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NETWORK HYDRODYNAMIC MODEL OF UNDERGROUND URANIUM LEACHING

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Abstract. Uranium is a strategic raw material widely used in nuclear energy. Among the existing methods of uranium mining, open and underground mining, as well as in-situ leaching (ISL), are widely applied. ISL is recognized as the most environmentally friendly and cost-effective method for developing hydrogenous uranium deposits. In Kazakhstan, all hydrogenous uranium deposits are developed using the ISL method. The efficiency of the process significantly depends on timely control of parameters, which emphasizes the need for mathematical modeling. This paper presents modern approaches to managing the ISL process based on

mathematical models. Particular attention is paid to the network hydrodynamic model, which, using data on uranium concentration, environmental permeability, and other geotechnological parameters, increases the profitability of deposit development. Measuring flow rates and nodal pressures in a well network allows calculation of the pressure drop in the ore body between injection and production wells, as well as hydraulic resistance. Determining these parameters is important for increasing production efficiency, reducing energy costs, and minimizing reagent consumption. The obtained results create a scientific basis for developing innovative solutions in the field of ISL process automation. These solutions can be used to design optimal well placement schemes and determine the most effective cell radius. In the future, this study will contribute to the creation of an intelligent control system for the uranium leaching process. The use of neural networks for modeling and analyzing the ISL process is of particular interest and is a promising direction for further development.

Keywords: underground leaching, uranium mining, control system, network model, intelligent control systems, network graph, operational field

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Аннотация. Уран – ядролық энергетикада кеңінен қолданылатын стратегиялық шикізат. Уранды өндірудің қолданыстағы әдістерінің ішінде карьерлік, шахталық және жерасты сілтісіздендіру әдістерін атауға болады. Соңғы әдіс гидрогендік уран кен орындары үшін экологиялық және экономикалық жағынан ең тиімді әдіс ретінде танылады және қазіргі таңда кеңінен қолданылады. Қазақстан Республикасында барлық гидрогендік уран кен орындары жерасты сілтісіздендіру әдісімен игерілуде. Бұл процестің тиімділігі оның параметрлерін уақтылы басқаруға тікелей байланысты болғандықтан, осы процестің нақты математикалық моделін жасау қажеттілігін көрсетеді. Бұл мақалада процестің математикалық моделіне негізделген жерасты шаймалау процесін басқарудың заманауи тәсілдері жан-жақты талқыланады. Әсіресе, уранның концентрациясы, орта өткізгіштігінің көрсеткіштері және басқа да геотехнологиялық сипаттамалар негізінде кен орнын игерудің тиімділігін арттыратын желілік гидродинамикалық модельге ерекше назар аударылады. Ағын шығыны мен тораптық қысымдар бойынша жүргізілетін өлшеулер айдау және сорғы ұңғымалары арасындағы кен орнында қысым айырмасын және гидравликалық кедергілерді нақты анықтауға мүмкіндік береді. Бұл параметрлерді дәл анықтау өндірістік тиімділікті арттыруға, энергия шығынын төмендетуге және реагенттерді үнемдеуге мүмкіндік береді. Алынған нәтижелер жерасты сілтісіздендіру процесін автоматтандыруда инновациялық шешімдерді әзірлеуге қажетті ғылыми негіз бола алады. Бұл шешімдер ұңғымаларды орналастырудың технологиялық схемасын жобалауға, ұяшықтың тиімді радиусын дәл анықтауға қолданыла алады. Зерттеу нәтижелері болашақта уран сілтісіздендіру процесін интеллектуалды басқару жүйесін құруда кеңінен пайдаланылатын болады. Жерасты сілтісіздендіру процесін зерттеуде нейрондық желілерді қолдану – ерекше ғылыми қызығушылық тудырады.

