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IN-SITU LEACHING TECHNOLOGY FOR URANIUM DEPOSITS

Kazakhstan possesses the world's largest resource base of proven industrial uranium reserves. The article discusses the geological features and provides a theoretical justification for the technology of in-situ leaching (ISL) of uranium deposits in the Republic of Kazakhstan. Explored reserves in Kazakhstan amount to about 1 million 560 thousand tons uranium. The presence in Kazakhstan of significant reserves, well-explored uranium deposits, well-developed uranium mining and processing facilities, as well as the current situation on the world uranium market predetermine the prospects for the development of the uranium mining industry in the republic. When preparing deposits of uranium deposits for development by the ISL method, an important role is given to the choice of schemes for opening deposits with production injection and production wells. The location of wells in the exploited reservoir depends on the morphological characteristics of the reservoir, the hydrogeological conditions of the productive horizon and the geotechnological parameters of the experimental work. Experimental work is a necessary step to substantiate the main parameters of the preparation and development of deposits by the ISL method (well layout, installation of filters, productivity for solutions, solution lifting means, consumption indicators for reagent, etc.).

The main performance indicators that determine the effectiveness of ISL application include: leaching rate; average concentration of uranium in productive solutions; reagent consumption; productivity for productive solutions; the degree of extraction of uranium from the bowels; the volume of solution consumed for the extraction of uranium from a unit of ore mass (ratio L: S).

Keywords: *Technology, borehole in-situ leaching, uranium, efficiency, deposit, solution, wells*

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Introduction

Currently, in many countries of the world: the USA, Canada, Australia, Russia, Uzbekistan, Kazakhstan use exactly the same technology for uranium mining, which includes production processes for leaching uranium: the supply of chemical solutions through injection wells and the delivery of productive uranium solutions through production wells for a day. surface for their processing. Moreover, these technological wells are located according to linear (in-line) or areal schemes. The existing uranium mining technology has a number of significant drawbacks: it does not meet the requirements of the market economy, is ineffective, is characterized by a low leaching rate, requires the use of a large number of expensive injection and pumping wells, a large consumption of chemical reagent, (to obtain 1 ton of uranium concentrate requires the consumption of 100 tons of sulfuric acid) [1–5].

However, compared to conventional mining, in-situ leaching allows uranium mining to be carried out with significantly lower capital and operating costs. At the same time, the effectiveness of ISL technology is largely associated with the choice of optimal schemes for opening productive formations, the design of production wells, the means of raising the solution used, the modes of pumping solutions, etc.

When preparing deposits of uranium deposits for development by the ISL method, an important role is given to the choice of schemes for opening deposits with production injection-pumping wells. The location of these wells depends on the morphological characteristics of the deposit being mined, the hydrogeological conditions of the productive horizon and the geotechnological parameters of the experimental work. Experimental work is a necessary step to substantiate the main parameters of the preparation and development of deposits by the ISL method (well layout, installation of filters, productivity of solutions, solution lifting means, consumption indicators of reagent, etc.) [1–5].

Methods

Uranium mining by in situ leaching through a system of wells drilled from the surface is most effective for the development of infiltration uranium deposits in the zones of formation and formation-soil oxidation.

After the start of the industrial application of an innovative technology for leaching uranium from ores of bed-infiltration (hydrogenic) deposits in the 50s of the last century, a kind of "boom" continues in the United States in all countries of the world in search of a similar type of uranium deposits of sedimentary origin, the development of which is carried out to the utmost a simple, therefore inexpensive method called the in situ leaching method.

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

Leaching chemical or biochemical solutions, injected through injection wells, are filtered through pores and cracks in the hydrogenous plate array to the nearest neighboring pumping wells. During filtration, chemical solutions, enriched with uranium concentration, become "productive solutions", which are pumped out to the day surface and fed to the processing shop, where the productive solution is processed using sorption and desorption processes, after which uranium is extracted. For this purpose, a set of various equipment is used, called a sorption plant. It consists of sorption and regeneration columns, pools for rich and lean solutions, tanks for finishing the chemical concentrate, pumps, piping systems and a set of auxiliary tanks for the preparation of various solutions for leaching, neutralization of waste and treatment mine waters. In-situ leaching technology is most effective for the development of hydrogenic uranium deposits with a filtration coefficient of more than 0.5 m/day. Thus, the technological scheme of underground leaching provides for the leaching of uranium metal in the natural occurrence of the ore deposit. An indispensable condition for its use is the presence of waterproofing in the roof and soil of the ore layer [2–8].

