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Application of radio-wave geointoscopy method to study the nature of spreading the solutions in the process of uranium underground leaching

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Abstract

Purpose. Assessment of the effectiveness of using the method of radio-wave geointoscopy of the inter-well space for three-dimensional mapping of the zone of the leaching solution actual propagation in the process of uranium mining by the method of underground leaching.

Methods. Experimental-industrial studies of the leaching process are conducted at technological block 68 of the Semizbay deposit (Kazakhstan). In experimental studies, special equipment is used for conducting radio-wave geointoscopy. Inter-well measurements are performed using the RVGI-06 equipment. The observations are conducted in a fan pattern within the filter section. The step between adjacent points along the wellbore is 1 m. At different stages of mining the technological block, maps of geoelectric resistivity have been compiled, with the help of which a comparative analysis is performed.

Findings. A tendency to an increase in the area of acidic solutions propagation over time has been revealed by comparing the fragments of RVGI geoelectric map at different stages of mining the block. The influence of a heterogeneous geological structure on the uniformity of the leaching solutions propagation has been proved. It has been determined that the resolving power of the radio-wave geointoscopy method is sufficient to detect changes in geoelectric conditions at small monitoring cycles in time. The spatial-temporal change in the front of the leaching solutions propagation makes it possible to determine the prevailing directions of solutions propagation and to assess the filtration characteristics of rocks.

Originality. The patterns have been determined of the leaching solutions propagation over time from the beginning of block acidification to active leaching. The first attempts have been made to use the geophysical well logging method in the practice of uranium mining by In-Situ Leaching (ISL) method.

Practical implications. Monitoring studies by radio-wave geointoscopy method at the stage of passive acidification can be recommended for further experimental and scientific testing at technological blocks of the Semizbay deposit for a quantitative assessment of the filtration characteristics of rocks and the dynamics of the acidification process development, as well as for the development of well-grounded recommendations on the optimal scheme for mining the blocks in specific geotechnical conditions.

Keywords: *underground leaching, geophysical methods, radio-wave geointoscopy, uranium, inter-well space*

1. Introduction

The technology of underground uranium leaching was first experimentally tested in the early 1960s in the United States. Over the past 20 years, the world has witnessed a significant increase in uranium mining by bore-hole in-situ leaching (ISL) method. For example, if in 2000 the share of uranium produced by ISL method was equal to 16% of the total world production, then in 2019 this figure became equal to 57% [1]. Thus, it can be concluded that the underground leaching technology is of great importance in the global uranium production at the present time.

Unlike traditional mining methods, in which the uranium mineral and host rock are recovered to the surface, when uranium is mined by bore-hole in-situ leaching, the host rock is not recovered to the surface [2]. The specificity of the ISL method is to selectively transfer natural uranium into solution directly in the bowels of the Earth.

Underground leaching is distinguished by a variety of methods, which are determined, first of all, by the thickness of the seam itself, its physical-mechanical and physicochemical properties, physical-mechanical characteristics of the host rocks, as well as the nature of the chemical reaction of the necessary components dissolution [3], [4]. The bore-hole

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in-situ leaching method involves the use of wells to inject solutions into the ore zone. This solution is commonly referred to as a leaching agent. Leaching solution dissolves uranium as it passes through the uranium-containing host rock [5]. A solution saturated with uranium is called a pregnant solution. Pregnant solution is pumped out to the surface through the extraction wells, after which it is delivered to the processing plant, where the valuable component (uranium) is extracted from the solution. The solution obtained after the uranium extraction, called the mother liquor, is sent back to the mining site, where, after additional strengthening with chemical reagents, it is again pumped into the ore zone [6].

Despite all the advantages, bore-hole in-situ leaching has the main disadvantage – the lack of complete control over the valuable components extraction and spreading of the solution, as a result of which the specific consumption of the reagent per unit of extracted ore increases.

When uranium is mined by bore-hole in-situ leaching method, the only source of reliable geological data is the core extracted during drilling the wells [7]. In practice, core-drill sampling is performed only in a small amount of constructed wells, and the vast majority of wells are constructed using non-core methods. This is conditioned by the high cost of core drilling. The lack of reliable information on the lithological structure of the productive horizon section during well construction, which is conditioned by the lack of a sufficient amount of core material, can be compensated for by conducting a complex of geophysical well logging (Geologic Information System, GIS) [8].

