Modeling, Diagnostics and Risk management in The Leaching of A Useful Component from A Man-made Deposit

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Abstract
A model for diagnostics, risk management, and assessment of the effectiveness of the application of technology for targeted modification of the geofiltration properties of man-made deposit in the vicinity of technological workings has been developed to increase the productivity of extracting the useful component during leaching.

Keywords
hydraulic fracturing, mathematical model, leaching, technogenic formation, man-maid deposits

1. Introduction

The main task of supporting the sustainable development of industrial production, in the conditions of depletion of natural resources and accumulation of anthropogenic waste, which are limiting factors of technological progress, is undoubtedly the preservation of natural resources and ensuring environmental protection and safe exploitation of anthropogenic resources. The above is possible due to the optimization of nature use by actively including production waste and resources of anthropogenic deposits in economic circulation and is the focus of the theory and practice of modern economic planning and development from the point of view of the conceptual principles of resource conservation. Therefore, the modern model of rational environmental management is based on the optimal use of technogenic waste to preserve natural assets, reduce production costs, improve the ecosystem and living conditions of the population.

Under these conditions, the primary tasks of reducing the impact on the environment are the processing of production waste, increasing the mineral and raw material base for the extraction of minerals by including secondary material resources in economic circulation, etc. This approach is especially relevant for the mining industry.

Resources obtained as a result of industrial activity have promising potential not only for the production of certain useful components of subsoil use, but also secondary ones. Mining industry waste is a unique source of many valuable rare metals. The exploitation of man-made deposits allows maintaining the required level of metal extraction even with a significant decrease in the extraction of metal ores. It should be noted that industrial waste is often similar in composition and properties to natural raw materials, and in some cases has an advantage [1]. For example, smaller fractions of metals can be extracted from waste dumps during their processing or used as materials for construction. At the same time, uncontrolled exploitation of an anthropogenic deposit, its chaotic existence, turns industrial dumps into a potential source of environmental pollution, since filtration and runoff of water into the underlying rocks of the anthropogenic deposit leads to mixing of

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aggressive, toxic substances with groundwater. The threat of environmental pollution and chemical release into the natural hydraulic system is growing catastrophically, which raises the issue of developing recommendations for predicting the chemical composition of water over time in waste dumps in order to reduce the threat of environmental pollution [2–3].

2. Relevance of the Research

Analysis of world scientific experience shows that modern approaches to objects with technogenic and ecological threats are shifting from passive monitoring to dynamic hydro-geochemical modeling in combination with scenario risk analysis. This creates a reliable methodological basis for solving a unique scientific and practical problem – manageng the risks of leaching of useful components in the conditions of a technogenic deposit.

Modern approaches to describing mass transfer in destructive mining and industrial massifs are based on end-to-end hydro-geochemical models of atmospheric leaching, which allow predicting the long-term dynamics of leaching of substances under the influence of infiltration waters [4]. In this case, the mathematical description of filtration and transport of elements in unsaturated (aeration) zones of a heterogeneous technogenic environment is of particular importance [5]. Taking into account the nonlinear rate of dissolution of a heterogeneous substrate in kinetic models of hydrometallurgical processes [6] creates a reliable theoretical basis for predicting similar processes of destruction and leaching of the matrix of fuel-containing masses under the influence of accidental or technological moisture inside a technogenic deposit.

Effective control over the migration of highly toxic components requires continuous diagnostics of solution chemistry, since fluctuations in the acid-base balance of the environment and the valence of metals radically change their solubility and ability to form mobile complexes [7]. Preventive monitoring of the geochemical stability of landscapes and the kinetics of ion migration under the erosive influence of water helps to timely identify zones of critical acidification or alkalization of the object [8]. In addition, comprehensive diagnostics should include the analysis of deformations and violations of the strength of building structures and foundations that arise as a result of suffusion phenomena and constant leaching of substances by aggressive filtrates from the porous layer of the object [9].

The management of environmental and technological threats at radiation-hazardous objects is shifting towards the application of the mathematical apparatus of Boolean and scenario modeling, which allows the creation of automated preventive management systems [10]. An important tool for visualizing the vectors of solution distribution and assessing the scale of radioecological consequences in the event of hydrodynamic accidents is GIS-oriented conceptual modeling of sites [11]. The assessment of leaching potential within the framework of human health risk analysis [12] combined with the concept of transition from passive containment of hazardous waste to its controlled reprocessing and decontamination [13] serves as a methodological basis for the safe management of liquid radioactive waste from a technogenic deposit.

