

Hydrodynamic Justification of the Effectiveness of Horizontal Wells for In-Situ Uranium Leaching in Low-Permeability Formations

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Received: August 28, 2026 Peer-reviewed: September 12, 2026 Accepted: September 28, 2026	ABSTRACT In-situ leaching (ISL) is the dominant method of uranium production from sandstone-hosted deposits, since its efficiency falls sharply in low-permeability ore horizons, where vertical wells create a narrow zone of hydraulic influence. This study quantifies how far a horizontal well can restore the productivity of such blocks and identifies the mechanism responsible for the gain. Steady-state Darcy flow was computed for a vertical well (Dupuit–Thiem) and for a 150 m J-shaped horizontal well (Joshi) using the parameters of Section 6–7 of the Budenovskoye deposit, Kazakhstan: $k_h = 1.0$ mD, $h = 8.0$ m, $k_z/k_x = 0.1$. The vertical-well solution was calibrated against measured field flow rates from the same section. The horizontal configuration raises productivity from 0.32 to 1.95 m³/day (a factor of 6.1), expands the swept pore volume by a factor of 2.9, and lowers the Darcy velocity at the sandface by a factor of 3.1. Assuming the same characteristic transport length and reaction parameters, the lower sandface Darcy velocity increases the relative Damköhler number by a factor of 3.1, indicating a greater potential for reaction during fluid residence. The effect on uranium recovery and non-target acid consumption requires validation using a fully calibrated reactive-transport model. Blocks with $k < 2$ mD and $h < 10$ m may therefore be recoverable with J-shaped wells.
	Keywords: in-situ uranium leaching, horizontal wells, low-permeability reservoirs, hydrodynamic modeling, reactive transport.
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1. Introduction

In recent decades, ISL has become one of the most effective and economically viable methods for the industrial recovery of uranium. This geotechnological approach is widely applied worldwide, including in Kazakhstan, Uzbekistan, the United States, and Australia. The fundamental principle of the method involves the non-invasive recovery of uranium-bearing ore through a system of wells that enables the injection of chemical reagents into the productive formation and the subsequent recovery of uranium-bearing solutions to the surface for processing. The method recovers uranium in place, through a system of injection and

production wells, without removing ore to the surface [1].

The Republic of Kazakhstan holds a leading position in the global uranium industry, accounting for approximately 40% of worldwide uranium production, almost entirely through in situ leaching (ISL) of sandstone-hosted deposits. Globally, ISL accounts for approximately 63% of uranium production [2].

Historically, vertical wells arranged in linear or grid patterns have been used to develop such deposits. The radial nature of fluid flow around a vertical wellbore produces a limited cylindrical drainage zone. Under low-permeability conditions, this requires substantial well-spacing reduction and

consequently leads to a sharp increase in capital expenditure.

The complexity of the ISL process is also associated with its specific geochemistry: the leaching reagent interacts not only with uranium-bearing minerals, such as uraninite and coffinite, but also with rock-forming minerals, including carbonates and clays. This results in the development of mobile geochemical barriers, where non-target acid consumption may reach hundreds of kilograms per kilogram of recovered uranium, and the resulting gypsum and Fe-Al precipitates progressively clog the pore space [[3], [4]].

One of the most promising approaches to improving ISL performance is using horizontal wells. Increasing the well-formation contact length to 150 m transforms the zone of influence from a cylindrical to an ellipsoidal geometry, substantially increasing the effective filtration area and promoting more uniform reagent distribution along the wellbore. Importantly, under ISR conditions, the effect of horizontal well exposure is expected to be more pronounced than in the oil and gas industry due to the specific characteristics of reactive transport: reduced filtration velocity increases the residence time of the reagent within the formation, thereby promoting more complete interaction with the target mineralization.

Horizontal completions have been standard practice in petroleum engineering for four decades, but their application to uranium ISL has been examined only recently. Chang et al. [5] compared horizontal-injection/vertical-extraction systems with conventional vertical patterns and found that horizontal injection suppresses low-velocity stagnant zones and concentrates the lixiviant within the ore body, although the total circulated volume was not necessarily higher. What has not been reported is a quantitative treatment of the case that matters most economically — an anisotropic, low-permeability ore horizon ($k < 2$ mD, $h < 10$ m) in which vertical wells fail outright — and an explicit link between the resulting flow field and the reaction regime. That gap defines the scope of the present work. This study has two objectives: (i) to quantify the productivity gain of a 150 m horizontal well over a vertical well under the anisotropic low-permeability conditions of Section 6–7 of the Budenovskoye deposit, and (ii) to establish whether that gain is hydrodynamic alone, or whether the accompanying reduction in filtration velocity also moves the leaching process into a more favourable reaction regime.

The scientific novelty of the study lies in the direct hydrodynamic comparison of well configurations under extremely low-permeability conditions ($k < 1$ mD), the identification of regularities governing the transformation of the leaching front, and the use of the Damköhler number to show that the advantage of a horizontal well in ISL is of a different nature from its advantage in oil production: here the reduced filtration velocity is itself part of the benefit, because it increases reagent utilisation rather than merely increasing throughput. The results provide a basis for considering the industrial implementation of J-shaped well trajectories for the development of hard-to-recover uranium reserves at the Budenovskoye deposit.

2. Materials and Methods

2.1 Mathematical Model of Fluid Flow

The conventional ISL configuration is based on a system of vertical injection and production wells. However, this well configuration has several limitations when applied to the development of low-permeability formations.

