Physico-chemical aspects of uranium extraction for investigation of underground well leaching control systems

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ABSTRACT

This article gives the physical and chemical aspects of uranium extraction from the zones of reservoir oxidation using ultrasonic technology and the theoretical justification for the technology of in-situ borehole leaching (ISL) of uranium deposits in Kazakhstan. Kazakhstan has significant reserves, well-explored uranium deposits, developed uranium mining and processing capacities, as well as the current state of the world uranium market, which determine the prospects for the development of the uranium mining industry in Kazakhstan. Ore deposits of uranium deposits localized at the fronts of seam oxidation zones are largely similar in terms of the chemical composition of host rocks. *Fe, Al, Mg, Ca, K, and Na* are among the most widespread petrogenic elements of rock-forming minerals. Uranium is observed in association with iron, vanadium, selenium, molybdenum, rhenium, and other elements. Uranium mineralization is represented by exogenous (secondary) minerals – pitchblende and coffinite. In the general balance of uranium minerals, pitchblende is about 30%, and coffinite is about 70%. Nasturan ($xUO_2 \cdot yUO_3 \cdot z$) is represented by an association of tetravalent uranium dioxide and hexavalent uranium trioxide with a variable composition (UO_2+UO_3) - 65-85%, coffinite - tetravalent uranium silicate $USiO_4$.

Keywords: Physico-chemical aspects, recovery, uranium, theoretical substantiation, recovery, uranium, theoretical substantiation, in-situ leaching, wells.

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Introduction

About 25% of the world's uranium reserves have been identified under the Republic of Kazakhstan. Uranium reserves are characterized by 75%. Of these, they are concentrated in deposits associated with regional zones of reservoir oxidation, which can be extracted by a relatively cheap and environmentally friendly in situ leaching method [1].

The development of the uranium mining industry in Kazakhstan is associated with the solution of key scientific and practical tasks. The modern uranium mining industry is characterized by high dynamism, the emergence of dangerous situations, in some cases radiation, and the need to make quick and effective decisions to eliminate them [[2], [3]]. The unique characteristics of each deposit require a certain amount of scientific research not only in the process of developing new deposits, but also in the application of well-known technological solutions. This situation objectively determines the high knowledge intensity of uranium mining production.

The analysis of the experience of exploitation of uranium deposits in the Chusar and Syrdarya regions shows the following [4]:

- In recent years, when developing large deposits (with optimal well placement grid sizes), a cellular arrangement of wells has been used;

- Reliable methods of well layout have not yet been developed, especially for deposits with complex structural conditions, such as the occurrence of ore bodies and hydraulic connections of aquifers;

- Well location schemes are selected on the basis of pilot tests and analogues.

The simplest, most effective and original method of developing hydrogen-containing uranium deposits is the method of underground borehole leaching. In principle, this leaching method can be successfully applied to the development of non-ferrous metal deposits in both underground and open-pit mining conditions [[1], [2], [3]].

Boreholes are the main technical facilities that provide an injection of a chemical or biochemical solution, control of its filtration process in the hydrogenous reservoir massif, uranium leaching processes, and delivery of productive solutions through pumping wells to the day surface for their processing. Thus, the system of boreholes for various purposes, drilled from the day surface to the depth of hydrogenous layers, is presented in the form of an underground mine.

For the opening of hydrogenous uranium deposits, the injection of biochemical solutions, as well as the pumping of productive solutions, are carried out using vertical wells. According to their purpose, they are divided into the following: technological, observational, control, and special [4].

In the exploitation of uranium deposits containing hydrogen, it is possible to use injection and extraction wells interchangeably. This means that each technological well can serve as both an extraction and injection well, allowing for a reversal in the direction of movement of working solutions in the productive horizon at a 180° angle. This reversal increases the degree of extraction of useful components from the deposit. The layout of technological wells, such as linear, areal, and combined, determines the scheme for opening the exploitation field of a hydrogenous uranium deposit.

Linear well arrangement systems consist of successively alternating rows of pumping and pumping wells over the area of deposits. Depending on the filtration coefficient and the homogeneity of the ore massif, the distances between rows and wells in a row vary widely (15-50 m or more). A production cell usually consists of two injections and one extraction well belonging to three consecutive rows.

In uranium deposits in the CIS (Commonwealth of Independent States) countries and other foreign countries, linear well arrangement systems were widely used, just as they are now. They are most effective in the development of extended hydrogenous uranium deposits composed of sedimentary, highly permeable ($K_F > 1.0$ m/day) ores and rocks and located in difficult hydrogeological conditions [[1], [5], [6], [7]].

Studies [[5], [7]] found that the most favorable of the tested is a linear system with a staggered arrangement of wells with a ratio of distances between wells in a row and between rows of 1:2, the least favorable is a system with a rectangular arrangement of wells with a ratio of distances of 1:1.

