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UNDERGROUND DEVELOPMENT OF MINERAL SUBSOIL USING MICROORGANISMS: A MINI-REVIEW

This mini-review is devoted to the analysis of the current state of the relatively rarely used underground bio-mining of natural minerals. On the basis of this analysis, it is substantiated that bacterial leaching technology has no alternative for environmentally safe and economically break-even mining of ore-bearing rocks and off-balance metal-bearing formations that are difficult to access, or unprofitable for traditional methods. It is emphasized that the efficiency of biotechnology depends on the accuracy of modeling and operational control of the working parameters of the process of biological extraction of metals, for which it is necessary to develop a new combined hydro-technical system with the possibility of the reverse technological influence on the regimes of leaching. Such controlled modes of the process are the intensity of forced aeration, pH level of the bacterial solution, amount of nutrient medium , and duration of leaching. To improve the accuracy of prediction and control of underground microbiological development, the use of a control method based on an adaptive-network-based fuzzy inference system (ANFIS) is recommended.

Keywords: *ANFIS controller, bacterial leaching, ore-bearing deposits, heavy metal extraction.*

Modern research shows that even with the current scale of mining and use of such widely consumed metals as copper, manganese, lithium, lead, zinc, tin, gold, silver, uranium, etc., their explored reserves of industrial significance will be depleted in our XXI century. That is why in recent years, in order to meet the growing needs of mankind, such measures as the development

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of metal-bearing deposits lying at great depths, the transition to the exploitation of poorer as well as shallower deposits, — to the utilization of accumulated waste, that is, to the processing of rocks with low (off-balance) content of valuable elements, etc. are intensively taken. Consequently, there is already a need to use complex ores and concentrates that cannot be processed by traditional methods. At the same time there are other difficulties, in particular, of ecological nature. Requirements for technological processes have increased significantly, where the advanced place is taken by the task of environmental protection, in particular reduction of emissions of solid and liquid harmful technogenic formations and reduction of energy intensity and minimization of greenhouse gas emissions.

One of the promising approaches to solving these problems is considered to be a biotechnological (microbiological) method of developing ore metal-bearing deposits [1]. At present, a promising rapidly developing scientific discipline — «biogeotechnology of metals» has already been thoroughly formed, which develops methods for metal extraction from ores, rocks, and solutions under the influence of microorganisms and their metabolites at normal pressure and temperatures from 5 to 80 °C [2—4].

Among the developed biogeotechnological approaches to metal mining, the most progressive and economically and ecologically safe method is an Underground Bacterial Leaching (UBL). This method allows using the subsoil more efficiently at the expense of involvement of poor off-balance ores in production, extraction, and processing, when traditional methods are unprofitable and associated with the formation of harmful waste on a particularly large scale. UBL is a selective extraction of valuable chemical elements from the target multi-component compounds, which is carried out through their decomposition by microorganisms in an acidic water environment. Owing to microbiological leaching, it is possible to extract metals in the form of their water-soluble compounds (mainly their sulfates), which makes it possible to separate from them such harmful impurities as quartz, limestone, alumina, arsenic, phosphorus, sulfur, etc.

On an industrial scale, for bacterial leaching, the most widely practiced is the use of thionic bacteria: *Acidithiobacillus ferrooxidans* (titer10^7—10^8 cells/mL), which can oxidize sulfide minerals such as Pyrite (FeS_2), Chalcopyrite ($CuFeS_2$), Arsenopyrite (FeAsS), oxide iron Fe^{++} to oxide Fe^{+++} (so-called iron bacteria), and *Acidithiobacillus thiooxidans* (so-called serobacteria), capable of oxidizing sulfur compounds. The ability of these bacteria to decompose metal sulfides causes the formation of acid mine waters, which creates a favorable environment for the extraction of target metals in the form of their sulfates. It is noteworthy that thionic bacteria are chemoautotrophs, i.e., the only source of energy for their vital activity is the processes of oxidation of the ferrous iron (II), sulfides of various metals, and elemental sulfur. This energy is used to assimilate carbon dioxide from the atmosphere or carbonate ore. The resulting carbon is used to build the cellular tissue of the bacteria. The most important factor in favor of bacterial leaching is the rapid regeneration of sulfuric oxide iron ($FeSO_4 \cdot 7H_2O$) by thionic bacteria (*A. ferrooxidans*), which accelerates the leaching process. The optimum temperature for the development of thionic bacteria is within 25—35°C and the acid-alkaline pH balance is 2 to 4. According to investigations [5—7], the noted and other thionic bacteria (e.g., *Acidithiobacillus caldus* and *Sulfobacillus thermosulfidooxidans*) accelerate the dissolution of chalcopyrite by 12 times, Arsenopyrite and Sphalerite by 7 times, and Covelin and Bornite by 18 times in comparison with the conventional chemical methods. Various countries (including Georgia) are conducting research on leaching of metals with the participation of mentioned thionic bacteria of local origin. Works on revealing prospects of application of bacteria of other species (*Bacillus mucilagino-*