Mining waste management is divided into main types depending on the type, in particular, the proposed processing technology is based on a mechanism for assessing their future behavior and impact on the environment, as well as their economic potential. The main task is to try to predict the consequences of waste processing over time.

Thus, a promising alternative to solving the problem of managing sites of man-made disasters, various sedimentation tanks is the proposal to consider these objects as a man-made deposit with a useful component, for the extraction of which the feasibility of using leaching technology is justified. An example of such an object can be the destroyed power unit of the Chornobyl nuclear power plant. In infiltration leaching, which is the most acceptable method for this technology, among the implementation of significant factors affecting the efficiency of the interaction of the useful component and the working agent, the main place is occupied by the problem of ensuring optimal penetration of leaching solutions into the volume of masses containing the useful component, as well as unhindered flow of productive solutions with their subsequent removal [14–16].

3. Statement of the Problem

Modern research shows that the involvement of man-made raw materials in the processing of can significantly increase economic potential and provide solutions to many pressing problems of subsoil use, in particular: more complete use of non-renewable natural resources; preservation of exhaustible mineral raw materials in the subsoil; increase in labor productivity and employment through cost-effective processing of extracted raw materials; creation of various cheap building materials and mineral additives; reduction or elimination of sources of environmental pollution; reclamation of vacant lands [14].

One of the most effective ways to prevent negative impact on the environment from the accumulation of industrial and domestic waste is the construction of various types of protective waterproof surfaces. Traditionally, waterproof barriers are made of low-permeable soils (clay and fine-grained sandy soils, clay concrete) or non-soil materials (concrete, reinforced concrete, bituminous materials) in the form of an upper or central waterproof prism, screen, diaphragm, core, gap, sheet pile, wall, cementing and other curtains, and if justified - in the form of a combined structure of soil and non-soil materials. Known results of solving the problem of waterproofing hazardous waste accumulations have significant drawbacks: the impossibility of waterproofing without access to an industrial waste storage facility; performing work in close proximity to the industrial waste site; the impossibility of creating a protective barrier in the event of solid rocks under the contaminated area; the impossibility of collecting, sending for processing and disposal of toxic solutions; further spread of hazardous substances in the subsoil, on the surface of the formed barrier [14, 17].

The main prerequisites for the activation of physicochemical processes during leaching are based on the following ratio of permeability and openness of cracks in the massif

$$\frac{K_n^w}{K_n} = \left(\frac{b^w}{b}\right)^m,$$

where K_n^w, b^w – permeability coefficient and crack width after geotechnological impact; m – degree index, varying within 2...3.

The graphical representation of the dependence shows a sharp quantitative jump between the parameters of permeability and crack openness (Fig. 1)

Intensity of input of useful component during leaching is characterized by the ratio

$$q(t) = \frac{A_0}{V} \cdot K_1 \cdot e^{-(K_1+\lambda)t},$$

where A_0 – initial reserves of the component, Ci; λ – decay constant, day^{-1}; $K_1 = ln\frac{2}{T_1}$ – half-life rate constant, day^{-1}; T_1 – half-life period, days.

The total input of useful component during leaching depends linearly on the interaction surface of solutions and host rocks

$$q_{sm} = e^{-\lambda t} \cdot N_0 \cdot S \cdot v,$$

where S is the interaction surface area; N_0 – initial surface concentration; v – leaching rate; t – time [18 – 20].

The main task of the study at the stage of theoretical justification of the feasibility of using leaching technology in the infiltration mode for extracting a useful component from a technogenic deposit is to develop an adequate model of hydrogeomechanical activation of the uranium leaching process, which allows optimizing reagent consumption by choosing rational parameters of its filtration rate and concentration. This task is solved in the case of creating a protective anti-filtration collector complex (AFCC), which will protect the subsoil from the penetration of toxic substances, collect and deliver liquid technogenic waste to the surface for processing and disposal.