The radial nature of fluid flow around a vertical well results in a limited drainage zone. Under the vertical-well configuration, flow is predominantly radial and well productivity is controlled by the formation thickness and by the logarithm of the ratio of drainage radius to wellbore radius [5].

$$Q_v = \frac{2\pi kh(P_{res} - P_{wf})}{\mu \cdot \ln\left(\frac{R_e}{r_w}\right)} \quad (1)$$

Where Q - Well flow rate

k - Permeability

h - Thickness of the productive formation

P_{res} - Reservoir pressure

P_{wf} - Bottom-hole pressure

μ - Dynamic viscosity of the solution

R_e - Drainage radius

r_w - Well radius

Eq. (1) is the Dupuit–Thiem steady-state solution for radial flow to a fully penetrating well in a confined formation.

Under low-permeability conditions, the effective drainage radius is relatively small, requiring a larger number of wells to achieve the required production rate. This results in a substantial increase in capital expenditure [[1], [4], [5]].

$$Q_h = \frac{2\pi k_h h (P_{res} - P_{wf})}{\mu \left[\ln \left(\frac{a + \sqrt{a^2 - \left(\frac{L}{2}\right)^2}}{\frac{L}{2}} \right) + \frac{\beta h}{L} \ln \left(\frac{h}{2r_{eH}} \right) \right]}, \quad (2)$$

$$a = \frac{L}{2} \left[0.5 + \sqrt{0.25 + \left(\frac{2r_{eH}}{L} \right)^4} \right]^{\frac{1}{2}},$$

$$\beta = \sqrt{\frac{k_h}{k_v}}.$$

where L is the length of the horizontal section, m ; a - half-length of the major axis of the drainage ellipse, m ; r_{eH} - drainage radius of the horizontal well, m ; k_v - vertical permeability, m^2 ; β - anisotropy coefficient, dimensionless. For a like-for-like comparison with Eq. (1), r_{eH} is taken equal to R_e .

Joshi's solution is derived under the condition $L/2 < 0.9 r_{eH}$; with $r_{eH} = R_e = 50$ m and $L = 150$ m, this condition is not met, so the productivity ratio obtained below is an upper bound. Taking $r_{eH} = 85$ m — the radius of a circle of the same area as the racetrack-shaped drainage zone of the horizontal well, $\pi R_e^2 + 2R_e L$ — gives $Q_h = 1.38$ m³/day and a ratio of 4.3. The effect is therefore bracketed between 4.3 and 6.1.

Eq. (2) accounts for horizontal-plane flow and restricted vertical inflow in an anisotropic formation. It is Joshi's steady-state solution for a horizontal well in an anisotropic confined formation [6].

In addition, a vertical well configuration does not always provide uniform reagent distribution throughout the formation, which may reduce the uranium recovery [[2], [7]].

2.2. Input Data and Hydrodynamic Model Assessment

To evaluate the effectiveness of the J-shaped well trajectory, numerical modeling was performed using the boundary conditions presented in Table 1. Figure 1 shows the design trajectory of the J-shaped well adopted in the calculations. The selected permeability value (1 mD) and formation geometry ($h = 8$ m) correspond to some of the most challenging development conditions at the Budenovskoye deposit, where conventional vertical wells fail to achieve the designed recovery level.

Numerical modeling of the hydrodynamic processes was performed using COMSOL Multiphysics, a specialized software platform for solving fluid-flow equations in anisotropic porous media. The computational mesh and time-stepping scheme were optimized to adequately resolve the ellipsoidal geometry of the drainage zone surrounding the 150-m-long horizontal wellbore. The model incorporated the vertical permeability

anisotropy ratio ($k_z/k_x = 0.1$), which was a key factor in substantiating the transition from radial to predominantly linear flow geometry along the entire length of the horizontal filter. Incorporation of chemical kinetic equations into the model enabled the dynamic variation in reagent-ore mineral contact time (residence time) to be accounted for, thereby providing a more accurate prediction of production intensification under low-permeability reservoir conditions.

Table 1 - Initial Parameters for Hydrodynamic Modeling

Parameter	Symbol	Value
Horizontal formation permeability	k_h	1.0 mD ($10^{-15} m^2$)
Productive horizon thickness	h	8.0 m
Horizontal section (filter) length	L	150 m
Reservoir porosity	ϕ	0.25 (25 %)
Wellbore radius (based on a 161 mm bit diameter)	r_w	0.0805 m
Dynamic viscosity of the H_2SO_4 solution	μ	1.05 mPa·s
Permeability anisotropy	k_z/k_x	0.1
Vertical formation permeability	k_v	0.1 mD ($10^{-16} m^2$)
Reservoir pressure (at the ore-horizon depth)	P_{res}	6.0 MPa
Bottom-hole pressure (during pumping)	P_{wf}	5.5 MPa
Radius of the pressure-support/drainage boundary	R_e	50 m
Solution density	ρ	1020 kg/m ³

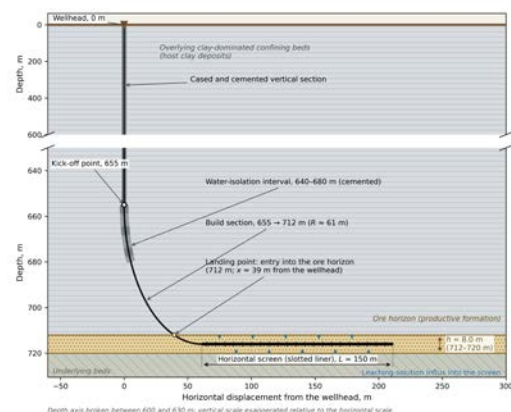


Figure 1 – Design trajectory of the J-shaped well in Sections 6-7 of the Budenovskoye deposit: kick-off point at 655 m, build section, and a 150 m horizontal screen within the 8 m ore horizon at 712-720 m. Vertical scale exaggerated; drawn from well-construction documentation

