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Managing the Horizon-oriented In-Situ Leaching for the Uranium Deposits of Mongolia

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Abstract

This paper summarizes the results of evaluating uranium in-situ leaching (ISL) parameters for hydrogenous deposits in eastern Mongolia. This method, also known as in-situ recovery (ISR) or solution mining was proposed for mining used to extract uranium from underground deposits without physically removing the ore. The studies included drilling, geophysical surveying, evaluations of rock properties and chemical composition of rocks and groundwater, as well as modelling coupled flow and transport for the "Ul'zit" deposit as a case study. The proposed horizon-oriented approach to process separate ore bodies at different depths allows for the mining process to be adapted to layered heterogeneity and allows successive leaching by wells of varying diameter and special design. This approach may reduce drilling costs and shorten the time for mining uranium deposits in Mongolia by 2 times on average. It was proven that this method is an environmentally friendly and cost-effective alternative to traditional underground or open-pit mining for uranium ore bodies. The economic evaluation confirms the effectiveness of the proposed solutions.

Keywords:
uranium; hydrogenous deposits; in-situ leaching; wells; managing horizon-oriented ISL

1. Introduction

Managing horizon-oriented in-situ leaching (ISL) which sometimes is called in-situ recovery (ISR) for uranium deposits involves a combination of technical, environmental, regulatory, and safety considerations. ISL is a mining method used to extract uranium from underground ore bodies without the need for conventional mining and milling processes (**Smetana et al., 2002**). Instead, it involves the injection of a leaching solution into the ore body to dissolve the uranium in place, followed by the extraction of the dissolved uranium from the solution (**Falshtynskyi et al., 2019**).

Horizon-oriented ISL for uranium deposits can offer advantages in terms of reduced environmental impact and operational costs compared to traditional mining methods (**Polyanska et al., 2022**). However, careful planning, robust technical solutions, and thorough environmental management are essential to ensure the sustainable and responsible extraction of uranium while minimizing negative consequences (**Boytsov and Pershin, 2018**).

The global economy crisis emerged the changes in the world's energy benchmarks, including those related to the use of nuclear fuel. Global uranium production is growing despite the depletion of its additional sources such as the warheads disposed in the U.S. and other countries (**Kono, 2007**). At the time being, more than 15% of the world's electricity is generated at nuclear plants, which makes uranium a product of strategical importance for the global economy (**Vladyko et al., 2022**). The widely used blasting works in such conditions must be decreased while keeping an eye on the operative

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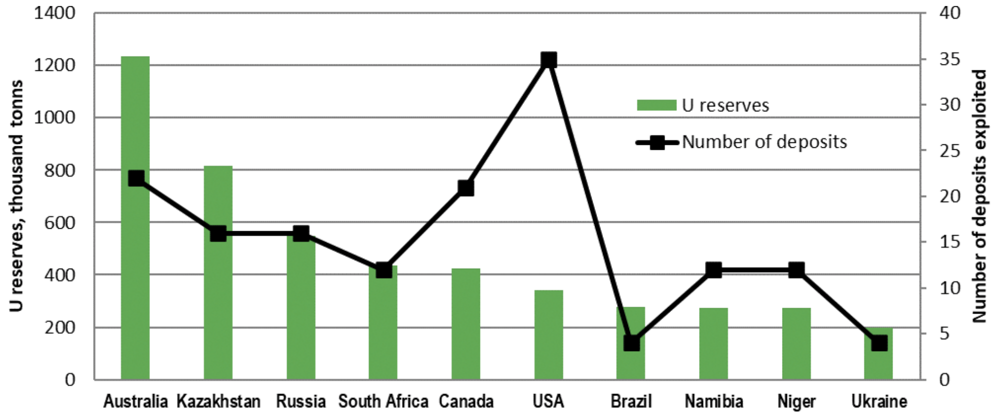

Figure 1: Global distribution of uranium reserves and deposits (except Mongolia)

