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THE MODELING OF URANIUM EXTRACTION PROCESS BY THE IN SITU LEACHING METHOD

1. INTRODUCTION

In-situ leaching (ISL) is a method for development of ore deposits without lifting the ore to the surface by selective transfer of ions of natural uranium into productive solution in subsurface. This method is realized by drilling wells through the ore deposit, pumping into leaching solution and metal-laden solution pumped back to the surface, and is extracted in a processing plant. The refine solution after addition solute component sends to the underground by injecting well, as illustrated in Figure 1.

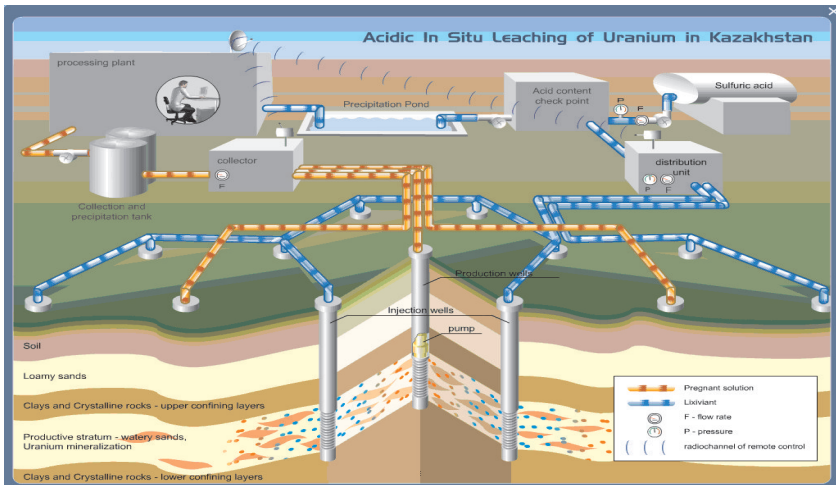


Fig. 1. Pictorial representation of the In-situ leaching process

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There are two main options for the leaching chemistry – acid or alkaline solutions. In general, acid solutions (such as sulfuric acid) will extract a higher proportion of uranium and at faster rates than alkaline solutions (such as sodium or ammonia bicarbonate). Solution of sulfuric acid and salt carbonate of ammonium, sodium, calcium are used as a reagent during the uranium mining. All uranium deposits in Kazakhstan are mining by in-Situ leach method using sulfuric acid solution. The ISL method is used in low concentrated and deep-laying deposits mining is the most cost-efficient and ecologically safe mining method known.

Under oxidizing conditions uranium exists in a highly soluble form, U^{6+} (an ion with a positive charge of 6), and is therefore very mobile. However under reducing conditions it converts to an insoluble form, U^{4+} , and is precipitated.

Governing reaction describing of uranium leaching process by sulfuric acid solution in schematic form [1]



Transfer reaction of useful element from solid phase to liquid phase is produced as



where:

M – gram-molecule of mineral (uranium) in solid phase,

R – gram-molecule of reagent (sulfuric acid),

P – gram-molecule of useful element of dissolved uranium,

W – gram-molecule of by-product in liquid phase (ex., water),

v_r, v_m, v_p, v_w – stoichiometric coefficient of reagent, mineral, useful element and water, respectively.

Mathematical and numerical models. The system of equation is considered with following conditions: the medium is homogeneous and isotropic, the density of solution and layer are constant, and solution flow on the layer border doesn't exist. Then this filtration process is described by conservation law and Darcy law

$$\operatorname{div} \vec{V} + \sum_{i=1}^{nw} q_{si} \delta(\vec{x} - \vec{x}_i) = 0 \quad (3)$$

$$\vec{V} = -K \operatorname{grad} H \quad (4)$$

Substituting equation (4) into the equation (3) and using $h = p/\rho g$, it's obtained equation for hydrodynamical pressure h in layer as following