The traditionally established complex of methods for geophysical well logging, which is performed at the fields, includes the following types [9]-[13]:

– gamma-ray logging (GR log) – shows natural radioactivity in the seam;

– electrical logging (apparent resistivity, spontaneous polarization, induction logging) – used to determine the host rock filtration properties, the degree of the ore mass “acidification”;

– directional logging – determines the well axis position in space;

– caliper logging – for determining the average wellbore diameter.

This complex of GIS methods has been formed for a long time and is characterized by high information content about the geophysical and geological parameters of the ore body and host rocks [14]. Geophysical well logging is the main source of measuring information on the composition and properties of rocks of the productive horizon, parameters of ore intervals and on the progress of the uranium leaching process.

The technology of underground uranium leaching, along with all its advantages, such as insignificant impact on the environment, preservation of the natural landscape, low cost, also has disadvantages associated with the specificity of the method. When drilling wells, ore acidification and block mining in conditions of a heterogeneous geological structure of the subsoil, it is rather difficult to obtain reliable data on the ore mass state. This is caused by the fact that widely used methods of geophysical well logging, such as electrical logging, gamma-ray logging, induction logging, and others, have limitations in the measurement range [15], [16]. The impossibility of a detailed study of the horizon lithological structure, penetrated by the well with the use of common geophysical methods of well survey is conditioned by various factors. The use of gamma-ray logging (GR log) for these purposes is impossible due to the abnormally high gamma radiation of uranium ores in the productive horizon. Spontaneous potential logging (SP log) is inapplicable due to the fact that in the conditions of industrial uranium mining and constant circulation of technological solutions in the ore horizon, there are various kinds of interference that significantly reduce the measurement accuracy [17].

When mining uranium by bore-hole in-situ leaching method, technological solutions within the ore horizon may spread unevenly because of the complex lithological structure [18]. In the course of mining the block, the valuable component is extracted unevenly, mainly from the most permeable zones. Low-permeability zones are less involved in leaching and may contain unmined reserves, stagnant zones [19]. The size of these zones and their position in the inter-well space is usually unknown. Reliable geological data is required in order to regulate the technological process in order to maximize the recovery of the valuable component and reduce mining costs. Currently, the only possible method that makes possible to obtain actual data on the propagation of solutions in inter-well intervals is the method of radio-wave geointoscopy [20].

The method of radio-wave geointoscopy has shown its high efficiency during the oil fields development [21][22]. The positive results of the test surveys performed in oil fields are a significant contribution to this study. The use of casing pipes made without the use of shielded materials (metal) has also contributed to successful experimental-industrial studies [23].

The research purpose is to study the method of radio-wave geointoscopy for practical application on an industrial scale.

With regard to the purpose set, the objectives of the research are:

– selection of a test site and study of the mining-and-geological peculiarities of the deposit;

– installation of a measuring unit for radio-wave measurements and preparation of a tomographic survey scheme;

– conducting experimental-industrial work;

– data collection and processing of experimental-industrial work.

Experimental-industrial studies of the radio-wave geointoscopy method are conducted at the Semizbay deposit, located in the Republic of Kazakhstan, on the territory of Akmola and North Kazakhstan regions. The Semizbay deposit belongs to the hydrogenous type. The technological blocks of the deposit are characterized by a complex section. Commercial mineralization is multi-stage. According to the area of propagation, it is complex and discontinuous [24].

The main Semizbay deposit structure is the erosion-tectonic depression with the same name, which is an ancient, long-developed valley formed by terrigenous Mesozoic-Cenozoic sediments of the alluvial-proluvial genotype. The ore-bearing sediments of the Semizbay Formation are a complex heterogeneous stratum characterized by alternating horizons of permeable and water-resistant rocks in a vertical section and a distinct areal facial-geochemical zoning. Uranium mineralization at the deposit is widespread in terms of areal propagation and concentrated in two aquifers: Lower Semizbay (NRG) and Upper Semizbay (VRG), separated by an intermediate aquiclude, up to 15-20 m thick, composed mainly of clays and siltstones. The ore deposits of the field are a series of contiguous ore bodies with uneven uranium mineralization, located at the same hypsometric level [25], [26].

