overestimation of the uranium leaching rate and underestimation of the mining time. Thus, in the numerical simulation of uranium mining by the underground leaching method, the reaction kinetics optimizes the expression of the water-rock reaction rate compared to the thermodynamic equilibrium, which makes the simulation more practical.

Another important aspect of the processing of such raw materials is effective methods of converting uranium into a solution. The most common method involves sulfuric acid leaching – borehole In-situ, vat and others (Li et al, 2024). The choice of a particular method is largely determined by the overall level of uranium and other valuable components, the form of presence in the minerals of the rock, the possibility of applying preliminary enrichment of raw materials. Thus, the content of uranium in carbon structures significantly complicates its extraction during leaching. Thus, the accumulation of uranium and other elements in carbide form forms the structure of particles that are not subject to oxidation processes under normal atmospheric conditions, as well as excluding the processing of this raw material by hydrometallurgical methods (Etschmann et al, 2024). Uranium-containing raw materials of quartz nature have their own distinctive features that affect leaching processes. Studies of microcomputer tomography of sandstone uranium ore showed changes in the porosity and structures of mineral grains during sulfuric acid leaching (Wang et al, 2024; Zhang et al, 2024; Jiang et al, 2024). In apatite rocks, the accumulation of uranium is presumably due to its ability to replace calcium, where it is also found in phosphorites (Aita et al, 2024). The structure and composition of mineral raw materials containing uranium largely affect the ion exchange processes that occur during leaching. Thus, one of the studies presents data on the influence of ion-exchange processes of analcymolytes on the hydrometallurgical technology of uranium mining – In Situ (Parrotin et al, 2024).

Methods of bio-leaching of uranium. Similar to the developed and improved technologies of bio-leaching of noble and non-ferrous metals, the search and implementation of methods of bacterial processing of uranium ores is carried out. The most widely used class of iron-oxidizing bacteria is Acidithiobacillus Ferrooxidans, which produce trivalent iron ions during their metabolism. Thus, in the field of modern studies of uranium leaching, the oxidative effect of iron ions with a concentration of 3 g/l at a pH of 1.7 was studied, which made it possible to achieve a recovery of 85.14% (Wang et al, 2018). Unlike ore mineral raw materials, which are composed mainly of quartz and silicates, with impregnations of iron-containing minerals, various types of organic compounds and carbon are also present in black shale rock. However, the presence of organic compounds can have some catalytic effect on the biological oxidation process. Thus, in studies of heap bio-leaching of uranium (Shiderin et al, 2024), an increase in the oxidation kinetics of ferrous iron was found due to the immobilization effect when using wood chips. At the same time, a number of organic compounds can have an inhibitory effect in standard methods of leaching metals from black shale raw materials, due to the formation of passivating layers. In turn, the use of bacterial treatment of black shale rock can largely neutralize this factor. Studies of the effectiveness of a number of mixed strains of bacteria showed that the symbiotic consortia of A. Ferrooxidans and A. Thiooxidans can prevent the formation of a passivating layer, and uranium extraction reached 97.5% (Xiao et al, 2025; Chen et al, 2022).

An additional effect of the use of biological oxidation in hydrometallurgical processes involving sulfuric acid leaching is the ability of a bacterial culture to produce an acidic medium during its metabolism, which ultimately reduces the total consumption of sulfuric acid. On the example of studies of biological leaching of uranium from slags (Wang et al, 2012), it was found that already when the uranium recovery rate is more than 50%, the acid consumption rate is 2.69% of the ore mass. As the practice of sulfuric acid leaching shows, the use of the biological oxidation method contributes to a further reduction in the total consumption of sulfuric acid when starting all hydrometallurgical cycles and leaching with circulating solutions (Koizhanova et al, 2023).

