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АКЦИОНЕРНОЕ ОБЩЕСТВО «НАЦИОНАЛЬНАЯ АТОМНАЯ КОМПАНИЯ «КАЗАТОМПРОМ»
АО «ВОЛКОВГЕОЛОГИЯ»

СБОРНИК ТРУДОВ

IX МЕЖДУНАРОДНОЙ НАУЧНО-ПРАКТИЧЕСКОЙ КОНФЕРЕНЦИИ

АКТУАЛЬНЫЕ ПРОБЛЕМЫ УРАНОВОЙ ПРОМЫШЛЕННОСТИ

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АО «НАЦИОНАЛЬНАЯ АТОМНАЯ КОМПАНИЯ «КАЗАТОМПРОМ»
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Часть 1

Алматы
2019

AUTOMATED DESIGN MODULE TO DETERMINE OPTIMAL WELL LOCATIONS FOR URANIUM DEPOSITS DEVELOPMENT WITH IN-SITU LEACHING METHOD

Shayakhmetov N.M., Aizhulov D.Y., Kurmanseiit M.B., Tungatarova M.S., Kaltayev A.
Satbayev University, Almaty, Kazakhstan

The automated design module (MAP) of uranium deposits will automatically determine the location of wells, deposit development modes (filters positions, flow rates and injectivity at wells) depending on the chosen well pattern, uranium distribution in the reservoir, flow rates at injecting wells, kinetics of chemical processes.

During the reporting period, a preliminary version of the automated design module was developed, which allows building cellular well patterns based on the results of geological modeling, which is performed in the mining and geological information module. As a result of geological modeling, the distribution of uranium in solid form, permeability, porosity and lithological composition of the formation are determined.

The choice of the field opening scheme directly depends on the hydrodynamic characteristics and the mineralogical composition of the formation, since, depending on the layout of the wells, the distribution of velocities and pressures in the formation changes. The main schemes for the well placement for uranium deposits during the extraction by the ISL method are row scheme and cellular schemes [1]. The hexagonal extraction pattern is a special case of cellular and is convenient from the point of view of geometry for filling any area; consequently, it is the most commonly used extraction scheme for rollfront uranium deposits in Kazakhstan.

Authors developed an algorithm to generate a hexagonal well pattern scheme depending on the distance between the injection and production wells (r). The algorithm allows building grids for almost any geometry of mineral distribution and consists of the following steps:

1 filling the calculated area with a network of producing wells. The coordinates of production wells x_p, y_p are determined depending on the distance between the injection and production wells and the size (width - x_A, length - y_A) of the computational area:

for uneven rows:

$$x_p = \sqrt{\frac{3}{4}}\, r + p_x \cdot \sqrt{3}\, r\,, \qquad 0 \le p_x < 1 + \frac{x_A - \sqrt{\frac{3}{4}}\, r}{\sqrt{3}\, r} \tag{1.1}$$

$$y_p = r + p_y \cdot \frac{3}{2} r, \qquad 0 \le p_y < 1 + \frac{2}{3}\left(\frac{y_A - r}{r}\right) \tag{1.2}$$

for even rows:

$$x_p = p_x \cdot \sqrt{3}\, r\,, \qquad 0 \le p_x < \frac{x_A - \sqrt{\frac{3}{4}}\, r}{\sqrt{3}\, r} \tag{1.3}$$

$$y_p = r + p_y \cdot \frac{3}{2} r, \qquad 0 \le p_y < 1 + \frac{2}{3}\left(\frac{y_A - r}{r}\right) \tag{1.4}$$