The productive stratum, which includes the NRG, the intermediate aquiclude and the VRG, occurs at a depth of 25-100 m from the surface and has, depending on the position in the depression, a variable thickness from 30 to 100 m. These conditions significantly complicate the control over the technological process of mining.

2. Methods

The method of radio-frequency surveying the inter-well space is based on the study of the intensity of electromagne-tic waves absorption by rocks located along the path of their propagation. A sufficiently high contrast of the electrical properties of the initial fluid and technological solutions usually contributes to the study of the leaching process by electromagnetic methods. The acid concentration in the technological solutions is 20 g/l with the mineralization of the initial fluid 2-5 g/l, which is reflected by a decrease in the electrical resistivity of permeable rocks of the ore horizon by 5 or more times.

The inter-well measurement scheme is shown in Figure 1. Well *1* includes a radiating element, loaded on an isolated electrical antenna, and well *2* contains a receiver with an antenna of a similar design. With a fixed position of the radiating element in the well *1*, the amplitude of the axial component of the electric field is measured along the wellbore of the adjacent well, after which the radiating element is shifted by a certain step and the measurements are repeated. Numerous overlapping of gamma-rays in different directions (tomographic survey) provides a high level of detail during the inter-well space study.

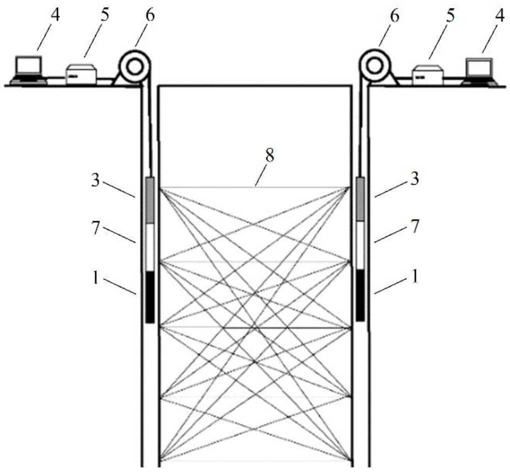

***Figure 1.** Measuring unit for radio-wave measurements and tomographic survey scheme: 1 – antenna; 2 – retransmission unit; 3 – optical isolator block; 4 – computer; 5 – retransmission unit; 6 – logging hoister; 7 – radiating element; 8 – gamma-rays*

Inter-well measurements are carried out using RVGI-06 equipment. The observations are performed in a fan pattern within the filter section. The step between adjacent points along the wellbore is 1 m. For a visual assessment of the detailed RVGI studies, Figure 2 schematically shows a vertical section of the RVGI measurement procedure. The black dashed lines indicate the gamma-rays connecting each station of the radiating element with the measurement points in the adjacent well.

Technological wells of block 68, selected for experimental-industrial work, are arranged in row-based network with a distance between wells of about 25 meters, both in the row of wells and between the rows of wells. With this configuration of the row-based network, the uniformity of the observation network is adhered, which is an important criterion for the conditions of inter-well radio-frequency surveying.

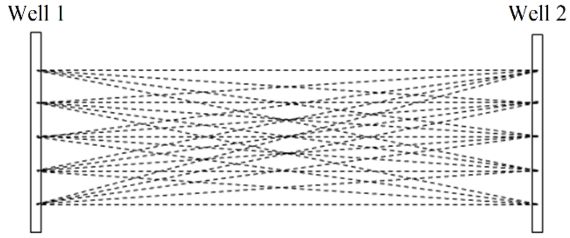

***Figure 2.** Detail of fan-type survey by RVGI method (vertical section with gamma-rays)*

At technological block 68, studies are carried out at the stage of passive acidification. The scheme for the RVGI study at the stage of passive acidification is shown in Figure 3.