Methods and materials. The main purpose of the research and tests was to improve the method of borehole bio-leaching of uranium, to implement the possibility of using this method to intensify the extraction of valuable components – uranium and vanadium from black shale, due to an additional temperature factor and aeration, affecting the diffusion coefficient of the solution reagents and the rate of chemical reactions. The implementation of this technology will make it possible to carry out borehole bio-leaching of uranium and vanadium while maintaining the optimal temperature regime in the layers of black shale deposits, regardless of the seasonal conditions. The main difference of this technique is that at the stage of pre-treatment with a biological oxidant, the solution containing a bacterial culture is fed through a system of borehole distributors located in equipped perforated pipes. Unlike deep wells of standard In-Situ leaching for conventional ores, wells of black shale deposits will be about 10 m. The assembly scheme of perforated pipes for gradual immersion in wells is shown in Figure 1.

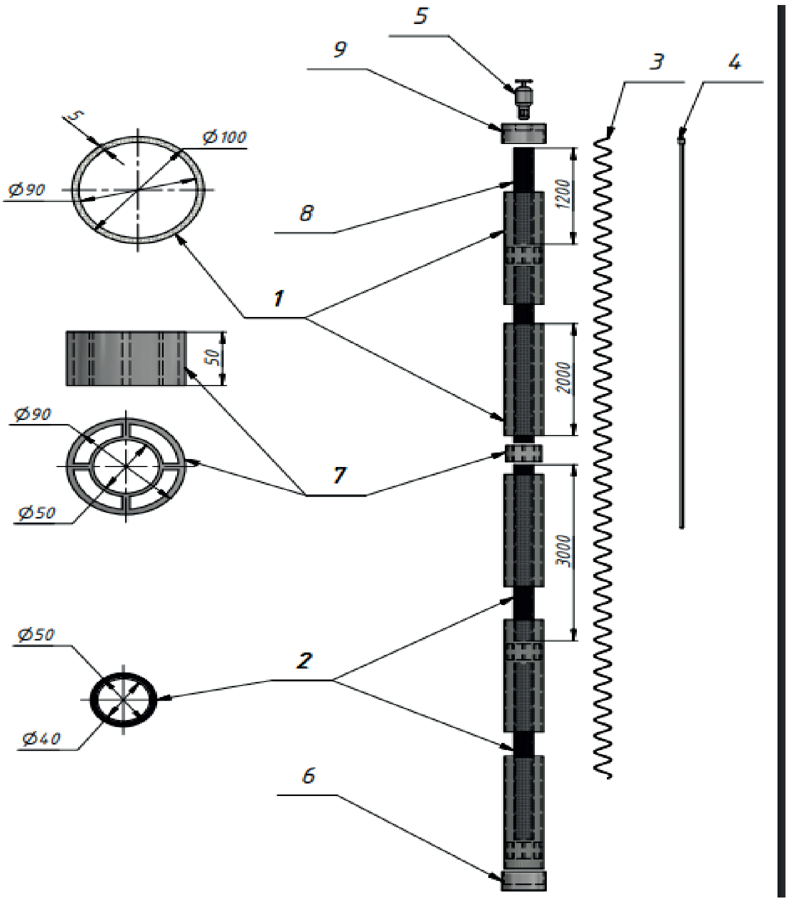

Figure 1. Assembly diagram of perforated pipes for a 10 m deep well
*1 – segments of external perforated pipes; 2 – segments of internal perforated pipes; 3 – thermal cable of the winding of internal pipes; 4 – thermal sensor; 5 – solution flow adjustment unit; 6 – plug of the external pipe at the base of the dump; 7 – alignment and fastening couplings of internal pipes; 8 – upper segment of the internal pipe; 9 – plug of the external pipe at the surface of the dump.