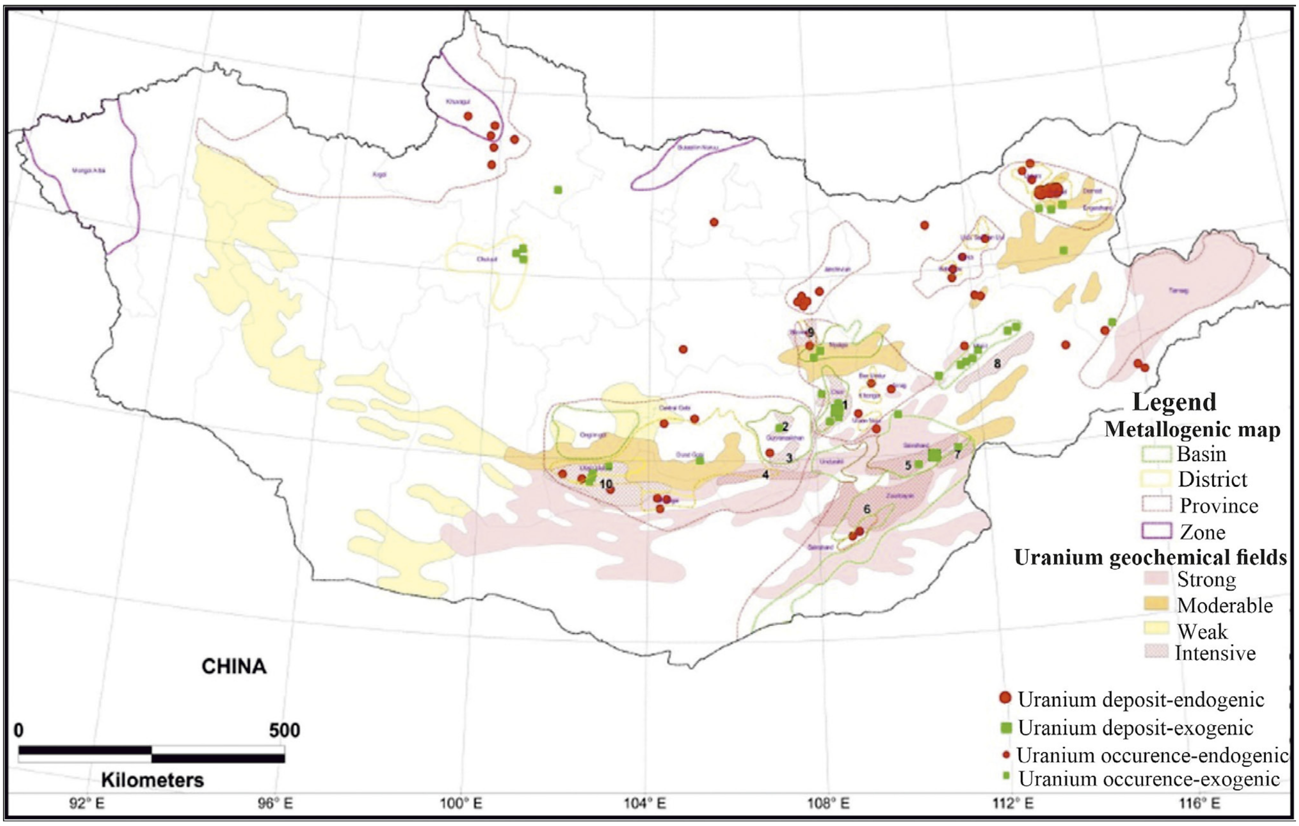

Figure 2: The map of explored uranium deposits in Mongolia

costs. It's essential to conduct thorough geological surveys, plan blast patterns carefully, and consider the specific characteristics of the material being blasted (**Brahimaj et al., 2022**).

The analysis of world trends in nuclear industry shows that the total generation capacity of power plants by 2025 will range from 450 GW to 530 GW, which means the increase from 22% to 44% above the current level; this will be equivalent to the annual uranium consumption of 80-100 thousand tons. If thermal reactors will only be employed in the uranium cycle, the nuclear industry will be faced with the shortage of uranium by 2050 (**Polyanska et al., 2023**). As pointed out in the IAEA report, this can be avoided in the case of putting fast breeder reactors into operation that will make uranium extraction from poor and small deposits profitable (**Nuclear Power Reactors, 2018**). Thus, overcoming the growing global energy deficit depends on the sustainable development of the nuclear industry throughout the world. These trends will only intensify in our globalized world (**Kononenko et al., 2023a**).

The global explored reserves of uranium (except Mongolia) are estimated at more than 5 million tons (see **Figure 1**). On this background, the explored uranium reserves in Mongolia (see **Figure 2**) estimated in the study shows that, at 1.475 million tons, this would guarantee one of the leading positions for the country among uranium producers in the future (**Khomenko and Rudakov, 2010**). A significant amount of accessible and prepared deposits in Mongolia with the reserves ready for exploitation, according to the assessment of **Gatfaoui (2020)**, may facilitate faster commissioning (see **Table 1**).

The accumulated world experience in mining uranium deposits by in-situ leaching (ISL) has proven to be a stable and effective operation for temperatures above 0°C. However, due to its geographic location in Central Asia and, consequently, sharply continental climate, the temperature in Mongolia is positive only during the summer season, whereas it often drops below –50°C in winter (**Enebish et al., 2019**). It was shown, that drilling and equipping the wells, installation and dismantling of equipment, treatment of solutions and processing of materials under such climatic conditions is seasonal, which limits the deposit exploitation period by the warm season (**Sudakov et al., 2017; Dychkovskyi et al., 2019**). The other feature of uranium deposits in Mongolia mentioned in the joint report (**Nuclear Power Reactors, 2018; NEA, 2018**), is that ore bodies in all hydrogenous deposits lie on 3 to 7 hypsometric levels with high variability in size, shape, and content of uranium and other satellite elements, which increases time and costs needed for mining.

According to the analysis, the opportunities to intensify uranium production at the relatively cheap cost of $35 per kg can be taken only by the companies that operate at unconformity-related deposits in Canada, hydrogenous deposits in Australia, Uzbekistan, Kazakhstan, and other countries, or companies dealing with accompanying mining in South Africa (**Pylypenko et al., 2023**).

The sharp continental climate of Mongolia predetermines the seasonal schedule of mining works. The underdevelopment of deposits and their considerable distances to the country's industrial centres, as well as the location of ore bodies at different depths in all hydrogenous deposits significantly constrain production efficiency (**Sala, and Bieda, 2019**). The existing conditions restrain the construction of new mining enterprises, which, for the sake of continuity of operation, should provide integrated development and accompanying extraction of several minerals. In this regard, a cyclical schedule of mining operations with the equipment installed in modular and mobile configurations would be reasonable (**Dychkovskyi et al., 2013**).