It is noted in [7] that in the domestic industry, a scheme of alternating linear rows of pumping and injection wells is mainly used with distances between wells in rows of 15–40 m, and between rows of 30–80 m. This well arrangement has a great advantage – the simplicity of construction and its operation. The most favorable for such a technological network are ore deposits of an elongated shape with good permeability. Depending on the specific conditions, the rows can be located along the strike or cross the strike. Under conditions of obtaining equal flow rates of pumping and injection wells ($Q0 = Q3$), the distance between wells in rows is also assumed to be the same.

Being in the group of actinides of the periodic system of elements by D.I. Mendeleev, the electronic structure of uranium, which determines the valence, is completed in the fifth shell from the top. Deep electrons, located on the fifth electronic level, due to the large atomic radius, are less firmly bound to the nucleus and, because of this, take part in the formation of valence bonds. Differences in the energy bonds of the electrons of the shells of the uranium nucleus are relatively small, but still exist, and this explains the multivalence of uranium. The main valence of uranium is 4, 5, 6. Variable valence leads to the formation of various complex compounds of uranium. Uranium mining by in-situ leaching through a system of wells drilled from the surface allows the most efficient exploitation of infiltration uranium deposits of in-situ and in-situ oxidation zones [[3], [7]].

When leaching in an acidic environment, uranium forms doubly charged uranyl cations (UO_2^{2+}), in an alkaline environment, uranate anions, and has a weak affinity for sulfur and a strong affinity for oxygen. As a result, simple and complex uranyl

sulfate ions are formed in HP solutions, depending on excess acidity. Additionally, in-situ leaching has a lower environmental impact compared to conventional mining methods. The use of injection and extraction wells allows for the control of the solution flow and prevents the release of harmful substances into the environment. The technology also reduces the amount of waste generated during the mining process, as only the useful components are extracted from the deposit.

However, there are also some challenges associated with in-situ leaching. One of the main challenges is the potential for groundwater contamination, which can occur if the solution used for leaching is not properly contained or if there are leaks in the well system. Another challenge is the potential for subsidence, which can occur if the pressure in the deposit is not properly maintained during the leaching process.

Overall, in-situ leaching is a promising technology for uranium mining, offering lower costs and environmental impacts compared to conventional mining methods. However, careful planning and monitoring are necessary to ensure the safe and effective extraction of uranium from hydrogenous deposits [8].

Research methods

Uranium compounds are relatively well soluble, which explains their migration ability with the formation of exogenous deposits of in-situ oxidation zones.

In solutions, uranium can exist in four valence states: U^{3+}, U^{4+}, U^{5+}, U^{6+} [1]. Aqueous solutions of salts of trivalent uranium are not very stable. Salts of tetravalent uranium form more stable solutions. Air oxygen oxidizes tetravalent uranium in aqueous solutions to hexavalent. Pentavalent uranium forms the uranyl radical (UO_2^+) in aqueous solutions in an extremely unstable form, which transforms into tetravalent and hexavalent uranium ions.

Quadrivalent uranium is slightly soluble in dilute solutions of sulfuric acid, and oxygen, permanganates, hydrogen peroxide, nitrogen-containing oxidizers, chlorine, chlorine-containing oxidizers, etc. can be used for its oxidation. Industrial applications are pyrolusite, melange, ferric iron salts, oxygen, and hydrogen peroxide [2]. For compounds of hexavalent uranium, the formation of the uranyl ion UO_2^{2+} is characteristic. Uranyl salts are highly hydrolyzed and have a pronounced acid reaction (pH 0.02M solutions of uranyl is 2.9) [[1], [4], [9]].

All salts are characterized by incomplete dissociation into ions.

In a sulfate medium, the uranyl ion is a strong complexing agent. In slightly acidic solutions with pH = 1-2, trisulfate and disulfate complex ions $[UO_2(SO_4)_3]^{4-}$ and $[UO_2(SO_4)_2]^{2-}$. In sulfate solutions, the ratio of simple and complex uranium ions depends on the excess acidity of the solution, the content of sulfate ions in it, and the concentration of uranium (Figure 1). For hexavalent uranium, the formation constants of the main complex ions in leaching solutions [[2], [6]]:

-   for uranyl cation UO_2^{2+} - 5,0-6,5;
-   for the neutral uranyl sulfate molecule $UO_2SO_4^0$ - 50-96;
-   for uranyl disulfate anion $[UO_2(SO_4)_2]^{2-}$ - 320-900;
-   for uranyl trisulfate anion $[UO_2(SO_4)_3]^{4-}$ - 2500.

