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PRODUCTIVE SUBSOIL DEVELOPMENT USING CONTROLLABLE PHYSICOCHEMICAL UNDERGROUND GEOTECHNOLOGIES

Over a thousand-year history of the development of mining, the technological principles of the subsoil use through its induced transformation remain unaltered, starting with the structural change of rock mass through its disintegration (destruction).

Geotechnologies based on disintegration, while still the main technologies in terms of their application range, have many limitations in the matters of completeness of the subsoil development, mining safety, labor productivity, cost of the final product and preservation of the high-quality natural environment.

'Productive subsoil development' should combine the resource-reproducing and resource-saving production of metals in the natural environment to be preserved unaltered in its natural diversity when supplemented by the secondary artificial 'manmade environment', which is coordinated with the geological set of phenomena, is unfound in nature and creates a new entity in the process of social production.

In the matters of the subsoil development, we are talking about physicotechnical and physicochemical geotechnologies, their combination varieties, and separately about technologies for the development of alluvial deposits.

For rock masses, the era of their development begins with the use of physicochemical geotechnologies based on imparting mobility to extracted components by changing their chemical or aggregative state through redox reactions, physicochemical and biochemical nature effects or influence of physical fields.

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Introduction

Physicotechnical geotechnologies (PTG), with the chemistry and aggregative state of a matter unchanged, and with only disintegration (fracture) of rock mass, which is commonly used in mineral mining, become a sticking point on the avenue toward creation of a new integrated concept of 'productive subsoil development' despite energetic and purposeful research activities aimed at improvement of mineral production performance. It is required to ensure obligatory adherence to the key conditions: manufacture of a final product in the form of a metal or concentrate using a resource-reproducing and resource-saving practice with controllable preservation of quality of the geological environment.

Irrespective of the positive effects of the natural-and-technical systems which almost totally eliminate losses and minimize dilution [1–3], with flow diagrams developed for processing of low-grade ore and tailings [4, 5], and with add-on extraction of metals earlier discarded and lost, PTG is a final solution.

Efficiency of PTG depends on the quality of blasting, loading, haulage inside extraction panels and, then, to processing factory, with -he subsequent crushing, milling and concentration, and haulage and placement of tailings, and thickening, drying and shipment of concentrates.

An alternative for the definitive problem solving connected with the controllable and full-blast 'productive subsoil development' for solid ores of non-ferrous, precious and ferrous metals is the physicochemical geotechnologies (PCG) [6–8].

The most effective, technologically feasible, safe and eco-friendly physicochemical method for the large-scale application is in-situ borehole leaching. According to the classification [9], this is a chemical and composite (physicochemical and chemico-bacteriological) technique with conversion of a mineral to fluidity in the form of a liquid melt or solution.

The bottom line of the use of PCG with in-situ leaching is:

—elimination of loss and dilution, with complete extraction of wanted metal(s);

—preservation of integrity of the subsoil and qualitative composition of the environment (air, underground and surface water, terrain, fertile soil layer, flora and fauna);

—cumulative safety and economic efficiency.

Scientific research in the field of technologies of in-situ metal leaching from hard and solid rock masses represents a set of problems connected with interaction between the geological and technological environments.

Sufficient information in this respect is given in the textbook on the Physicochemical Geotechnology, in description of physicochemical geotechnologies, their content and interdisciplinary communication, including the general methodological principle of a 'three-aspect unity'. It is based on the following postulate: 'no event, process or engineering system in mineral mining can be adequately described and explained beyond the scope of a system of three coordinates representing geological–hydrogeological, physicochemical and techno-economic conditions'.

Implementation of this principle involves minimization of ecological impact.