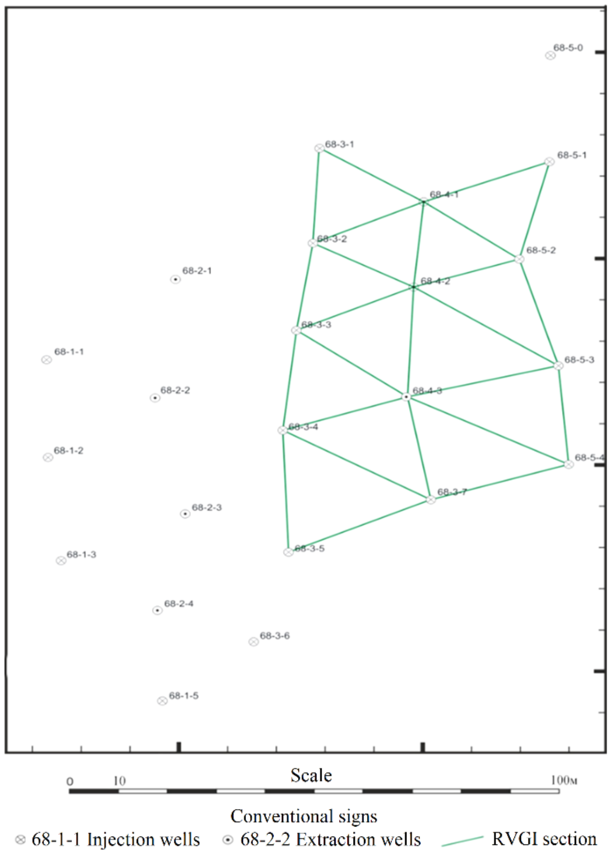

***Figure 3.** Scheme for the RVGI study at the stage of passive acidification*

The passive acidification stage precedes the active leaching stage. In case of passive acidification, injection solutions are supplied to the wells of the block in bulk or under pressure. When filling, in the absence of a pressure gradient, solutions of sulphuric acid (H_2SO_4) spread within the ore-bearing horizon under the impact of liquid column pressure in the wells and the action of gravity. Then the block is settled for about a month, after which the wells are involved in the pumping mode.

At technological block 68, starting from September 24, 2019, H_2SO_4 solutions have been supplied to the extraction wells. The concentration of the solutions increased smoothly from 4 to 25 g/l. From September 3, 2019, the H_2SO_4 concentration in the supplied solutions was maintained at the level of 25 g/l.

This site has been chosen for a number of reasons. Heterogeneous filtration structure. According to radio-wave geointoscopy, before the acidification occurrence in the space around the well 68-4-1, in the upper part of the section, there are low-permeable terrigenous rocks in the upper part of the filter setting interval. Well-permeable rocks occur in the space around the 68-4-3 extraction well in the lower part of the filter setting interval. In the well 68-5-0 in the middle part of the filter setting interval, a seam of carbonate rocks with a thickness of about 1 m is noted. The selected site is characterized by a heterogeneous filtration structure, which can affect the propagation of leaching solutions (LS) in the process of passive acidification and offers opportunities for determining the permeability coefficient for rocks of different lithological-filtration types.

At the selected test site, between the rows of injection wells 68-3 and 68-5, at the stage of technological drilling, the survey is carried out both along a row-based network (25 m) and on discharged observation networks using the radio-wave geointoscopy method. This makes it possible to have a reliable comparison base for monitoring studies by RVGI at the stage of passive acidification.

The intervals for setting the filters of extraction wells 68-4-2 and 68-4-3, to which sulphuric acid (H_2SO_4) solutions are supplied at the passive acidification stage, are located above the filters of the injection wells. At the selected site, there is a total immersion of the filter setting interval in the north direction. Thus, between wells 68-4-1 – 68-5-2 in the interval of setting the filters, the distance is 22.7 m, and between wells 68-4-3 – 68-5-4, the distance is 36.8 m (with a design distance of 25 m). Therefore, at the selected site, it is possible to assess the effect of uneven network of wells and filter setting intervals on the spreading of leaching solutions during passive acidification.

3. Results and discussion

The research is performed in 4 cycles with a frequency of 5 days (between the day of the beginning of each cycle) at the stage of passive acidification, as well as in 1 cycle with a duration of 5 days at the stage of active leaching.

The periods of the research cycles are shown on the graph and marked in blue, the changes in the sulphuric acid concentration in the solution over time at the stages of block mining are shown in Figure 4.

