SHAYAKHMETOV NURLAN

OPTIMIZATION OF EXPLOITATION REGIMES DURING THE DEVELOPMENT OF DEPOSITS USING IN-SITU LEACHING METHOD

ANNOTATION

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

General Description of the Work. The dissertation is dedicated to optimizing exploitation regimes in the development of deposits using the in-situ leaching method. The study investigates the properties of the well pattern, as well as the application of enhancement techniques to increase extraction efficiency.

Relevance of the Work. Historically, the decline in uranium prices was attributed to the emergence, in 2009, of 'cheap' (<40 USD/kg) uranium produced through the in-situ leaching method. Kazakhstan was the primary producer of this uranium, accounting for 28% of global production.

Since then, uranium prices have remained relatively low, with occasional minor fluctuations. However, in recent years, there has been a resurgence of interest in nuclear energy as a low-carbon energy source, which has raised expectations for potential price recovery.

There are several methods of uranium extraction:

– open-pit mining – this is the most common method of uranium extraction, where large open pits are created to access uranium deposits.

– underground mining – in some cases, uranium deposits may be too deep to be mined using open-pit methods, so underground mining is employed instead.

– in-situ leaching – this method of extraction involves injecting a leaching solution into the ore-bearing horizon to dissolve the ore, which is then pumped to the surface for processing.

In-situ leaching, accounting for 97% of the world's recoverable uranium reserves, is the most common method for extracting uranium from low-grade, cost-effective deposits. It is important to note that the market price of uranium has remained around 40 USD/kg since 2009. As a result, other extraction methods are currently not profitable.

The primary challenge of uranium extraction using the in-situ leaching method is the inability to fully and directly monitor the process. Partial monitoring is achieved through the drilling of observation wells, which allow for pinpoint determination of uranium concentration directly along the well. Additionally, during the design phase, it is impossible to determine the most effective extraction scenario.

The developed methods described in this dissertation will allow for the determination of optimal pattern of technological wells and the reversal of wells to increase mineral extraction.

The aim of this work. Development of methods and a program for optimizing operational modes in the development of deposits using the in-situ leaching.

The tasks of the work.

– study the mathematical model of hydrodynamic and chemical processes to optimize processes occurring during uranium extraction using the in-situ leaching;

– developing a method to determine the best mining scheme based on the developed physico-chemical model of mineral extraction using the in-situ leaching;

– developing a method to determine the most effective well reversal regime.

The research methods Methods for modeling mass transfer in porous media considering chemical interactions between components; methods for solving systems of differential equations; optimization methods; information technologies for modeling and determining optimal characteristics of mining schemes.

The scientific novelty of the problem lies in the creation and automation of selecting the distance between wells, resulting in the proposal of an optimal mining scheme with well coordinates based on mathematical modeling and optimization methods. These methods are also developed into a module integrated into software with a user interface and visualizer. Currently, in Kazakhstan's deposits, the selection of mining schemes is done based on recommendations that do not take into account the specific properties of individual blocks or deposits. The proposed methodology and software product account for these properties.

The technique of well reversal was considered only within the framework of a specific technological block, which does not provide objective regularities of the behavior of technological solutions in general. The research presented in this dissertation allows determining the nature of changes in the degree of depletion with and without the use of reversal for comparing the efficiency of extraction. Additionally, based on the research results, the reversal time and the well pattern are presented, at which the maximum efficiency of well reversal technique application is achieved.

Both tasks presented in this work require the same conditions for comparing well patterns and reversal modes, which in turn can only be achieved based on mathematical modeling.

The scientific positions proposed for defense include.

– an algorithm for automatic well placement considering the balance reserves and their distribution.

– a methodology for automatic determination of the optimal distance between wells, considering geological properties of the reservoir, geotechnological parameters of extraction, capital and operational costs based on a mathematical model of hydrodynamic and physicochemical processes.

– well reversal allows for an increase in extraction efficiency by 3-18% when wells are arranged in a row, considering the cost of constructing all-purpose wells.

– the efficiency of the hexagonal well pattern was on average 26.2% higher than the row pattern without using well reversal technology, with the same values of extraction efficiency.

– the most effective scenario is one in which well reversal occurs immediately after the moment when the average concentration of the productive solution in the producing wells reaches its maximum value.

The main results of the research.

– it was determined that the relationship between the time of solution attainment and the distance between wells is non-linear, leading to a significant increase in the time of deposit depletion with an increase in the distance between wells;

– the most optimal distance between wells for minimizing total costs in a hexagonal well layout scheme is 42 meters, which aligns with recommendations used in enterprises of NAC Kazatomprom;

– automation of calculations was achieved through the development of: an algorithm for constructing a well grid with a given distance between wells; a methodology for finding the optimal distance between wells; and a software module integrated into a complex for analysis and optimization of uranium extraction using in-situ leaching;

– it was determined that optimality largely depends on the placement of boundary injection wells. When the boundary injection wells are outside the balance mineral zone, the flow of the productive solution is directed towards the extraction wells of that block. Conversely, when the boundary injection wells are within the balance zone, the flow of the productive solution is directed away from the technological block, necessitating extraction wells around the perimeter of adjacent blocks;

– when achieving similar levels of extraction efficiency, the efficiency of the hexagonal well layout scheme was on average 26.2% higher compared to the row layout scheme without well reversal;

– quantitative analysis indicates that applying reversal in the hexagonal scheme, unlike in the row scheme, does not significantly affect the profitability of production with a given mineral extraction efficiency;

– economic evaluation of two reversal options showed higher efficiency in both cases compared to the row scheme without reversal. Economic assessment revealed that the application of reversal has the potential to increase production efficiency within the range of 3-18%, depending on the chosen reversal option.