Of the various layouts of the linear system for the location of technological hydrogenous deposits, the most common in the practice of operating hydrogenic uranium deposits is a three-row system, consisting of the first injection row, the second pumping row and the third injection row. In this case, the distance between rows and wells in a row is taken respectively 50 and 15 m or more.

It can be seen from the above that the production cell usually consists of two injection wells and between them one pumping well, belonging to three successive rows.

The depth of occurrence of ore-bearing horizons has a significant influence on the choice of schemes for opening deposits. A feature of all deep-seated stratal-infiltration uranium deposits is a significant load on the top of the horizon, due to a high static level of groundwater – from the first meters to spontaneous outflow (North Karamurun, South Karamurun, South Moinkum, North Kanzhugan deposits). In this regard, the main problem in the development of deep-seated formations is the forced injection of solution into them. Excessive pressure of 3–5 atm. provides injectivity of wells within only 2–3 m^3/hour, while pumping rates reach 15–20 m^3/hour. This circumstance dictates the need to increase the ratio of the number of injection wells to pumping ones to a level of at least 3:1. Under such conditions, with a linear well layout and a row spacing of 50 m, achieving this ratio will require a "thickening" of the injection wells network up to 25 m, which in deep-seated fields is practically difficult to implement due to the deviation of wellbores with depth and, accordingly, the formation of zones of mutual influence arising compression domes (radius 20 m at a pressure of 4 atm.), which further complicate the injection of solutions.

If we follow the path of increasing the distance between the wells in the pumping rows to 40–50 m, then the problem of the formation of unworked "dead" zones (up to 30% of the worked area) inevitably arises. Consequently, the most acceptable solution for the development of deposits of such fields are hexagonal cell penetration schemes that provide an injection wells to pumping ratio at the level of 2.5–4: 1 with a simultaneous increase in interwell distances in the injection system. During the development of the North Karamurun field, the use of a hexagonal well network with a radius of 40–50 m, as the main drilling scheme, has fully justified itself, and is an illustrative example for other fields [1–7].

Based on the experience of developing uranium deposits by the ISL method, the following schemes are recommended for opening deposits of various widths (**Fig. 1**).

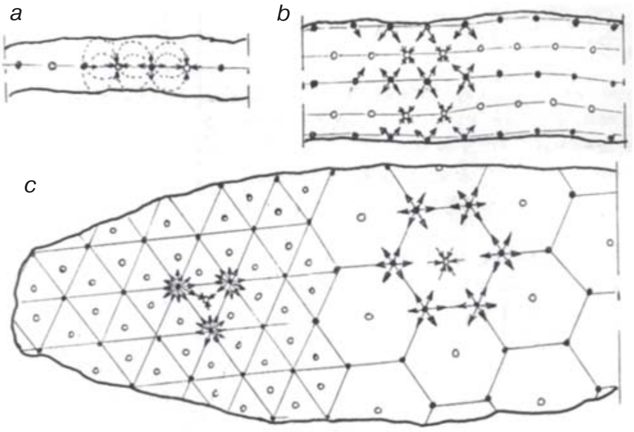

Fig. 1. Layouts of technological wells depending on the morphology of ore bodies. Layout of deposits:
a – up to 50 m wide; *b* – 50–200 m wide; *c* – more than 200 m wide

Determination of the required amount of productive solutions (V) at an annual mine productivity *P* of 1000 tons of uranium per year and an average concentration *C* of 70 mg/L of uranium in productive solutions (PS) is determined by the formula [1–5]:

$$V = P/C. \quad (1)$$

We have determined the methods of supplying chemical solutions to the block array [2–8]:

The first way. The supply of biochemical or chemical solutions to the array of blocks is carried out through injection wells, and the delivery to the surface of productive solutions obtained by leaching various metals, including uranium, is carried out through pumping wells.