To validate the developed model, we compared the calculated performance indicators with actual data from the pilot-scale operation of Sections 6-7 at the Budenovskoye deposit, as well as with results from an independent uranium ISR field experiment previously conducted at the adjacent Section No. 2 of the same deposit. The validation process was carried out in two stages:

- Verification of the base scenario. Given the specified geological and technical parameters ($k=1.0$ mD, $h=8$ m), the model successfully reproduced the actual flow rate of vertical wells operating in this area. The calculated value $Q_v=0.32$ m³/day matched the field performance indicators, confirming the adequacy of the selected boundary conditions and filtration parameters.

- Convergence by radius of influence. The effective filtration radius for vertical wells established in the model (25–35 m) is consistent with the acidification zones observed in practice within the low-permeability blocks of the deposit, including field data from Section 2.

The convergence of results in the base (vertical) scenario provides a sufficient degree of reliability to interpret the predicted horizontal well flow rate (1.95 m³/day) for the purposes of this study. However, as noted in Section 4.4, direct field confirmation of the forecast for the horizontal configuration at this deposit is currently pending.

2.3. Drilling Technology and Trajectory Control

In the vertical well configuration, the effective radius of influence is determined by the following expression:

$$R_{eff} = R_e (r_w/R_e)^\alpha, \quad \alpha = 0.05-0.10 \quad (3)$$

R_{eff} is defined as the radius at which the drawdown has decayed to a fraction α of the drawdown at the wellbore. For $R_e = 50$ m and $r_w = 0.0805$ m this gives $R_{eff} = 36$ m at $\alpha = 0.05$ and 26 m at $\alpha = 0.10$. In the steady-state formulation, this radius is controlled by the geometry (R_e , r_w) and not by permeability; the resulting 26–36 m range is consistent with the acidification zones observed in the low-permeability blocks of the deposit. For a horizontal well, the influence zone acquires an ellipsoidal shape and encompasses a significant portion of the reservoir along the borehole axis. The effective area of filtration contacts increases proportionally to the length L . This is particularly critical in thin reservoirs characterized by pronounced vertical anisotropy ($k_z/k_x < 0.1$) and the presence of clay interlayers.

To ensure the target J-shaped or horizontal trajectory, directional drilling systems from the oil and gas industry, adapted for In-Situ Recovery (ISR) conditions, are employed: downhole hydraulic motors, rotary steerable systems (RSS), MWD (Measurement While Drilling) telemetry systems, LWD (Logging While Drilling) logging systems, and inclinometric sensors.

Wellbore trajectory is controlled by continuously measuring inclination, azimuth, and borehole curvature. Modern telemetry systems provide real-time information on drilling parameters, enabling high-precision well placement within the productive formation. The technical system comprises three main components: steering (rotary steerable systems (RSS) and downhole mud motors), navigation (measurement-while-drilling (MWD) and logging-while-drilling (LWD) systems for real-time lithological characterization), and drilling parameters, including drilling with three-blade PDC bits ($\varnothing 161$ mm) and roller-cone bits ($\varnothing 190$ mm) at a weight on bit of 200–800 kgf and a spindle rotational speed of 166–288 rpm, according to the geological and technical documentation for well construction.

2.4. Well Design and Materials

The well design must ensure chemical resistance to aggressive fluids and maintain annular integrity in accordance with the well construction regulations applicable to the Budenovskoye deposit [[6], [8], [9]]. Threaded connections of unplasticized polyvinyl chloride (uPVC) casing pipes must be thoroughly degreased with a solvent and bonded using a specialized adhesive to ensure complete casing-string integrity.

Quality control of well construction is completed through an acceptance procedure, under which the well is considered ready for operation only after confirming the absence of annular leaks, completion of all scheduled geophysical surveys, and verification that radiation levels do not exceed the established control limit. The concentration of suspended solid particles in the produced water must not exceed 50 mg/dm³.

- Materials: unplasticized polyvinyl chloride (uPVC 90 × 8) casing pipes; threaded connections are degreased and secured using a specialized PVC adhesive.

- Filter: wire-wrapped screen (KDF 118 × 90 × 0.8).

- Isolation: annular-space sealing over the 640–680 m interval is monitored by thermometry; the temperature anomaly associated with the cement sheath must be at least 1.8 °C.

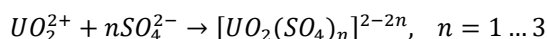
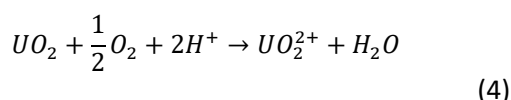
- Accuracy: the permissible deviation of the actual well position from the designed target point must not exceed 1 m.

This set of measures enables the potential of horizontal well exposure to be realized under conditions where conventional vertical wells fail to provide an economically viable level of uranium recovery [[10], [11]].