The installation of perforated pipes is carried out in the wells, in a vertical position from the surface of the deposits to the required depth. The material for the manufacture of pipes is acid-resistant plastic. The diameter of the outer perforated pipes (1) is 100 mm, the perforation size is 2.5 mm. Internal perforated pipes (2) with a diameter of 50 mm are installed inside the external ones, while the perforation of the internal pipes, from bottom to top, is made with an increase in the size of the holes - 0.5 mm, 1.5 mm, 2.5 mm - for every 3 m of pipe. The thermal cable (3) and temperature sensors (4) are interposed in the internal space. The inner space between the pipes is filled with an inert moisture-permeable filler, quartz sand, mineral wool and other water-permeable inert materials without sorption properties are used as the filler, the pressure flow of the leaching solution is controlled by means of an adjustment unit (5) mounted on the surface of the pile on each inner pipe, including an adjustment valve, barometers and flow meters. The placement of the outer perforated pipe in the ore dump is carried out after drilling a well with a diameter of 120 mm to a depth of 10 m. The supply of the outer perforated pipe with a diameter of 100 mm is carried out by gradually lowering the segments by 2-3 m, after vertical hydraulic soldering. The lower pipe segment is supplied with a plug installed serving as the bottom of the first segment (6). The first segment of the perforated pipe is filled with an inert filler at a level of 15 cm, and then the segment of the inner perforated pipe with a diameter of 50 mm, with perforation holes of 0.5 mm, is fed with a plug at the end. The length of the inner pipe segment should allow its soldering with a subsequent segment or connection using a coupling. In addition, the inner pipe is equipped with fragments for centering in the outer 100 mm pipe, the coupling flange of the connection with holes (7) can act as such a device. Before filling the outer pipe with inert filler, the inner pipe with a wrapped thermal cable is placed. A temperature sensor is installed in the central segment. The length of the upper segment of the inner pipe (8) is 1.2 m and excludes perforation on the part overlooking the dump surface. On the upper segment of the outer pipe, located at the surface of the dump, a plug (9) is installed with the output of the upper segment of the inner pipe.

The image of assembled experimental model is illustrated in Figure 2, which shows the technological scheme of the perforated pipe in the well of black shale deposits, with the following references to the positions of the elements: 1 – solution flow control unit; 2 – external perforated pipe (d=100 mm); 3 – internal perforated pipe (d=50 mm); 4 – thermal cable; 5 – inert filler (mineral wool, sand, etc.); 6 – thermal sensor.

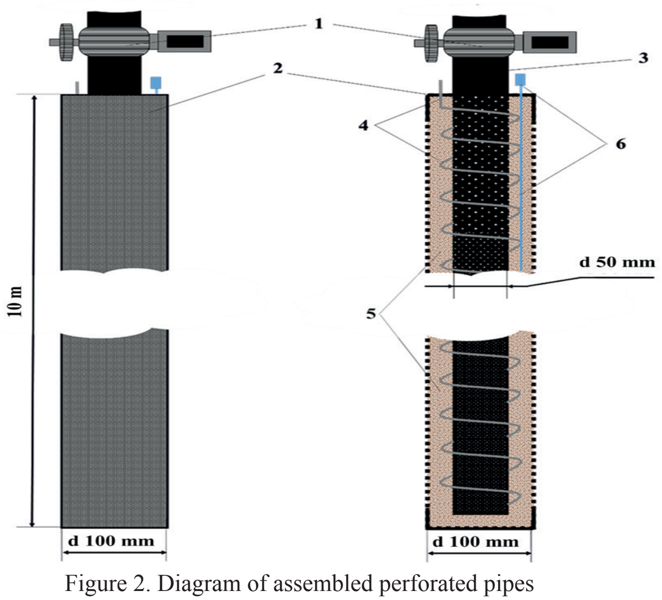

Figure 2. Diagram of assembled perforated pipes
*1 – solution flow adjustment unit; 2 – external perforated pipe (d=100 mm); 3 – internal perforated pipe (d=50 mm); 4 – thermal cable; 5 – inert filler (mineral wool, sand, etc.); 6 – thermal sensor

Experimental part. Before the start of enlarged tests, the averaged sample of black shale raw materials was analyzed for the initial chemical and phase composition. The following equipment was used to study the composition of raw materials:

- X-ray fluorescence wave dispersion combined spectrometer "Panalytical" (Netherlands);
- Diffractometer D8 ADVANCE "Bruker Elemental GmbH" (Germany) Purpose: quantitative qualitative X-ray phase and analysis; determination of crystal sizes, parameters and crystal lattice symmetry of organic, inorganic materials in liquid and solid form and thin films;
- Quadrupole inductively coupled plasma mass spectrometer "Thermo Scientific ICAP-Qc" (USA)
-Carbon analyzer G4 series ICARUS TF "Bruker Elemental GmbH" (Germany).

The detailed composition of the initial black shale raw materials obtained as a result of these studies is presented in Table 1.