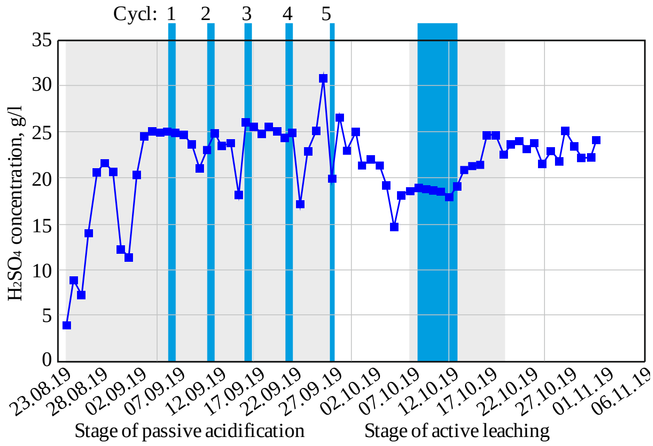

Figure 4. Graph of changes in the concentration of the supplied H_2SO_4 solutions over time

According to the graphs presented in Figure 4, during the research periods, the concentration of sulphuric acid in the solution remains at the level of 25 mg/l at the stage of passive acidification and 17-18 g/l at the stage of active leaching. Strict adherence to technology regulations for the sulphuric acid concentration of at the stages of passive acidification and active leaching is a mandatory factor for creating stable and optimal research conditions in order to reduce measurement errors and improve their accuracy.

The research methodology provides for the preparation of maps of the effective geoelectric resistivity for the block (R_{ef}).