The supply and evacuation of solutions is carried out by pumps.

Second way. The supply of biochemical or chemical solutions and the pumping of productive uranium solutions are carried out after their processing in a cavitator (heat generator), where they are activated.

For leaching of useful components (metals), mainly uranium, mainly only a chemical solution is supplied to the massif of a hydrogenous uranium deposit. A chemical solution is an aqueous medium containing sulfuric acid at the rate of 3 g per liter of water.

For activation, chemical solutions are heated to a temperature of 50–60 °C. All these factors accelerate the process of leaching of uranium and other metals.

Third way. Development of each uranium block, in which the processes of pumping and injection of both chemical and productive uranium solutions will be carried out using reciprocating wells (received a patent of the Republic of Kazakhstan).

A piston well is a well that can perform the functions of both pumping and injection wells [2–9].

With the use of reciprocating wells, injection wells are eliminated. To develop one block, only 4 piston wells are required, and not 3×8 = 24 pumping and injection wells, which makes it possible to increase the economic efficiency of the ISL.

Comparative studies have shown that the effectiveness of the proposed method of underground borehole leaching of hydrogenous uranium deposits is based on the effect of activation of a chemical solution supplied to the massif of a hydrogenous uranium stratum and other useful components. In the process of activation, the chemical solution is heated to t = 70 °C, water in such a solution becomes a good solvent. Another way to increase the efficiency of ISL is to use a chemical solution of sulfuric acid with manganese oxide in a concentration of 2.1 ÷ 9%, of them:

- sulfuric acid – 0,1–5 %;
- manganese oxide – 2–4 %.

Pumping wells are used as reciprocating wells without changing the design, i.e. pumping wells are also used as injection wells. When using this technology, the process of underground borehole leaching of uranium and other useful components (metals) is sharply accelerated and the consumption of sulfuric acid is reduced.

The efficiency of the in situ borehole leaching process according to the proposed method is presented in **Table 1**.

In the practice of underground leaching of uranium, the specific consumption of the reagent is 50–150 kg per 1 kg of metal, which is due to the reaction of the acid with other minerals and the spreading of solutions. Carbonates almost completely react with acid (1 kg of sulfuric acid is consumed per 1 kg of $CaCO_3$), minerals of iron oxide dissolve well (40–50%), ferrous iron and some aluminosilicates (up to 10%) dissolve less intensively [1–13]. At the stage of formation acidification, the consumption of the reagent (sulfuric acid) is usually 8–10 g/l for ores with increased carbonate content and 20–30 g/l for carbonate-free ores. At the leaching stage, the concentration of sulfuric acid in working solutions ranges from 8 to 15 g/l.

Given in table 1, the data can be used to assess the effectiveness of the use of in-situ leaching in the field. The developed system of classification of signs of suitability of infiltration uranium deposits for leaching is recommended for use in the design of ISL technology at deposits in Kazakhstan [1–13].

The conditions for the formation of exogenous infiltration deposits are associated with the behavior of uranium in the upper parts of the earth's crust, in the zone of the so-called hypergenesis, where the migration of chemical elements occurs at low temperatures and pressures. The formation of exogenous uranium deposits is associated with the epigenetic accumulation of uranium minerals during their migration and deposition.

Under the surface conditions of the hypergenesis zone, under the influence of water, air and organic matter, minerals of ore-bearing rocks are oxidized and uranium migrates (transport) by infiltration flows. Natural waters of the hypergenesis zone are true and colloidal solutions of various concentrations. The intensity of migration of chemical elements depends on the acidity and alkalinity of natural waters.