Table 1. Composition of the initial sample of black shale raw materials (ICP analysis)

Compound Name	Chemical formula	Content, %
Uranium	U	0.02
Vanadium	V	1.31
Carbon (coal)	**C**	9.2
Carbon (organic)	$\mathbf{C}_nH_{2n+}$	6.1
Sulfur	S	1.2
Iron	Fe	4.3
Quartz-α | Silicon Oxide	SiO_2	71.05
Muscovite	$H_2KAl_3Si_3O_{12}$	4.035
Kalsilite, syn	$KAlSiO_4$	2.1
Other elements	Fe, Cu, Ca, Pb, Y….	0.685

Enlarged tests of the technology of borehole leaching of uranium and vanadium were carried out for 120 days (from November to March) in conditions of open unheated rooms and winter temperatures from minus 20°C to plus 2-3°C (Figure 3). The tests involved simulating borehole leaching on a limited volume of black shale rock. The supply of leaching solutions was carried out continuously in order to avoid their solidification.

Figure 3. Experimental borehole leaching system in winter conditions

In modes that do not provide for bio-oxidation and thermal effects, the temperature of the solutions fed for leaching was 5-6°C, and productive ones after the passage of the ore mass was 2-3°C. In the method with preliminary bio-oxidation without thermoregulation, the treatment of the black shale rock with a bacterial culture was carried out in advance, during periods of warm temperatures. In the proposed experimental model of borehole bio-leaching, the temperature in the perforated pipe was maintained at plus 20°C. Thus, 4 comparative leaching options were worked out, including the following parameters:

1) The basic method is sulfuric acid leaching, without bio-oxidation and heating system;

2) Bio-oxidation only - sulfuric acid leaching after 15 days of oxidation of raw materials by bacterial culture, without a heating system;

3) Well heating only – sulfuric acid leaching when wells are heated to 20°C, without preliminary oxidation with a bacterial culture;

4) Experimental method – sulfuric acid leaching after 15 days of oxidation of raw materials by bacterial culture, additional heating of wells to 20°C.

Experiments involved sequential leaching steps. During the first two months, leaching was carried out with a solution of sulfuric acid with a concentration of 2.5%, which created conditions for the selective extraction of uranium from black shale raw materials. After 60 days of experiment and the maximum possible extraction of uranium into the productive solution for each variant, the process of vanadium leaching was started. Taking into account the properties and specifics of the vanadium content, leaching in each variant was carried out with a solution of sulfuric acid with a concentration of 10.0%. In experiments involving an additional temperature factor, heating was carried out to 30°C.

Results and discussion. In tests involving bacterial oxidation, A. Ferrooxidans bacterial culture was pre-injected into the wells, with a parallel aeration system in operation. At the time of launch of option 2 - bio-leaching without heating, the solution temperatures were in the range of plus 10-15°C, with a gradual natural decrease to plus 6-8°C. The pH of the bio-oxidation variants was 2.2-2.3. Prior to major sulfuric acid leaching, the bio-oxidation solutions were analyzed for uranium and vanadium content. As a result, it was found that at the stage of preliminary bio-oxidation for 15 days, 6.54% of uranium was extracted into the solution in the option without thermoregulation, and in the option with heating the well to 20°C, the extraction of uranium reached 12.5%. The presence of vanadium in solutions from bacterial oxidation was not found, which is a favorable factor, since the technology of further leaching provides for the separate extraction of uranium and vanadium. After oxidation treatment, the process of basic leaching of uranium with a solution of sulfuric acid with a concentration of 2.5% was started. The dynamics of the extraction process of each variant is shown in Table 2.

Table 2. Dynamics of uranium extraction by various leaching options, %

Duration, days	Option 1	Option 2	Option 3	Option 4
	H_2SO_4 2.5% only	Bio-oxidation, H_2SO_4 2.5%	Heating up to 20°C, H_2SO_4 2.5%	Heating up to 20°C, bio-oxidation, H_2SO_4 2.5%
0*	-	6.54	-	12.5
5	2.13	14.30	13.43	20.49
10	5.27	21.51	17.54	25.09
15	8.12	30.12	19.86	35.54
20	11.12	36.60	23.54	42.50
25	17.41	42.21	28.38	50.81
30	21.28	48.10	33.21	54.74
35	26.89	52.65	38.53	71.80
40	32.30	57.20	44.82	82.53
45	39.56	60.97	53.52	93.24
50	44.10	63.58	55.65	96.08
55	46.23	65.90	58.36	96.17
60	46.81	67.83	59.61	96.26

* recovery into bio-oxidation solutions at the time of leaching start.