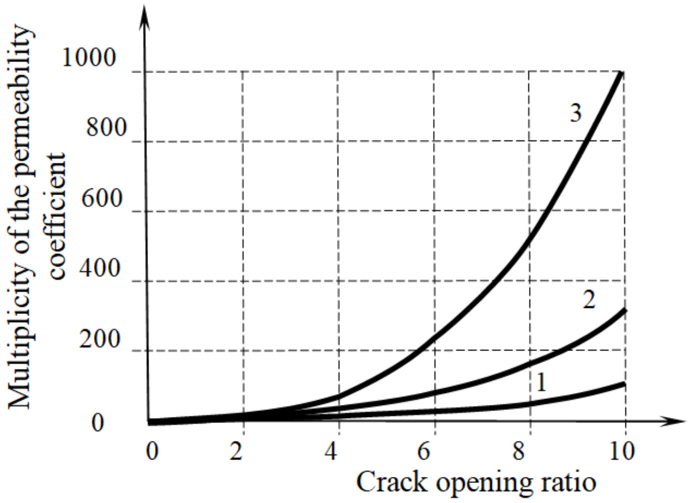

Figure 1: Dimensionless ratio of fracture openness and permeability: 1, 2, 3 – respectively for m=2.0; 2.5; 3.0.

4. Research Results

The main element according to the technological scheme (Fig. 2) is a system of underground mining workings – an inclined opening workings 1, main 2 and sectional workings (3), which provide opening of the rocks underlying the contaminated area and allow creating a protective collector screen in the subsoil, which provides directed gravity collection of anthropogenic solutions containing aggressive chemical or radioactive components into a collector made in the form of a sump 6.

An inclined working 1 with an inclination angle not exceeding 30° is passed from the surface of the earth in the underlying rocks 4. A concrete portal 5 is created at the mouth of the face, a lifting machine and ventilation equipment are installed. Upon reaching the face of the inclined working at the design level, the main 2 and sectional preparatory workings 3 are passed. In the end part of the face 2, a sump 6 is passed, which is equipped with pumps – main, reserve and spare. At the stage of revealing the underlying rocks of the technogenic object, preparatory work is carried out, pumping equipment is used for drainage (not shown in the diagram), and at the stage of operation of the AFCC – for delivering technogenic solutions to the industrial site for processing and further disposal.

The workings 3 pass through a certain interval from the preparatory workings 2, which pass at an angle to the horizon relative to the upper level of the sump 6. The axes of the sectional workings are directed at a right angle to the main workings, and the passage of the sectional workings 3 is carried out at an angle α to the base of the main workings 2, which will additionally ensure hydraulic transportation by gravity in the direction 11 of liquid industrial waste 12, which is formed as a result of the seepage of filtration flows of technogenic solutions 9 into the sump 6. The length of each preparatory working is not less than the width of the industrial waste site 7. The inclined opening of the working, the preparatory main and sectional workings are fixed in a continuous pattern with concrete 13.

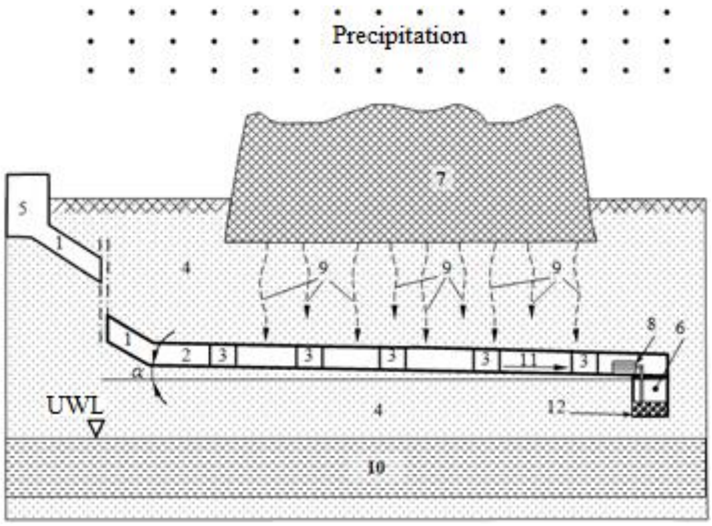

Figure 2: Scheme of stripping and preparation of the underlying rocks for the creation of the underground coal mine

When creating the AFCC, the main pipeline pumps the slurry to the surface, and during operation, the liquid industrial waste 12 collected in the sump 6, are pumped out for processing and disposal.