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) = - \sum_{i=1}^{nw} q_{si} \delta(\vec{x} - \vec{x}_i) \quad (5)$$

here:

ρ – liquid density,

K_{xx}, K_{yy}, K_{zz} – filtration coefficient (permeability) in the direction of x, y, z correspondingly.

$$\frac{\partial \bar{C}_m}{\partial t} = -\gamma \epsilon C_R^0 \bar{C}_m \bar{C}_r \quad (6)$$

$$\begin{aligned} \frac{\partial \epsilon \bar{C}_r}{\partial t} = & \operatorname{div}(\epsilon D \operatorname{grad} \bar{C}_r - \bar{V} \bar{C}_r) - v_1 \gamma \epsilon C_m^0 \bar{C}_m \bar{C}_r - \sum_d q \delta(x_d, y_d, z) \bar{C}_r + \\ & + \sum_p q \delta(x - x_{0p}, y - y_0, z) \end{aligned} \quad (7)$$

$$\frac{\partial \epsilon \bar{C}_p}{\partial t} = \operatorname{div}(\epsilon D \operatorname{grad} \bar{C}_p - \bar{V} \bar{C}_p) + v_1 \gamma \epsilon C_m^0 \bar{C}_m \bar{C}_r - \sum_p q \delta(x - x_{0p}, y - y_0, z) \bar{C}_p \quad (8)$$

where

$$\bar{C}_m = \frac{C_m}{C_m^0}, \quad \bar{C}_r = \frac{C_r}{C_r^0}, \quad \bar{C}_p = \frac{C_p v_1}{C_r^0 v_2}, \quad v_1 = v_r R / v_m M, \quad v_2 = v_p P / v_m M,$$

here:

- C_m – concentration of uranium in solid phase,
- C_m^0 – initial content of mineral in layer,
- C_r – concentration of sulfuric acid in solution,
- C_r^0 – concentration of reagent on producing well,
- C_p – concentration of useful element (uranium) in solution,
- \bar{V} – filtration rate,
- q – debit of well,
- ϵ – porosity of layer,
- γ – coefficient, characterizing reaction rate,

$D_{i,j,k}$ – hydrodynamic dispersion coefficient, defined as

$$\left\{ \begin{aligned} D_{xx} &= \frac{\alpha_l u^2}{|V|} + \frac{\alpha_t v^2}{|V|} + \frac{\alpha_t w^2}{|V|} + D^* \\ D_{yy} &= \frac{\alpha_l v^2}{|V|} + \frac{\alpha_t u^2}{|V|} + \frac{\alpha_t w^2}{|V|} + D^*, \\ D_{zz} &= \frac{\alpha_l w^2}{|V|} + \frac{\alpha_t u^2}{|V|} + \frac{\alpha_t v^2}{|V|} + D^* \\ D_{xy} &= (\alpha_l - \alpha_t) \frac{uv}{|V|} + D^* \end{aligned} \right. \quad (9)$$

where:

α_L – longitudinal dispersive,

α_T – transverse dispersive.

Equations (6)–(8) are solved at initial and boundary conditions, respectively: mineral distribution in layer is known, concentration of solution and dissolved useful element doesn't exist at initial time.

$$C_m|_{t=0} = C_m^0, \quad C_r|_{t=0} = C_r^0, \quad C_p|_{t=0} = C_p^0 \quad (10)$$

$$C_m|_S = 0, \quad C_r|_S = 0, \quad C_p|_S = 0$$

The differential equation for hydraulic head (5) is solved by over relaxation iterative method. The filtration rate is defined from Darcy law using computed solution of head pressure. And transfer equation of reagent concentration in liquid phase (7), equation of useful element concentration in solid phase (6), and its transition to liquid phase (8) are solved by “Classics” scheme with upstream difference.