Such explanation of PCG totally conforms with the 'productive subsoil development' persuaded by the present authors. In this connection, it should be mentioned that practical flow diagram rests upon a wrong basis of interaction between the geological environment and geotechnical systems:

1) Manmade impact through regular and leaching wells. Seemingly, this is very simple. But the relevant analog works relative to hydrogenous deposits (for example, uranium) which have natural aquifuges. The main leaching condition is neglected in case of a hard-rock monolith—it lacks the necessary jointing, porosity and permeability, owing to which it is required to design and create artificial permeability and jointing throughout the whole volume. The artificial permeability and jointing ensure ubiquitous access of leach solution to all nests of metals, including uneconomic pockets, and to metals in enclosing rocks, and in primary

and secondary geochemical envelopes and barriers, if there is no need to create artificial screening to prevent access of leach solution;

2) The second approach offered in scientific literature is block caving with ore shrinkage and sprinkling with leach solution. In this case, all disadvantages of PTG remain within the process flow diagram, and even worsen as two technologies get fused; therefore PTG should be totally replaced by PCG;

3) In-situ leaching of metals from a hard rock monolith can become greatly more effective in terms of performance and economy if the metal-pregnant solution is collected per sections in underground space, for the bulk–selective separation with final recovery of target metals within an integrated process of minerallurgy and pregnant solution production.

Thus, the problem involves some physicochemical methods and techniques governed by in-situ leaching and allowing 'productive subsoil development' within the framework of resource reproduction and resource saving in the controllable mode of preservation of the qualitative natural environment.

Research methods

Controllable operation of PCG frames the activity of a mining and processing plant in conformity with the proposed concept of the science-based 'productive subsoil development'. The PCG scenarios for the widely ranged varieties of geological and geotechnical factors characterizing the geological environment, at the resource reproduction, resource saving and natural equilibrium preservation are created by manmade systems which are not to induce structural damage of rock mass.

Such nature-and-manmade approaches are formulated from the analysis of mining analogies tested at a laboratory scale using the laws of physics and chemistry. The in-situ borehole leaching process should provide that the leach solution pervades the whole volume of a mineral deposit and influences all nests of metals generated during geological process of mineralization.

To this end, the analytical conclusions should be supported using the engineering mineralogy and industrial geology [13]. Minerals engineering, or minerallurgy, being a framework for mineral dressing, provides an informational support of the leach process in PCG. The pre-design rating of a mineral deposit defines the engineering activities on creation of a comprehensive artificial permeability network composed of induced fractures and pores in a hard rock monolith. The top-priority scientific problem and production task is the development of equipment and technology for cumulative blasting, calculation of explosive charge capacity, design patterns for horizontal and vertical holes in an ore body. Cumulative blasts are meant to create the required network of cracks and pores but the rock mass should preserve its integrity, without fracturing and outbursts [14].

Preliminary laboratory testing of complete extractability of each metal from ore and wall rocks to chemical solution can help determine the composition of chemical reagents, their concentration, feeding regime of the solution from leach boreholes with perforated casing. The composition of a bulk or selective solution should be adjusted along and across the strike of an ore body and through its thickness depending on information obtained from mineral engineering mapping.

The natural sequel of readiness of the geological environment, through its properties conditioned by geological history, to interaction with geotechnical systems in the subsoil are the physicochemical properties of rocks and the events initiated in rocks by the physicochemical effects. The analysis of these properties, events and factors governing physicotechnical and chemical parameters of rocks can enable scientific justification of pathways toward the goals of complete extraction of minerals from the subsoil and preservation of qualitative natural characteristics of the subsoil and terrestrial environment [15, 16].

Implementation of these objectives becomes a well-founded synergistic domain of mining sciences, with laws revealed by the interdisciplinary research by A. G. Betekhtin, N. M. Fedorovsky, I. N. Plaksin, V. I. Revnivtsev, V. V. Rzhevsky, A. M. Bybochkin and A. M. Galperin [17–22].

Application of PCG in ore extraction is one of the final stages of formation of mining sciences in the modern history of metal recovery from the subsoil. The decision on the priority of the in-situ borehole leaching meets the standards of choice of the most economically efficient physicochemical methods for metal recovery.