An analysis of the graph shows that an increase in the acidity of the solution from pH = 3-3.5 to pH = 2-1.5 leads to a decrease in the content of the uranyl cation and, due to an increase in the content of sulfate ions, to a sharp increase in the complex ions of uranyl sulfate in the solution with the transition from a neutral molecule $UO_2SO_4^0$ to the anion of uranyl disulfate and uranyl trisulfate.
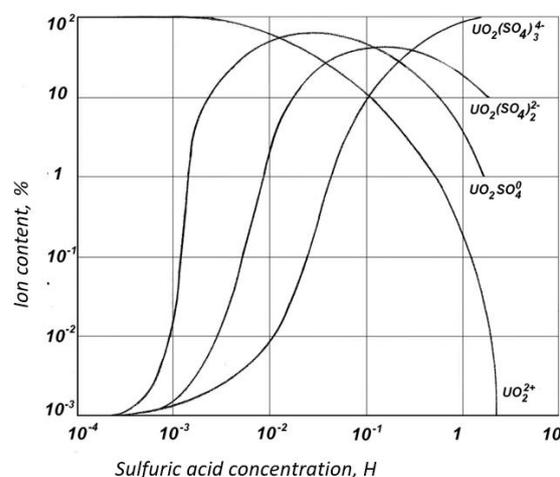
Figure 1 - Ionic composition of uranium compounds in sulfuric acid solutions at different acidity

Further, increase in acidity (up to pH=0.5-0.3) leads to a decrease in the content of $UO_2SO_4^0$; $[UO_2(SO_4)_2]^{2-}$, since in acidic solutions at pH < 2-1.5 the most stable form of uranium is the uranyl trisulfate anion $[UO_2(SO_4)_3]^{4-}$. If the solution is again raised to pH > 2.5, ion polymerization will appear with the formation of tri- and disulfate uranyl dimer $[UO_2O_5(SO_4)_3]^{4-}$, $[UO_2O_5(SO_4)_2]^{2-}$ due to hydrolysis of

complex ions, which leads to a significant increase in capacity of anion exchangers [[4], [10]].

Therefore, it is advisable to start uranium leaching in a mild mode at pH>2.5 (H_2SO_4 - 3.0-5.0 g/l), increasing the concentration in the uranyl sulfate solution to 50-60%. Then, increase the acidity of the solution to pH - 1.5-1.0 (H_2SO_4 - 10-15 g / l) and bring it to pH - 05.-0.3 (H_2SO_4 - 20-25 g / l), concentrating uranium in solution for uranyl trisulfate up to 95-100%. Then, at the outlet, quench the solution with soda to an acidity of pH - 2.5-4.0, facilitating the formation of well-sorbed uranyldimer trisulfate ions as much as possible.

In [10], the authors note that areal (cellular) well location systems are usually used to develop deposits confined to sedimentary layered heterogeneous ores and rocks of horizontal or slightly inclined occurrence, under conditions of relatively low water permeability of ores ($K_F \approx 0.1 \div 1$ m/day). These systems represent a uniform alternation of pumping and injection wells on the deposit area, forming cells (triangular, square, hexagonal, etc.) with small interwell distances (8÷20 m). In the CIS countries, the cellular arrangement of wells was rarely used.

With further involvement in the development by the IW method of more morphologically complex ore deposits with relatively low filtration coefficients (up to 1 m/day), large variability in the physicochemical properties of ores and host rocks, as well as when using high-rate pumps for pumping solutions, areal pumps (cellular) well layouts will be widely used.

In [[1], [11]] it is noted that cellular systems of wells are less common in domestic practice. So for isothermal ore deposits with relatively low, but allowing to obtain equal well flow rates ($Q_0 \approx Q_3$) permeability parameters of the massif, a square grid of alternating pumping and injection wells is taken.

For ore deposits of complex irregular shapes with low permeability parameters, it is advisable to use a hexagonal network of injection wells with a pumping well in the center of each cell. The ratio of debits in such a scheme $Q_o = 3Q_3$. Extraction wells are half as many as injection wells.

Other layouts of technological wells are also possible, in particular, triangular and pentagonal cells.

Bacterial leaching, also known as bioleaching, uses microorganisms to extract metals from ores. This method has several advantages over traditional mining methods, including lower energy consumption, reduced environmental impact, and higher metal recovery rates. Bacteria can be used to extract a wide range of metals, including copper, gold, silver, and uranium.

In the case of uranium, bacterial leaching can be used to extract the metal from low-grade ores that are not economically viable to mine using traditional methods. The process involves introducing bacteria into the ore deposit and allowing them to break down the minerals that contain the uranium. The uranium is then extracted from the solution using conventional methods.

The high efficiency of the method of bacterial leaching of gold from ore can be shown in the following example. In October 2001, the Polyus gold mining company announced that the first in Russia technological complex for extracting gold from ore using special bacteria was put into operation at one of the country's largest Olimpiada deposits, located 600 km north of the city of Kazan. Krasnoyarsk. Since 2002, Polyus has been annually giving the country 30 tons of gold. This is about a fifth of all precious metal mined in Russia. If we consider that 720 gold mining companies throughout the Magadan region mine 30 tons of gold per year, then one Polyus company replaces 720 companies, thanks to the use of bacterial leaching technology. The Polyus company employs only 1,000 people, while similar Western or Russian firms employ 11,000 workers.

Every year in the USA, 300 thousand tons of copper and 4 thousand tons of uranium are mined by leaching. Extensive research is being carried out on the extraction of Cu, Zn, Pb, Mn and other metals by leaching.