Natural waters contain almost all chemical elements in the form of ions and undissociated molecules, most of which are in a state of strong scattering (of the order of n × 10–5 g/l or less) and only Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}, Na^+, K^+, Mg^{2+}, Ca^{2+}, SiO_2 are contained in significant quantities. H^+ and OH^- ions have a strong influence on the physicochemical characteristics of natural waters. The oxidizing properties of groundwater are characterized by the content of free oxygen, the redox potential Eh> 0.1v, often above 0.4v, sometimes up to 0.6–0.7v. Uranium is in the U^{6+} form, iron is predominantly in the Fe^{3+} form, and Fe^{2+} can exist only in strongly acidic media. Sulfur is found exclusively in the SO_4^{2-} form. Under certain conditions, there are VO_4^{3-}, SeO_3^{2-} and SeO_4^{2-}, MoO_4^{2-}, MoS_2, ReS_2 [14].

Figure 2 shows that hexavalent uranium is almost completely complexed to form uranyl dicarbonate and uranyl tricarbonate ionic complexes.

Table 1. Comparative data for assessing the effectiveness of the process of in-situ leaching of uranium

Name	Extraction of uranium, %
Uranium content in the original in situ leaching technology	40–60
According to the proposed method	70–85

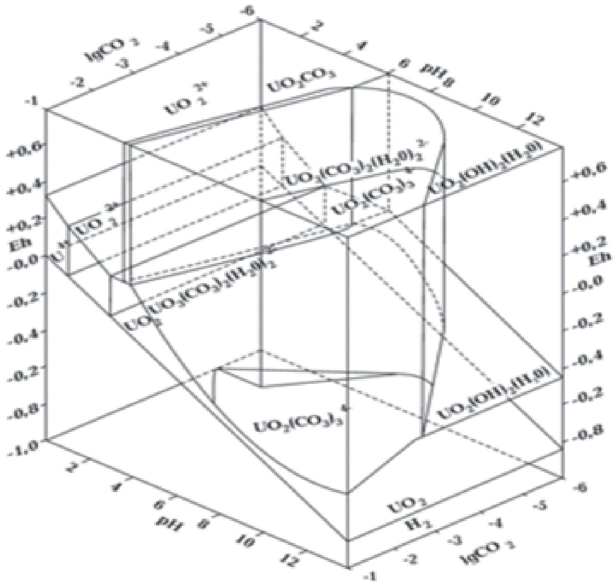

Fig. 2. Dependence of stable uranium compounds on pH, Eh and concentration of carbonate components at t = 25 °C and 0.1 MPa of formation pressure

A reducing environment without H_2S – water does not contain free oxygen, Eh is usually below 0.4v, sometimes below zero. Under these conditions, iron and manganese are in the form of Fe^{2+} and Mn^{2+} and easily migrate. If H_2S is present in the waters, then Eh < 0, iron, manganese, copper, zinc and other chalcophilic elements are precipitated. Uranium precipitates to form U^{4+} compounds. The presence of dissolved oxygen in natural waters increases the solubility of primary uranium minerals in an acidic sulfate medium, and less intensively in an alkaline carbonate medium. Oxides of tetravalent uranium and mixed oxides are completely dissolved in a carbonate medium only in the presence of oxidants. Silicates, phosphates and humates of uranium dissolve in an alkaline medium. In natural waters, depending on the general mineralization, chemical composition, pH of the medium and the concentration of uranium in water, ions may be present: UO_2^{2+}, $UO_2(OH)^+$, $[UO_2(CO_2)_2\ (H_2O)_2]^{2-}$ $[UO_2(CO_3)_3]^{4-}$, as well as undissociated molecules $UO_2(OH)_2$. Chemical reactions in the hypergenesis zone occur at a pressure close to 1 atm. and a temperature not exceeding the first ten degrees [15].

The conditions for the existence of uranium compounds in the hypergenesis zone are graphically depicted by a diagram in the parameters Eh, pH, CO_2 pressure, since these parameters are the most important characteristics of natural waters. The diagrams depict equilibrium conditions, i.e. relationships between compounds after reaching thermodynamic equilibrium.

