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Article

Evaluation of efficiency and environmental safety of leaching metals from ore : ways of development and prospects

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EVALUATION OF EFFICIENCY AND ENVIRONMENTAL SAFETY OF LEACHING METALS FROM ORE: WAYS OF DEVELOPMENT AND PROSPECTS

The object of research is traditional mining technologies and technical means in combination with underground block leaching (UBL) of metals from rock ores with their preliminary crushing with explosives in installations mounted in mine workings. One of the most problematic areas is the difficulty of achieving a given crushing quality, as well as the required height of ore storage in the chamber for the subsequent leaching of metals and a loosening factor, taking into account the control of the energy of explosive destruction of rock ores.

The study used:

- data from literary sources and patent documentation in the field of technologies and technical means for UBL of metals from ores in energy disturbed massifs, substantiation of technological parameters of operational blocks;
- laboratory and production experiments;
- physical modeling of metal extraction from ores from the average linear size of a piece of blasted ore.

Analytical studies, comparative analysis of theoretical and practical results using standard and new methods were carried out with the participation of the authors. It was found that the most intensive infiltration leaching occurs when the size class of ore lumps is $-100+0$ mm. Metals are extracted from fractions $-200+100$ mm less intensively and for a longer time. To neutralize and flush the spent ore mass, it is recommended to treat it with lime solution and mine water through wells for supplying leaching solutions (irrigation system). The protection of the hydrogeological environment is carried out by silting the bottom of the chamber for collecting productive solutions with clay solution and by constant monitoring of mine water pollution in the zone of UBL influence. On the basis of the positive results obtained from the study and implementation of technologies for UBL of metals from rock ores during the development of block 5–86, in accordance with the recommendations issued, the same approach was used for blocks 5–84–86 and 5–88–90, as well as industrial experimental block 1–75–79. Due to the involvement in the production of substandard ores, the raw material base for the extraction of metals, at the operating mines, can be increased by 1.4–1.6 times.

The research results can be used in underground mining of ore deposits of complex structure in Ukraine, the Russian Federation, the Republic of Kazakhstan and other developed mining countries of the world.

Keywords: ore deposits, underground mining, block leaching, mine workings, environmental safety.

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1. Introduction

There is a problem in the mining industry: on the one hand, the extraction and processing of ore are highly costly, and on the other, the ores that are mined are classified as poor in terms of the content of the useful component. The world experience in the application of mining and chemical technology in the extraction of metals by underground (mine) method from rock ores indicates that this technology has not yet been developed enough. It is possible to increase the efficiency of metal extraction through

the introduction of an integrated technology, including a traditional chamber system with solidifying backfill, and underground block leaching (UBL) from rock ores [1, 2]. Therefore, the substantiation of technology and technical means for underground leaching of metals from rock ores, providing an increase in the economic efficiency of their extraction and environmental safety, is an urgent scientific, practical and social task [3, 4]. This work is a continuation of research with the participation of the authors, the main scientific and practical results of which are most fully presented in works [5, 6].

2. The object of research and its technological audit

The object of research is traditional mining technologies and technical means in combination with UBL of metals from rock ores with their preliminary crushing with explosives in installations mounted in mine workings.

There are various technological schemes of UBL, of which the leaching of metals from permeable ores in natural occurrence through wells drilled from the surface is widely used. It is also possible to use a scheme with preliminary crushing of rock ores by explosives.

One of the most problematic areas is the difficulty of achieving a given crushing quality, as well as the required height of ore storage in the chamber for the subsequent leaching of metals and a loosening factor, taking into account the control of the energy of explosive destruction of rock ores.

3. The aim and objectives of research

The aim of research is to assess the technology and technical means for underground leaching of metals from rock ores in installations mounted in mine workings of operating blocks. This will ensure the protection and rational use of mineral resources, increase the economic efficiency and environmental safety of ore mining.

To achieve this aim, it is necessary to solve such problems.

1. To analyze the theory and practice of drilling and blasting preparation and breaking of large volumes of ore masses for UBL of metals from rock ores.

2. To investigate and substantiate the parameters, and select rational schemes for the preparation of treatment blocks for joint mining of ores by the traditional method and leaching of UBL metals.

3. To develop recommendations for design solutions for UBL, to conduct their pilot tests at the Ingul mine of the State Enterprise «Vostochny Ore Mining and Processing Plant» (SE «VostGOK», Zhovti Vody, Ukraine) Mychurin field.

4. Research of existing solutions to the problem

A number of scientists have contributed to the theory and practice of leaching. Thus, the greatest successes have been achieved in the leaching of copper, uranium, gold and zinc, to which the authors of works [7, 8] devoted their works. Despite the positive experience of industrial leaching, so far only of uranium, copper, gold, insufficient knowledge of the process prevents the widespread introduction of the method in rocky deposits of ores of other metals. Underground leaching in blocks without taking into account all natural and technogenic factors can discredit the idea; therefore, the main task of the development of the method is to develop the scientific foundations of a new technology [9, 10].

Mine systems of underground metal leaching in production blocks from chipped and stocked ores are used in deposits characterized by low active porosity (less than 5 %) and low filtration capacity of ores ($K_f < 0.1$ m/day). At the same time, ores are broken off in the blocks at the place of occurrence. Development system options include bore-hole breaking of ores in a confined environment with a loosening coefficient $K_l < 1.2$.