In addition, Kazatomprom officially stated that "depending on the configuration of the uranium ore body, two different types of landfill opening can be used: linear or hexagonal."

During the construction of uranium mines and their operation, the use of both triangular and hexagonal arrangements of technological wells causes large-scale economic damage, which is unacceptable.

One of the main advantages of bacterial leaching is its lower environmental impact compared to traditional mining methods. Bacteria do not produce toxic waste products, and the process does not require large amounts of water or energy. Additionally, bacterial leaching can be used to extract metals from ores that are too deep or too difficult to access using traditional mining methods.

However, there are also some challenges associated with bacterial leaching. One of the main challenges is ensuring that the bacteria are able to

survive and thrive in the harsh conditions of the ore deposit. This requires careful selection of the appropriate bacteria and optimization of the leaching conditions. Another challenge is controlling the leaching process to ensure that only the target metal is extracted and that other metals or contaminants are not released into the environment.

Overall, bacterial leaching is a promising technology for extracting metals from ores in a more environmentally friendly and cost-effective way. Further research and development are needed to optimize the process and ensure its safety and effectiveness in a range of mining conditions.

The main advantages of this method of in-situ uranium in-situ leaching compared to traditional mining methods of deposit development are as follows [12]:

–	the possibility of involvement in the exploitation of poor and off-balance ore deposits with complex geological and hydrogeological conditions of occurrence, but having large reserves of uranium;

– significantly reduce capital investments and the time of putting deposits into operation;

– labor conditions are improved, the number of miners is reduced and labor productivity increases by 2.5 times;

– the negative impact of uranium mining on the environment is reduced.

The supply of the leaching brine is ensured by trunk pumps located in the pumping station, which can provide pressure up to 7 bar. The productive stratum is brought to the surface by submersible pumps installed in the pumping wells.

The peculiarity of the development system with piston wells is that all pumping wells work in a pulsating mode, during the cycle of changing the pumping and pumping modes (T) [[6], [7], [13]]:

- Cycle 1 - pumping wells of row 2 work for a given period (T) in injection mode, while pumping wells of row 1 work in pumping mode during the same period (T). All injection wells of row 2 are in operation, and all injection wells of row 1 are stopped.

- Cycle 2 - The injection wells of row 1 operate for a given period (T) in injection mode, while the injection wells of row 2 operate in pumping mode for the same period (T). All injection wells of row 1 are in operation, and all injection wells of row 2 are stopped.

In order to allow the pumping well to work in pumping and injection modes, it is necessary to install a sealed cap on the well casing and tie up each pumping well with leaching solution distribution (LSD) and productive rastor reception (PRR) units with pipelines.

- leaching solution outlet (6), which is connected to the leaching solution distribution unit (LDSU);

- leaching solution pumping outlet (8), which is connected to the productive solution reception unit (PRR).

Injection mode:
- submersible pump in off-state;
- valve of this well in PRR in a closed position;
- valve of this well in LSD in the open position, which provides a supply of leaching rastor under pressure. The pressure is created in the leaching solution pumping station at the plant site.

Outflow mode:
- Valve of this well in LDSU in a closed position;
- Valve of given well in PRR in open position:

The submersible pump is in the off position, which ensures that the pay zone is lifted into the PRR and further into processing.

The radius of oxidized mining mass at a distance of 62.5 m between wells is taken from the ratio of 2/3 and is equal to 42 m. Such a radius allows to share 1/3 of the distance with adjacent wells.

Mathematical and physical models investigate one-dimensional filtration flows, while in real conditions the flows, as a rule, have multidimensional character, due to which the models do not objectively reflect the leaching process dynamics [[6], [14]].

Extrapolation of such modeling results to real conditions of this or that deposit, without production determination of parameters of uranium extraction process, is very conditional and, as a consequence, modeling data do not provide optimality of accepted technological decisions. In this regard, it is necessary to develop fundamentally new hydrodynamic models that take into account the multidimensional dynamics of the in-situ leaching process.

In most cases, the parameters used to design in-situ leaching facilities do not reflect the true picture of the development of uranium recovery in the specific conditions of the deposits under development, which leads to significant losses of productive solutions, failure to recover uranium from the subsurface and its contamination.

The actual sulfuric acid consumption for extraction of 1 kg of uranium is still significant and may reach hundreds or more kilograms due to the lack of accounting for the acid capacity of the host rock without ore.

There remain significant losses of solutions beyond the contours of the blocks (up to 20% or more).

The filtration zones of the pumping wells are colmatized within the radius of 1.5-2.5 m by clay particles and chemical sludge, which leads to the loss of up to 50.77% of the surplus head, obtained by level reduction, and negatively affects the productivity of the wells [[15], [16]].

There are no reliable instrumental methods of controlling the movement of geochemical, redox barriers.

Used pumps, relatively quickly fail due to abrasion of units by mechanical impurities, wear of stator motor sleeves, etc.