sus, *Paenibacillus mucilaginosus*, *Rhizobium phaseoli*, *Escherichia coli*, etc.) are conducted and the use of bicultural and other composite bacterial solutions is tested [8—10].

The simplicity of equipment for bacterial leaching and the possibility of rapid reproduction of bacteria, especially when used solutions containing living microorganisms are returned into the process, opens up the possibility of creating fully automated plants for obtaining metals from off-balance or inaccessible ore formations directly from the Earth, bypassing complex mining and beneficiation complexes and processing plants. The introduction of UBL is of great economic importance as it leads to the expansion of the base of available raw materials, makes the technological processes of extraction cheaper, reduces the harmful anthropogenic impact on the environment, reduces the load, and prolongs the life cycle of deposits developed by traditional methods. In addition, UBL provides a comprehensive and more complete (95—99%) use of mineral raw materials, increases the culture of production, does not require the creation of expensive mining complexes, is not associated with the release of greenhouse gases, and is safe for the underground ecosystem [11—13].

In the industry of Georgia, which is a priority interest for the authors of this article, the most promising direction of the technological approach to the underground microbiological of ore formations is the development of rocky deposits of carbonate and carbonate-silicate manganese ores of the Chiatura deposit. The bacterial method of extraction can also be successfully applied to the processing of accumulated here slime of ore beneficiation (Gurgumela sludge dump, — quantity of accumulated slime is 10—15 million tons). The relevance and environmental significance of such a resource-saving approach are well substantiated in the study [14]. Underground biotechnological extraction of minerals can achieve an extension of the life cycle of the existing mines of high-quality oxide and oxidizes manganese ores suitable for conventional metallurgical processing. The effectiveness of microbiological extraction of manganese from poor off-balance ores and beneficiation wastes of noted ores of different mineral compositions has already been shown by us in preliminary studies [15].

The accumulated scientific and practical experience and the results achieved, which are quite fully described in the studies [16—21], make it possible to conclude that increasing the productivity of the processes of underground microbiological mining of ore deposits is associated with the need for operational control and regulation of such technological parameters as temperature of the working bacterial solution, acidity level pH, concentration of oxygen dissolved in it, degree of oxidation of the released Fe, S, As ions, redox potential of the resulting solution Eh, degree of forced aeration and oxygen absorption coefficient, level of assimilation of the nutrient sulfide medium, titer of bacteria cell/ml, etc. With the adequacy and promptness of regulation of technological parameters, it is possible to reduce the cycle duration of the underground processes from 5—7 to 2—3 years. It is obvious that technical and organizational difficulties in the practical realization of continuous control and management of underground leaching processes remain the main challenges now and in the nearest future. They are the most perturbing factor in the intensive development of the metal biogeotechnology industry. The mentioned problem is relatively easy to solve using the technologies of heap or tank bacterial leaching of metals where the direct accessibility of control and measuring devices, reference sensors, and levers of reverse impact to the studied environment are facilitated by many times. Thus, in the case of underground biomining, more accessible and justified means of monitoring and control become modern methods of simulation modeling of running processes. A review of the target literature shows that Softcomputing [22], Computational Fluid Dynamics (CDF-Simulation) [23], ANN modeling (Artificial Neural Network Modeling) [24], or ANFIS-simulation [25] can be used for this purpose. The last of these approaches is the most progressive, accurate, and highly productive way of modeling, but it brings to a unified industrial level suitable for all possible scenarios of bacterial leaching processes and requires further improvement of analytical algorithms. Possibilities for improving the ANFIS forecasting model for time series based on a fuzzy cluster analysis algorithm are outlined in the study [26].