The most recent studies in modelling the transport of uranium and leachates focused on kinetics parameters and chemical effects under simplified geometry or a specific form of the flow and transport domain, for example, the studies of (**Sadovenko et al., 2010; Ben Simon et al., 2014; Johnson et al., 2016; Sadykov, 2019**). The performance of real sites of uranium recovery with ISL was the focus of mostly technical reports using predominantly simple numerical techniques (**Kalka et al., 2006; Dyczko, 2023**). In this paper, we will focus on the evaluation of ISL performance parameters using the numerical modelling tools for multiple wells grouped in several blocks for uranium recovery at an ore body of the uranium deposit in Mongolia. The overall purpose of the study is to increase the intensification of uranium leaching, taking into account the specifics of hydrogenic deposits in Mongolia.

Table 1: Uranium reserves in Mongolia explored in details

Deposit	Ore reserves, Million tons	U content, %	U reserves, thousand tons
Accessible reserves			
“Kharaat”	28.10	0.026	7.29
“Khairkhan”	11.80	0.071	8.42
“Gurvansayhan”	12.50	0.067	4.38
“Ul’zit”	6.70	0.036	3.01
Prepared reserves			
“Marday”	1.80	0.160	2.90
“Gurvanbulag”	14.70	0.170	22.00
“Dornod”	16.50	0.175	32.00

2. Research methodology

To evaluate the parameters of horizon-oriented ISL for isolated ore bodies, a special design of a well with varying diameter has been proposed by **Zhanchiv et al. (2013)** for all well parts beginning from the filter zone of deep horizons to the collar. The final diameter of the well must pass through the required flow rate and perform all necessary technological operations. For higher efficiency, thorough grouting of the annular space should be performed to fill the gaps between the sections of different diameter. The final diameter of the drilling tool can be evaluated from the formula:

$$D_{dt} = D_{cc} + 2b, \tag{1}$$

where D_{dt} is the drilling tool diameter, mm; D_{cc} the diameter required for the casing collar, mm; b the gap size, mm. At D_{dt} = 250 mm the parameter b should range from 20 to 50 mm. Regarding the experience of drilling oil and gas wells the smaller values of b from 7 to 15 mm are recommended, which is possible to achieve only using high-quality cement grouting keeping standards when cementing wells (**Kononenko et al., 2023b; Simonyants, 2020**).

The proposed horizon-oriented ISL approach for deposit preparation provides a higher intensity of mining operations owing to grouping the wells without the need to drill separate wells for isolated ore bodies below. The well group design allows successive leaching of several ore bodies at different elevations; well columns should contain umbrella-type glands, filters, flushing holes, and gland seals of appropriate diameters. Isolated ore bodies of uranium should be leached depending on the thicknesses and permeability of enclosing rocks either separately from each other or together, down or bottom-up (**Altankhuyag et al., 2019**), to separate each horizon of acidification or leaching from the others considering the experience of uranium (**Zhang et al., 2019**).

Cementation of annular space is not obligatory for horizon-oriented ISL, which is the other advantage of this approach because small annular gaps and mud solution circulation in the wellbore practically block solution movement along the annular gaps formed successively from one filter to another (**Kozhevnykov et al., 2014**). The highest efficiency can be achieved with the use of polyethylene pipes placed to a depth of 300 m below the ground, with joining the junctures by welding. The pump type, the design of filters and appropriate equipment crucial for long-term effective operation should be adjusted with the physical and chemical composition of rocks and groundwater (**Sudakov et al., 2019**).

3. Results and discussion

The horizon-oriented in-situ leaching for uranium deposits means providing laboratory and field studies. In the discussion section, we provide the theoretical evaluation of the received results. The end results of the research are developing the technological parameters of horizon-oriented ISL.

3.1. Field studies

Field studies included geophysical surveying that combined acoustic, radiometric, electrometric, and electrical methods, analysis of geological settings of deposits, drilling, and sampling of uranium-bearing and enclosing rocks, testing their mechanical and physical properties including fragility, as well as flow properties, and estimation of fracture parameters. The results of these studies, including laboratory tests and field experiments at uranium deposits in Mongolia (**Khomenko et al., 2018**).

Drilling of described wells was the main type of field work conducted at hydrogenous deposits. The distance between the wells in each section varied depending on the scale, and features of ore bodies; it ranges from 50-100 m for well-formed ore bodies to 400-800 m in other cases. Oxidation was the main criterion to limit the drilling depth used by (**Dreus et al., 2016**), with most of the drilled wells reaching depths of 150-250 m, sometimes 300 m. Two Mongolian companies conducted drilling operations, they are “Ord Geo” company operated at the “Ul’zit” deposit, and the company “Tanan Impex” consistently performed drilling at the “Khairkhan”, “Gurvansayhan” and “Kharaat” deposits. In addition, the company “Denison Mines Mongolia” as part of the joint Mongolian-American enterprise “Gurvansayhan” made prospecting works for uranium in the entire Gobi region of Mongolia.

The diameter of boreholes used for drilling ranged from 93 to 112 mm. Apart from the proper selection of drilling tools, the wellbore wall stability was ensured by the continuous circulation of drilling mud fabricated based on high-quality bentonite powders. Double-core tubes with a replaceable core receiver provided the highest core output. Carbide and diamond tools were used to penetrate the rock layers of boulders, conglomerates, and blocky inclusions of crystalline rocks. Sedimentation sections with aquifers of considerable thickness were cased with metal pipes. Similar drilling rigs were used for hydrogeological drilling. The hydrogeological well design proposes to use casing pipes and PVC filters with cementing of annular space. The core yield reached at least 75%, which is a prerequisite for the prospecting of such kinds of uranium deposits (**Dreus et al., 2016**). For 11 wells drilled at the “Ul’zite” deposit, the core yield averaged 90.3%.