Up to 50% of injection wells fail during the first 23 years of operation due to failure of production strings integrity, filters destruction and poor insulation of annular space.

Not all the wells are equipped with the heads, preventing overflow of working solutions, which leads to contamination of the surface of in-situ leaching sites. In many cases there are no elementary flow meters, to say nothing of electrified valves for automatic regulation.

Uranium prices on the world market are rising, but uranium is mined under specific orders and, accordingly, the development of new deposits will be under orders.

NAC Kazatomprom has established permanent dosimetric monitoring and determines radiation levels in water, air, and dust [17].

Methods of intensification of in-situ leaching of uranium consist of raising the level of the aquifer, intensification of the leaching process, and differentiated supply of leaching solutions. As a result of the new methods of preparation and intensification of in-situ leaching, off-balance uranium deposit areas will be involved in development, reagent consumption will be reduced and the development of uranium deposits will be reduced. These research results will enable the following: uranium output per 1 km of deposit area will be differentiated by 20-30%; uranium production will be reduced by 15-20%; environmental safety of uranium production will be improved; the economic effect will amount to 60-80 mln tenge a year.

Discussion of results

In the leaching process, the reaction of the solvent with rock-forming minerals forms mobile geochemical barriers (acid-alkali and redox) with alternating acts of uranium dissolution and precipitation due to changes in pH and Eh of the environment. In this case, acids are used not only and not so much for uranium leaching but for the dissolution of rock-forming minerals, and in real conditions they may amount to tens and hundreds of kilograms per kilogram of uranium. The main acid-intensive minerals are carbonates (calcium, dolomite, magnesite) and some types of clay minerals.

Because of the consumption of H_2SO_4 for reaction with rock-forming minerals, its concentration front moves significantly slower than if only uranium leaching occurred. In this case, the concentration front of the dissolved uranium tends to overtake the acid front, but this does not happen, because as the acidity of the solution decreases at the acid concentration front, uranium hydrolysis and redeposition occur according to the scheme [17]:

$$UO_2^{2+} + OH^- = UO_2OH^+$$
$$UO^+ + OH^- = UO_2(OH)_2 \downarrow$$
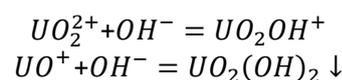
In this case, the concentration front of the acid plays the role of a mobile alkaline barrier. Then, when new portions of acid approach, the redeposited substance dissolves again, i.e. the reaction goes in the opposite direction. Repetitive steps lead to an increase in the concentration of H_2SO_4 at the mobile barrier to the saturation concentration.

It is not possible to determine the spatial and temporal position of the geochemical barrier under conditions of underground leaching by computational methods. Changes in parameters of pH and Eh, its ionic composition are monitored only by observation wells and at the outlet of pumping wells.

There are no in-situ leaching process models related to thermodynamics that answer the questions of spatial and temporal control of redox processes of uranium leaching in the deposits of formation oxidation zones yet. The creation of a generalized mathematical model of Redox potential control for these conditions remains an extremely difficult and, perhaps, as yet unsolvable task.

It is known that the Redox potential value is directly related to the concentration of the potential-determining components of the system:

$$E = E_o + \frac{0,059}{n} \ell g \frac{/O_к/}{/B_o/}.$$

From the point of view of potential-determining systems, the association of uranium and iron is of greatest interest at these deposits. The reaction between uranium and iron in an acidic environment goes in the direction of oxidation of uranium and reduction of iron.

Oxidation potentials for iron:

$$Fe \xrightarrow{-0,44} Fe^{2+} \xrightarrow{+0,771} Fe^{3+} \xrightarrow{<+1,9} FeO_4^{2-}.$$
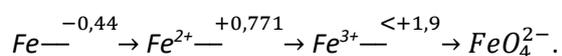
In turn, at Eh +0.35c the tetravalent uranium transforms into the hexavalent hydrated oxide $UO_2(OH)_2$ and then at Eh +0.407c into the hexavalent divalent cation-uranium form UO_2^{2+}.

The oxidation of uranium involving trivalent iron ions proceeds by the reaction $UO_2 + 2Fe^{3+} \rightarrow UO_2^{2+} + 2Fe^{2+}$, where uranium is oxidized to the hexavalent form and iron is reduced to the divalent form.

Under real conditions of underground uranium leaching, in addition to iron ions, the solution always contains other cations of variable valence and ions that affect the redox potential value. However, the role of these ions in establishing the redox potential, as compared to iron ions, is insignificant. Iron ions play the role of catalysts in the uranium oxidation process.