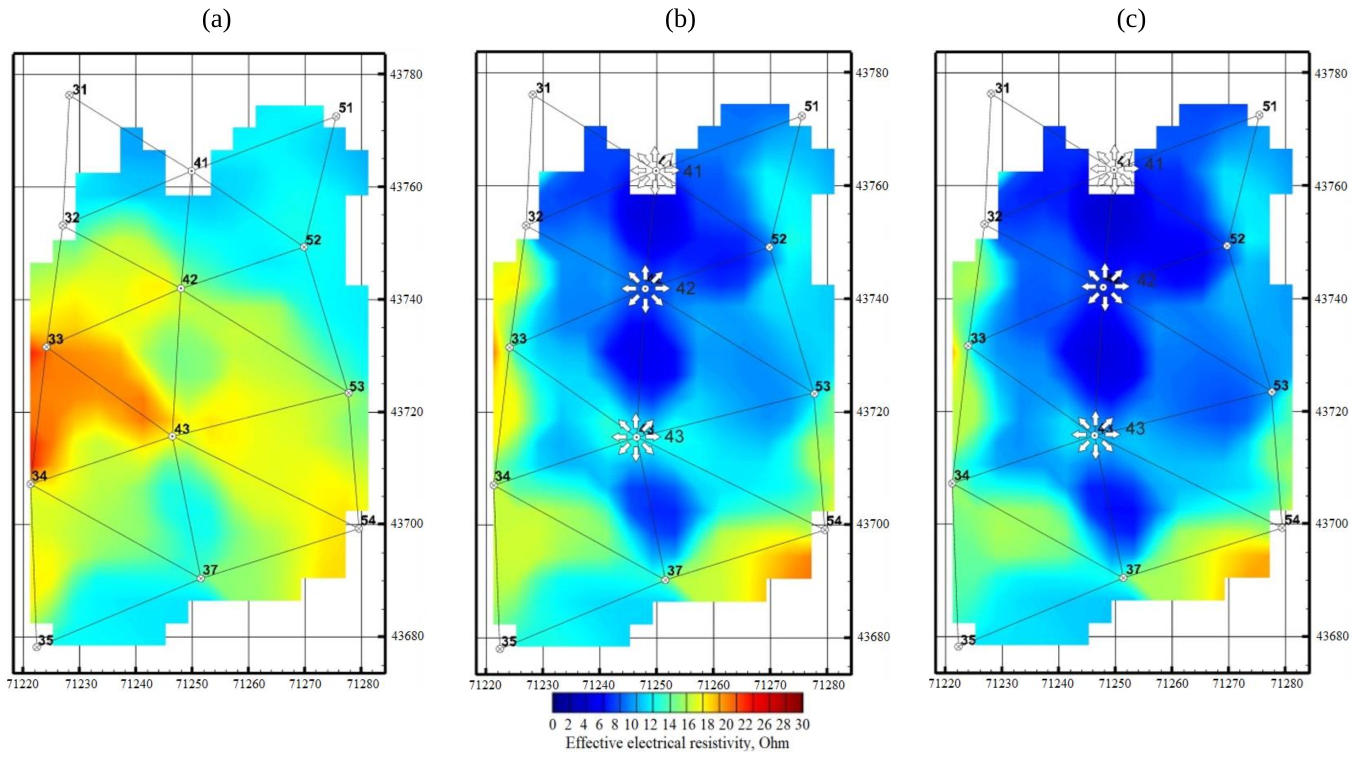

Figure 5. Fragments of 3D geoelectric map by RVGI at the stage of technological drilling: (a) prior to the acidification; (b) 14 days after the start of acidification; (c) 24 days after the start of acidification

Such maps, compiled at different stages of mining, make it possible to track changes in the area of solutions propagation over the block over time.

Figure 5 shows fragments of 3D geoelectric maps according to RVGI data before the occurrence of acidification, after 14 days and after 24 days of passive acidification – horizontal plans at a depth of -30 m of absolute mark.

By comparing the fragments of the RVGI geoelectric map at different stages of block mining (Fig. 5), it can be conclu-ded that there is a tendency to increase the area of acidic solutions propagation over time. After 14 days from the beginning of passive acidification, according to RVGI data, a significant decrease is recorded in the effective resistance values along the line of wells 68-4, which were supplied with H_2SO_4 solutions. According to the research data, after another 10 days, a further decrease in the level of effective resistance is noted, which indicates the replacement of the natural solution by the supplied H_2SO_4 solutions. Arrows indicate wells from which leaching solutions containing sulphuric acid are propagated. With increasing depth, the volume of leaching solutions increases due to the action of gravity.

This is most clearly seen on the 4D geoelectric map in the acidification rate isolines for a period of 14 days of passive acidification (Fig. 6a). At the initial stage of the passive acidification process, the most actively supplied solutions fill the space between wells 68-4-1 – 68-4-2 – 68-4-3.

The leaching solutions propagation in the process of passive acidification can be observed by 4D geoelectric maps in the isolines of the monitoring coefficient, which characterizes the change in effective resistance between research cycles (Fig. 6b). It can be seen from Figure 6b that in the process of research there is a significant change in the effective resistance between measurement cycles, which indicates a gradual replacement of groundwater with technological solutions.

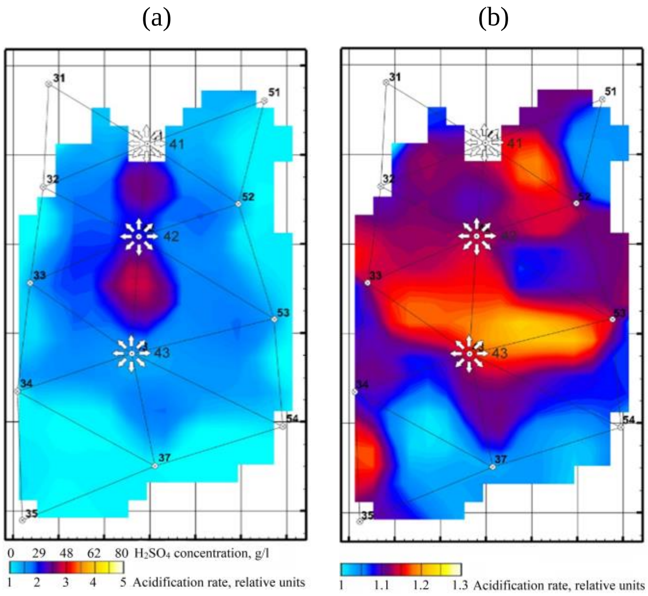

Figure 6. Fragment of 3D geoelectric map by RVGI: (a) monitoring coefficient after 14 days of passive acidification; (b) monitoring coefficient after 24 days of passive acidification

4. Conclusions

The experimental-industrial work performed at the Semizbay deposit at the main stages of mining the technological blocks testifies to the feasibility and efficiency of using the RVGI technology for solving the following main tasks.

At the stage of technological drilling (before the acid solution is supplied):

– identification of the lithological-filtration structure of the studied block;

– drawing up a spatial 3D map of the filtration properties distribution of rocks in the ore-bearing horizon;

– identification and localization of zones with low-permeable rocks.

