KURMANSEIIT MAKSAT

THE STUDY OF PHYSICAL AND CHEMICAL PROCESSES AT THE MINERALS EXTRACTION BY LEACHING

ANNOTATION

Dissertation for the degree
Doctor of Philosophy (PhD) in specialty
6D060300 – "Mechanics"

General Description of the Work. The dissertation work contains studies of the influence of the gravitational descent due to the density differences of the solutions; as well as research conducted on the reactive transport processes during uranium production via In-Situ Leaching (ISL) using parallel computing and the streamline method.

Relevance of the Work. The ISL method is widely used in the development of uranium deposits. The ISL method involves injecting an acidic or alkaline solution, called a leaching solution, directly into an ore deposit through a network of injection wells and pumping out the pregnant solution containing dissolved uranium through production wells. This mining method is used to develop low concentration mineral deposits in highly permeable geological formations.

Although Kazakhstan has the second largest uranium reserves in the world, there are significant recoverable problems with the remaining available uranium reserves. Today, Kazakhstan is developing deposits of cheap uranium with relative operating costs of less than $80 per kilogram. However, according to the Organization for Economic Cooperation and Development (OECD), over the past 15 years, reserves of such resources have decreased by almost 55%, leaving approximately 2.0 million tons of uranium resources. Currently, it is necessary to exploit deeper mineralized layers with less fine- and medium-grained sandstone enriched in clay minerals.

Therefore, to better control acid consumption and reduce production costs for uranium recovery, it is necessary to change the approach to planning the extraction process. One of the possible ways to increase the profitability of operation is to conduct a detailed numerical study both during geological modeling and when designing a geotechnological test site and production modes at the field.

In the course of a detailed analysis, it was shown that the task of modeling the process of mineral extraction using the ISL method is a resource-intensive task and imposes certain requirements on computing resources. Acceleration of calculations when simulating uranium mining using ISL can be achieved through the use of a method based on streamlines and parallel computing technology on graphics processing units.

Streamline-based modeling allows to transform a 3D problem into set of 1D problems along streamlines that can be easily parallelized and speed up computational time.

The aim of this work. Development of a model of mineral dissolution and reactive transport of solutions at uranium mining by In-Situ Leaching, which taking into account different forms of uranium and acid consumption for dissolving ore-rock, as well as usage of streamlines based method and CUDA technology to speed up computations.

The tasks of the work.

– develop an effective algorithm for calculating the pressure distribution on a graphics processing units (GPU) and study the influence of the difference of solution and groundwater densities on the gravitational subsidence of the solution in the formation;

– perform an analysis of the effectiveness of applying the streamlines based method to simulate the process of uranium mining by the ISL;

– develop a chemical model of reactive transport that takes into account the consumption of acid for interaction with rock at uranium mining by ISL and determine the dissolution rates of uranium compounds and rock components with an aqueous solution of sulfuric acid;

– to study the effect of solution filtration rate on the extraction of uranium by the ISL;

– investigate the influence of the mineralogical composition of the rock on the extraction of uranium by ISL;

– to apply the developed reactive transport model to a full-scale section of the uranium deposit.

The object of the research is the reactive transport processes in porous media during the uranium recovery by In-Situ Leaching.

The subject of the research is the development of reactive transport in porous media and the application of methods for its effective study using high-performance computing.

Research methods. Methods for numerical and analytical study of reactive transport processes in porous media using parallel calculations and the streamline based method by the Pollock algorithm.

Scientific novelty of the problem consists of: (i) the development of physical, chemical, mathematical and 3D numerical models of reactive transport models in porous media arising at uranium recovery by ISL using the streamline based method and acceleration of calculations on a graphics processing processor; (ii) establishing the patterns of reactive transport processes in the ore-bearing formation, taking into account the dissolution of tetravalent and hexavalent uranium compounds, and rock components by sulfuric acid.

Scientific provisions submitted for defense.

– algorithm for calculating solution flow in permeable rock using modern methods of high-performance computing on a graphics processing units (GPU) allowed acceleration of calculations by 24 times;

– gravitational descent of the solution is significant when the density difference of the solution and groundwater is over 5%;

– an approximate analytical solution of reactive transport model along a streamline,

obtained under the assumptions of uniform mineral distribution and a constant solution velocity;
– mathematical model of reactive transport model in porous media arising at uranium recovery by ISL, taking into account the dissolution of UO3, UO2 and ore-bearing rock;
– reaction rate constants for the dissolution of UO3, UO2 compounds and ore-bearing rock with sulfuric acid with a deviation (NRMSD) of the experimental and calculated uranium concentration at the outlet of the tube of no more than 7%;
– the increasing the filtration velocity from 0.59 to 0.99 m.day $^{-1}$ leads to a reduction in uranium recovery by 6% and a reduction in extraction time by 65%.