Main working 2 houses life support equipment, mining equipment, a pipeline for supplying pressurized water, and a pipeline for supplying hardening aggregate (e.g., cement mortar) to create a protective screen to prevent groundwater contamination 10.

The effectiveness of hydrogeomechanical activation of the leaching process of a useful component from the massif of a technogenic deposit was assessed by modeling one-dimensional vertical non-stationary migration of a two-component mixture “leaching solution – useful component” (Fig. 3). The leaching process model is written as a system of mass transfer equations under non-equilibrium kinetics conditions [14, 18 – 20]

$$D\frac{\partial^2 C_r}{\partial z^2} - v\frac{\partial C_r}{\partial z} - \gamma C_r = n_{f,1}\frac{\partial C}{\partial t}, \quad (1)$$

$$D\frac{\partial^2 C_k}{\partial z^2} - v\frac{\partial C_k}{\partial z} + \frac{\partial N_k}{\partial z} = n_{f,2}\frac{\partial C_k}{\partial t}, \quad (2)$$

$$\frac{\partial N_k}{\partial t} = -\gamma\frac{C_r}{N_{k,0}}N_k, \quad (3)$$

$$\gamma = \omega k, \qquad k = \frac{NuD_0}{d}\chi, \quad (4)$$

where C_r and C_k are concentrations of reagent and useful component in liquid phase, N_k is concentration of useful component in solid phase; ω is a specific surface of cracks, m^{-1}; k – parameter of dissolution rate [20], ; D_0 – diffusion coefficient, d – characteristic size of dissolved blocks, Nu – Nusselt’s number for flow in cracks, χ is the parameter characterizing tortuosity of cracks and their availability for solvent.

Mass transfer equations (1) – (4) reflect the regularity of the decrease in the leaching rate in the technogenic massif near the fault surface. The experimentally confirmed dependence of the increase in the intensity of mass transfer on the filtration rate [19] is taken into account. The effective porosity coefficients $n_{f,1}$ and $n_{f,2}$ allow us to take into account the sorption effects during the migration of solutions.

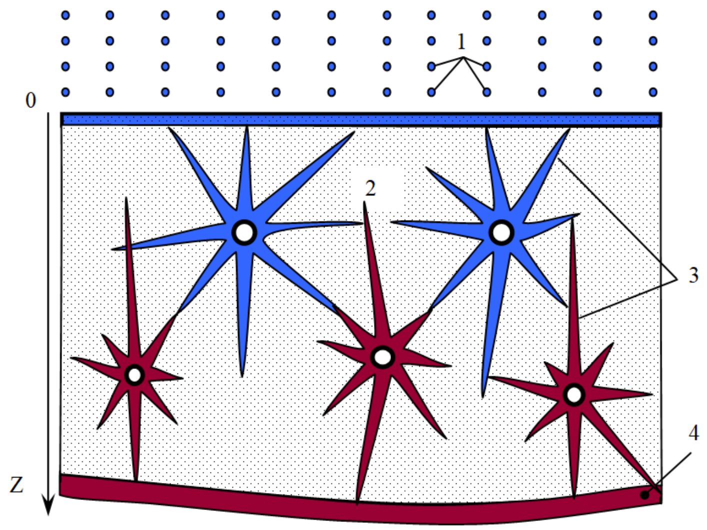

Figure 3: Scheme of leaching activation estimation: 1 – leaching solution; 2 – technogenic deposit; 3 – fracture cracks; 4 – saturated productive solution.

The initial and boundary conditions for the system (1) – (4) are formulated as follows. For the solvent, a zero initial and non-zero input concentration at the upper boundary are given:

$$C_r(z,0) = 0, \qquad C_r(0,t) = C_0(t). \tag{5}$$

In general, the input concentration can change with a decrease in the content of the useful component in the solid phase, with a change in the type of reagent, etc. For a dissolved component, the zero input and initial concentrations are established in the mass layer containing the component:

$$C_k(z,0) = 0, \qquad C_k(0,t) = 0. \tag{6}$$

It is assumed that the input of the useful component into the solution is possible only due to an internal source – the summand $\frac{\partial N_k}{\partial z}$ in equation (3).