2 removal of wells in the off-balance zone (zone with a uranium content below the profitability threshold from the user's point of view):

$$\text{if } C_{SM}(x_p, y_p) = 0, \text{then } x_p = y_p = 0 \tag{1.5}$$

3 constructing a hexagonal network of injection wells around each production well:

$$\begin{aligned} \xi_i &= x_p - r \cdot cos\left(n_{ip} \cdot \frac{2\pi}{N_{ip}}\right) \\ \zeta_i &= y_p - r \cdot sin\left(n_{ip} \cdot \frac{2\pi}{N_{ip}}\right) \end{aligned} \tag{1.6}$$

where, for hexagonal network of wells: $N_{ip} = 6, \quad 1 \le n_{ip} < N_{ip} + 1$,

4 search and delete wells located at the same point:

$$\text{if } \xi_i = \xi_k \text{ и } \zeta_i = \zeta_k \text{ then } \xi_k = \zeta_k = 0 \tag{1.7}$$

5 centering of the network of wells is performed relative to the geometric center of the ore body.

Based on the above algorithm, automated design module was developed. The interface of the computer-aided design module is a form with controls: a control panel; input data entry panel; panel display information about the geological model; well information display panel; map display panel.

The control panel of ADM is designed to allow user: start the calculation, control the displayed elements (hide/show the injection wells, production wells, grid and cell borders) and enable/disable the manual control mode. Upon starting calculation, the location of wells, project wells are created using the algorithm shown above. The location of the project wells is determined depending on the data entered in the input data panel.

In the input panel, the user enters the main characteristics of the deposit extraction scheme using the ISL method. At the beginning, the well grid type is selected: cellular or row swell patterns. In the field “injection production (I/P) ratio in one cell”, the ratio of the number of injection and production wells in one technological cell is entered. For hexagonal scheme I/P ratio is equal to six. The distance between the injection and production wells in meters are entered in the field “Distance between injection to production wells”, which is used to calculate the number of technological cells in the block under consideration. The off-balance condition determines the concentration and permeability at which the extraction is profitable, which depends on the prime cost of uranium at the present time and is determined by the economic state of the market.

The panel “Information on the geological model” displays the basic properties of the geological model: Lx, Ly, Lz - the length of the region along the x, y, z axes, respectively; dx, dy, dz is the size of one cell of the computational grid (not to be confused with the technological cell) along the x, y, z axes, respectively; Nx, Ny, Nz - the number of nodes of the computational grid along the coordinate axes.

The position of the “Average to Z” checkbox determines the image displayed on the map. If the checkbox is on, the map displays regions that are profitable by the average uranium concentration and permeability, and the color changes from blue to red depending on the ratio of uranium concentration and permeability in the reservoir. If the check box is turned off, the slider becomes active and the values of the ratio of uranium concentration and permeability on the *K* layer of the computational grid are displayed on the map. By moving the slider, the user can change the displayed layer from the bottom to the top along the Z axis. This allows user to see well patterns in the context of the mineralization distribution (projected to Z axis).

Upon clicking the button for calculating the location of wells, the “Grid Information” panel displays the main characteristics of the well grid for given input data and geological model, namely the number of wells (injecting and producing), the number of injecting wells, the number of producing

wells, the ratio of injecting and producing wells in the entire deposit (not to be confused with the ratio in a single cell).

The map displays the main elements of the field - these are wells, cell boundaries and a computational grid. The injection and production wells are marked in yellow and purple, respectively. Also, lines on the map mark the boundaries of the technological cells and nodes of the computational grids. When well is hovered over by the cursor, coordinates of the location of this well are displayed.

Manual well control mode allows the user to change the location of wells along the calculated grid by pointing and moving the cursor. At the same time, it is possible to select and move several wells by pressing the CTRL button on the keyboard (Figure 1).