The set of conditions and influencing parameters, characterized by V.Zh. Arens as a 'physical geological situation', defines the natural-and-manmade systems of real-time and fruitful interaction between the geological environment and ore mining technologies.

Mineral mining is a 'big system' which should be administered by an ensemble of correlated and controllable subsystems welded together by a common objective of performance [23]. The notion of the 'big system' appeared as an expression of a system approach to formulation and solving of problems connected with functional and operating activities. The present authors understand the functional activities as the fulfillment of the mission and designated purpose of the system, and maintenance of its operation capability, i.e. conformity of the natural conditions and the capacities of the manmade systems of the subsoil development. The operating activities is planning of sets of operations connected with management of resources and evolvement of the subsystems.

The notion of the 'big system' plays a key role in solving the main task of maintenance of the demand for production of metals of different quality, quantity and types.

Results and discussion

When proposing PCG for the mining and processing practice (exactly, as this geotechnology implements most optimally and effectively two successive processes of extraction and, then, beneficiation), it is essential to commemorate the pioneer scientists and originators who invented the idea of PCG. In the USSR, where this concept started, this is, for the first turn, Professor and Academician of the Russian Academy of Natural Sciences V.Zh. Arens. Starting from the initial publications on in-situ leaching in 1967, he pursued the research and did a titanic job in this field [24, 25]. Moreover, he got together a team of researchers, which is being refilled with new enthusiasts.

At the same time, no specific design of an in-situ leach mine is defined so far, neither theoretically nor practically, although it would seem that there are no obstacles left on the way of constructing such mine in the recent decades.

In the authors' opinion, the proposed research can draw nearer the moment of the 'first-birth' design of such mine.

Fulfillment of the condition of preservation of qualitative natural environment in complete extraction of minerals from the subsoil can be ensured using PTG with cemented paste backfill. At the same time, PCG with full-blast leaching is more ecologically and economically effective.

The notion of the 'qualitative natural environment' voiced by Academician K.N. Trubetskoy is interpreted by the present authors as an environment existing before anthropogenic invasion and consisting of a subsoil area where minerals are extracted and the space around this area, including the land forms, fertile soil layer, flora and fauna, air and water flows.

The diversity of geological and geotechnical factors [26], which govern designs and process flowsheets of manmade systems, including PCG, dictates solving complex theoretical and practical problems. In this regard, the process flowsheets are developed and proposed for the in-situ borehole leaching in combination with PCG-based minerallurgy of metals from pregnant solution (**Figs. 1*a*–1*c***).

Commercial-scale implementation of the in-situ borehole leaching process has an end goal to create a mining and processing plant which, as against the current subsoil development using geotechnology and