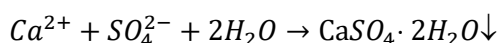
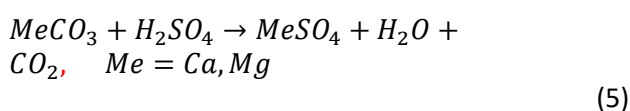
2.5. Physico-chemical reactive transport model

To adequately model ISR processes in the low-permeability reservoirs of the Budenovskoye deposit, the hydrodynamic filtration model was coupled with chemical kinetics equations. Reactive transport is described by a system of advection-diffusion equations considering chemical sources and sinks.

The process of uranium dissolution by sulfuric acid in the presence of an oxidant is described by the generalized equation:



Acid consumption due to reactions with the host rock (primarily carbonates) is also accounted for. This is critical for low-permeability reservoirs as it can lead to gypsum formation, which reduces the contact area between the solution and the ore mineral. Carbonate dissolution is represented by Eq. (5):



where Me denotes divalent cations (Ca^{2+}, Mg^{2+}) present in the host rock matrix. Subsequently, the accumulation of dissolved calcium and sulfate ions leads to secondary gypsum precipitation. The coupled reactive-transport formulation and Darcy flow velocity are defined by Eq. (6):

$$\frac{\partial(\phi C_i)}{\partial t} + \nabla \cdot (u C_i) = \nabla \cdot (\phi D_i \nabla C_i) - \sum_j v_{ij} R_j, \quad (6)$$

$$u = -\frac{k}{\mu} \nabla P.$$

where C_i is the concentration of the i -th aqueous species [$mol \cdot m^{-3}$], ϕ is the formation porosity [-], D_i is the hydrodynamic dispersion tensor [$m^2 \cdot s^{-1}$], v_{ij} is the stoichiometric coefficient of species i in reaction

j [-], R_j is the rate of reaction j [$mol \cdot m^{-3} \cdot s^{-1}$], u is the Darcy filtration velocity [$m \cdot s^{-1}$], k is formation permeability [m^2], μ is dynamic viscosity [$Pa \cdot s$], and P is reservoir pressure [Pa].

The uranium dissolution rate (R_u) is assumed to depend on the concentration of active sulfuric acid and the specific surface area of the solution-rock contact, the specific surface area is a property of the ore, but the total screen area in contact with the lixiviant is significantly larger for a horizontal well:

$$R_u = k_{chem} A_s [C(H_2SO_4)]^n \quad (7)$$

k_{chem} [$mol \cdot m^{-2} \cdot s^{-1} \cdot (mol \cdot m^{-3})^{-n}$], A_s [$m^2 \cdot m^{-3}$], and n [-].

where k_{chem} is the reaction rate constant, A_s is the specific mineral surface area, and n is the reaction order.

$$Da = \frac{k_{chem} A_s L_c \phi}{u} = \frac{t_{adv}}{t_{reac}} \quad (8)$$

where L_c is a characteristic transport length, and u is the Darcy velocity. Da compares the time a reagent spends in a rock volume with the time it needs to react. At $Da \ll 1$, the acid is swept past the mineral surface before reacting, and is consumed downstream on non-target carbonates; at $Da \approx 1$, reagent utilisation is highest. Eq. (8) is written for a first-order reaction ($n = 1$); for $n \neq 1$ the right-hand side must be divided by C^{n-1} to remain dimensionless. Because k_{chem} , A_s and L_c have not been measured for the ore of Section 6–7, only the ratio of Damköhler numbers between the two configurations is evaluated here, not their absolute values.

Because k_{chem} , A_s , and ϕ are properties of the ore and not of the well, the ratio of Damköhler numbers between the two configurations reduces to the inverse ratio of filtration velocities at the sandface:

$$\frac{Da_h}{Da_v} = \frac{u_v}{u_h} = \frac{7.95 \times 10^{-2}}{2.57 \times 10^{-2}} = 3.1$$

The horizontal well therefore operates at a Damköhler number three times higher than the vertical well under identical reservoir chemistry. This - not the flow-rate increase alone - is the reason the effect of horizontal completion in ISL is qualitatively different from its effect in oil production, where the reaction term is absent.

Da compares advective residence time with reaction time. The expression is consistent with the kinetic form used above.

Coupling these equations to the flow model gives a quantitative estimate of the horizontal well advantage. By reducing the filtration velocity (transitioning from radial to linear flow), the residence time of the reagent in the rock increases. This leads to higher saturation of the pregnant solution while maintaining a lower specific acid consumption rate [12].

3. Results

3.1. Comparative analysis of well productivity

Based on the equations for radial and linear filtration, the following flow rate indicators were obtained for a reservoir permeability of $k=1.0$ mD and a thickness of $h=8.0$ m:

- Vertical configuration: the calculated flow rate (Q_v) was $0.32 \text{ m}^3/\text{day}$ ($0.013 \text{ m}^3/\text{h}$);
- Horizontal configuration: with a horizontal filter length of $L=150$ m, the flow rate (Q_h) increased to $1.95 \text{ m}^3/\text{day}$ ($0.081 \text{ m}^3/\text{h}$).

The transition to a horizontal completion therefore increases productivity by a factor of 6.1.