Opening the deposits showed that they have an identical nature of origin, thus, they were of similar type, geological settings, and enclosing rock composition. In addition, the ore body parameters in all deposits range within the same intervals, particularly, the size from 200 to 4000 m and average uranium content from 0.036% to 0.066%. The ore body shape was found to be similar (horizontal, layer and rolls, lenticular, ribbon- and nest-shaped bodies) and typical for hydrogenous uranium deposits. All ore bodies are in the aquifers with a transmissivity of 0.2-370 m^2/d, conductivity of 0.1-10 m/d, and mineralization of 0.7-7.0 g/dm^3. The results of opening the deposits “Kharaat”, “Khairkhan”, “Gurvansayhan” (see **Figure 3**) look more favourable than for the “Ul’zit” deposit, which indicates that technological parameters for these groups of deposits are different and should be evaluated separately.

Among all uranium deposits of Mongolia, the “Ul’zit” deposit was studied the most thoroughly. The conductivity of ore-bearing rocks at this deposit varies from 0.1 m/d to 10 m/d, transmissivity of enclosing rocks is below 25 m^2/d but in some cases reaches 50 m^2/day. Groundwater head within the deposit occurs at a depth

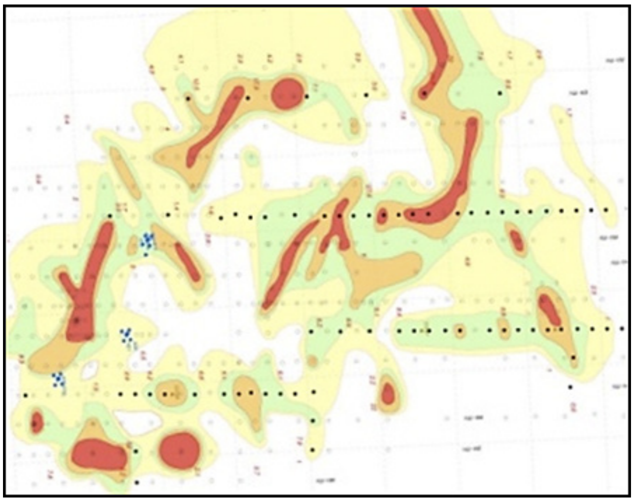

Figure 3: Horizontal projection of the “Khairhan” deposit

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Table 2: Leaching parameters for uranium ore samples taken at the "Ul'zit" deposit

Technology parameter	Dimension	Ore samples			
		G 1	G 2	G 3	G 4
Actual content of U in uranium ore	ppm	295.40	134.70	29.00	9.40
Calculated content of U in uranium ore	ppm	398.00	103.70	13.580	9.34
Dry sample mass	g	2500	2500	2500	2500
Reagent		H_2SO_4	H_2SO_4	H_2SO_4	H_2SO_4
Reagent concentration in leaching solution	g/l	5.0	5.0	10.0	20.0
Additional oxidizer	-	KCl_3	-	-	-
Oxidizer concentration	g/m^3	28.57	-	-	-
Volume of pregnant leaching solution	ml	271774	281719	276105	283073
Relation of the leaching solution volume to the ore volume (Liquid/Solid)	-	0.18	0.19	0.19	0.19
Leaching period	min	44585	44357	44568	44942
Solution discharge	ml/min	6.10	6.35	6.20	6.30
Mass of U leached	mg	1.60	2.30	3.30	2.30
Amount of U leached	ppm	5.90	9.40	12.0	8.20
Solution acidity, pH	-	1.36	1.34	1.20	1.08
Eh value	мВ	437.00	376.07	363.60	373.60
U extraction rate	%	67.60	86.00	96.70	97.80

of 1.4-7.5 m below the ground surface. Groundwater chemical composition at the deposit is chloride-sulphate, magnesium-sodium, less frequently sodium waters of 3 to 5 g/ dm^3 mineralization have a neutral or slightly alkaline reaction; the total hardness of water varies from 7.5 meq/dm^3 to 34.0 meq/dm^3. Groundwater does not contain ferric oxide; it contains small amounts of iron sulphate oxide (2.8-7.3 mg/dm^3) and hydrogen sulphide at concentrations below 10.2 mg/dm^3. The uranium content in groundwater ranges from 3×10^{-5} g/dm^3 to 3×10^{-4} g/dm^3 decreasing adown.

3.2. Laboratory studies

Laboratory studies aimed to identify chemical composition and properties of rocks sampled at uranium deposits, mostly at the "Ul'zit" deposit. 359 core samples have been investigated in the laboratories of Mongolia, Canada, and Russia. All samples were examined by the ICP+ICP/MS method to identify 62 radioactive elements; water samples were examined by the ICP-MS method in the laboratory of ActLabs (Canada). For quality control, 43 samples were analysed by X-ray spectral, radiometric, and flame-photometric methods in a specialized laboratory of State Enterprise "Sosnovgeologiya" (Russia). Furthermore, 44 samples have been analysed with X-ray fluorescence analysis; chemical and mineralogical composition of ore-bearing rocks in the Central Geological Laboratory of Mongolia (**Khomenko and Maltsev, 2013**).

The results of geochemical studies revealed the presence of uranium satellite elements and evaluated their concentration in ores. It was found that uranium ISL requires additional use of oxidizing reagents, which was confirmed by the experiments conducted at the Central Geological Laboratory of Mongolia. The experiments showed the possibility of stable uranium extraction with a continuous addition of hydrogen peroxide as an artificial oxidant at the average concentration of 0.06 g/l or trivalent iron as a natural oxidant (see **Table 2**).