In the process of in-situ leaching, complexation has a great influence on changes in the oxidative environment. During acid leaching, in addition to uranyl sulfate complexes UO_2SO_4 ; $[UO_2(SO_4)_2]^{2-}$, $[UO_2(SO_4)_3]^{4-}$, about half of calcium, magnesium, and manganese are bound to sulfate complexes $CaSO_4^0$, $MgSO_4^0$, $MnSO_4^0$. Up to 80% of aluminum and over 90% of iron $FeSO_4^+$, $Fe(SO_4)_2$, $AlSO_4^+$, $Al(SO_4)_2^-$ are bound into sulfate complexes. The proportion of simple ions decreases as the total concentration in the solution of sulfate sulfur increases, pH and Eh change, and the content of free SO_4 ions decreases. Complexation causes the acidity of in-situ leaching solution to shift towards increasing pH value and to maintain the process of uranium oxidation and dissolution on geochemical barriers, the H_2SO_4 flow rate has to be increased.

However, taking into account the fact that in the process of multiple circulations of sulfuric acid solutions between pumping and injection wells, up to 0,05 mol/l and more of ferrous oxide sulfate $FeSO_4$ in divalent form (Fe^{2+}) is accumulated in circulating solutions, maintenance of redox potential at the required level can be maintained without additional consumption of sulfuric acid and other oxidizing reagents. For this purpose, one should pay attention to the effects of the chemical action of ultrasound.

It is known that the kinetics of sound-chemical reactions in liquid media (water, solutions) is determined by the rate of formation and expenditure of radicals.

It can be assumed that under ultrasonic action on recycled water solutions in the cavitation mode, water molecules, going to the excited state [[1], [13], [18]], split into H, OH radicals, ionized with the formation of hydrated electrons e_{ag}^- and further in the presence of dissolved oxygen transformed to HO_2, O_2^- и OH and H_2O_2. The formed hydroperoxide radicals are oxidized by Fe^{2+}:

$$HO_2 + Fe^{2+} + H^+ \rightarrow Fe^{3+} + H_2O_2,$$
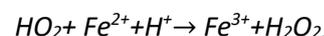
and the formed hydrogen peroxide H2O2 will additionally oxidize two Fe^{2+} ions by the reactions

$$H_2O_2 + Fe^{2+} + H^+ \rightarrow Fe^{3+} + OH + H_2O,$$
$$OH + Fe^{2+} \rightarrow Fe^{3+} + OH^-$$
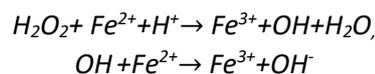
The equation of the chemical-acoustic yield of Fe^{3+}, in this case will be written as:

$$Fe^{(O_2)}(Fe^{3+}) = 3F_{HO_2}^{(O_2)} + F_{HO}^{(O_2)} + 2F_{H_2O_2}^{(O_2)}$$

Energy output $Fe^{(O_2)}(Fe^{3+})$ = 7,85.

Determination of the required number of productive solutions (V) at the annual capacity of the mine (P) 1000 tons of uranium per year and the average concentration (C) 70 mg/l uranium in the productive solutions (PS).

In all countries, including our country, uranium mining is carried out using underground in-situ leaching.

To develop each block, a linear system of three rows of wells is used: two rows of injection wells, and one row of withdrawal wells between them. There are 8 wells in each row.

In total, for one block there are 8 wells, the distance between them is assumed to be 25 m, the distance between the rows of wells is 50 m, and the number of injection and injection wells in the block is 3 × 8 = 24.

There are several methods of feeding chemical solutions into the block array in bacterial leaching. When applying the first method, a solution is used that contains special reagents that are capable of dissolving uranium and other metals, but do not interact with the rest of the components of the array. The solution passes through the porous structure of rocks and leaches uranium from the ore. The productive solution is then pumped to the surface and further processed to extract uranium.

The second method is used in IS technology and allows to extract uranium from hydrogen-containing deposits efficiently and economically. However, the second method is considered more efficient and environmentally friendly, as it allows you to extract more uranium from the ore and minimize the impact on the environment.

The chemical solution is an aqueous medium containing sulfuric acid at the rate of 3 g per liter of water.

The water in the solution becomes a good solvent, the chemical solution is heated to a temperature of 50-60 ° C. All these factors accelerate the leaching of uranium and other metals.

The third way.

A piston well is a well that can perform pumping and injection functions [18]. When using full piston wells, rows of spray wells are eliminated. After the beginning of the industrial application of advanced uranium purification technology from ores of permeable (water-intensive) deposits in the 50s of the last century, a kind of "boom" continues in the USA in all countries of the world to search for this type of deposits of uranium of sedimentary origin, the extraction of which is carried out in the simplest and therefore inexpensive way, known as the in-situ leaching method.

The essence of the technological scheme of this process is as follows.

Chemical or biochemical filtrates pumped through pumping wells are filtered through the holes and slits of the hydrogen plate to the nearest neighboring producing wells. During filtration, chemical solutions enriched to a concentration of uranium become "production solutions", which are pumped to the surface and transported to treatment facilities, where the production solution is subjected to absorption and desorption treatment, after which the uranium is extracted. To do this, a combination of various devices known as an adsorbent is used. It consists of absorption and regeneration columns, a

tank for rich and dilute solutions, a tank for finishing chemical concentrates, a pump, a pipeline system and a set of auxiliary tanks for the preparation of solutions. filtration, neutralization of wastewater and mine treatment waters. In-situ filtration technology is most effective for the enrichment of hydrogenated uranium mines with filtration coefficients of more than 0.5 m/day.