With noticeable ΣCO_2, the stability field of uranyl oxide hydrate is displaced. Such complexation proceeds so efficiently that at a relatively high value of ΣCO_2, the fields of these complexes displace the stability field of UO_2 (uraninite). Hence it becomes clear that carbonate-containing waters are strong solvents of uranium. Watering the hypergenesis zone with waters containing up to 8–10 mg/L of oxygen increases the Eh of water and promotes the conversion of U^{4+} into U^{6+}. If natural water contains up to 2 g/l or more of carbon dioxide, then uranium migration also increases.

Hydrogen sulfide H_2S present in water, which reduces uranium to a tetravalent state, promotes its precipitation from solution [16].

When uranium minerals are dissolved by natural waters in the hypergenesis zone, especially under oxidizing conditions, the state of chemical equilibrium between the solid and liquid phases is practically not achieved due to the mobility of water and the buffering effect of the host rocks on the pH of the waters. The forms of uranium in natural waters are very diverse. According to V. V. Shcherbina [17], in the hypergenesis zone uranium in aqueous solutions can be transported in the following forms:

- readily soluble uranyl sulfate UO_2SO_4;
- colloidal solution of hydroxide of composition $[UO_2(OH)_2]_n$, carrying a negative charge;
- readily soluble complex carbonates of composition $Na_4[UO_2(CO_3)_3]$;
- readily soluble complex alkaline-humate compounds.

The possibility of uranium migration in aqueous solutions in the form of compounds follows from the chemical properties of uranium, its ability to react with other elements, form ions of various valences, form soluble complexes and be sorbed by colloids.

Natural waters have a high dissolving power. The dissolving ability of water is due to the large dipole moments of the molecules ($\mu = 1.8$) and the high dielectric constant (80.0) of water [1–3].

There is a relationship between solubility, heat and entropy of dissolution [1–3]:

$nRT\ln a = L + T\Delta S = L + T\sum S^{i}_{L}$,

where n is the number of ions forming a uranium salt molecule; a is activity in a saturated solution; L is heat of dissolution; T is absolute temperature; ΔS is entropy of dissolution; $\sum S^{i}_{L}$ is the sum of ions of the entropies of dissolution, equal to the change in the entropy of an ion when it passes from the crystal lattice to a solution with an activity equal to 1.

The leaching rate is a value equal to the quotient of dividing the length of the ore layer worked out by the solution by the time during which a certain fraction of the metal is extracted from this layer. The leaching rate V_w is related to the filtration rate V_f by a linear relationship $V_w = \beta V_f$; where β is a constant coefficient for specific combinations of «ore – solvent». The most important geotechnological parameter is based on this regularity – the ratio L:S, i.e. the ratio of liquid to solid (the ratio of the volume of solution to the volume of the ore mass) [1–3].

The consumption of the reagent for in situ leaching of uranium depends on the reagent capacity of the ore-bearing rocks, the type and nature of uranium mineralization, the carbonate content of the rocks, the productivity and effective thickness of the seams, and the hydrodynamic conditions for pumping solutions through ore-bearing seams.

Results and discussion

The main advantages of the in situ leaching method in comparison with traditional mining methods of field development are as follows [18]:

- the possibility of bringing into operation poor and off-balance ores of deposits with complex geological and hydrogeological conditions of occurrence, but having large uranium reserves;
- a significant reduction in capital investments and the timing of putting fields into operation;
- improving working conditions, reducing the number of miners and increasing labor productivity by 2.5–3.5 times;
- reducing the negative impact of uranium mining on the environment.

The basis for the development and implementation into the practice of uranium mining of the method of in-situ leaching was the achievements in the field of geological exploration and industrial evaluation, epigenetic deposits of regional zones of formation and soil oxidation, achievements in the field of hydrodynamics, geochemistry, hydrometallurgy.

In-situ leaching technology can rightfully be attributed to a revolutionary technology that has changed the conditions and economics of uranium production. The successful solution of a set of technical problems in the development of the method of underground leaching of uranium was associated with the development and implementation of special technical means and technologies for the construction and operation of wells, instrumentation, as well as with the development and industrial development of sorption and desorption technology in uranium hydrometallurgy using ion exchange resins.