The design of ISL well fields varies greatly depending on the local conditions such as permeability, sand thickness, deposit type, ore grade and distribution. The scheme of linear location of well is shown in Figure 2. At this Figure 2 it is seen that the given area could be divided into symmetry blocks (area denoting with dashed line). According to the symmetry test calculation is realized for block of deposit width 20 m, and length 40 m, consisting of three wells: two injecting and one producing in the middle (Fig. 2b).

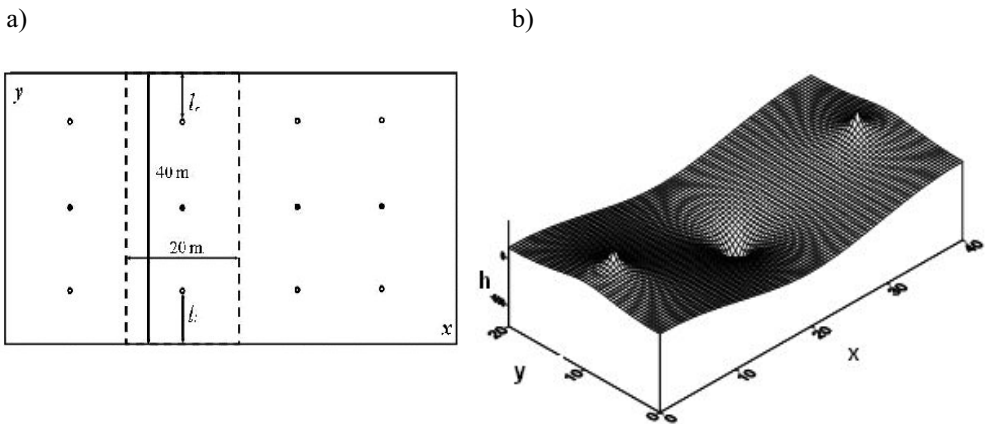


Fig. 2. Schematic picture of considering area (a); pressure distribution (b)

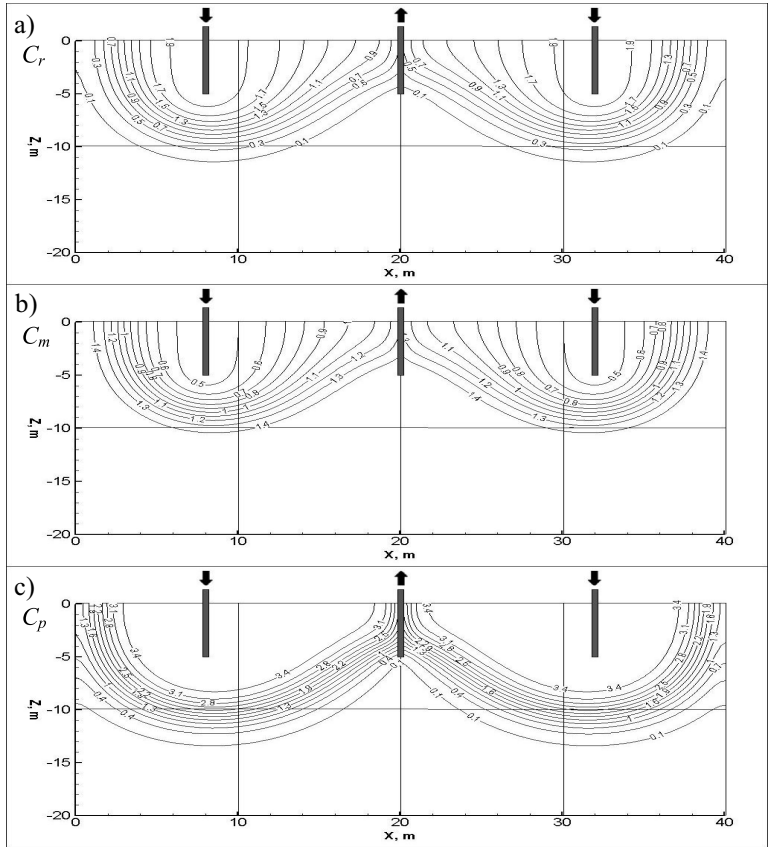


Fig. 3. Concentration isoline: a) reagent; b) mineral in solid phase; c) mineral in fluid phase, in layer at $t = 100$ day (vertical section along the well)