For the useful component in the solid phase, the initial concentration distribution over the thickness of the technogenic deposit is given:

$$N_k(z,0) = N_0. \tag{7}$$

Given the insufficient study of the permeability of the confining masses with height before and after hydraulic fracturing, it is acceptable to assume that these fractured rocks are quasi-homogeneous, and their permeability is determined in accordance with theoretical concepts [14, 18].

At the initial, lower boundary of the confining masses for the reagent and the dissolved component, the following conditions are set:

$$\frac{\partial C_r}{\partial t} = 0, \quad \frac{\partial C_k}{\partial t} = 0. \tag{8}$$

These conditions correspond to the equality of convective flows and the insignificant diffusion of these substances coming from fractured rocks into the underlying sediments, which can be assumed at a high filtration rate.

The system of equations (1) – (8) was solved by the finite difference method using a stable implicit scheme [2] using the developed calculation program. Based on the developed mathematical models, an specialized software has been created to provide comprehensive simulation of the leaching process of valuable components from the technogenic deposit of the Shelter object and to predict the efficiency of uranium recovery. In contrast to conventional approaches, the proposed system integrates a mathematical model of hydrogeomechanical activation of the leaching process with tools for optimization of technological parameters through adaptive modification of input variables. This integration enables the analysis of process behavior under varying operational conditions and supports the identification of parameter combinations that maximize extraction performance.

The developed software provides simulation of reagent infiltration processes, prediction of uranium recovery dynamics, and decision support for the selection of optimal leaching parameters.

The implemented functionality enables quantitative assessment of process efficiency and facilitates evaluation of alternative technological scenarios.

The software has been developed using the .NET 8 platform, which ensures high computational performance, efficient utilization of multithreaded processing capabilities, simplified software maintenance, and seamless integration with scientific computing libraries. The graphical user interface has been implemented using Windows Presentation Foundation (WPF), providing a modern and scalable visualization environment based on the Model-View-ViewModel architectural pattern and supporting the development of advanced data visualization components.

The software system is organized according to a three-layer architecture (Fig. 4) comprising the presentation, business logic, and data layers. User interaction is performed through a WPF-based graphical interface, which provides parameter input and visualization of simulation results. The business logic layer implements the mathematical model of the leaching process and supports parameter optimization as well as process diagnostics based on the input data and configuration parameters. The generated modeling results are stored within the data layer and subsequently transferred to the visualization module, enabling the presentation of computed outcomes to the user. Configuration data serve as input to the mathematical model, ensuring consistent execution of simulation, optimization, and diagnostic procedures (Fig. 5).

The initial data for modeling and evaluation of technological parameters were selected for the man-made uranium deposit at the Chernobyl NPP accident site and are defined as follows.

According to the proposed infiltration leaching scheme, the main part of the useful component should be extracted within 3-5 years. During this period of time, according to the experience of developing uranium deposits with a low uranium content in the rock [14], at least 80% of uranium from the solid phase passes into solution. Even according to underestimated estimates, a layer of fuel-containing masses up to 10 m thick with an area of 15,000 m2 contains 150 tons of uranium, which gives a lower estimate of the initial uranium concentration that can be extracted by leaching: 0.8 kg/m3.

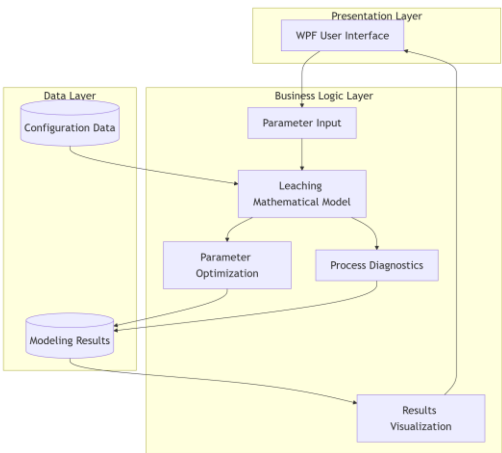

Figure 4: Developed software architecture.

Figure 5: Developed software user interface.