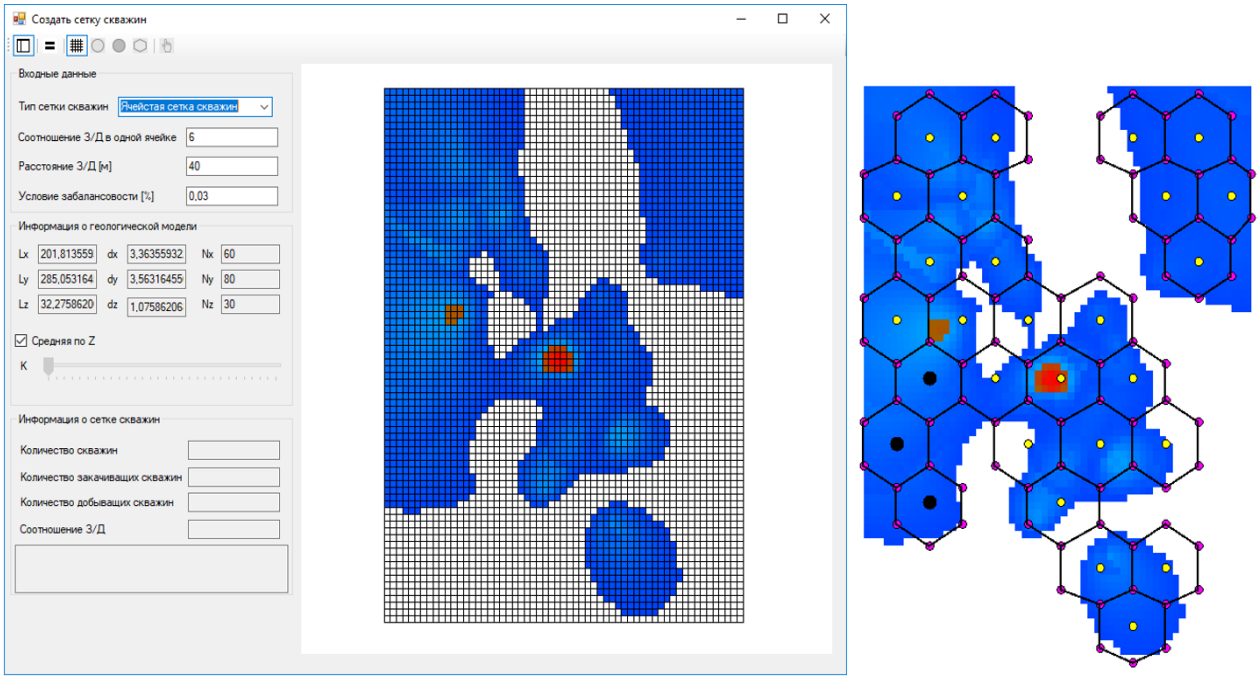

Figure 1 – Automated Design Module Interface

Performers conducted studies to find the optimal distance between the injection and production wells (r) using the computer-aided design module. As a geological model of the field, a rectangular area measuring 300x300 meters with a rectangular mineralization located in the center was taken, since such “ideal” forms allow a qualitative analysis of the leaching behavior for various properties of the well grid (Figure 2).

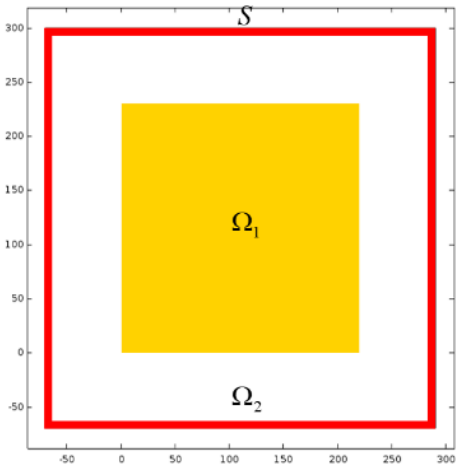

Figure 2 – The computational area under investigation: S is the boundary of the computational area, Ω_1 is the area with mineralization, Ω_2 is the area without mineralization

For the calculations, simple dissolution kinetics of hexavalent uranium sulfuric acid solution was used. For the proposed kinetics of uranium dissolution based on the law of mass action [2], a mathematical model of uranium leaching was constructed.