The analysis of uranium leaching experiments allowed for the obtainment of an exponential correlation between the acid concentration in the solution and time with the kinetic parameter a, which is similar to that used by (**Smith et al., 1966**) for uranium extraction in mines:

$$C_{ac} = 100\left(1 - e^{-(T_l - 60)\alpha}\right), \% \qquad (2)$$

where a is the metal extraction rate, a = 0.003 – 0.01 hr^{-1}, T_l is leaching period, hr.

Based on the results of laboratory studies, we recommend the acidification of uranium-bearing rocks using solutions with concentrations of 10-15 g/l, and the leaching of uranium using solutions with acid concentrations of 8-12 g/l (**Khomenko and Maltsev, 2013**). To intensify the process, it is necessary to increase the time of interaction between leaching fluids and rocks, which can be achieved by increasing the distance between the wells to 25-50 m in case of sufficient permeability of ore bodies and enclosing rocks, which corresponds with (**Omori, et. al., 2019**).

3.3. Evaluation of the results.

These studies aimed to develop and test a mathematical model of flow and transport during uranium ISL using the finite-difference method. This method is implemented in the software ModFlow designed to solve dif-

Table 3: Parameters of ISL of the ore body 1 at the "Ul'zit" deposit

Section no.	Cell colour (Fig. 3)	Pumping-in wells			Pumping-out wells			Leaching period, d	Imbalance, %
		N	$Q_{0,1}$, m^3/d	$Q_{S,1}$, m^3/d	N	$Q_{0,2}$, m^3/d	$Q_{S,2}$, m^3/d		
1	Red	31	20	620	9	80	720	0 – 60	13.9
2	Green	31	20	620	9	80	720	60 – 120	13.9
3	Orange	31	20	620	9	80	720	365 – 425	13.9
4	Blue	30	21	630	9	80	720	425 – 485	12.5

ferential equations of flow and transport in saturated rocks (**Langevin et al, 2008; Langevin et al, 2017**). When specifying the flow domain boundaries, it was assumed that hydrodynamic and physic-chemical disturbances in low-permeable uranium-bearing sandstone are limited to the boundaries of ore bodies and a small contour zone around them with a width of up to 50 m. To correctly reproduce the isolated flow domain the model boundaries were positioned at a distance of at least 200 m from the contour of the widest ore body. Such a simplification can be accepted because of slow water flow, thus, low velocity of natural groundwater flow and infiltration rate, which is typical for the desert-type areas of eastern Mongolian deposits (**Zhou et al., 2020**).

Leaching fluid flow, acid and dissolved uranium transport in ore-bearing rocks during ISL are governed by the simultaneous differential equations:

$$div\left(KgradH\right)+Q=n\frac{\partial H}{\partial t}, \tag{3}$$

$$div\left(DgradC_1-vC_1\right)-\beta_1C_1+q_1=n_a\frac{\partial C_1}{\partial t}, \tag{4}$$

$$div\left(DgradC_2-vC_2\right)-\beta_2C_2+q_2=n_a\frac{\partial C_2}{\partial t}. \tag{5}$$

In equations 3-5 H is the groundwater head; t is time, K the rock conductivity tensor; Q is the sum of pumping well rates; n is the porosity; C_1 and C_2 are the concentration of acid and dissolved uranium in groundwater respectively; D the dispersion tensor; v the flow velocity; n_a is active porosity; b_1 is the kinetic coefficient that quantifies acid consumption resulted by reactions with enclosing rocks; b_2 is the kinetic coefficient characterizing uranium absorption during its transport in the flow domain; q_1 is the rate of acid injection through the wells, q_2 is the rate of uranium dissolution, depending on the acid concentration in the solution and the uranium content in the solid phase. The tensor coefficients D_x, D_y, D_z are calculated as:

$$D_x = \mathrm{d}\times v_x,\ D_y = \mathrm{d}\times v_y,\ D_z = \mathrm{d}\times v_z, \tag{6}$$

where d is rock dispersity.

Mass exchange parameters were assumed constant during leaching (**Kutnii et al., 2016**).

The terms q_1, q_2, b_1 and b_2 is governed by equations accessible in the software Modflow for first-order kinetic dual-domain mass transfer and parent-daughter reactions assuming dissolved uranium as a product of acid reaction with ore bodies. The term q_1 is calculated as:

$$C_{1,0}\sum\nolimits_{i=1}^{Ni}Q_i(x,y), \tag{7}$$

where is the acid concentration in pumping wells, Ni is pumping-in well number, is the function equal to a flow rate in the well and zero otherwise.

The term q_2 is calculated as an area source governed by the first-order parent-daughter reaction in the Modflow software (**Langevin et al., 2017**). Kinetic coefficients of uranium leaching on a large scale of a mined area can be evaluated by laboratory studies (**Yousef et al., 2019; Zeng et al., 2022; Chen et al. 2022**) or by the equations of dissolution/precipitation (**Baqer et al., 2023**). Note, that the results obtained for small samples need an upscaling and can significantly differ from those used in the model in the field conditions due to heterogeneity. For the numerical model, we evaluated kinetic coefficients based on the aforementioned approaches. Parameter b_1 was derived from a in Eq. 2 considering slower chemical reactions in-situ in comparison to more favourable mass-exchange conditions in the laboratory. Parameter b_2 was evaluated by the dissolution/precipitation equations (**Baqer et al., 2023**) considering chemical heterogeneity due to the difference between the acid-saturated zone and the rest of the flow domain.