Түйін сөздер: жерасты шаймалау, уран өндіру, басқару жүйесі, желілік модель, интеллектуалды басқару жүйелері, желілік график, пайдалану өрісі

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СЕТЕВАЯ ГИДРОДИНАМИЧЕСКАЯ МОДЕЛЬ ПОДЗЕМНОГО ВЫЩЕЛАЧИВАНИЯ УРАНА

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Аннотация. Уран является стратегическим сырьём, широко применяемым в ядерной энергетике. Среди существующих методов добычи урана можно выделить методы: карьерный, шахтный и подземного выщелачивания. Последний метод признан наиболее экологичным и экономически эффективным для гидрогенных урановых месторождений. В Республике Казахстан методом подземного выщелачивания разрабатываются все гидрогенные урановые месторождения. Эффективность данного процесса в значительной степени зависит от своевременного управления его параметрами, что подчёркивает необходимость разработки математической модели процесса. В данной статье рассматриваются современные подходы к управлению процессом подземного выщелачивания на основе математической модели процесса. Особое внимание уделено сетевой гидродинамической модели процесса, которая позволяет на основе данных о концентрациях урана, показателях проницаемости среды и других геотехнологических характеристиках повысить рентабельность разработки месторождений. Измерения расходов потоков и узловых напоров в сети позволяют определять перепад давлений на рудном теле между закачной и откачной скважиной и гидросопротивление рудного тела. Определение этих параметров направлено на повышение производственной эффективности, сокращение энергозатрат и расхода реагентов. Полученные результаты создают научную основу для разработки инновационных решений в области автоматизации процесса подземного выщелачивания урана. Эти решения могут быть применены для проектирования технологической схемы расположения скважин и определения оптимального радиуса ячейки. В дальнейшем результаты данного исследования будут применяться для создания интеллектуальной системы управления процессом выщелачивания урана. Особый интерес представляет применение нейронных сетей для исследования процесса подземного выщелачивания урана.

Ключевые слова: подземное выщелачивание, добыча урана, система

управления, сетевая модель, интеллектуальные системы управления, граф сети, эксплуатационное поле

Introduction.

The development of a hydrogenous uranium deposit is carried out by the simplest, highly effective method of in-situ leaching (ISL) (Laverov et al., 1998). Uranium is extracted from the ore body through a system of process wells. A working solution, usually consisting of a sulfuric acid solution capable of dissolving uranium-containing minerals, is fed into the productive horizon through injection wells. As a result of the physicochemical interaction of the leaching solutions with the ore-forming minerals in the productive horizon, a productive solution is formed containing useful components, which is then extracted to the surface using a system of pumping wells (Beletsky et al., 1997). The main objectives of managing the geotechnological process of in-situ leaching are to increase the profitability of deposit development, increase the share of uranium extracted from the productive horizon, and reduce groundwater pollution (Zhiganov et al., 2001). To solve these problems, information is needed on the hydrogeological state of the productive horizon and groundwater, as well as methods of deposit development (Muzaparov, 2011). Hydrogeological initial data include information on the permeability of ores and host rocks, the position of the piezometric level of groundwater, the pressure of various aquifers found in the deposit section and the nature of their connections with each other, the temperature and composition of groundwater (Ravshanov et al, 2025). These data are needed to determine the isolation zones in wells, select the number of columns when designing wells, determine the type of well pump for pumping out productive solutions and select the design of the receiving part of the wells (Istomin et al., 2013).

In the Republic of Kazakhstan, the underground leaching method is used for all hydrogenic uranium deposits. The advantage of the method is the processing of large reserves of poor ores, as well as individual deposits with small reserves of the useful component. Despite this, the efficiency of this process largely depends on the timely management of its parameters, which emphasizes the need to develop a mathematical model of the process. The existing practice of managing the technological process of underground leaching is aimed at maintaining the balance flow characteristics of leaching and productive solutions. In this case, the tasks for flow characteristics are determined empirically. Thus, the process is controlled under conditions of insufficient information on the current characteristics of the ore body.

This paper proposes the development of a network hydrodynamic model of the in-situ leaching process, designed to optimize uranium mining by the in-situ leaching method, allowing the selection of the optimal method for developing a deposit.

In practice, depending on the location of injection and extraction wells, the

scheme for opening the production field of a hydrogenous uranium deposit is determined (Altayev et al., 2003).

Materials and methods

The objective of ISL process management is to increase the efficiency of uranium extraction from the subsoil and reduce the cost of uranium mining. This can be achieved by creating optimal physical and chemical conditions for the transition of uranium from ore to process solutions and optimal hydrodynamic conditions for uranium extraction to the surface with the productive solution through pumping wells. Factors that negatively affect the efficiency of ISL are incorrect layout of process wells, dilution of the productive solution with formation waters, the release of process solutions beyond the ore deposits, uneven leaching of uranium in the block and the formation of pillars, and low intensity of uranium extraction (Bugenov et al., 2006). These phenomena lead to an increase in the terms of block development, an increase in the specific consumption of acid and the L:S ratio, a decrease in the concentration of uranium in the productive solution, and, as a consequence, an increase in material and financial costs per unit of output (Dzhakupov, 2019).