These data can be used to adjust recoverable reserves, improve the scheme for mining the subsequent technological blocks.

At the stage of active leaching:

– obtaining a reliable three-dimensional pattern of leaching solutions actual spreading in the inter-well space for a given period of time;

– quantitative assessment of the acidification degree, both in individual zones and of the block as a whole;

– distinguishing and localization in the inter-well space of weakly permeable zones and zones of leaching solution excess concentrations (stagnant zones);

– identification of zones where the leaching solution spreads outside the contour, both vertically and laterally;

– assessment of the dynamics of the acidification process development in space and time.

The obtained research data confirm the uneven spreading of leaching solutions during passive acidification both in plan and in depth. The resolving power of the radio-wave geointoscopy method is sufficient to detect changes in geoelectric conditions in time during small monitoring cycles. The spatial-temporal change in the front of the leaching solutions propagation makes it possible to determine the prevailing directions of solutions propagation and to regulate the technological process in order to maximize the extraction of valuable component, reduce the cost of production.

The presented materials make possible to note the following peculiarities in the lithological structure of the blocks and the heterogeneity of their acid processing.

1. The results of processing the RVGI data on technological block 68 before acidification with geological materials and the results of logging (apparent resistivity, induction logging) have been compared, as well as the peculiarities in the lithological-filtration structure of the block have been revealed. Block 68 has quite inhomogeneous geoelectric and, consequently, the filtration structure. According to RVGI data, in the inter-well space in interval of setting the filters, areas of reduced R_{ef} values are distinguished, confined to low-permeable and impermeable rocks, such as clays and siltstones, mainly in the upper part of the filter intervals and the peripheral parts of the site. There are areas of increased R_{ef} values, which are composed of well-permeable sand-gravel deposits, mainly in the lower part of the filter intervals. Also, according to the highest R_{ef} level, zones composed of impermeable carbonate rocks are localized.

2. At the stage of active leaching, 45 days after the occurrence of acidification, the results of RVGI studies before the occurrence of acidification are compared, 4D geoelectric maps are calculated in the isolines of the acidification rate

(K_z) and the sulphuric acid concentration in the leaching solution. The comparison is accompanied by the analysis of geological materials and the results of induction logging at the stage of active leaching.

Both in the horizontal and vertical directions, a number of large anomalies of increased and decreased values of K_z are noted, which indicates to uneven leaching solutions propagation in the space of the block. In the vertical direction, there is a significant gradient of K_z values. In the lower part of the studied interval, in relation to the upper one, the acidification of rocks is significantly higher. This effect is conditioned by sinking the leaching solution, due to well-permeable rocks, into the lower part of the filter setting interval and, possibly, below the ore-bearing horizon, which can lead to the loss of uranium and non-production excessive consumption of sulphuric acid solutions.

5. Recommendations

The results obtained make it possible to recommend experimental-industrial tests of the RVGI technology at the main stages of mining the Semizbay deposit in order to increase the efficiency of mining operations.

The results of performed 4 cycles of RVGI regime observations at the stage of passive acidification of block 68 have confirmed the expediency of a detailed and comprehensive analysis of the obtained materials for the development of a method for quantitatively determining the actual filtration properties of rocks and the rate of acidification process development in the inter-well space to optimize technological schemes for drilling and mining technological blocks in specific conditions of Semizbay deposit.

Monitoring studies by RVGI at the stage of passive acidification can be recommended for further experimental and scientific testing at technological blocks of the Semizbay deposit for a quantitative assessment of the filtration characteristics of rocks and the dynamics of the acidification process development, as well as for the development of well-grounded recommendations on the optimal scheme for mining the blocks in specific geotechnical conditions.

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Застосування методу радіохвильової геоінтроскопії для дослідження характеру розтікання розчинів у процесі підземного вилуговування урану

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Мета. Оцінка ефективності застосування методу радіохвильової геоінтроскопії міжсвердловинного простору для об'ємного картування зони фактичного розподілу вилуговуючого розчину в процесі видобутку урану методом підземного вилуговування.