Therefore, the scheme of underground filtration technology provides for the leaching of metallic uranium in the natural occurrence of an ore deposit. An indispensable condition for its use is the presence of aquifers on the roof and bottom of the ore formation. Among the various schemes of linear systems for the placement of technological hydrogen deposits, the most common in the practice of developing hydrogenated uranium deposits is a three-row system consisting of the first row of pumps, the second and third row of pumps. cargo pump. At the same time, the distance between the rows and wells in a row is 50 and 15 m or more, respectively. From the above it can be seen that the production cell usually consists of two injection wells and a production well between them, in three consecutive rows. In passive zones, during the operation of pumping wells, the previously permeable chemical solution will be partially filtered back into some pumping wells, which is unlikely, i.e. as soil-hydraulic screens [18]. The leakage of production solutions formed in the passive zones P1 and P2 towards the active zones A1 and A2 due to the pressure drop created by the operation of the pumps also occurs with significant losses.

In all mines of hydrogenous uranium deposits, linear well arrangements are widely used, consisting of successively alternating rows of pumping and pumping wells over the area of the deposit. A production cell usually consists of two injections and one extraction well belonging to three consecutive rows. In this case, a row of pumping wells is located between two rows of injection wells [[19],[20]].

The flow of the chemical solution supplied through the injection wells into the array of the hydrogenous reservoir is filtered in a circular area around each injection well. Both the chemical solution and the productive solution formed in the areas S_1 and S_2 cannot penetrate a number of pumping wells, since their return path is obstructed by the flows of chemical solutions supplied through the injection wells to the hydrogen reservoir mass. In addition, the pressure gradient created on the

suction side of the pump can have an effect at a distance of no more than 3-5 m.

Conclusions

This article describes the physical and chemical aspects of uranium extraction from the zones of reservoir oxidation using ultrasonic technology and the use of ISL technology in Kazakhstan has several advantages, such as reducing the environmental impact of mining activities, minimizing the need for surface infrastructure, and reducing the cost of production. The technology involves injecting a solution into the ore deposit through a borehole, which dissolves the uranium and other metals present in the deposit. The solution is then pumped back to the surface, where the metal is extracted.

The result of these works is the development of a technology for underground borehole leaching of uranium in Kazakhstan. To implement the ultrasonic method of acid-free increase in the redox potential of leaching solutions in industrial conditions, complex devices and high specific power of ultrasound are not required. Ultrasonic impact on the HP solution can be carried out in settling tanks using submersible magnetostrictive transducers with a flat radiating surface (PMS-6, PMS-38, etc.) and a frequency of up to 50 kHz, with a power consumption of 0.4 to 4 kW, or directly in sorption columns using ring magnetostrictive transducers operating at frequencies from 4 to 400 kHz with a power consumption of 2.5 to 10 kW, produced by the Taganrog and Tallinn machine-building plants.

ISL technology is one of the most effective methods for uranium mining, as it minimizes the loss and depletion of valuable minerals. The solution used in the process dissolves only the desired metals, leaving the rest of the minerals intact. This results in a higher recovery rate and a lower waste generation rate compared to traditional mining methods.

Accurate measurement and evaluation of the loss and depletion of valuable minerals are crucial for effective decision-making in mining operations. This information is used to determine the optimal mining method, estimate reserves, evaluate productivity, and optimize the development and production processes. In the simplest case, when a mineral with an average balance grade is lost, and the impoverishing rocks do not contain useful components, one ton of balance reserves can be represented as a rectangle, losses as part of this rectangle, and dilution as part of the rock added to the recoverable part of the balance reserves. At the same time, it must be borne in mind that the quality of the lost mineral and the quality of the impoverished rocks can be different. Therefore, in each specific case, it is necessary to take into account all the features of the geological structure of the deposit and the possible change in the quality of loss reserves and impoverishing rocks. For such cases, the term "contamination" introduced at the time, which characterizes only some addition to the recoverable balance reserves of the rock, is completely inappropriate.

For example, in ferrous metallurgy mines, the iron content in impoverishing rocks or off-balance ores usually ranges from 25 to 50% of its content in balance reserves. It is not clear what in such cases should be considered "garbage".

In the coal industry, the term "ash content" introduced instead of impoverishment does not fully characterize the quality of the mined coal. Therefore, the content of sulfur, phosphorus, moisture, etc. is additionally taken into account. All these qualitative indicators could be taken into account in one indicator - impoverishment, using an appropriate method for determining losses and impoverishment. The fact is that with the same ash content of the mined coal, its dilution can differ quite significantly, and vice versa.

The ash content can be significantly less than the dilution when the diluting rocks are carbonaceous shales with fairly high carbon content. In this case, dilution causes less damage than with rocks that do not contain carbon. Or, conversely, containing sulfur or phosphorus in large quantities than in balance reserves.