Results. One of the main indicators of the underground leaching process is the pressure difference on the ore body between the injection and extraction wells, which is determined by Darcy's law (Mukhanov at al., 2016).

$$\triangle P_i = r_i Q_i \tag{1}$$

where r_i – is the hydraulic resistance of the ore body.

The value r – of hydraulic resistance to filtration of a liquid solution in a porous medium during plane-radial movement is determined by the expression (Rogov et al., 2000):

$$r = \frac{ln\frac{R_0}{R_c} + C_k}{2{,}3K_\Phi H} \tag{2}$$

The process of underground leaching includes the simultaneous operation of N process wells, consisting of $N_{эс}$ injection wells and $N_{ос}$ pumping wells.

$$N = N_{эс} + N_{от} \tag{3}$$

In addition, depending on the location of the process wells, linear, hexagonal and square underground leaching schemes are distinguished (Tsoy et al., 2016).

Thus, the well network with the technological layout scheme and with the ore-bearing permeable layer, as well as with surface pipelines and pumps form a single network hydrodynamic structure. This network structure is a very complex artificial network system (wells, filters, pipelines, pumps), interacting with an even more complex natural system - a rock massif containing an ore-bearing layer (Ismanova et al., 2021).

Using the principle of superposition of the potential field △P of pressures on wells, taking into account the interaction of all N wells with each other for a

stationary steady flow, we obtain the following system of equations (Rogov et al., 2000).

$$\begin{cases} r_{11}Q_1 + r_{12}Q_2 + \cdots + r_{1N}Q_N = \triangle P_1 \\ r_{21}Q_1 + r_{22}Q_2 + \cdots + r_{2N}Q_N = \triangle P_2 \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ r_{N1}Q_1 + r_{N2}Q_2 + \cdots + r_{NN}Q_N = \triangle P_N \end{cases} \quad (4)$$

where Q_i – is the productivity of the i-th well.

The productivity of a pumping well is determined by the expression (Yazikov, 2014).

$$\frac{1{,}157 \cdot n \cdot 2\pi \cdot K_ф \cdot M_э \cdot (S_н + S_o)}{100 \cdot (ln\frac{R_o}{R_c} + S_k)} \quad (5)$$

We determine the productivity of the injection well, that is, the injection of the working reagent into the formation per unit of time:

$$Q_э = \frac{1{,}157 \cdot n \cdot 2\pi \cdot K_ф \cdot M_э \cdot S_н}{100 \cdot (ln\frac{R_o}{R_c} + S_k)} \quad (6)$$

Where,

R_o –optimal cell radius, m;

R_c –actual cell radius, m;

$K_ф$ –filtration coefficient in the ore part of the horizon;

$M_э$ –effective capacity of the productive horizon;

$S_н$ – pressure at injection wells, m H2O;

S_k – depression in pumping wells, m of water column;

n –the ratio of the number of injection wells to the number of pumping wells.

The optimal cell radius is determined from the following expression (Yazikov et al., 2005) for the hexagonal scheme:

$$R_o = \sqrt[4]{\frac{S \cdot (n+1) \cdot H \cdot C_{ckk} \cdot K_ф \cdot \beta \cdot (n \cdot S_н + S_o) \cdot \pi \cdot \ln\,(ln\frac{R_I}{R_c})}{395 \cdot f \cdot \rho_n \cdot C_э}} \quad (7)$$

Where

$$\beta = \frac{4{,}23}{\left(ln\frac{R_I}{R_c} + S_k\right) \cdot \ln\,(ln\frac{R_I}{R_c})} \quad (8)$$

Optimal radius of the linear process flow diagram:

$$R_o = \sqrt[4]{\frac{S \cdot (n+1) \cdot H \cdot C_{ckk} \cdot K_ф \cdot \beta \cdot (n \cdot S_н + S_o) \cdot \pi(\xi^2 + 0{,}25)^2 \cdot \ln\,(ln\frac{R_I}{R_c})}{160 \cdot f \cdot \rho_n \cdot C_э \cdot \xi(\xi+1)^2}} \quad (9)$$

$$\beta = \frac{11{,}04}{\alpha \cdot \left(ln\frac{R_I}{R_c} + S_k\right) \cdot \ln\left(ln\frac{R_I}{R_c}\right)} \quad (10)$$