Методика. Проведено дослідно-промислові дослідження процесу вилуговування на технологічному блоці 68 родовища Семізбай (Казахстан). У процесі експериментальних досліджень використовувалася спеціальна апаратура для проведення радіохвильової геоінтроскопії. Міжсвердловинні вимірювання проводилися апаратурою РВГІ-06. Спостереження проводилися за віяловою схемою в межах фільтрової частини. Крок між сусідніми точками по стволу склав 1 м. На різних етапах розробки технологічного блоку були побудовані карти геоелектричного питомого опору, за допомогою яких було проведено порівняльний аналіз.

Результати. Виявлено шляхом порівняння фрагментів геоелектричної карти РВГІ на різних стадіях відпрацювання блоку тенденцію збільшення площі поширення кислих розчинів з плином часу. Доведено вплив неоднорідної геологічної будови на рівномірність розподілу вилуговуючого розчину. Встановлено, що роздільної здатності методу радіохвильової геоінтроскопії досить для виявлення змін геоелектричних умов при малих циклах моніторингу в часі. Просторово-тимчасова зміна фронту поширення вилуговуючого розчину дозволяє встановити домінуючі напрямки поширення розчинів і оцінити фільтраційні властивості порід.

Наукова новизна. Встановлено закономірності розподілу вилуговуючого розчину з плином часу від початку закислення блоку до активного вилуговування. Виконано перші спроби використання методу геофізичних досліджень у практиці видобутку урану методом підземного вилуговування.

Практична значимість. Моніторингові дослідження методом радіохвильової геоінтроскопії на етапі пасивного закислення можуть бути рекомендовані для подальшого експериментально-наукового випробування на технологічних блоках родовища Семізбай для кількісної оцінки фільтраційних характеристик порід і динаміки розвитку процесу закислення, розробки обгрунтованих рекомендацій з оптимальної схеми відпрацювання блоків у конкретних геолого-технологічних умовах/

Ключові слова: *підземне вилуговування, геофізичні методи, радіохвильова геоінтроскопія, уран, міжсвердловинний простір*

Применение метода радиоволновой геоинтроскопии для исследования характера растекания растворов в процессе подземного выщелачивания урана

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Цель. Оценка эффективности применения метода радиоволновой геоинтроскопии межскважинного пространства для объемного картирования зоны фактического распределения выщелачивающего раствора в процессе добычи урана методом подземного выщелачивания.

Методика. Проведены опытно-промышленные исследования процесса выщелачивания на технологическом блоке 68 месторождения Семизбай (Казахстан). В процессе экспериментальных исследований использовалась специальная аппаратура для проведения радиоволновой геоинтроскопии. Межскважинные измерения проводились аппаратурой РВГИ-06. Наблюдения проводились по веерной схеме в пределах фильтровой части. Шаг между соседними точками по стволу составил 1 м. На разных этапах разработки технологического блока были построены карты геоэлектрического удельного сопротивления, с помощью которых был проведен сравнительный анализ.

Результаты. Выявлено путем сравнения фрагментов геоэлектрической карты РВГИ на различных стадиях отработки блока тенденцию увеличения площади распространения кислых растворов с течением времени. Доказано влияние неоднородного геологического строения на равномерность распределения выщелачивающих растворов. Установлено, что разрешающей способности метода радиоволновой геоинтроскопии достаточно для выявления изменений геоэлектрических условий при малых циклах мониторинга во времени. Пространственно-временное изменение фронта распространения выщелачивающих позволяет установить преобладающие направления распространения растворов и оценить фильтрационные характеристики пород.

Научная новизна. Установлены закономерности распределения выщелачивающих растворов с течением времени от начала закисления блока до активного выщелачивания. Выполнены первые попытки использования метода геофизических исследований в практике добычи урана методом подземного выщелачивания.

Практическая значимость. Мониторинговые исследования методом радиоволновой геоинтроскопии на этапе пассивного закисления могут быть рекомендованы для дальнейшего экспериментально-научного опробования на технологических блоках месторождения Семизбай для количественной оценки фильтрационных характеристик пород и динамики развития процесса закисления, разработки обоснованных рекомендаций по оптимальной схеме отработки блоков в конкретных геолого-технологических условиях.

Ключевые слова: *подземное выщелачивание, геофизические методы, радиоволновая геоинтроскопия, уран, межскважинное пространство*