Regarding the low thickness of permeable rocks and the absence of almost impermeable layers, the ISL domain was simulated as quasi-homogeneous. We used the following parameters in calculations: conductivity 1 m/d, infiltration rate 5 mm/a, porosity 0.1, active porosity 0.05. A constant groundwater head was set at 1.030 m a.s.l. on the flow domain boundary. We simplified vertical heterogeneity using 10 layers each of 20 m thickness with the initial content of uranium in the solid phase attributed according to the average value for each part of the deposit using the technique (**Sudakov et al., 2016**).

A model like that developed by **Rudakov et al. (2012)** was applied to evaluate the ISL parameters focusing on the possibility to intensify leaching. We simulated ISL for the case of the ore body 1 of the open section of the "Ul'zit" deposit in the case of applying the hexagonal positioning of wells (see **Table 3**).

The nomenclature in **Table 3** is the following: N is well number; Q_0 the well flow rate; Q_S the total well flow

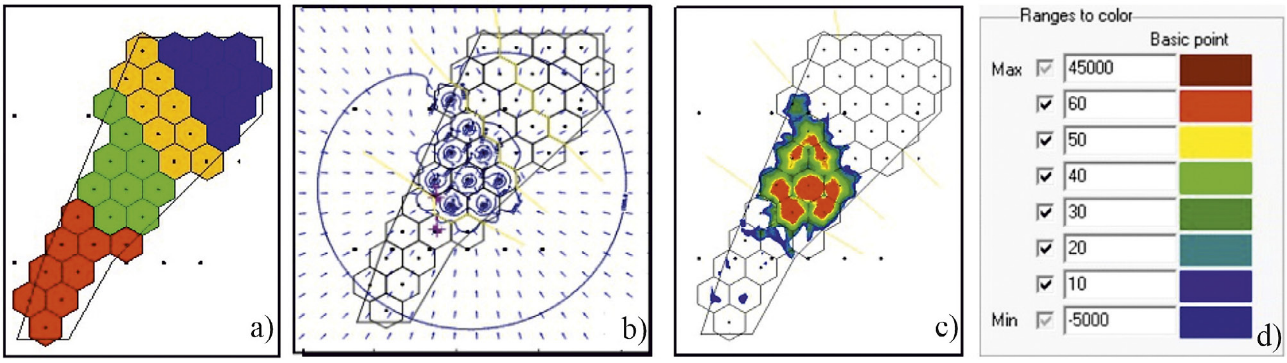

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Figure 4: Proposed sequence of leaching the ore body 1 of the "Ul'zit" deposit: a) coverage of the ore body with cells; b) groundwater head and flow velocity field at the final stage of processing of section 2; c) concentrations of dissolved uranium; d) colour scale at the final stage of uranium leaching in section 2.

rate. The imbalance defined as the ratio of the difference between the total flow rate of pumping-in and pumping-out wells to the total flow rate of the pumping-in wells was calculated as follows:

$$\eta = \frac{Q_{\Sigma,2} - Q_{\Sigma,1}}{Q_{\Sigma,2}} 100\%. \qquad (8)$$

Transport of a leaching agent and dissolved uranium near the ore body within an area of about 60.000 m^2 and the elevations ranging from 840 to 1020 m a.s.l. is three-dimensional. Considering technology features it is proposed to leach five ore bodies no. 1-5 successively in the descending sequence and processing the sections covered by hexagonal cells. We propose to leach the ore body 1 located on the top at an elevation of 1010-1020 m a.s.l. successively processing four sections each consisting of 9 cells (see **Figure 4a**).

The application of hexagonal sectioning allows for rationally arranging wells on the site and using them successively for different ore bodies lying at different depths. The proposed sectioning covers more than 90% of the ore body area. In fact, due to a gradual shifting of the area with lowered groundwater head leaching fluid will seep through all space occupied by the ore body albeit at different intensities.

Zero concentrations of the acid and dissolved uranium were set as the initial conditions and boundary conditions on the sides of the flow and transport domain.

Having applied the model, we evaluated groundwater head and flow directions during the leaching period of the ore body (see **Figures 4b** and **4c**). A depression cone around each section formed when leaching leads to the sinking of the water level in pumping-out wells by 3 m below the initial groundwater head, with flow velocity at the vicinity of wells reaching 2 m/d. Due to the incomplete covering of the ore body by hexagonal cells, a part of the used solutions may potentially escape the contours of leaching by 5-10 m; thus, minor residues of these solutions with unreacted acid may remain outside the ore body contours for several months. The expected average concentration of uranium in the pregnant solution ranges from 30 to 80 mg/l, which can provide extraction of up to 10 tons of uranium from the ore body. Based on the calculation results and conclusions (**Pradhan et al., 2022**) for mining of uranium we provided recommendations how to activate ISL and prevent clogging.

In **Figure 4**, the areas marked in red (section 1), green (section 2), orange (section 3), and blue (section 4) are the proposed sequence of leaching the ore body 1 of the "Ul'zit" deposit. Black lines are cell contours, and yellow lines are boundaries between the sections (see **Figure 4b**).

3.4. Technological parameters of horizon-oriented ISL.

The recommended well-to-well distance in a cell of hexagonal arrangement varies from 12.5 to 44.3 m, which for seasonal conditions of ISL operations allows for flexible control of the production unit configuration. Considering this range, we evaluated the intervals of ISL parameters for the selected uranium deposits (see **Table 4**). The parameters calculated by (**Khomenko et al., 2017**) vary within the intervals typical for uranium ISL under similar geological conditions in Kazakhstan, Uzbekistan, Ukraine, and other countries that were analysed by **Peganov et al. (2015)**.