Table 2 - Comparative Characteristics of the Hydrodynamics of Vertical and Horizontal Wells

Parameter	Vertical well	Horizontal well
Flow regime	Radial (Dupuit–Thiem)	Quasi-linear with elliptical end effects (Joshi)
Drainage-zone geometry	Cylindrical, $R_e = 50$ m	Elongated ellipsoid along the wellbore axis
Flow-rate equation	Eq. (1)	Eq. (2)
Effective radius of influence, Eq. (3)	26–36 m	26–36 m normal to the axis, over $L = 150$ m
Flow rate at $k = 1.0$ mD, $h = 8.0$ m	$0.32 \text{ m}^3/\text{day}$ ($0.013 \text{ m}^3/\text{h}$)	$1.95 \text{ m}^3/\text{day}$ ($0.081 \text{ m}^3/\text{h}$)
Productivity ratio	1.0	6.1
Darcy velocity at the sandface	$7.95 \times 10^{-2} \text{ m/day}$	$2.57 \times 10^{-2} \text{ m/day}$
Swept pore volume	$1.57 \times 10^4 \text{ m}^3$	$4.57 \times 10^4 \text{ m}^3$
Damköhler number, relative	1.0	3.1

The comparative characteristics of the hydrodynamic performance of vertical and horizontal wells are presented in Table 2. The results demonstrate the transformation of the flow regime and drainage-zone geometry associated with the transition from vertical to horizontal well exposure.

Figure 2 shows the well flow rate as a function of the horizontal screen length L , computed from Eq. (2) for the parameters of Table 1, together with the field-calibrated vertical-well flow rate obtained from Eq. (1).

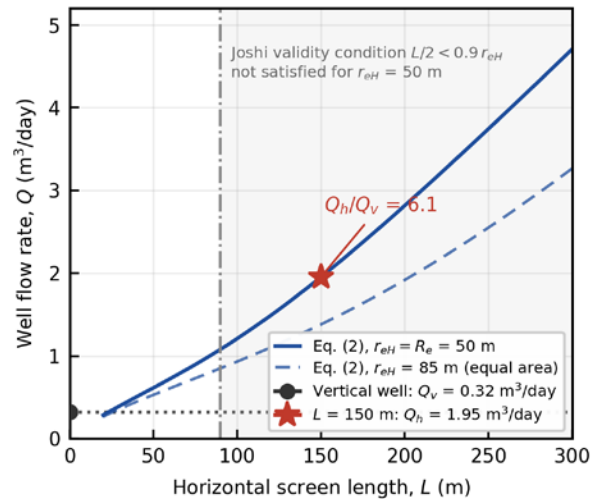


Figure 2 – Well flow rate as a function of horizontal screen length L , computed from Eq. (2) for $k = 1.0$ mD, $h = 8.0$ m, $k_z/k_x = 0.1$ and $r_{eH} = 50$ m. The field-calibrated vertical-well flow rate (Eq. 1) is shown for reference. The dashed curve is the same calculation with $r_{eH} = 85$ m, the radius of a circle of the same area as the racetrack drainage zone; the shaded band marks screen lengths for which the Joshi validity condition $L/2 < 0.9 r_{eH}$ is not satisfied at $r_{eH} = 50$ m

3.2. Transformation of the Zone of Filtration Influence

Analysis of the flow structure revealed a change in the geometry of the process when transitioning between well configurations:

- Radius of influence: In the vertical well configuration, at a permeability of $k = 1.0$ mD, the radius at which the drawdown has decayed to 5–10 % of its wellbore value is 36 and 26 m, respectively, resulting in the formation of “stagnant” zones between wells.
- Shape of the zone: For a horizontal well, the zone of influence transforms from a cylindrical to an ellipsoidal geometry, extending along the entire wellbore axis ($L = 150$ m). This increases the formation – wellbore contact area in proportion to the filter length.

Figure 3 shows the corresponding steady-state pressure fields around the vertical and horizontal wells, illustrating the transformation of the drainage-zone geometry from cylindrical to ellipsoidal described above.

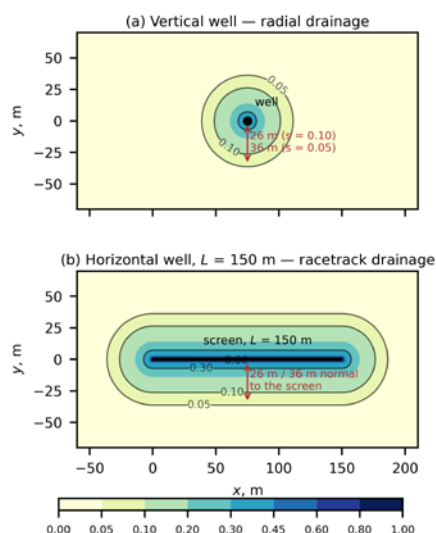


Figure 3 - Normalized steady-state drawdown ($P_{res} - P$)/($P_{res} - P_{wf}$) in the ore horizon around (a) a vertical well and (b) a 150 m horizontal well, computed with the parameters of Table 1. Both panels use the same colour scale and the same spatial extent, and the vertical well is placed at the midpoint of the horizontal screen so that the two drainage zones can be compared directly. The labelled isolines correspond to the 36 m ($s = 0.05$) and 26 m ($s = 0.10$) radii quoted in Section 2.3.

The comparison in Figure 3 shows that the two configurations differ not in the magnitude of the pressure drawdown, which is identical by construction, but in its spatial distribution. In the vertical case the pressure gradient is concentrated within the first few metres of the wellbore and has decayed to 10 % of its wellbore value at 26 m, leaving the volume beyond that radius effectively immobile. In the horizontal case the same gradient is distributed along 150 m of screen, so that the low-gradient region is confined to the two ends of the racetrack rather than occupying most of the block. It is this redistribution, rather than the increase in total flow rate, that removes the stagnant zones reported between vertical wells in low-permeability blocks [7].