Based on the modern achievements of geotechnological science and practice, the development of uranium mining by the in situ leaching method follows the path of introducing computer technologies for production management based on the full automation of all production processes; optimization of schemes of opening, preparation and development of deposits; introduction and development of new technical means for the construction and development of wells, new construction materials; reducing the cost of solvents, ion-exchange resins; introduction of electrodialysis units, devices for sorption-desorption concentration of the SDC type, polymer flushing fluids, hydraulic fracturing and hydraulic washing of formations, new methods of electro-ultrasonic intensification of leaching processes and repartition of productive solutions; introduction of effective methods for monitoring hydrogeochemical parameters of underground leaching sites and ecological rehabilitation of depleted deposits [1–3].

Conclusions

This article sets out the basics of the use of borehole leaching in the development of infiltration uranium deposits in Kazakhstan. When using this technology, the process of leaching of uranium and other useful components (metals) is sharply accelerated and the consumption of the main reagent, sulfuric acid, is reduced. In comparison with the well-known works in this area of knowledge, the proposed study on the development of innovative technologies for the exploitation of hydrogenic uranium deposits will be important in the development of minerals in difficult mining and geological conditions not only in Kazakhstan, but also in other mining regions of the world [1–3].

The result of this work is the development of a technology for in-situ leaching of uranium in the fields of Kazakhstan. The distribution of reserves and resources by geological and industrial types of uranium deposits in Kazakhstan is shown in **Table 2**.

Table 2. Reserves and resources by geological and industrial types of uranium deposits in Kazakhstan

Field type	Stock categories B+Ci+C_2		Reserves and resources B+Ci+C_2+Pi	
	thousand tons	%	thousand tons	%
Deposits associated with regional formation oxidation zones	603	65.0	1160	75.3
Deposits associated with zones of soil-formation oxidation	82	8.8	97	6.0
Deposits of organogenic-phosphate type	29	3.2	29	1.8
Vein-stockwork deposits in folded complexes	214	23.0	274	16.9
Total	928	100	1560	100

Kazakhstani uranium deposits associated with regional zones of formation oxidation were formed in the Shu-Sarysu and Syrdarya depressions of the platform cover of the northern part of the Prityan-Shan uranium megprovince (North, East and West group of deposits). Deposits associated with zones of soil-formation oxidation are manifested in the Ili river basin, outside the zone of industrial enterprises and in the Akmola region of Northern Kazakhstan. Uranium deposits suitable for development by sulfuric acid leaching through a system of wells drilled from the surface belong to the subgroup of infiltration (hydrogenic). These deposits are the basis of the raw material base of the uranium industry in Kazakhstan and are concentrated in Shu-Sarysu (Mynkuduk, Inkai, Budenovskoye, Zhalpak, Sholak-Espe, Uvanas, Moinkum, Kanzhugan) and Syrdarya (Irkol, Karamurun, Kharasan, Zarechnoye, Asarchik, Zh., Chayan, Lunnoye) uranium ore provinces. The largest of the deposits of the zone of soil-formation oxidation and promising for development is the Semizbay deposit [1–3, 19, 20].