Table 4: Recommended ISL parameters for uranium deposits in Mongolia

Deposit	**"Kharaat", "Khairhan", "Gurvansayhan"**	**"Ul'zit"**
Parameter		
Hexagonal cell radius, m	22.5 – 44.3	12.5 – 26.1
Withdrawal pumping well rate, m^3/d	121.0 – 196.3	41.7 – 84.3
Acidification period of a section, d	7.5 – 10.1	16.8 – 20.1
Leaching period of a section, d	28.3 – 33.7	63.2 – 75.4
U content in pregnant leach solution, mg/l	48.7 – 53.9	66.7 – 111.8

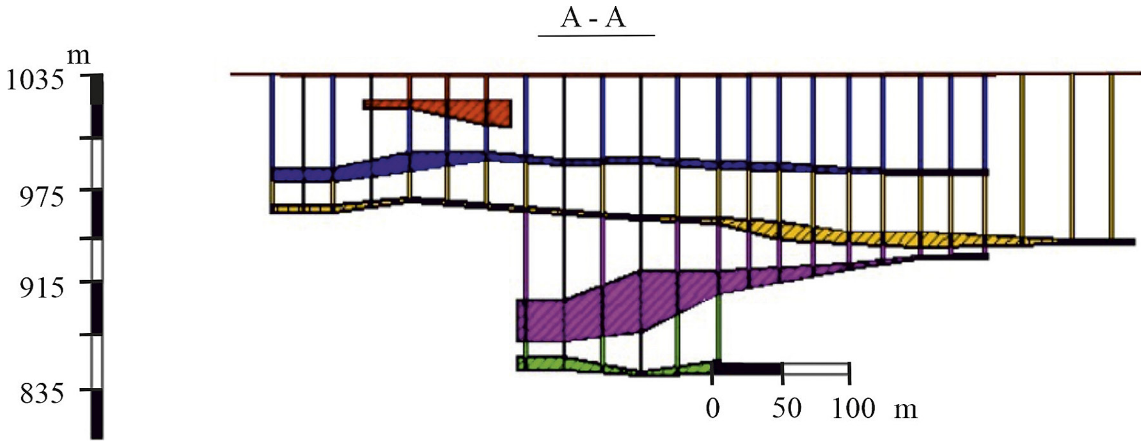

Figure 5: Technological design of horizon-oriented ISL for the preparation of isolated ore bodies at the "Ul'zit" deposit in section presented A – A (a) (b). Ore body and wells at each horizon are marked with a specific colour as follows: 1 – red, 2 – blue, 3 – yellow, 4 – lilac, 5 – green.

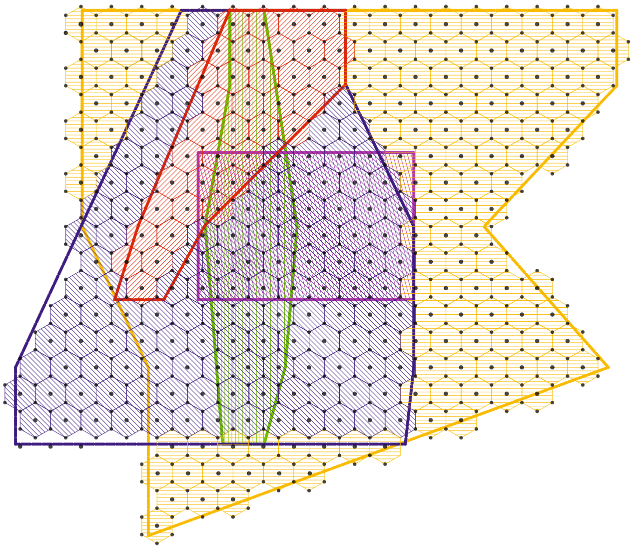

Figure 6: Horizontal projections of ore bodies at the "Ul'zit" deposit. Horizon colour notations as follows: 1 – red, 2 – blue, 3 – yellow, 4 – lilac, 5 – green.

Based on the simulation results, using the methods of National Atomic Company "Kazatomprom" (**Panova et al., 2021; Kopbaeva et al., 2016**) to calculate ISL parameters, we evaluated technological parameters of hexagonal well arrangement for five ore bodies located at different depths (see **Figures 5** and **6**).

The application of the horizon-oriented approach to preparing isolated ore bodies at different depths is justifiable because of the layered structure of rocks with the conductivity varying from 0.85 to 8.5 m/d. The approach allows for the grouping of ore bodies using combined wells of different diameters and filter designs and, eventually, reducing drilling costs by up to 62%, as well as shortening the time of mining uranium deposits in Mongolia on average by 2 times. For the opened section of the "Ul'zit" deposit, the horizontal projections of ore bodies no. 1 and 3 are overlapped by 60.000 m^2 and 360.300 m^2 respectively, with their total area overlapping up to 62%. Under these conditions, the minimum density of well placing equals 0.002 m^{-2} at the cell radius R_o = 25 m and vertical distances between ore bodies of 20-150 m. Thus, applying the horizon-oriented approach to prepare isolated ore bodies at the "Ul'zit" deposit may considerably reduce drilling costs by combining the wells for the overlapped ore bodies, which is estimated at 50 thousand running meters of boreholes at a total cost of $2.508 million. Using the recommended radius of a leaching cell with a hexagonal well arrangement at the "Kharaat", "Khairkhan" and "Gurvansayhan" sites makes it possible to save up to $0.9 million for each deposit. Besides, we proposed measures to prevent the clogging of filters and filter zones of wells, which is in line with the appropriate proposals (**Pastukhov and Pershin, 2014**).