4. Discussion

4.1 Role of Reactive Transport and the Damköhler Number

The results obtained demonstrate that the effect of horizontal well exposure in in-situ uranium leaching is substantially more pronounced than in

the oil and gas industry [[13], [14], [15], [16], [17], [18]]. This difference is attributable to the fundamental characteristics of reactive reagent transport under conditions of mineral dissolution [16]. In this context, the Damköhler number (Da) serves as a mathematical criterion of process efficiency, reflecting the balance between the rate of chemical dissolution and the rate of fluid filtration.

In conventional vertical wells, the radial flow regime results in an anomalously high filtration velocities in the near-wellbore zone. Consequently, the reagent does not have sufficient time to react completely with the ore minerals, leading to non-target acid consumption. In the horizontal well configuration, predominantly linear flow provides a more favorable range of Da . This enables the acidification front to propagate more uniformly along the entire filter length (150 m), thereby maximizing the residence time of the solution in contact with the formation. This mechanism minimizes the extent of under-leached zones and reduces the risk of premature solution breakthrough through high-permeability interlayers, which is particularly important for thin formations with a thickness of less than 10 m.

4.2. Comparison with Existing Studies

A critical review of global practices in acid ISL shows that the vast majority of operating deposits - in the United States and Australia, as well as across the post-Soviet region, including uranium deposits in Kazakhstan - have historically been developed using vertical well configurations arranged in five-spot or seven-spot patterns [17]. Despite the maturity of horizontal well technologies in the oil and gas industry [19], their application to in-situ uranium leaching remains limited. The results of the present study are consistent with the general direction of industry development identified in recent sectoral reviews [9] and indicate that horizontal well exposure may render some previously uneconomic low-permeability blocks economically viable for development. The permeability anisotropy ratio adopted in the model, $k_z/k_x=0.1$, is consistent with the typical ranges reported for sandstone-hosted uranium-bearing reservoirs in the specialized hydrogeological literature [9], providing indirect support for the validity of the selected boundary conditions.

For a more comprehensive assessment of the scientific novelty and practical significance of the proposed approach, it is necessary to compare it with existing alternative technologies for formation exposure, well placement, and intensification of ISL.

4.2.1 Analysis of Conventional Well Placement Patterns

In conventional uranium ISL practice in the CIS countries, linear systems of vertical wells with alternating rows of injection and production wells are the most widely used configurations [[3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18]]. In domestic industrial practice, the standard layout provides for well spacing within a row of 15 – 40 m and inter-row spacing of 30 – 80 m [18]. Such linear well patterns demonstrate high efficiency primarily in the development of laterally extensive ore bodies hosted by sedimentary, high-permeability formations with a filtration coefficient of $K_{\phi} > 1.0$ m/day [8]. Under low-permeability reservoir conditions (permeability below 1–2 mD), the radial flow regime around vertical wells sharply reduces the effective drainage radius [1]. Compensating for this limitation requires a substantial increase in the density of the vertical well pattern, resulting in a critical increase in capital costs [20].

As an alternative for complex and low-permeability deposits ($K_{\phi} \approx 0.1 \div 1.0$ m/day), areal (pattern-based) well placement systems—including triangular, square, and hexagonal patterns with small interwell spacings of 8–20 m - are sometimes considered [13]. However, experience indicates that the construction and operation of such areal well patterns at uranium mines are associated with extremely high costs and may result in substantial economic losses [14]. Furthermore, reliable design methods for areal well patterns in deposits with complex geological structures and variable permeability have not yet been developed, and their selection often remains empirical [15].

4.2.2 Reversible (push–pull) process wells

Reversible (push–pull) process wells operating in a pulsating mode, with periodic alternation between pumping and injection cycles, have also been proposed [16]. Despite their potential to improve formation sweep efficiency, the implementation of such systems is technically challenging, as it requires the installation of sealed wellheads on the casing of each well and the construction of an extensive distribution network with manifolds for the distribution of leaching solution and the collection of pregnant solution [7].

4.2.3 Alternative Biotechnological Approaches

In global practice, bacterial leaching (bioleaching) methods are being investigated for the development of low-grade and off-balance uranium ores [[10], [20]]. The use of chemolithoautotrophic microorganisms theoretically makes it possible to

bring resources that are uneconomic for conventional geotechnological methods into production [18]. However, the key technological limitations of bioleaching include the low survival rate of bacterial strains under harsh formation conditions, the need for complex optimization of environmental parameters, and substantial difficulties in ensuring the targeted delivery of bioreagents into low-permeability zones of the reservoir [18].

4.2.4 Fundamental Differences and Advantages of the Proposed Horizontal Technology

The J-shaped (horizontal) formation exposure technology proposed in this study differs fundamentally from the approaches described above from both hydrodynamic and physicochemical perspectives:

1. Transformation of the Flow Regime: The proposed horizontal configuration changes the spatial organization of fluid flow compared with conventional vertical-well systems. As demonstrated in Sections 3.1 and 3.2, the extended filter provides a more distributed hydraulic interaction with the ore-bearing formation than the localized radial flow characteristic of vertical wells [19].

2. Enhanced Well Productivity: The proposed horizontal configuration provides a substantial improvement in well productivity under the low-permeability conditions considered in this study. The quantitative increase in flow rate is presented in Section 3.1, while its potential economic implications are discussed in Section 4.3. In contrast to conventional vertical-well systems, the proposed configuration achieves this improvement through extended formation exposure rather than through an increase in the density of the vertical-well pattern.