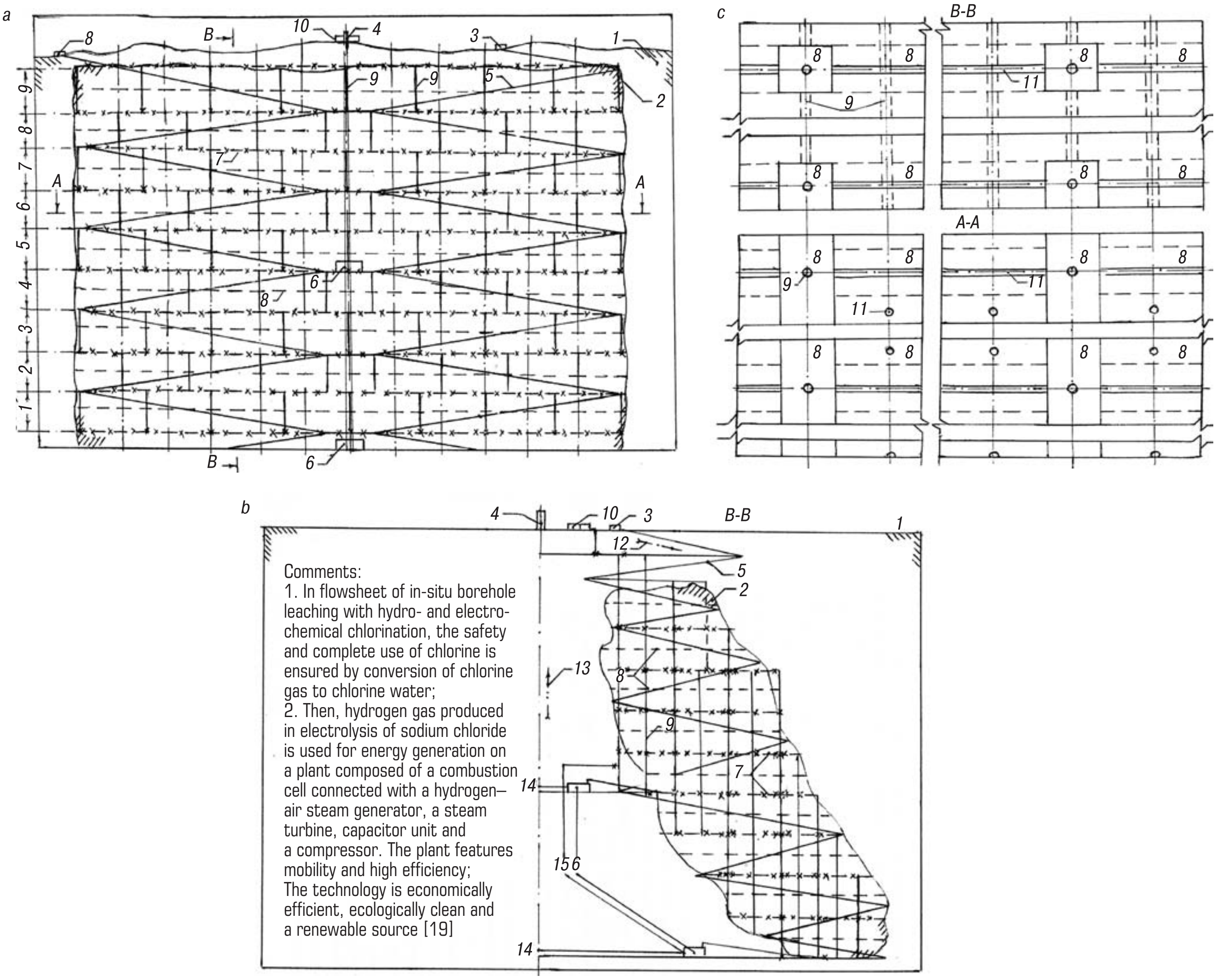

Fig. 1. Process flowsheet and design of preparation and extraction of reserves using PCG with in-situ leaching and minerallurgy (*a*); elevation profile *B–B* of extraction panel (*b*); elevation profile *B–B* of sections of extraction panel and layout *A–A* of sections of extraction panel (*c*):

1–surface; *2*–ore body; *3*–decline portal; *4*–skip-and-cage shaft; *5*–decline; *6*–conjoint underground facility for collecting and processing of pregnant solution; *7*–section drifts and crossdrifts for pressure–intake and conveyor pipes; *8*–section drifts and crossdrifts for horizontal and vertical fracture-generating holes with cumulative charges; *9*–vertical and horizontal section pressure–intake holes for feeding leaching and pregnant solutions; *10*–surface facility for preparation and feeding of leaching solution; *11*–vertical and horizontal holes with cumulative charges to generate artificial permeability; *12*–blowing fresh air; *13*–return air; *14*–marketable product after jigging, selection and sorption; *15*–recycling solution

minerallurgy, extracts and converts to a marketable product the whole volume of metal contained in an extraction panel being treated and assessed by a traditional procedure as proven reserves.

Leaching can economically efficiently replace drilling and blasting with subsequent upward stoping with cemented paste backfill only if all conventional proven reserves can be transformed to a marketable product upon condition of complete preservation of qualitative natural environment.