As a result of the first stage of sulfuric acid leaching of black shale raw materials, an active increase in the extraction of uranium into the solution was noted in the experimental version with preliminary bio-oxidation and subsequent leaching with maintaining the temperature at 20°C. Uranium recovery exceeded 90% already on the 45th day of leaching and reached a final maximum of 96.26% on the 60th day of the experiment. Thus, the combination of pre-bio-oxidation and temperature maintenance system makes it possible to double the efficiency of uranium extraction compared to basic sulfuric acid leaching. Comparison of the dynamics of uranium extraction by various combinations of leaching methods is shown in the graphs of Figure 4.

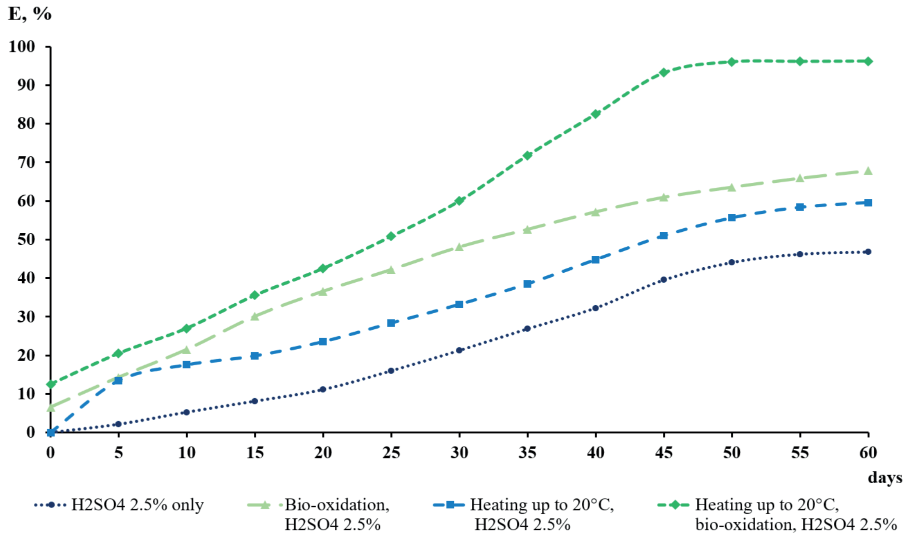

Figure 4. Dynamics of uranium extraction, by 4 test methods of leaching.

Analyses of productive solutions of uranium leaching with 2.5% sulfuric acid showed sufficiently low concentrations of vanadium, and its recovery did not exceed 0.1%. This made it possible to ensure the most selective extraction of uranium at the first stage of leaching. Leaching of vanadium was carried out at the second stage according to the technological parameters described earlier for each option – 10.0% sulfuric acid solution, heating options 3 and 4 to 30°C. The total duration of the leaching experiment was similar to the first step of 60 days, with the exception of the pre-bio-oxidation period. The results of vanadium recovery are presented in Table 3.

Table 3 – Dynamics of vanadium recovery by various leaching methods, %

Duration, days	Option 1	Option 2	Option 3	Option 4
	$H_2SO_4$10% only	Bio-oxidation, H_2SO_4 10%	Heating up to 30°C, H_2SO_4 10%	Heating up to 30°C, bio-oxidation, H_2SO_4 10%
5	1.84	10.11	10.4	18,9
10	4.29	17.42	15.96	28.35
15	7.65	26,68	22.49	36.65
20	10.53	34.18	28.61	44.7
25	14.92	39.9	35.13	52.44
30	19.8	45.56	41.26	60.77
35	24.0	49.69	45.33	66.4
40	27.25	54.5	50.21	72.27
45	30.73	59.87	55.38	76.4
50	34.16	65.15	61.19	79.87
55	37.54	69.47	64.5	81.55
60	40.63	72.63	66.22	83.6

Similar to the uranium leaching step, the highest vanadium recovery efficiency of -83.6% was observed in the Option 4 well, where the maximum uranium recovery had previously been achieved, which was also two times higher than the indicators of the basic standard method. In addition to less significant indicators of vanadium recovery in other variants of technological combinations, associated leaching of residual uranium was also observed, which in itself reduced the selectivity of these methods for uranium and vanadium. The dynamics of vanadium extraction, the corresponding variants are shown in the graphs of Figure 5.