The filtration rate in fuel-containing masses depends on their permeability and the flow rate of the supplied reagent. In the adopted leaching scheme, it corresponds to the rate of flow of gravity water supplied by hydraulic monitors onto the surface of fuel-containing masses, which occurs with a gradient close to unity. Before hydraulic fracturing, the filtration rate cannot exceed 0.1 m/day, and the hydraulic fracturing rate cannot exceed 0.01. After hydraulic fracturing of fuel-containing masses, the rock filtration coefficient increases to 10-30 m/day, which is sufficient for non-pressure downward filtration of the reagent with an assumed flow rate of 10-25 $\frac{l}{m^2 \cdot hr}$ or a rate in the range of 0.25-0.62 m/day [14, 18].

When determining the range of parameter γ of mass transfer rate, it is necessary to take into account its complex character. For narrow channels $Nu \sim 10^2 - 10^3$, values of diffusion coefficient in rocks do not exceed , and geometric parameter $d \sim n \cdot 10^{-1}\ m$. The surface area ω of cracks, which is proportional to their density, increases after hydraulic fracturing from a value within $10^{-1} - 10^0$ to a value on the order of $10^1 m^{-1}$. Taking into account these changes, as well as an increase in the flow velocity in the crack, which also increases the Nusselt number, the parameter γ will increase from $n \cdot 10^{-2}$ to $n \cdot 10^{-1} day^{-1}$ for these conditions.

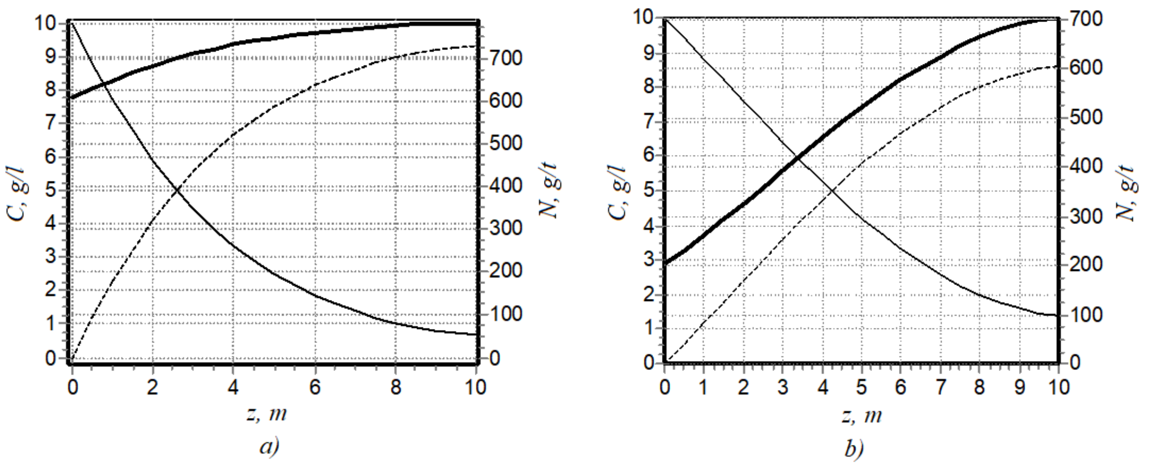

Figure 6: Distribution of soluble uranium concentration in solid phase (1) and in solution (2), reagent concentration (3) in the containing masses layer without preliminary fracturing $\gamma = 0.02\ day^{-1}$): a) 1 year after the beginning of leaching; b) 15 years after the beginning of leaching.