The optimal radius of a square cell is determined by the following expression:

$$R_o = \sqrt[4]{\frac{S \cdot (n+1) \cdot H \cdot C_{ckk} \cdot K_ф \cdot \beta \cdot (n \cdot S_н + S_o) \cdot \pi(\xi^2 + 0{,}25)^2 \cdot \ln\left(ln\frac{R_I}{R_c}\right)}{331 \cdot f \cdot \rho_n \cdot C_э \cdot \xi(\xi+1)^2}} \quad (11)$$

Where ξ – the ratio of the distance between rows to the distance between pumping wells in a row;

R_l – approximate cell radius, m;

f – W:T ratio;

ρ_n – density of rocks of the ore horizon;

$C_э$ – daily operating costs for the mine;

C_{ckk} – cost of 1 linear meter of a technological well;

α –distance between pumped wells in a row, m.

$$\xi = \frac{b}{d}$$

b –distance between pumping and injection rows, m;

d – distance between pumping wells in a row, m.

Let us consider the arrangement of the sets of injection $N_э$ and extraction N_o using the example of a network graph (Figure 1).

Considering that $\triangle P_i = P_{эi} - P_{oj}$ in accordance with the graph $G_o = (U, \Gamma)$ (Figure 1), we have expenses along the arcs [13]:

$$\begin{cases} q_{1-1} = \frac{1}{r_{11}} \Delta P_1 \\ q_{2-2} = \frac{1}{r_{22}} \Delta P_2 \\ \dots\dots\dots\dots\dots\dots \\ q_{i-j} = \frac{1}{r_{ij}} \Delta P_{ij} \end{cases} \quad (12)$$

From equations (12) we obtain the flow rates of all $N_{эс}$ and N_{oc} in the form of expenses along arcs $i - j$.

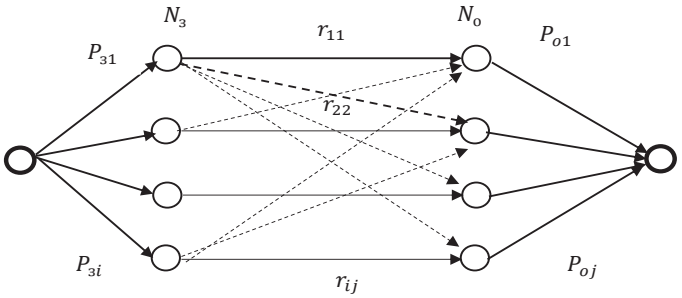

Figure 1-Graph G0 hydrodynamic system of underground leaching of uranium

For injection wells:

$$\begin{cases} Q_1 = \sum_{j=1}^{N_{oc}} q_{1-j} \\ Q_2 = \sum_{j=1}^{N_{oc}} q_{2-j} \\ \cdots\cdots\cdots\cdots\cdots \\ Q_i = \sum_{j=1}^{N_{oc}} q_{i-j} \end{cases} \quad (13)$$

Similarly for pumping wells:

$$\begin{cases} Q_1^o = \sum_{j=1}^{N_{зc}} q_{j-1} \\ Q_2^o = \sum_{j=1}^{N_{зc}} q_{j-2} \\ \cdots\cdots\cdots\cdots\cdots \\ Q_i^o = \sum_{j=1}^{N_{oc}} q_{j-i} \end{cases} \quad \text{t (14)}$$

For an ideal network $G_o = (U, \Gamma)$ the law of conservation of mass will always be observed in the form (Omelchenko A., 2018):

$$c_{зc} \sum_{i=1}^{N_{зc}} Q_i = c_{oc} \sum_{j=1}^{N_{oc}} Q_j^o \quad (15)$$

where $c_{зc}$ – is the density of the solution at the input, $т/м^3$;

c_{oc} –solution density at the outlet, $т/м^3$

In the case where the productivity of injection wells is greater than the productivity of pumping wells, the solution spreads beyond the geometric contour of the geological block.

$$c_{зc} \sum_{i=1}^{N_{зc}} Q_i > c_{oc} \sum_{j=1}^{N_{oc}} Q_j^o \quad (16)$$

In cases where the productivity of injection wells is less than the productivity of pumping wells, the solution becomes diluted with water.

$$c_{эс}\sum_{i=1}^{N_{эс}} Q_i < c_{ос}\sum_{j=1}^{N_{ос}} Q_j^o \quad (17)$$

If the pressure at injection wells and the depression at pumping wells is a function of time S_н=f(t) and $S_k = f(t)$, then, accordingly, $\Delta P_i = f(t), t \in (0,T), i = 1,N$.