At the same time, the exchange and/or redox reactions to convert useful metal compounds to soluble forms should be organized in an artificially created permeable medium of a hard rock monolith so that pregnant solution catches metals which are assessed as the low-grade and uneconomic reserves based on the geological exploration data, and are omitted by today's conventional technologies [27, 28].

Considering such possibility, which should logically become a necessity, leaching can be extended to enclosing rock mass that can contain metal nests (though with much less content of metals). Later on, to a certain economic limit, it would be possible to discuss catchment of metals from primary and secondary geochemical envelopes which are presently used by geochemists as indicators of a mineral deposit.

In this manner, in the natural environment, PCG with in-situ borehole leaching will create a resource-reproducing and resource-saving setting for the efficient performance of a mining and processing plant. Resiliency in the regime of the controllable 'productive subsoil development' can be presented as a dependence of economically sound complemental reproduction of metals on PTG and PCG being used (**Fig. 2**). Using this nomogram, it is possible to determine the amount of metal producible as an end product using the new manmade

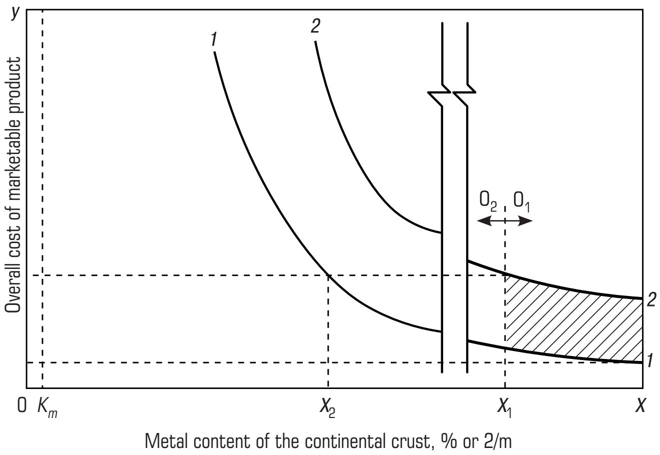

Fig. 2. Economic efficiency and reproducibility of subsoil resources versus geotechnologies in use (PTG and PCG):

1 – new physicochemical geotechnologies; *2* – conventional and new physico-technical geotechnologies; O_1–economically efficient application domain of PCG (curve *1*) and PTG (curve *2*); O_2–economically efficient application domain of PCG; X_1–minimal permissible commercial content of metal in ore for PTG application; X_2–minimal permissible commercial content of metal in extraction from all sources within 'new mining boundaries' using PCG; K_m–metal abundance ratio

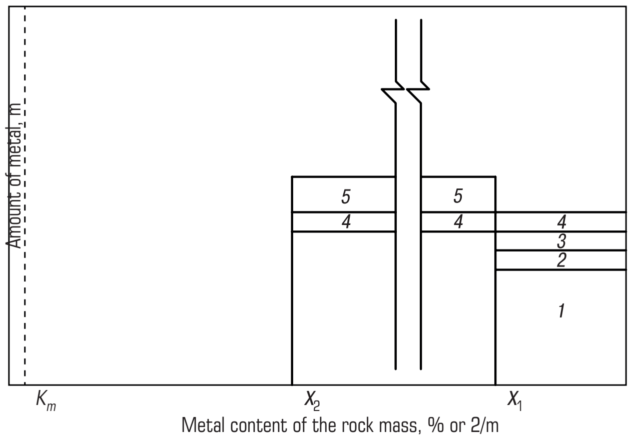

Fig. 3. Amount of metal producible using PCG and PTG with new manmade systems of resource reproduction and saving in addition to conventional reserves:

X_1–minimal permissible commercial metal content for PTG application; X_2–minimal permissible commercial metal content in extraction from all sources within 'new mining boundaries' using PCG; K_m–metal abundance ratio; *1*–primary proven georesources extracted from ore bodies using PTG; *2*–additional amount of metal owing to application of complete mining and processing cycle; *3*–additional amount of metal using PCG owing to complete extraction during leaching and minerallurgy; *4*–additional amount of metal extraction using PCG from uneconomic reserves of ore bodies and from enclosing rock mass; *5*–additional metal extraction using PCG from geochemical envelopes and barriers thanks to reduction of value X_2

systems of PTG and PCG in addition to the conventional proven reserves (**Fig. 3**).