Scientific novelty of the obtained results. As a result of the research, methods and software have been developed that allow for the automatic determination of the optimal well pattern, as well as the conditions under which well reversal is most effective. Within the scope of the research, three articles were published in international scientific journals indexed in the Scopus and Web of Science databases, and three articles were published in scientific publications recommended by the Committee for Quality Assurance in the Field of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan for publishing the main results of scientific activity.

Practical significance of the work. The practical significance is characterized by the ability to apply the developed methodologies for automatic well placement and determination of distances between wells directly at the field development stage.

Additionally, the recommendations for well reversal can be utilized to enhance extraction efficiency during the operational phase.

The methods, algorithms, and results presented in this dissertation are part of a project aimed at developing a geotechnological complex for the analysis and optimization of uranium extraction using in-situ leaching. Some of the methodologies have been integrated into the software complex as modules, and this complex is currently being utilized at the mining enterprises "Ortalyk", "Inkai" and “Semizbay”.

The connection of the work with state scientific programs. This dissertation was conducted within the framework of the following projects:

– BR05236447 "Intelligent control and decision-making systems for the development of uranium and oil deposits" targeted program funding for scientific research from the Ministry of Education and Science of the Republic of Kazakhstan, 2018 – 2020, project number GR 0118RK01275

– AP08052470 «Digital technology for the efficient positioning and management of technological wells for uranium extraction with In-Situ Leaching method», grant funding for scientific research from the Ministry of Education and Science of the Republic of Kazakhstan, 2020-2022, project number GR 0120RK00063.

The individual contribution of the doctoral candidate to the preparation of articles.

– Shayakhmetov N.M., Alibayeva K.A., Kaltayev A., Panfilov I. Enhancing uranium in-situ leaching efficiency through the well reverse technique: A study of the effects of reversal time on production efficiency and cost // Hydrometallurgy. – 2023. – V. 219. – P. 106086. https://doi.org/10.1016/j.hydromet.2023.106086 (Quartile – Q1, Percentile – 89, SJR – 1.012). The dissertation author participated in formulating the problem, developing the software code, conducting calculations, and drafting the article. First author.

– Shayakhmetov N.M., Aizhulov D.Y., Alibayeva K.A., Serovajsky S., Panfilov I. Application of hydrochemical simulation model to determination of optimal well pattern for mineral production with In-Situ Leaching // Procedia Computer Science. – 2020. – № 178. – P. 84-93. https://doi.org/10.1016/j.procs.2020.11.010 (Quartile – Q2, Percentile - 68, SJR – 0.507). The dissertation author contributed to problem formulation, development of method for determining the optimal well pattern, software code development, calculations, and article drafting. First author.

– Shayakhmetov N.M., Kurmanseiit M.B., Aizhulov D.Y. Study of the optimality of hexagonal well location modes during the in-situ leaching of mineral // Kompleksnoe ispolzovanie mineralnogo syra. – 2019. – № 2. – P. 76-82. https://doi.org/10.31643/2019/6445.19 (Quartile - Q3, Impact Factor – 0.7). The dissertation author participated in problem formulation, developing the methodology for determining the optimal well pattern, software code development, conducting calculations, and drafting the article. First author.

– Shayakhmetov N.M., Kurmanseit M.B., Aizhulov D.E. Modeling of the mineral leaching process by in-situ leaching method // Bulletin of KazNPU named after Abay. – 2018. – Vol. 63. – No. 3. – P. 309-315. The dissertation author participated in

problem formulation, developing mathematical and numerical models, software code development, conducting calculations, and drafting the article. First author.

– Shayakhmetov N.M., Alibayeva K.A., Aizhulov D.Y. Identification and research of factors affecting the optimal distribution of well flow rates in space // Bulletin of NEA RK. – 2021. – V. 82. – № 4. – P. 204-214. https://doi.org/10.47533/2020.1606-146X.134. The dissertation author contributed to problem formulation, software code development, conducting calculations, and drafting the article. First author.

– Shayakhmetov N.M., Kurmanseiit M.B., Alibayeva K.A. Gravity effect on well screens alignment during the in-situ leaching // Bulletin of KazNPU named after Abay. – 2022. – V. 70. – № 3. – P. 91-98. https://doi.org/10.51889/7670.2022.18.32.011. The dissertation author participated in formulating the problem, developing the software code, conducting calculations, and drafting the article. First author.

In addition to this, the dissertation author has presented 5 abstracts at international scientific conferences, being the speaker at 4 of them. Furthermore, they have obtained 5 authorship certificates for methods and corresponding software modules developed within the framework of the dissertation.