Taking into account that the well parameters change depending on time, the system of equations (4) can be written in the form of partial differential equations:

$$\begin{cases} r_{11}\frac{\partial Q_1(t)}{\partial t} + r_{12}\frac{\partial Q_2(t)}{\partial t} + \cdots + r_{1N}\frac{\partial Q_N(t)}{\partial t} = \frac{\partial \triangle P_1(t)}{\partial t} \\ r_{21}\frac{\partial Q_1(t)}{\partial t} + r_{22}\frac{\partial Q_2(t)}{\partial t} + \cdots + r_{2N}\frac{\partial Q_N(t)}{\partial t} = \frac{\partial \triangle P_2(t)}{\partial t} \\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\ r_{N1}\frac{\partial Q_1(t)}{\partial t} + r_{N2}\frac{\partial Q_2(t)}{\partial t} + \cdots + r_{NN}\frac{\partial Q_N(t)}{\partial t} = \frac{\partial \triangle P_N(t)}{\partial t} \end{cases} \quad (18)$$

Using the finite difference method $\Delta t_1, \Delta t_2, \ldots, \Delta t_N$ we find the solution to equations (18). In this case, the system of equations (4) is valid at each time interval Δt_i.

Discussion.

Analysis of modern methods of underground leaching of uraniumshows that the efficiency of the leaching process depends most of all on the technological scheme of the well arrangement, the distance between rows, the distance between pumping wells in a row, the distance between injection wells in a row, i.e. on the hexagonal, triangular, square or linear scheme of the well arrangement (Alibaeva, 2013). Hydrodynamic flows in this case depend on the hydraulic resistance of filtration of the liquid solution in the porous medium, the filtration coefficient and the thickness of the ore-bearing filter layer (Galtsev et al., 2018). The flow rate of the pumping and injection well is directly proportional to the values of depressions and compressions in the pumping and injection wells and inversely proportional to the hydraulic resistances of the arcs of the graph between the pumping and injection wells (Terovskaya et al., 2021). For the most efficient metal recovery, the volume of the injected acid solution should be equal to the volume of the extracted productive solution. In this case, the balance of ore flows is regulated by pumping pumps. Selecting the optimal parameters of the well network allows for effective management of the process of underground leaching of uranium.

The main element of the control of the underground leaching process are mathematical models describing the processes occurring during uranium mining by the underground borehole leaching method. The mathematical model of the technological network allows determining the productivity of pumping and injection wells with known values of the network nodal pressures and the coefficient of hydraulic resistance of filtration. With known values of Q_i, Q_i^o and ΔP_{ij}, network models allow us to calculate the values of r_{ij}. Determining the values of r_{ij} of the

hydraulic resistance to filtration allows us to predict the costs along the network arcs, which allows us to effectively manage the process of underground leaching of uranium, adapt to changes in raw materials and optimally extract valuable components, which leads to increased productivity and reduced costs in the mining industry. Thus, the location of process wells along the geometric contour of a geological block with given network parameters is an important indicator of the process of underground borehole leaching of uranium.

Conclusions.

The results of the study confirm the high importance of the network approach in modeling and managing the process of underground leaching of uranium. The developed hydrodynamic model, based on graph theory and filtration equations, allows taking into account the spatial structure of the well system and predicting changes in flow parameters in real field conditions. Calculations of optimal cell radii for various well placement schemes (hexagonal, square, linear) allow a reasonable approach to the design of the production field. Measurements of reserves and nodal heads in the network allow for accurate determination of pressure differences between injection and pumping wells, as well as the hydraulic resistance of the ore body. This is critically important for maintaining flow balance, reducing solution losses and increasing the uranium recovery factor.

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