In addition, in real-life in-situ conditions at a certain deposit, the local geology in combination with the surrounding manmade objects, individually or jointly, define the need of creating artificial screens to prevent propagation of leaching solution beyond certain limits. In this case, extraction of additional metals outside the ore body boundary should be discussed depending on a problem encountered.

In our study, PCG should obligatory work within a unified underground production process, without its involvement in operation of a surface concentration factory.

Figure 2 displays the main advantages of PCG, for instance, in-situ leaching within 'new mining boundaries':

1) At the same deposit, PCG, as against PTG, can produce additional amount of metal in in the range of its content in the continental crust between X_1 and X_2 at the same cost;

2) The dashed area between curves 1 and 2 to the right of the minimal permissible metal content of ore in the use of PTG represents the economic effect of PCG (curve 1) as compared with the economic effect of PTG (curve 2);

3) The amount of metal produced additionally with PCG at the same cost as PTG involves is determined as the difference from the overall metal amount and the maximal limit content individually for a deposit and a metal, similar for both geotechnologies, to the minimal limit defined by X_2.

Based on the aforesaid and with regard to the sources of metals, which generate potential production output, metal amount is determined for PTG and PCG at each separate deposit and for each metal (see Fig. 3).

Additional extraction of metal from enclosing rocks, geochemical envelopes and barriers is possible if propagation of leaching solution is unlimited by an ecologically required screen.

The presented process flowsheet assumes elimination of pumping of pregnant solution via boreholes to ground surface, while end products obtained by jigging, selective and adsorptive separation are distributed between skips, cages or cars for winding to the surface depending on metal content.

The comparative economy of the current technology with the complete cycle of PTG and the proposed PCG with in-situ leaching is calculated by the present authors based on the figure of production of 1 Mt of ore from a conditional deposit with the average monometal content of 1% (i.e. ore contains 10 Kt of monometal):

1) PTG application extracts 98% from conventional proven reserves, i.e. 9800 t of metal to marketable product;

2) PCG application extracts low-grade reserves with metal content under 0.3% (average content 0.2%, i.e. 2000 t of metal) additionally to extraction of 10 Kt of proven reserves;

3) additionally from enclosing rock mass and geochemical envelopes, depending on economically efficient limit of minimal commercial content for PCG with in-situ leaching, it is possible to extract more 0.05%, i.e. every 1 Mt of high-grade ore is added with more 500 t of metal;

4) in this manner, the use of PCG can allow production of 12500 t of metal at the proven reserves of 10 Kt and at extraction of 9800 t of ore, which is higher by 27.5%;

5) additional production to add-up proven reserves totals 2500 t, which is 25% higher than the reserves explored and proved by the conventional standards.

Conclusions

1. The research findings prove attainability of higher mining efficiency using PCG with in-situ leaching toward productive subsoil development.

While preserving natural diversity of the environment and integrity of the subsoil, PCG in the proposed design and engineering version is a source of resource reproduction and saving.

The preliminary calculations, to be refined later, show an increased metal extraction from the subsoil by 25% at 100% extraction of proven reserves at the conventional deposits.

2. The technology and design ensemble of the proposed natural–manmade system is the framework of a new layout of in-situ borehole leaching and stands out amongst the possible variants as the safest and

most economically efficient approach to implementation of the productive subsoil development concept.

3. The process flowsheet design is optimized to be applicable in morphologically variable geological environment (thick isometric, gently dipping and inclined, thin, chimney- and cone-like stockworks, etc.).