4. Conclusions

Based on field study results obtained for the opened hydrogenous deposits of Mongolia, we described the properties of uranium ores and ore bodies varying horizontally and vertically. Ore body structure, origin, chemical composition, shape, and size, as well as uranium content and hydrogeological conditions have identical origin for studies sites and completely satisfy the conditions of in-situ leaching. Ore-body parameters are typical for hydrogenous deposits with a uranium content of 0.036-0.066%. Generally, ore bodies of up to 7.0 m thickness lay at 3-7 elevations located within the range from 18 to 300 m below the ground. All ore bodies are in aquifers of highly variable transmissivity from 0.2 m^2/d to 370 m^2/d.

Groundwater chemical composition and radiological properties of uranium satellite elements studied in the laboratory showed low to medium water mineralization of 0.7-7.0 g/dm^3, the absence of ferric oxide, and the presence of hydrogen sulphide to 10.2 mg/dm^3. The content of ferrous iron ranges from 2.8 to 7.3 mg/dm^3, and uranium from 3×10^{-5} g/dm^3 to 3×10^{-4}g/dm^3. Under these conditions, the acidification of ores to be performed with the solutions at a sulphuric acid concentration of 10-15 g/l should be followed by leaching with solutions at an acid concentration of 8-12 g/dm^3. Uranium recovery under a continuous supply of hydrogen peroxide at the average concentration of 0.06 g/l and ferric iron as oxidizers can be fitted with a time-dependent exponential correlation.

Based on the finite-difference method implemented in software Modflow, a mathematical model of uranium leaching has been developed and tested for the case of the “Ul’zit” deposit. The model describes coupled flow and transport of a leaching solution and dissolved uranium in a part of the aquifer that contains uranium ore bodies and covered by pumping wells arranged hexagonally. In simulations we focused on the successive leaching of four neighbouring sections that cover ore body no. 1, located at the highest elevation closest to the ground surface. Water level in wells is expected to sink up to 3 m with flow velocity at the vicinity of wells up to 2 m/d. Based on the average concentration of uranium in leaching solution, we evaluated the expected output of up to 10 tons of uranium from the ore body 1 at the uranium recovery rate estimated under laboratory conditions. The recommended well-to-well distance in an ISL hexagonal cell ranges from 12.5 to 44.3 m.

The horizon-oriented approach to prepare isolated ore bodies at different depths allows grouping ore bodies with combined wells of different diameters and filter designs, which reduces drilling costs by 62%. The maximum saving of resources is expected to be achieved when drilling wells to the deepest ore bodies. The use of the horizon-oriented approach for preparing isolated ore bodies at the “Ul’zit” deposit may reduce drilling costs by combining the wells up to $2.508 million. In addition, this approach allows for a shorter time to be spent for ISL mining of deposits in Mongolia by more than 2 times on average. Following the recommendation on the radius of an ISL cell with a hexagonal well arrangement at the “Kharaat”, “Khairkhan” and “Gurvansayhan” sites makes it possible to save up to $0.9 million for the mining of each deposit.

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SAŽETAK

Upravljanje horizontalnim terenskim izluživanjem na mongolskim ležištima urana

U radu su sažeti rezultati procjene parametara pridobivanja urana izluživanjem za hidrogene naslage u istočnoj Mongoliji. Ova metoda, poznata i kao pridobivanje otapanjem, predložena je kao rudarska metoda za eksploataciju urana iz podzemnih ležišta bez fizičkoga transporta rude. Studija je uključivala bušenje, geofizičko istraživanje, procjene svojstava stijena, kemijskoga sastava stijena i podzemnih voda, kao i modeliranje spojenoga protoka i transporta ležišta Ul'zit kao studije slučaja. Predloženi pristup po horizontu za pridobivanje odvojenih slojeva na različitim dubinama omogućuje upravljanje rudarskim procesom prilagodbom slojevitoj heterogenosti te omogućuje uzastopno izluživanje pomoću bušotina različitoga promjera i specifičnih parametara. Tim se pristupom mogu smanjiti troškovi bušenja i skratiti vrijeme rudarenja ležišta urana u Mongoliji u prosjeku za dva puta. Dokazano je da je ova metoda ekološki prihvatljiva i isplativa alternativa tradicionalnomu podzemnom rudarstvu ili rudarstvu u površinskim kopovima za rudna tijela urana. Ekonomska evaluacija potvrđuje učinkovitost predloženih rješenja.

Ključne riječi:
uran, hidrogene naslage, terensko izluživanje, bušotina, upravljanje horiznotalnim ISL-om

Author's contribution

Khomenko Oleh (Dr. Sc. Professor) – description of the problem and analysis of the drawbacks of mining technologies; development of approaches to the decomposition of the mining enterprise to achieve the research goals. **Rudakov Dmytro** (Dr. Sc. Professor) – development of the algorithm for calculation and determination of technological parameters; description of the technologies research; performance of the preliminary calculation; analysis of research results; development of graphic elements of the work. **Lkhagva Tsandgjav** (PhD., Associated Professor) – participation in the formation of a management system for the extraction of uranium reserves, the justification of the ecological aspects. **Sala Dariusz** (PhD., Associated Professor) – formed the mathematical model, conducted the preliminary calculations. **Buketov Valentyn** (Post Graduate Student) **–** processed the results of research. **Dychkovskyi Roman** (Dr. Sc. Professor) – formed the object and the subject of the research; development of the idea of work and the methodology for achieving results; analysis of research; description of the data for the development of mining processes.