Notably, the «ANFIS controller» modeling and control system has been successfully used in such advanced industries as medicine, aviation, and automotive (autopilot optimization system), electronic, and computer engineering, etc. Similar approaches have been used to optimize traditional mining operations. For example, a system «smart excavator» has been created capable to determine the trajectory and depth of the necessary work and to get ore with a given particle size. There has also been created a system of «unmanned smart dump truck» with the function of self-weighing, self-alignment, auto dispatching, and ensuring safety by scanning the roads with ultrasonic, optical, laser sensors, GPS system, etc. [27]. Similar success is available in the management of charge preparation systems and operation modes of melting furnaces [28].

The first cases of successful application of ANFIS to the control of biotechnological processes are reported in the study [29]. According to this study, ANFIS was developed and trained by entering 75% of all factor combinations together with the corresponding output data obtained using a conventional system of experiments. The trained system was tested on the remaining 25% of the factor combinations. The error of the training phase and the testing phase reported by the ANFIS system itself, expressed as a dimensionless error value, was 0.084 and 0.126, respectively, which is quite acceptable when dealing with limited actual experimental results. The results of a similar machine learning approach are reported in a study [30], according to which the use of algorithms based on regression analysis of experimental data on bacterial leaching led to an accuracy indicator of metal extraction rate prediction at the level of 77%.

These results point to the key role of human intelligence and the degree of completeness of the experimental database at its disposal, in the training of the ANFIS intelligent network. The need for such synergy, the scientific rationale for which is separately outlined in the study [31], becomes particularly acute in the case of solving the target for us multifactorial complex problem of underground biotechnological development of metal-bearing subsoil.

All of the above suggests that the potential of the underground microbiological mining of minerals is not fully disclosed, it deserves a deeper and more foresighted approach, both from the modern scientific and technological sector and industrial operators. In order to digitally ensure and improve the efficiency of management of underground biotechnological mineral extraction processes, cooperation of mining and biotechnological industry specialists with specialists of modern digital technologies capable of creating neural networks of diagnostics and control of the leaching process is required.

Conclusions. The industry of underground mining of ore deposits is a promising, environmentally and economically safe direction of metal mining, from both off-balance and inaccessible ores, and previously buried technogenic formations, therefore, it should be included in the list of development priorities for both private and state-owned companies engaged in mining and processing mineral resources.

The efficiency of the technology of underground microbiological development of ore and technogenic deposits depends on the accuracy of modeling and operational control of the performance (input and output) parameters of the leaching process, for which a new combined technical system with the possibility of reverse technological influence on the leaching zone should be developed. Such controllable process modes are the intensity of forced aeration, pH level of bacterial solution, amount of nutrient medium fed into it, and leaching duration.

To improve the efficiency of underground microbiological processing of ore formations, mining enterprises must implement a computer simulation program of an adaptive neuro-fuzzy output system — ANFIS and configure it using artificial intelligence specially trained for this purpose.

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ПІДЗЕМНА РОЗРОБКА МІНЕРАЛЬНИХ НАДР З ВИКОРИСТАННЯМ МІКРООРГАНІЗМІВ: МІНІ-ОГЛЯД

Поданий міні-огляд присвячений аналізу сучасного стану порівняно малопоширеної на практиці галузі підземного біодобування корисних копалин. На основі цього аналізу обґрунтовано безальтернативність технології бактеріального вилуговування для екологічно безпечної та економічної беззбиткової розробки рудоносних скельних порід та бідних забалансових металоносних покладів, важкодоступних або нерентабельних для традиційних способів. Наголошено, що ефективність біотехнології залежить від точності моделювання та оперативності управління робочими параметрами процесу біодобування металів, для чого необхідно розробити нову комбіновану гідротехнічну систему з можливістю зворотного технологічного впливу на режими вилуговування. Такими регульованими режимами процесу є: інтенсивність примусової аерації, рівень pH бактеріального розчину, кількість живильного середовища, що подається в ньому, і тривалість вилуговування. Для підвищення точності прогнозування та управління підземною мікробіологічною розробкою рекомендовано використовувати систему керування, засновану на комп'ютерно-симуляційній штучній нейронній мережі ANFIS.

Ключові слова: *контролер ANFIS, бактеріальне вилуговування, рудовмісні родовища, вилучення важких металів.*