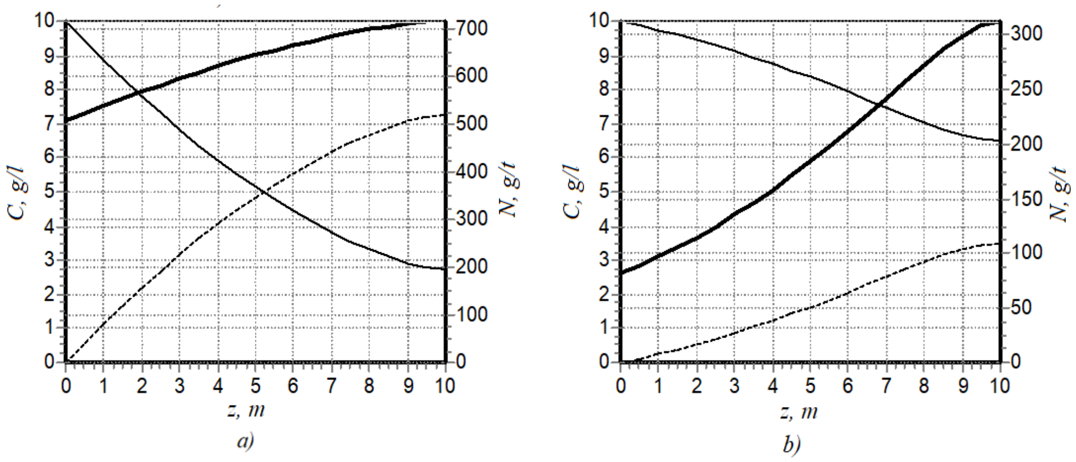

Figure 7: Distribution of soluble uranium concentration in solid phase (1) and in solution (2), reagent concentration (3) in the containing masses layer low impact pre-fracturing $\gamma = 0.1\ day^{-1}$): a) 1 year after the beginning of leaching; b) 5 years after the beginning of leaching.

A full numerical analysis of the process is impractical due to the significant number of parameters, the reliable values of which cannot be determined. Therefore, the purpose of the modeling was to obtain numerical estimates of the main leaching characteristics in the range of known values of the technological parameters of the field development. The modeling results are presented in Fig. 6, Fig. 7 and Table 1. Uranium leaching before hydraulic fracturing (Fig. 6) in the initial period of geotechnological production actually occurs only in the upper layers of fuel-containing masses.

At the same time, the total removal of the useful component during this period will not exceed 10 tons or 8.3% of the initial soluble uranium reserves. Due to weak mass transfer (at a small parameter γ), from 10 to 15% of the supplied reagent passes through the fuel-containing mass layer without interacting with uranium in the solid phase.

The use of hydraulic fracturing, even at low intensity (Fig. 7), significantly accelerates the leaching process, namely, 5 years after the start of solution supply, more than 76% of the uranium available for dissolution will be removed from the host masses.

An increase in the filtration rate with incomplete crack opening can lead to excess reagent consumption in the range from 30% to 50%, especially at the final stage of leaching.

The highest extraction efficiency is achieved by hydraulic fracturing the formation with the maximum possible crack opening (Fig. 8). For example, by the end of the third year of extraction of the useful component from a technogenic deposit by the leaching method, almost 85% of soluble uranium can be extracted. In this case, excess reagent consumption is possible only at the final stage of the process.

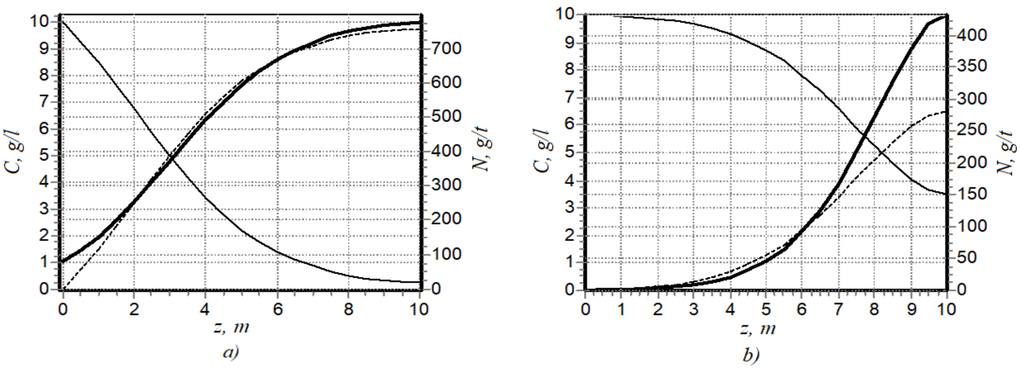

Figure 8: Distribution of soluble uranium concentration in solid phase (1) and in solution (2), reagent concentration (3) with high impact pre-fracturing $\gamma = 0.5\ day^{-1}$): a) 1 year after the beginning of leaching; b) 3 years after the beginning of leaching.

Table 1 below shows the estimated values of the intensification of the process of extracting a useful component by hydraulic fracturing a technogenic deposit using the leaching method, containing efficiency indicators for both the undisturbed massif and the massif after hydrogeomechanical impact.