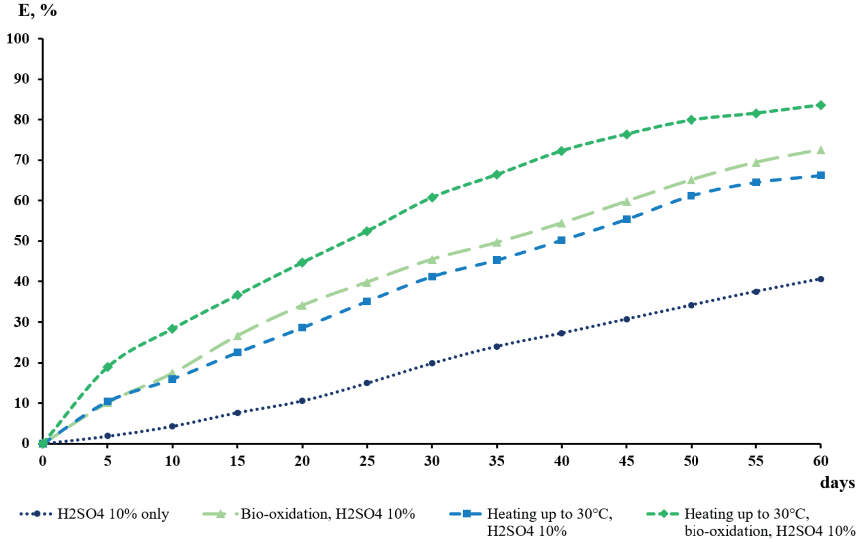

Figure 5. Dynamics of vanadium extraction, by 4 test methods of leaching.

Conclusions. As a result of the experiments, the most effective method for separate borehole leaching of uranium and vanadium from black shale raw materials was determined. The In-Situ method, in hydrometallurgical uranium production, remains one of the common methods of many uranium deposits. At the same time, to involve in the processing of uranium deposits represented by black shale rock, which also has acceptable technological concentrations of vanadium, the use of innovative combined methods is required. Standard borehole leaching – In-Situ, similar to mineral raw materials, has a low extraction efficiency of uranium and vanadium, and is also not able to fully ensure their maximum complete separation into productive solutions. Alternative methods of processing black shale ore – enrichment, autoclave and vat leaching, are advisable if there are acceptable contents of other rare earth metals in the composition of raw materials, in addition to uranium and vanadium. Based on the listed factors and the composition of the studied black shale ore sample, represented mainly by uranium and vanadium, the possibility of improving the existing borehole leaching technology was studied. As a result of the experiments, it was found that equipping process wells with a heating and aeration system allows for effective bio-oxidation of deposits of black shale raw materials and, as a result, doubles the extraction of uranium and vanadium compared to basic sulfuric acid leaching. Thus, the treatment of black shale raw materials with Acidithiobacillus Ferrooxidans bacterial culture while maintaining the temperature regime at 20°C and aeration of the well provides 96.26% of uranium extraction during the subsequent first stage of leaching with a sulfuric acid solution with a concentration of 2.5%. After the maximum complete extraction of uranium, an increase in the concentration of sulfuric acid to 10.0% and a temperature to 30°C makes it possible to extract 83.6% of vanadium from black shale raw materials. Thus, preliminary biological oxidation, with the equipment of perforated well pipes with a thermal cable to maintain the temperature and an aeration system, contributes to the activation of oxidation processes in the depth of deposits of black shale raw materials, which ensures high efficiency and selectivity of uranium and vanadium extraction, even in the winter season.

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