Equation of dissolution and transport of liquid components in the reservoir:

$$\underbrace{\phi\frac{\partial C_{BP}}{\partial t} + \underbrace{\rho\vec{U}grad C_{BP}}_{\text{transport}} = \underbrace{-k_1 C_{BP} C_{TM}}_{\text{reactions}} + \underbrace{Ni \cdot C^0_{BP} \cdot Qinj_i \delta(x-\xi_i, y-\eta_i)}_{\text{injection wells}} -}$$

$$\underbrace{- Np \cdot C_{BP} \cdot Qprod_p \delta(x-x_p, y-y_p)}_{\text{production wells}}$$

$$\underbrace{\phi\frac{\partial C_{ПР}}{\partial t} + \underbrace{\rho\vec{U}grad C_{ПР}}_{\text{transport}} = \underbrace{k_1 C_{BP} C_{TM}}_{\text{reactions}} - \underbrace{Np \cdot C_{ПР} \cdot Qprod_p \delta(x-x_p, y-y_p)}_{\text{production wells}}}$$

Dissolution of solid components:

$$\underbrace{\phi\frac{\partial C_{TM}}{\partial t} = \underbrace{-k_1 C_{BP} C_{TM}}_{\text{reactions}}}$$

where ϕ is porosity, C_{BP} is concentration of leaching solution, $C_{ПР}$ is concentration of productive (leached) solution, C_{TM} is concentration of solid mineral, $\vec{U}$ is velocity vector, k_1 rate of reaction coefficient, $Qinj_i$ debit i indexed injection well, $Qprod_p$ is injectivity of p-th production well, δ - Dirac delta function, ξ_i, η_i - coordinates of I indexed injection well, x_p, y_p coordinates of p numbered production well, Ni, Np - number of injecting and production wells respectively, t time variable, x, y - space variables.

The calculation of the distribution of pressure and velocity is based on the Darcy law and the Law of Mass Action:

$$div\left(\vec{U}\phi\right) = \underbrace{Ni \cdot Qinj \cdot \delta(x-\xi, y-\eta)}_{\text{injection wells}} - \underbrace{Np \cdot Qprod_p \delta(x-x_p, y-y_p)}_{\text{production wells}}$$

$$\vec{U}\phi = -\frac{K}{\mu} grad\ p$$

$$Ni \cdot Qinj - Np \cdot Qprod_p = 0$$

where p is pressure, K is permeability, μ is liquid viscosity.

The region is chosen so that the boundary conditions do not affect the nature of the flow inside the mineralized region, then boundary conditions are taken in the following form:

$$p(\vec{x} \in S, t) = 0$$
$$\frac{\partial C_{BP}(\vec{x} \in S, t)}{\partial \vec{h}} = \frac{\partial C_{ПР}(\vec{x} \in S, t)}{\partial \vec{h}} = 0$$

where S is a border of computational domain, $\vec{h}$ normal vector to the border of computational domain.

The initial conditions for the concentration of the production solution, the leaching solution and the solid mineral are shown below.

$$C_{BP}(\vec{x} \in \Omega_1 \text{ Y } \Omega_2, t = 0) = C_{ПР}(\vec{x} \in \Omega_1 \text{ Y } \Omega_2, t = 0) = 0$$
$$C_{TM}(\vec{x} \in \Omega_1, t = 0) = C^*_{TM}$$
$$C_{TM}(\vec{x} \in \Omega_2, t = 0) = 0$$

where Ω_1 is a mineralization area, Ω_2 is area without mineralization, C^*_{TM} is initial uranium concentration at the deposit (in real conditions is a field of values and is determined by the geological model).

At the same time, in order to preserve the law of continuity of flow, well debits must comply with the following equation:

$$Qprod_p = 10[м^3/час]$$
$$Qinj_i = \frac{N_p}{N_i} Qprod_p$$

As a result of the study, several different well patterns were considered (Figure 3).