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References

1. Altaev Sh. A., Chernetsov G. E., Oryngozhin Ye. S. Development technology of hydrogenic uranium deposits in Kazakhstan. Almaty, 2003. 294 p.
2. Oryngozhin Y. S., Yeremin N. A., Metaxa G. P., Alisheva Zh. N. Underground uranium borehole leaching. *News of the national academy of sciences of the Republic of Kazakhstan – Series of geology and technical sciences.* 2020. Vol. 4, No. 442. pp. 62–69.
3. Tsoy S. V., Oryngozhin Ye. S., Metaksa G. P., Zhangalieva M. Zh. et al. Assessment of the existing technology and development of an alternative method for the exploitation of hydrogenic uranium deposits. *International conference "Actual achievements of European science"*. Sofia, Bulgaria, 2018. pp. 40–44.
4. Bitimbayev M. Zh., Krupnik L. A., Aben Kh. Kh., Aben E. Kh. Adjustment of backfill composition for mineral mining under open pit bottom. *Gornyi Zhurnal.* 2017. No. 2. pp. 57–61. DOI: 10.17580/gzh.2017.02.10
5. Krupnik L. A., Bitimbayev M. Zh., Shaposhnik S. N., Shaposhnik Y. N. et al. Validation of rational backfill technology for Sekisovskoe deposit. *Journal of Mining Science.* 2015. Vol. 51(3). pp. 522–528.
6. Abney C. W., Mayes R. T., Saito T., Dai Sh. Materials for the recovery of uranium from seawater. *Chemical Reviews.* 2017. Vol. 117(23). pp. 13935–14013.
7. Ahmad M., Yang K., Fan Y., Shah T. et al. Modified tubular carbon nanofibers for adsorption of uranium (VI) from water. *ACS Applied Nano Materials.* 2020. Vol. 3(7). pp. 6394–6405.
8. Kuo L. J., Gill G. A., Tsouris C., Rao L. et al. Temperature Dependence of uranium and vanadium adsorption on amidoxime-based adsorbents in natural seawater. *Chemistry Select.* 2018. Vol. 3(2). pp. 843–848.
9. Kuo L. J., Jankeet C. J., Wood J. et al. Characterisation and testing of amidoxime-based adsorbent materials to extract uranium from natural seawater. *Industrial & Engineering Chemistry Research.* 2016. Vol. 55, Iss. 15. pp. 4285–4293.
10. Noskov M. D. et al. Application of geotechnical simulation for ISL uranium mining higher operational efficiency. *VIII International Conference "The topical Issues of the Uranium Industry": Book of Papers.* Astana, 2017. pp. 108–113.
11. Petrov I. I., Yazikov V. G., Aubakirov Kh. B. et al. Uranium deposits of Kazakhstan (exogenous). Almaty : Gylym, 1995. 64 p.
12. Zhivov V. L., Boitsov A. V., Shumilin M. V. Uranus. Geology, mining, economics. Moscow : ARMZ, 2012. 301 p.
13. Kultyshev V. I., Galinov Yu. N., Reshetnikov A. A. Solidifying backfill in the development of uranium ore deposits. *Gornyi Zhurnal.* 1993. No. 3. 264 p.
14. Kultyshev V. I., Ovseichuk V. A., Reshetnikov A. A. Features of the development of complex-structured uranium deposits in Transbaikalia. *Gornyi Zhurnal.* 1999. No. 12. pp. 26–30.
15. Trubetskoy K. N., Chantiriya V. A., Kaplunov D. R., Chaplygin N. N. Mining sciences – mining production. *Gornyi Zhurnal.* 2003. No. 10. pp. 13–19.
16. Oryngozha Ye. Ye., Vorobiev A. Ye., Zhangalieva M., Uteshev I. Zh. Study of mining-geological characteristics of uranium deposits of Kazakhstan for development by underground well leaching. *News of the National Academy of Sciences of the Republic Of Kazakhstan. Series of geology and technical sciences.* 2020. Vol. 5, No. 443. pp. 156–164.
17. Shcherbina V. V. Geochemistry of uranium in the zone of oxidation of ore deposits on the basis of experimental research. *Proceedings of the Second International Conference on the Peaceful Uses of the Atom*. Geneva, 1958. pp. 7–12.
18. Vorobev A. Y., Metaxa G .P., Bolenov Y. M. et al. Digitization of the mining industry. concept and modern geotechnology. *News of the National Academy of Sciences of the Republic of Kazakhstan. Series of Geology and Technical Sciences.* 2019. Vol. 4(436). pp. 121–127.
19. Lewandowski K. A., Kawatra S. K. Binders for heap leaching agglomeration. *Minerals and Metallurgical Processing.* 2009. Vol. 26(1), No. 1. pp. 1–24.
20. McNab B., Crushing I. Exploring HPGR Technology For Heap Leaching of Fresh Rock Gold Ores. *IIR Crushing & Grinding Conference.* Townsville, Australia, 2006. pp. 29–30.