Table 1
Influence of the intensity of hydrogeomechanical impact on the technogenic deposit massif on the efficiency of the leaching process

		Without fracturing	Low-impact hydraulic fracturing (Fig. 4)	High-impact hydraulic fracturing (Fig. 5)
M_e	1 year	3.38 t (2.8 %)	24.744 t (20.6 %)	41.987 t (35 %)
	3 years	9.98 t (8.3 %)	64.514 t (53.8 %)	101.858 t (84.9 %)
	5 years	16.36 t (13.6 %)	91.288 t (76.1 %)	119.549 t (99.6 %)
$\tau_{0.5}$		20.8 years	2.75 years	1.5 years

In Table 1: M_e – mass of extracted uranium (tons and % of initial mass), $\tau_{0.5}$ – time period of extraction of 50 % soluble uranium.

Forecasting the dynamics of the concentration of dissolved uranium at the lower, underlying boundary (Fig. 9) allows us to determine the period of the most effective extraction and the beginning of a decrease in process productivity. After 1-2 years, depending on the scale of hydraulic fracturing, it is recommended to reduce the concentration of the supplied reagent by 15-25% or change its type to avoid overexpenditure.

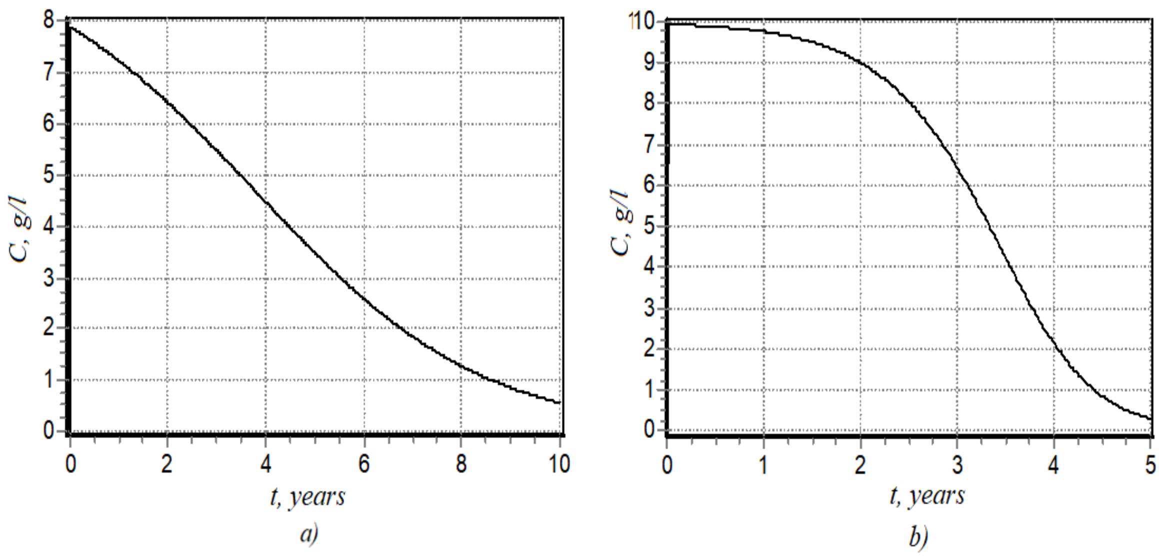

Figure 9: Dynamics of dissolved uranium concentration flowing into bedrock after hydraulic fracturing: (a) at low impact (a) at high impact.

The obtained estimates confirm the technical feasibility of hydraulic fracturing of rock masses containing a useful component before leaching the useful component from them. Increasing the permeability of rocks and the area of their contact with the reagent accelerates the process by an order of magnitude, which allows extracting up to 80% of the useful component within 3-5 years with intensive reagent supply.

5. Conclusions

An effective method of purposeful change of geofiltration properties of technogenic crushed stone near technological workings and management of its condition is the technology of hydraulic fracturing of the formation, which follows from the analysis of foreign practice and experimental data of mining operations. When hydraulic fracturing of the formation is applied to the rocks of the technogenic deposit, a sudden increase in the rate of leaching of the useful component is observed due to the increase in the permeability of the crushed stone rocks and the area of their contact with the reagent, which allows optimizing the reagent consumption by choosing a rational parameter of its filtration flow rate and concentration. The leaching intensity with cracks of the fracture type in the massif increases several times within five years compared to the massif without hydrogeomechanical activation.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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