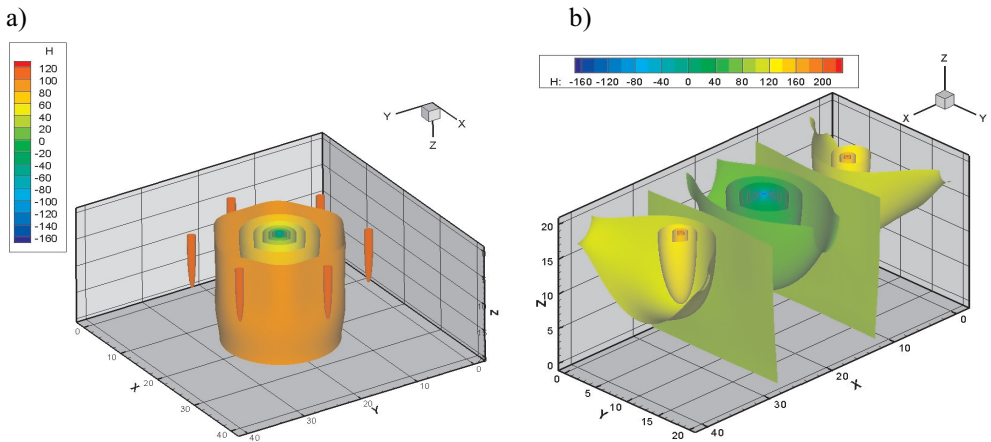


Fig. 4. Pressure isoline: a) hexagonal well location; b) linear well location

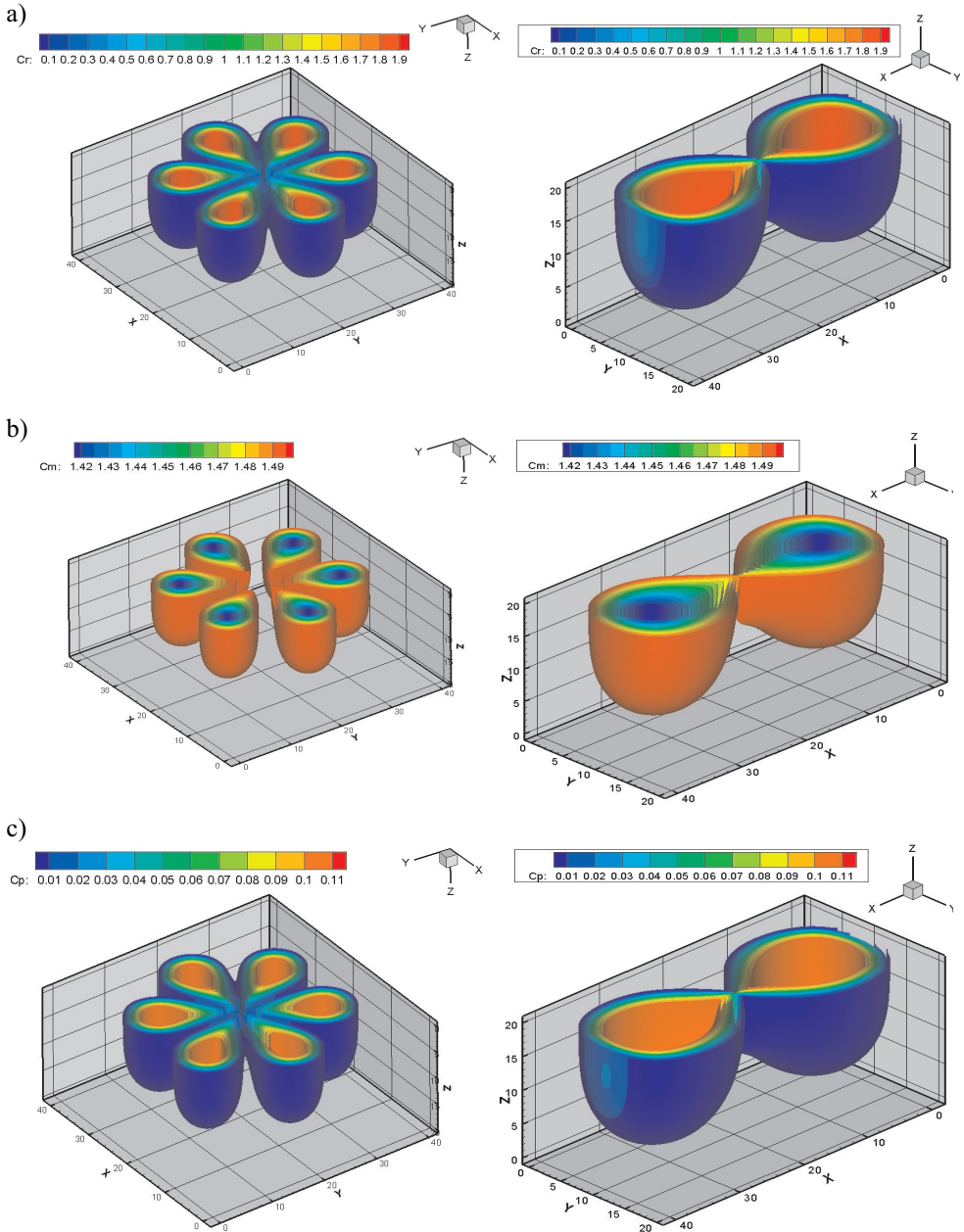


Fig. 5. Concentration isoline: a) distribution of reagent concentration; b) distribution of mineral in solid phase; c) distribution of mineral in liquid phase (hexagonal and linear well location, 3D)

The absolute stable method of “Classic” is used in the solution of 3D problems. The use of this method for 3D simulation is checked its accuracy by comparing results with 2D

simulation. It is supposed that the layers have been opened by wells from roof to the rare and hydrodynamic characteristics did not change in z-axis direction. The comparison shows that the given method has been correctly used for a three-dimensional simulation. The three-dimensional and two-dimensional both simulations have qualitatively and quantitatively identical results. The results of comparison of 3D and 2D simulations both are given below:

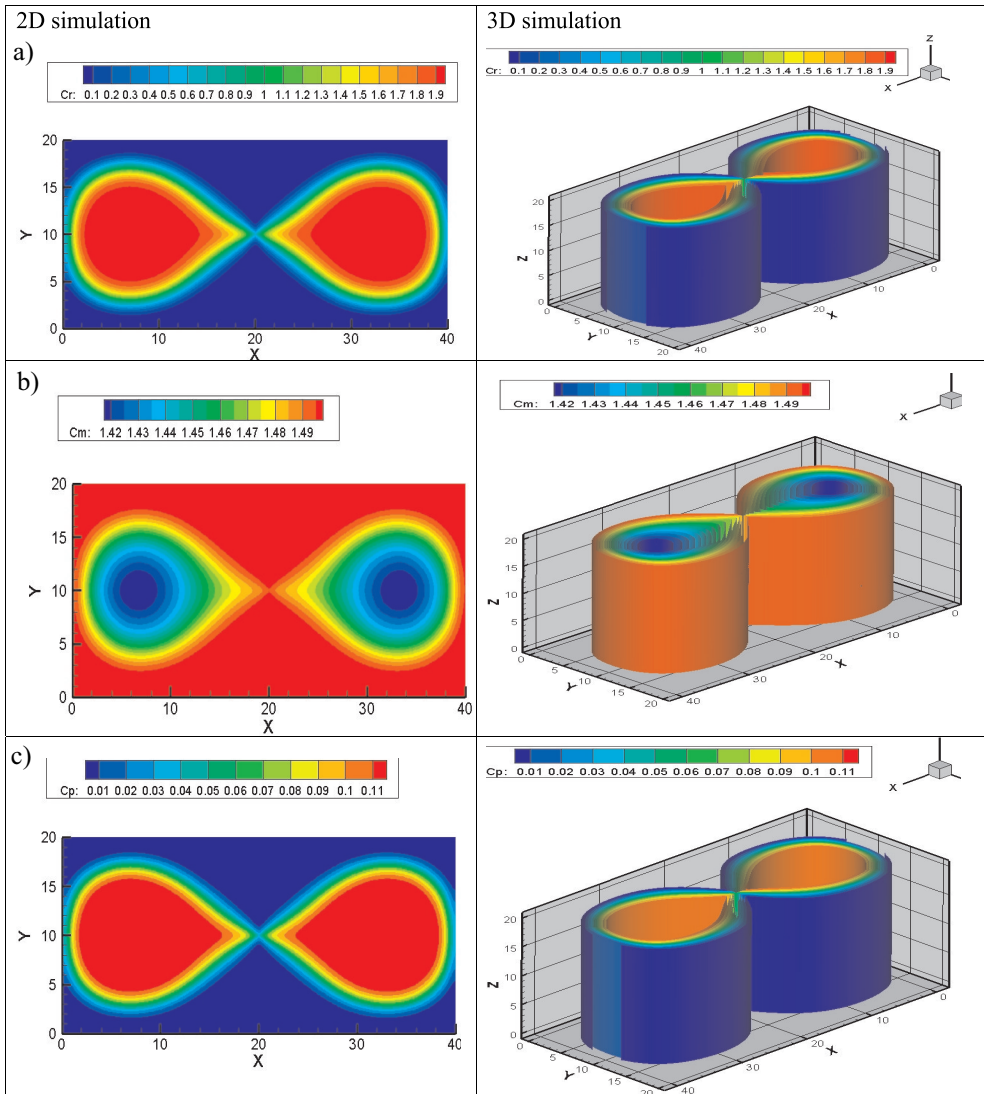


Fig. 6. Concentration distribution: a) reagent; b) mineral in solid phase; c) mineral in liquid phase

2. CONCLUSION

The model building describing processes which proceeds in the operational block at extraction of a mineral by the ISL method will allow choosing an optimum well location for maximum extraction of a mineral; defining optimum volumes of injecting solution; carrying out monitoring and forecasting at operation of deposits.

The processes proceeding at minerals extraction by ISL method are described by using the following equations: hydrodynamic pressure equation, the Darcy law, mineral dissolution equation and transfer equations of liquid solution and the dissolved mineral in a layer.

Because of nonlinearity of the pressure equation in general, its decision is driven using of the high relaxation iterative method. The field of speeds is defined from the Darcy law using the found values of a hydrodynamic pressure.

The system of the equations of mineral dissolution, transports of a liquid solution and the dissolved mineral are solved jointly. The algorithm of the decision of these equations is as follows: on each step of time, the reagent transport equation is solved by „the classics” scheme, distribution in a layer is defined from the analytical decision of the dissolution mineral equation on the obtained reagent distribution, the field of the dissolved useful component concentration is defined using the obtained mineral and reagent distributions in a layer.

In present work, the linear and hexagonal well locations are considered. The mathematical and numerical models, algorithm of calculation of uranium extraction process by the ISL method are elaborated. Distributions of a reagent, mineral in a solid and in a liquid phase are obtained. Influence of wells location on the extraction degree is investigated at the mineral extraction using the in-situ leaching method.

Using of elaborated computer program can essentially reduce expenses on extraction of mineral’s mass unit because of decreasing of wells number and reduction of duration of deposit’s exploitation because of control of wells functioning. In-situ leaching method can also be applied to other minerals such as copper and gold.

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