3. Improved Formation Coverage: Under low-permeability conditions, the proposed horizontal configuration can provide more continuous formation coverage than conventional vertical-well patterns. As demonstrated in Section 3.2, extending the formation–well contact along the horizontal section reduces the dependence of productive-zone coverage on the limited hydraulic influence of individual vertical wells. This may reduce the occurrence of poorly swept portions of the ore-bearing formation between wells.

4. Reactive-Transport Advantage: The proposed configuration also differs from conventional vertical-well systems in the coupling between hydraulic flow and reactive transport. As discussed in Section 4.1, the altered flow regime affects the balance between

fluid transport and mineral dissolution, which is represented by the Damköhler number. This provides a potential advantage for controlling reagent residence time and the spatial propagation of the leaching front, particularly in thin, low-permeability ore-bearing formations.

4.2.5 Prospects for Integration with Physicochemical Intensification

While conventional methods for intensifying ISL are primarily aimed at artificially raising the formation pressure or locally increasing hydraulic head, the proposed J-shaped technology can be effectively combined with advanced physicochemical stimulation methods.

A substantial synergistic effect can be achieved through the use of ultrasonic cavitation treatment of recirculating process solutions [21]. Exposure to ultrasound at frequencies of up to 50 kHz and power levels of 4–10 kW induces cavitation-induced water molecule dissociation, generating H and OH radicals, which subsequently form hydroperoxyl radicals (HO_2) and hydrogen peroxide (H_2O_2) [2]. These compounds promote the intensive oxidation of ferrous iron to ferric iron ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$) [20]. Ferric ions (Fe^{3+}) act as natural oxidizing agents, oxidizing poorly soluble tetravalent uranium in the ore to the readily soluble hexavalent form, the uranyl ion (UO_2^{2+}) [[5], [7]]. Integration of ultrasonic oxidation into horizontal well blocks makes it possible to maintain an optimal oxidation–reduction potential (Eh) without additional input of expensive chemical oxidants or increased volumes of sulfuric acid, thereby substantially improving the overall economic efficiency of uranium recovery [21].

4.3. Economic Interpretation of the Results

Based on the preliminary calculated productivity ratio of 6.1, a single horizontal well could deliver approximately the same solution flow rate as six vertical wells under the assumed reservoir conditions. However, its estimated swept pore volume is only 2.9 times that of a single vertical well; therefore, this flow-rate equivalence does not imply equivalent reservoir coverage or uranium recovery [[7], [14]]. A reduction in the number of production wells could potentially lower the requirements for wellhead equipment and surface piping. Nevertheless, these potential savings must be evaluated against the higher cost of horizontal well construction and the well-field layout required to achieve comparable reservoir coverage and uranium recovery [[7], [15]].

At the same time, translating this ratio into specific monetary indicators, such as drilling costs and payback period, requires data on the actual costs of directional drilling and telemetry services, as

well as information on the operating costs of a specific production block. These data are beyond the scope of the present study and should therefore be addressed in a separate techno-economic assessment [[12], [13], [14]].

4.4. Limitations of the Study

– The COMSOL Multiphysics model treats the formation as a homogeneous anisotropic porous medium at the production-block scale. The kinetics of pore-space plugging by gypsum, which has been reported in carbonate-bearing reservoirs [16], were not explicitly incorporated into the model and may reduce the actual productivity of the horizontal filter over time.

– The predicted flow rate of the horizontal well ($1.95 \text{ m}^3/\text{day}$) is based on a model calibrated against the vertical-well scenario and has not yet been validated by direct field testing of a horizontal well in Section 6–7. An experimental-industrial pilot test is therefore required.

– The calculations were performed for a single set of reservoir parameters ($k = 1.0 \text{ mD}$, $h = 8.0 \text{ m}$). The sensitivity of the results to variations in permeability and anisotropy within the study area was not quantitatively assessed. It should be noted that in the steady-state formulation the productivity ratio itself is independent of permeability, which cancels between Eqs. (1) and (2); permeability controls the absolute flow rates and hence the economic threshold, not the magnitude of the horizontal-well effect.

– The model describes a steady-state (or quasi-steady-state) flow regime over a timescale of months. Long-term effects, including reagent degradation and changes in near-wellbore permeability, were not considered.

– The economic interpretation presented in Section 4.3 is indicative and order-of-magnitude in nature and does not replace a comprehensive techno-economic model based on actual cost parameters.

5. Conclusions

Under the low-permeability conditions of Sections 6–7 of the Budenovskoye deposit ($k = 1.0 \text{ mD}$, $h = 8.0 \text{ m}$, $k_z/k_x = 0.1$), a 150 m J-shaped well raises steady-state productivity from 0.32 to $1.95 \text{ m}^3/\text{day}$ - a factor of 6.1 - and increases the swept pore volume by a factor of 2.9.

The productivity gain is accompanied by a 3.1-fold reduction in the estimated sandface Darcy velocity. Assuming identical reaction parameters and characteristic transport lengths, this corresponds to a 3.1-fold increase in the relative

Damköhler number and indicates longer effective reaction time. However, its effect on uranium recovery and acid consumption must be confirmed by calibrated reactive-transport simulations and field testing.