The reliability and validity of the scientific provisions, conclusions and results of the dissertation are determined by the using of fundamental laws of mechanics: the mass conservation, Darcy's Law and Law of Mass Action at reactive transport model developing for simulating physical-chemical transformations in a porous medium, the Pollock algorithm for streamline construction, as well as the applying of proven sufficiently accurate numerical methods for the research. The reaction rate constants for the dissolution of the leaching solution with rock components were determined from known experimental data on material from the Tortkuduk deposit. The developed reactive transport model was applied to the full-scale Budenovskoye site, the results showed good agreement between the experimental data and the modeling results.

Theoretical and practical significance of the research. The theoretical significance of the results lies in the development of a reactive transport model for uranium recovery by the ISL. Practical significance is characterized by the possibility of using the developed model to study the development process of uranium deposits by calculating various mining scenarios to increase the efficiency of mineral extraction, forecasting the operation of deposits developed by ISL, as well as analyzing the rate of mineral recovery. The developed mass transfer model and computer program are part of the project to develop a geotechnological complex for the analysis and optimization of uranium mining using the ISL method called "Geostat", which was tested at the Ortalyk , Inkai and Semizbay deposits.

Connection of work with state scientific programs. This dissertation work was carried out within the framework of the following projects:
– 3290/GF4 "Development of a geotechnological information-modeling complex for optimizing the extraction of useful components by underground borehole leaching", State Fund of the Committee for Education and Science of the MSHE of the RK, 2015 - 2017, No. GR 0115RK00771;
– BR05236447 "Intelligent control and decision-making systems for the development of uranium and oil deposits", Committee of Science of the MSHE of the RK, 2018 - 2020, No. GR 0118RK01275;
– AP19676743 "Development of methods for calculating the solution imbalance scheme, operating modes of a geotechnological test site and the creation of a geotechnological information system for effective production by underground leaching", Scientific Committee of the MSHE of the RK, 2023-2025, No. GR0123RK00564.

Approbation of work.

The main results and provisions of the dissertation were reported and discussed at the following scientific events:

- 9th International Young Scientists Conference in Computational Science, September 5-13, 2020;
- IX International Scientific and Practical Conference "Actual Problems of the Uranium Industry", Almaty, November 7 – 9, 2019;
- International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018), IAEA, Vienna, Austria, 25-29 June 2018
- Research for Integrative Numerical Geology (RING) meeting, Nancy, France, 2017;
- VIII International Scientific and Practical Conference "Actual Problems of the Uranium Industry", Astana, August 3 – 5, 2017.

Individual contribution of the doctoral student to the preparation of articles.

The author of the dissertation participated in the problem statement, developing the program code, obtaining and analyzing the results, and preparing the articles. He has 3 publications included in the Scopus database (listed below) and 3 articles in journals recommended by Ministry of Science and Higher Education, and he is the first author in 5 publications.

1. M. B. Kurmanseiit, M. S. Tungatarova, J.-J. Royer, etc. Streamline-based reactive transport modeling of uranium mining during in-situ leaching: Advantages and drawbacks. Hydrometallurgy, 2023, 220, 106107. (WoS: Q1, Scopus: percentile -89, SJR -1.012)

2. Kurmanseiit, M. B.; Tungatarova, MS; etc. Reactive Transport Modeling during Uranium In Situ Leaching (ISL): The Effects of Ore Composition on Mining Recovery. Minerals 2022, 12, 1340. (WoS: Q2, Scopus: percentile -68, SJR -0.53)

3. MS Tungatarova, MB Kurmanseiit, N. Shayakhmetov GPU accelerated modeling of In-Situ Leaching process and Streamline based reactive transport simulation. - Procedia Computer Science. – 2020.– V. 178, p. 145-152, (WoS: Q2, Scopus: percentile -68, SJR -0.507, Conference paper)

In addition, the author of the dissertation published 5 papers in the proceedings of international scientific conferences, which he was a speaker, and 2 copyright certificates were received for the software modules developed as part of the dissertation work.

The main content of the dissertation.

The introduction reflects the following points: the relevance of the research topic, the main goals of the work, novelty, theoretical and practical significance of the research, testing of the work at scientific and scientific-practical conferences.

The first section of the dissertation examines the modeling of solution flow in permeable ore rock by the influence of wells network in homogeneous formation with one hexagonal cell. It has been shown that gravitational descent of the solution is significant when the density difference of the solution and groundwater is over

5%. To reduce computing time an algorithm for parallelizing calculations on a graphics processing unit (GPU) was used.

In the second section, modeling of reactive transport processes at uranium extraction by the ISL was performed with streamline based method. Using the 2nd order approximation, an asymptotic solution of the indicated system for simple chemical kinetics is obtained.

In the third section, a reactive transport model that takes into account the dissolution of UO3, UO2 and ore bending rock at uranium recovery by ISL is proposed. The reaction rate constants were numerically determined from empirical data. The study of the influence of solution velocity and the ratio between tetravalent and hexavalent uranium compounds on mineral recovery were carried out. The developed reactive transport model was applied to a full-scale section of the Budenovskoye deposit.

The conclusion provides an analysis of the main results with quantitative data, an assessment of the completeness of the solutions to the assigned problems, recommendations for the use of research results, an assessment of the technical and economic efficiency of implementation and the scientific level of the work performed in comparison with the best achievements in this field.