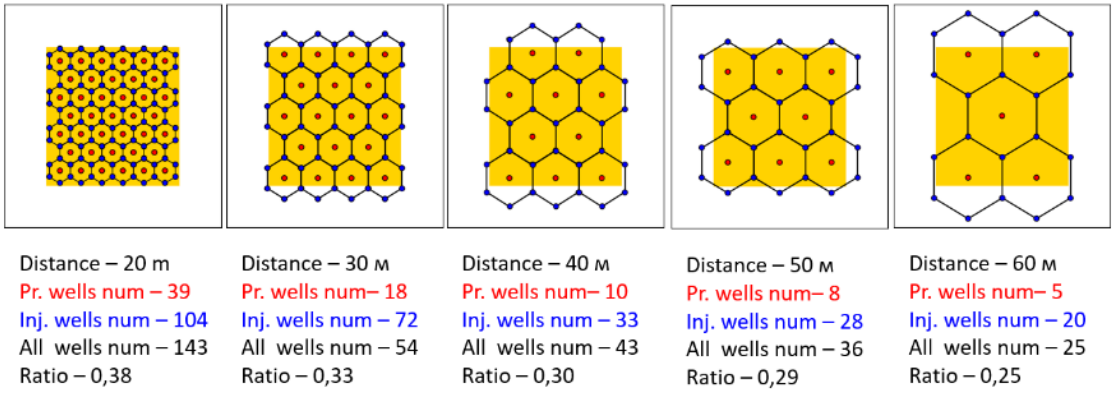

Figure 3 – Well patterns examined in the study

The optimality evaluation was carried out on the basis of the cost described in [3]: depreciation deductions; repayment of mining preparatory work; reagents; energy consumption; salary; general enterprise costs.

Depreciation charges, energy costs, salaries and general costs for an enterprise directly depend on the time the deposit is developed. The cost of repaying the mining preparatory work is determined by the number of wells, which in turn varies depending on the distance between the injection and production wells. The cost of reagents is determined by the volume of the injection fluid, which is determined by the ratio of the mass of leach solution to the mass of ore (L:S).

As a result of the research, the behavior of the degree of development over time was obtained depending on the distance between the wells (Figure 4).

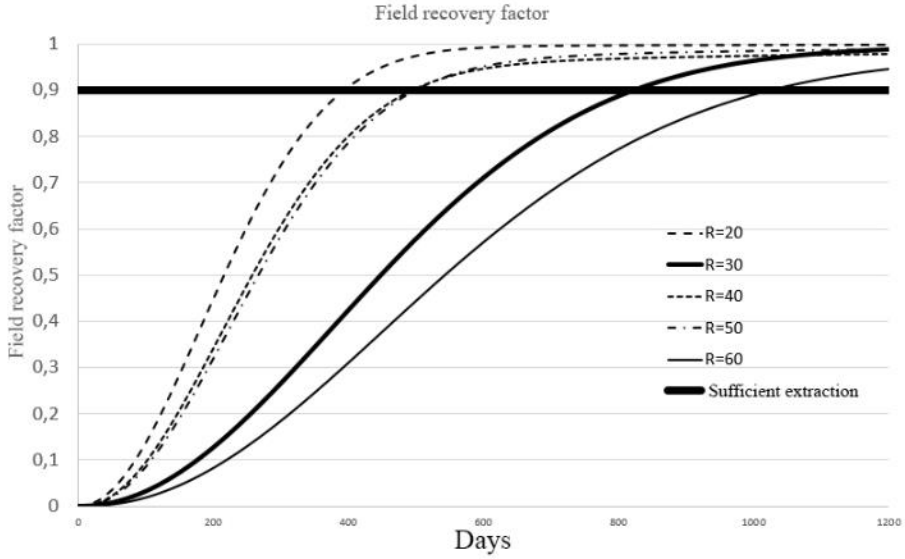

Figure 4 – The degree of development of the deposit depending on the different well patterns