By Eq. (2), the gain scales with screen length rather than with well count: $L = 300$ m would yield a factor of 14.6 under the same conditions. In blocks with $k < 2$ mD and $h < 10$ m, screen length is thus the primary design variable. At $L = 300$ m, however, the Joshi solution is applied far outside its validity range for $reH = 50$ m, so this figure is an upper bound that a dedicated sensitivity study must confirm.

Future work. Four steps follow directly from these findings: a pilot horizontal well in Sections 6-7 to validate the predicted flow rate; coupling of gypsum-precipitation kinetics to the flow model, since clogging is expected to erode the advantage of a long screen faster than that of a short one; a sensitivity study over $k = 0.5$ -5 mD and $k_z/k_x = 0.01$ -1.0 to delimit the conditions under which the

configuration pays; and a techno-economic comparison of one horizontal well against the six vertical wells it replaces, based on actual directional-drilling and telemetry costs.

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Төмен өткізгішті қабаттарда уранды жерасты шаймалау кезінде көлденең ұңғымалардың тиімділігін гидродинамикалық негіздеу

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ТҮЙІНДЕМЕ

Жерасты ұңғымалық шаймалау (ЖҰШ) — құмтас типті кен орындарынан уранды өндірудің негізгі әдісі болып табылады, алайда төмен өткізгіштігі бар кен қабаттарында оның тиімділігі күрт төмендейді, себебі тік ұңғымалар гидродинамикалық ықпал аймағын тарылтады. Зерттеудің мақсаты — горизонтальды ұңғыманың мұндай блоктардың өнімділігін қаншалықты қалпына келтіре алатынын сандық түрде бағалау және нәтижесіндегі өсімнің механизмін анықтау. Бүденевское кен орнының (Қазақстан) 6–7 учаскелерінің геологиялық-техникалық параметрлері бойынша тік ұңғыма (Дюпюи–Тим) және горизонталь бөлігінің ұзындығы 150 м болатын J-тәрізді ұңғыма (Джоши) үшін Дарси заңы бойынша орныққан ағыс есептелді: $kh = 1,0$ мД, $h = 8,0$ м, $k_z/k_x = 0,1$. Тік ұңғыма моделі сол учаскеде өлшенген нақты дебиттер бойынша калибрленді. Горизонталь конфигурация ұңғыма өнімділігін 0,32-ден 1,95 м³/тәулікке дейін (6,1 есе) арттырады, қамтылған кеуектік көлемді 2,9 есе ұлғайтады және ұңғыма қабырғасындағы Дарси сүзу жылдамдығын 3,1 есе төмендетеді. Тасымалдың сипаттамалық ұзындығы мен реакция параметрлері бірдей деп қабылданған жағдайда, ұңғыма қабырғасындағы Дарси сүзу жылдамдығының төмендеуі салыстырмалы Дамкөлер санының 3,1 есе артуына әкеледі. Бұл ерітіндінің қабатта болу уақыты ішінде реакцияның жүру әлеуеті жоғарылайтынын көрсетеді. Аталған әсердің уранды өндіру дәрежесіне және қышқылды өнімсіз шығындауна ықпалы толық калибрленген реактивті тасымалдау моделі арқылы растау қажет. Бұл $k < 2$ мД және $h < 10$ м болатын блоктарды игеруге тартуға болатынын көрсетеді.

Түйін сөздер: уранды жерасты шаймалау, көлденең ұңғымалар, төмен өткізгішті коллекторлар, гидродинамикалық модельдеу, реактивті тасымал.

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Гидродинамическое обоснование эффективности горизонтальных скважин при подземном выщелачивании урана в низкопроницаемых пластах

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Поступила: 28 августа 2026 Рецензирование: 12 сентября 2026 Принята в печать: 28 сентября 2026	АННОТАЦИЯ Подземное скважинное выщелачивание (ПСВ) — основной способ добычи урана из месторождений песчаникового типа, однако его эффективность резко снижается в низкопроницаемых рудных горизонтах, где вертикальные скважины формируют узкую зону гидродинамического воздействия. Цель работы — количественно оценить, в какой степени горизонтальная скважина восстанавливает продуктивность таких блоков, и установить механизм получаемого прироста. Стационарное течение по закону Дарси рассчитано для вертикальной скважины (Дюпюи–Тим) и J-образной скважины с горизонтальным участком 150 м (Джоши) при геолого-технических параметрах участков 6–7 месторождения Буденовское (Казахстан): $kh = 1,0$ мД, $h = 8,0$ м, $kz/kx = 0,1$. Модель вертикальной скважины откалибрована по фактическим дебитам того же участка. Горизонтальная конфигурация повышает продуктивность с 0,32 до 1,95 м³/сут (в 6,1 раза), увеличивает охваченный поровый объем в 2,9 раза и снижает скорость фильтрации Дарси на стенке скважины в 3,1 раза. При условии одинаковой характерной длины переноса и идентичных параметров реакции снижение скорости фильтрации Дарси на стенке скважины приводит к увеличению относительного числа Дамкёлера в 3,1 раза, что указывает на повышение потенциальной степени протекания реакции за время пребывания раствора в пласте. Влияние данного эффекта на извлечение урана и непроизводительный расход кислоты требует подтверждения с использованием полностью откалиброванной модели реактивного переноса. Это указывает на возможность вовлечения в отработку блоков с $k < 2$ мД и $h < 10$ м.
	Ключевые слова: подземное выщелачивание урана, горизонтальные скважины, низкопроницаемые коллекторы, гидродинамическое моделирование, реактивный перенос.
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