4. Application of PCG with in-situ borehole leaching presents theoreticians and practitioners with complex challenges in the form of collections of interrelated problems of mining geology, minerals engineering, physics of rocks, mining in hard rock monoliths via creation of full-blast artificial permeability, designs of cumulative explosive facilities and their layout in conformity with blasting patterns inside crack-forming holes [29].

5. A part of ore produced in heading of declines, section drifts and crossdrifts for laying pipelines for leaching and pregnant solutions, and in drilling horizontal and vertical crack-forming holes totals 6% of the whole reserves, and represents uniformly and finely disintegrated rock mass as a result of blasting. It can be qualitatively treated on ground surface by continuous heap leaching [30].

6. Application of chemical reagents containing free gas products which can be hazardous in decomposition requires some precautions to be undertaken on ground surface. For instance, chlorine gas should be completely dissolved in chlorine water, which ensures safety and economic efficiency simultaneously. The same should be done with free hydrogen which can be totally utilized as an in-house energy source [31].

References

1. Bitimbayev M. Zh., Yusopov Kh. A., Aben E. Kh. et al. Innovation process flowsheets of hybrid geotechnologies. *Problems and Prospects of Integrated Subsoil Development and Preservation : V International Conference Proceedings of Academician K. N. Trubetskoy School*. Moscow : IPKON RAN, 2022. pp. 12–16.
2. Joel Loow. Understanding technology in mining and its effect on the work environment. *Mineral Economics*. 2022. Vol. 35. pp. 143–154
3. Efremovtsev N. N., Rukhman A. A. Application of integrated physicochemical effects on high-energy materials and rocks toward enhancement of mineral mining efficiency. Synergistic effects. *Problems and Prospects of Integrated Subsoil Development and Preservation : VI International Conference Proceedings of Academician K. N. Trubetskoy School*. Moscow : IPKON RAN, 2024. pp. 72–74.
4. Bitimbayev M. Zh., Shemyakin V. S., Skopov S. V. X-Ray Radiometric Treatment of Copper and Copper–Zinc Ore in Kazakhstan. Almaty : Doklady NAN RK, 2016. No. 5. pp. 34–41.
5. Kozhogulov K. Ch., Bitimbayev M. Zh., Zhumabayev E. I. Improvement of technical and economic characteristics of heap leaching of gold. *Mezhdunarodniy Zhurnal Prikladnykh i Fundamentalnykh Nauk*. 2016. No. 8-2. pp. 131–135.
6. Bitimbayev M. Zh., Yusupov Kh. A., Jumabaev E. I., Fedotenko N. A. Mixed-type geotechnologies are the basis for cost-effective, safe and ecologically balanced development of ore deposits. *Eurasian Mining*. 2023. No. 1. pp. 37–41
7. Driban V. A., Hohlov B. V., Dubrova N. A., Rozhko M. D. Practice of new approach to permeability assessment of undermined rock mass. *Problems and Prospects of Integrated Subsoil Development and Preservation : VI International Conference Proceedings of Academician K. N. Trubetskoy School*. Moscow : IPKON RAN, 2024. pp. 84–87
8. Konareva T. G. Applicability of nature-like process of manmade formation oxidation in physicochemical geotechnology. *Problems and Prospects of Integrated Subsoil Development and Preservation : VI International Conference Proceedings of Academician K. N. Trubetskoy School*. Moscow : IPKON RAN, 2024. pp. 237–240
9. Arens V. Zh., Bogouslavskiy E. I., Gridin O. M. et al. Physicochemical Geotechnology: Textbook. Moscow : Gornaya kniga, 2021. 816 p.