Consider an example. The excavation thickness of the seam is 1.3 m, the thickness of clean coal packs is 1.1 m, and the thickness of the rock layers is 0.2 m. In this case, the dilution determined by the direct method will be 68%. The rock layer is carbonaceous shale containing carbonaceous matter and having the following qualitative characteristics: ash content of 75%, sulfur content of 0.5%. With an ash content of clean coal packs of 12%, the ash content of the extracted rock mass is 6.8%, i.e. dilution will be 9.7%. With the sulfur content in clean coal packs, the sulfur content in the extracted rock mass will be %, i.e. as a result of the admixture of the rock layer, the sulfur content will decrease by 0.23%. When setting the price in mutual settlements between the mine and the processing plant, the coefficient of additional

payment (penalty) for a deviation of 1% from the base indicators for ash content is 2.5, and for sulfur 5.

When applying ultrasound to sorption columns, a double effect can be obtained - the intensification of sorption of uranium and the oxidation of Fe^{2+} to Fe^{3+}, to increase the redox potential of the solution leaving the sorption columns and sent to injection wells.

The use of ultrasonic technology to increase the oxidation potential of the HP circulating solution will significantly reduce the cost of sulfuric acid at uranium leaching facilities and significantly reduce the cost of its production.

Conflict of interest. The authors of this study do not cooperate with other publishers on this topic.

Жер асты ұңғымаларын шаймалауды басқару жүйелерін зерттеу үшін уран алудағы физика-химиялық аспектілер

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ТҮЙІНДЕМЕ

Бұл мақалада ультрадыбыстық технологияны қолдана отырып, қабаттың тотығу аймақтарынан уран алудың физика-химиялық аспектілері және Қазақстанның уран кен орындарын жерасты ұңғымалық шаймалау (ЖҰШ) технологиясының теориялық негіздемесі келтірілген. Қазақстанда қорлары бойынша елеулі, жақсы барланған уран кен орындарының, дамыған уран өндіру және өңдеу қуаттарының болуы, сондай-ақ әлемдік уран нарығының қазіргі заманғы конъюнктурасы Қазақстанның уран өндіру өнеркәсібін дамыту перспективасының жоғары екендігін көрсетеді. Қабаттың тотығу аймақтарының фронттарында локализацияланған уран кен орындарының кендері негізінен жанас жыныстардың химиялық құрамына ұқсас. Жыныстарды құрайтын минералдарда ең көп таралған петрогендік элементтерінің қатарына Fe, Al, Mg, Ca, K, Na жатады. Уран темір, ванадий, селен, молибден, рений және басқа элементтермен байланыста болады. Уранның минералдануы экзогендік (қайталама) минералдар – настуранмен және кофинитпен білінеді. Уран минералдарының жалпы балансында настуран шамамен 30%, кофинит шамамен 70% құрайды. Настуран ($xUO_2 \cdot yUO_3 \cdot z$) төрт валентті уран диоксиді мен алты валентті уран үш оксидінің ауыспалы құрамынан (UO_2+UO_3) – 65-85%, коффинит – $USiO_4$ төрт валентті уран силикатынан тұрады.

Түйін сөздер: физика-химиялық аспектілері, экстракциялар, уран, теориялық негіздеме, жер асты шаймалау, ұңғымалар.

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Физико-химические аспекты извлечения урана для исследования систем управления подземного скважинного выщелачивания

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АННОТАЦИЯ

В этой статье даны физико-химические аспекты извлечения урана из зон пластового окисления с использованием ультразвуковой технологии и теоретическое обоснование технологии подземного скважинного выщелачивания (ПСВ) урановых месторождений Казахстана. Наличие в Казахстане значительных по запасам, хорошо разведанных месторождений урана, развитых добывающих и перерабатывающих уран мощностей, а также современная конъюнктура мирового рынка урана предопределяют перспективу развития уранодобывающей промышленности Казахстана. Рудные залежи урановых месторождений, локализуемые на фронтах зон пластового окисления, во многом сходны по химическому составу вмещающих пород. К числу самых распространенных петрогенных элементов породообразующих минералов относятся *Fe, Al, Mg, Ca, K, Na*. Уран наблюдается в ассоциации с железом, ванадием, селеном, молибденом, рением и другими элементами. Урановая минерализация представлена экзогенными (вторичными) минералами – настураном и коффинитом. В общем балансе урановых минералов настуран составляет порядка 30%, коффинит порядка 70%. Настуран ($xUO_2 \cdot yUO_3 \cdot z$) представлен ассоциацией двуокиси четырехвалентного и трехокиси шестивалентного урана с переменным составом (UO_2+UO_3) – 65-85%, коффинит – силикатом четырехвалентного урана $USiO_4$.

Ключевые слова: физико-химические аспекты, извлечение, уран, теоретическое обоснование, подземное выщелачивание, скважины.

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