Assuming, 90% (in fractions of 0.9) extraction degree is considered sufficient, according to Figure , an increase in the number of wells leads to a reduction in the time of mining to the level of sufficient extraction, and to a decrease in depreciation, energy, salary and total costs. However, with an increase in the number of wells, the costs of repaying the mining preparatory work, that is, the construction of wells, increase. However well pattern at the distance of 30 meters does not comply with aforementioned logic, since the location of wells at a given distance was not ideal and incomplete extraction was achieved, which proves that such studies should be carried out directly at the deposit and the nature of production depends significantly on the geological model of the field. As a result of the calculations, cost curves were constructed depending on the distance between the wells (Figure

5), and, to simplify the calculation of costs, the costs were divided into three classes: assumed construction cost - redemption of mining preparatory work; assumed acid costs - reagents; assumed operating costs - depreciation, as well as energy, salary and total costs for the enterprise.

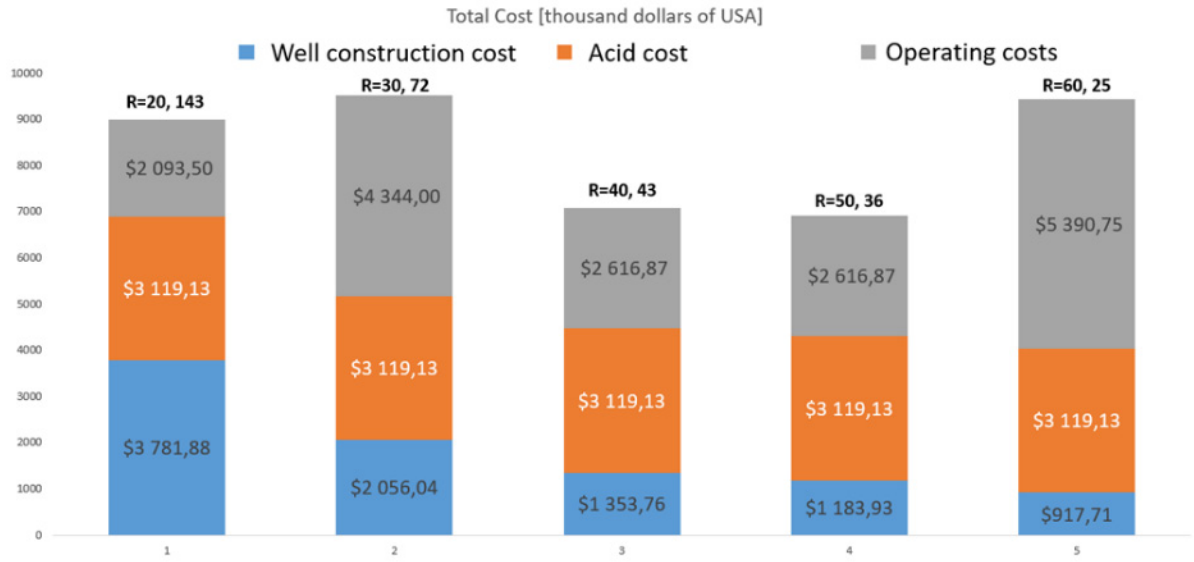

Figure 5 – the cost of exploitation the deposit with expenditure items depending on the distance between the wells

In conclusion, we can say that so far the distance between the wells of 40-50 meters is found to be optimal. This distance is recommended in most uranium mining literatures. However, for the reasons described above, such a distance is optimal only under “ideal” conditions; under real conditions, the optimal distance can vary significantly. The work was supported by the Ministry of Education of Kazakhstan through the program of targeted financing BR05236447.

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РАЗДЕЛ II
АКТУАЛЬНЫЕ ВОПРОСЫ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ И ИНТЕНСИФИКАЦИИ ТЕХНОЛОГИИ ПОДЗЕМНОГО ВЫЩЕЛАЧИВАНИЯ УРАНА