10. Golik V. I., Dmitrak Yu. V., Dzaparov V. Kh., Dzeranov B. V. Completeness of resources use at underground block leaching of metals. *Mine Surveying and Subsurface Use*. 2021. No. 2(112). pp. 42–47.
11. Oryngozhin E. S., Zhangalieva M., Alisheva Zh. N., Oryngozha E. E. Technology of underground downhole leaching at uranium deposits in Kazakhstan. *Mine Surveying and Subsurface Use*. 2019. No. 6(104). pp. 40–43.
12. Sakhnov A. V., Golik V. I. Alternative underground mining technology Kekura deposits. *Mine Surveying and Subsurface Use*. 2023. No. 1(123). pp. 29–35.
13. Ershov V. V. Fundamentals of Mining Geology. Moscow : Nedra, 1988. 326 p.
14. Tsoi S.V., Tambiev P.G. Innovation Technologies of Mining and Processing Natural and Manmade Materials: Monograph. Almaty, 2019. pp. 86–106.
15. Betekhtin A. G. Course on Mineralogy: Tutorial. Moscow : KDU, 2010. 735 p.
16. Eshkin V. Yu. Exploration Mineralogy and Mineral Mapping. Leningrad : LGI, 1989. 86 p.
17. Rzhevskiy V. V., Novik G. Ya. Elements of Physics of Rocks. 3rd Revised and Enlarged Edition. Moscow : Nedra, 1978. 390 p.
18. Galperin A. M., Ermolov V. A. Some problems of mining geology. *Izvestiya Vuzov, Seriya Geologiya I Razvedka*. 1993. No. 3.
19. Plaksin I. N. Influence of mineral composition on extraction conditions of noble metals in complex ore processing. *Izvestiya AN SSSR*. 1943. No. 9-10. pp. 39–45
20. Revnivtsev V. I. Role of mineral engineering in mineral processing. *Zapiski VMO*. 1982. No. 4. pp. 443–449.
21. Cai M., Li P., Tan W., Ren F. Key engineering technologies to achieve green, intelligent and sustainable development of deep metal mines in China. *Engineering*. 2021. Vol. 7, Iss. 11. pp. 1513–1517.
22. Kuikui Hou, Mingle Zhu, Yingjie Hao, Yantian Yin, Long An. Stability analysis and evaluation of surrounding rock of ultra-deep shaft under complicated geological conditions. *Frontiers in Earth Science*. 2023. Vol. 11. ID 1216667.
23. Great Soviet Encyclopedia. Vol. 3, 3rd Edition. Moscow : Sovetskaya Entsiklopedia, 1970. 531p.
24. Arens V. Zh. Geotechnical Methods of Mineral Mining. Moscow : Nedra, 1975. 263 p.
25. Sekisov A. G., Lavrov A. Yu., Rubtsov Yu. I. et al. Physicochemical Geotechnologies of Mineral Mining in the Far Eastern Federal District. Chita : Transbaikal State University, 2021. 305 p.
26. Mining: Glossary. 5th Edition. Trubetskoy K. N., Kaplunov D. R. Moscow : Gornaya kniga, 2016. 635 p.
27. Rizhova L. P. Geoethical approach to selection of business evaluation method in mineral sector. *XVI International Conference Proceedings: New Ideas in the Earth Sciences*. Moscow : MGRI, 2023. pp. 302–304.
28. Zaernyuk V. M. Ethical swing in the mining industry. *XVI International Conference Proceedings: New Ideas in the Earth Sciences*. Moscow : MGRI, 2023. pp. 279–281.
29. Dawes J. Modern mining—Responsible and sustainable. *The 26th World Mining Congress Proceedings*. Australia. 2023.
30. Lu Y. Theory and technology of deep metal ore development by combining high pressure abrasive water jet and in-situ stress. *The 26th World Mining Congress Proceedings*. Australia. 2023.
31. Morozov Yu. P., Valtsev A. I., Bitimbayev M. Zh. et al. Improvement of ecological and economic safety of hydro- and electro-chlorination using electrolytic hydrogen for power generation. *Science and Practice of Ore and Manmade Material Processing: XXIX International Conference Proceedings*. Yekaterinburg : UGGU, pp. 81–84. EM