When choosing the parameters of drilling and blasting operations and determining the lumpiness of the broken-off ores required for UBL, in each specific case, their structure and texture, the nature of the distribution of ore mineralization and the degree of fracturing are taken into account. The disadvantage of these UBL systems is the lack of substantiated parameters of drilling and blasting operations that provide a given quality of crushing and technological conditions aimed at a more complete use of the energy of explosive destruction, except for delayed separation and blasting in a compressed environment. In addition, the stable parameters of the operational units of the UBL have not been determined, which, without taking into account the control of the energy of explosive destruction, can lead to the collapse of their structural elements. As a result, one of the most problematic areas is the difficulty of achieving a given crushing quality, as well as the required height of ore storage in the chamber for subsequent leaching of metals and a loosening factor, taking into account the control of the energy of explosive destruction of rock ores [11, 12].

The scheme of metal leaching from permeable ores in natural occurrence through wells drilled from the surface is shown in Fig. 1.

A solvent is fed into the wells, which, filtering through the reservoir, leaches useful components and then is pumped out through other wells. A feature of the wells is the use of polyethylene pipes. This technology was used to develop the deposits of Ukraine «Devladovo», «Bratskoe» and «Safonovka» of SE «VostGOK» in the period from 1959 to 1984. At present, all areas worked out by the technological scheme of underground leaching (UL) have been reclaimed, and the lands have been transferred to the land user. A specialized laboratory monitors the pollution of the hydrogeological environment in water samples taken through wells in the zone of influence of the specified mining object [13, 14].

Based on the analysis of the technologies used for underground mining of rocky deposits, it is proposed to introduce a new, cheaper technology for the extraction and processing of poor ores – a combined one, consisting of a traditional mining technology and PBB. In the experimental block, the balance reserves, in terms of the content of the useful component, were mined at the deposit of Northern Kazakhstan, folded by a lenticular ore body in sheared sedimentary rocks with a strength of 4–6 on the scale of prof. Protodyakonov. The preparation of ore bodies for leaching at the Bykogorske deposit is shown in Fig. 2 [15, 16].

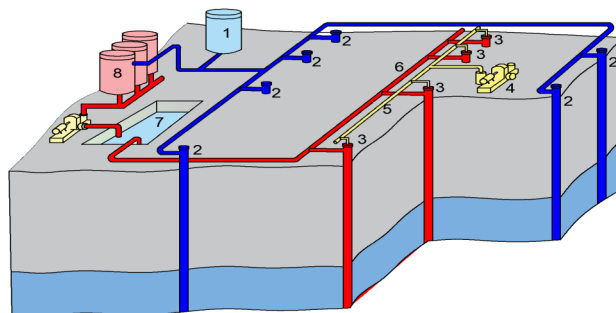


Fig. 1. Scheme of development of a seam deposit by leaching through wells (such as «Devladovo», «Safonovka» and «Bratskoe», Ukraine): 1 – solution preparation unit; 2 – injection well; 3 – drainage well; 4 – compressor; 5 – air line for airlift; 6 – reservoir for productive solution; 7 – sump; 8 – installation for solution processing

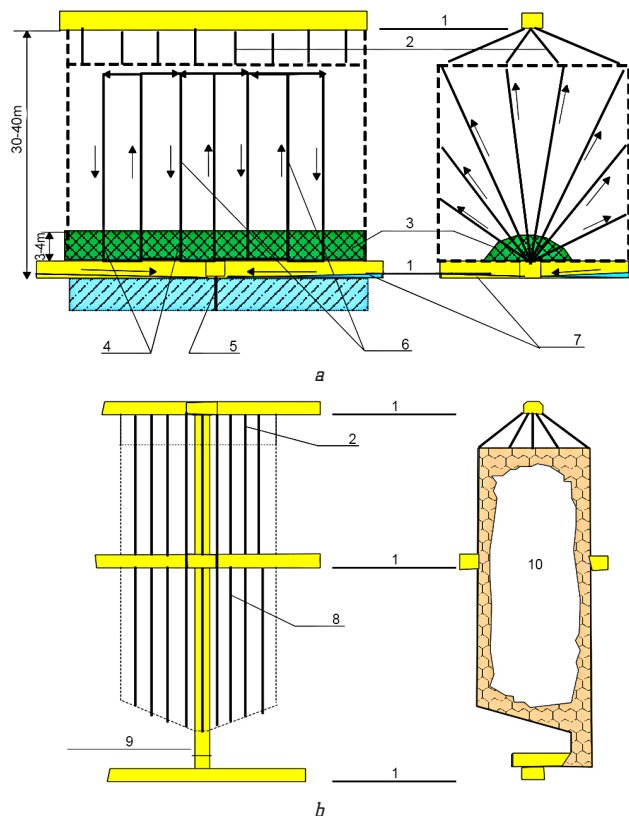


Fig. 2. Preparation of ore bodies for leaching at the Bykogorske deposit: *a, b* – respectively, without crushing and with crushing of ore by explosive charges in wells; 1 – Haulage horizon; 2 – Irrigation wells; 3 – Plugging; 4 – Drainage wells; 5 – Bypass well; 6 – Supply well; 7 – Waterproofing; 8 – Blast holes; 9 – Detachable uprising; 10 – Ore infiltration

The authors point out that this method can significantly reduce the operations used in the traditional production system. In addition to such as the creation of a compensation space, the release and delivery of up to 30 % of the magnetized ore from the PMB chamber, etc.

At the mines of the Priargunsk Industrial Mining and Chemical Association (JSC PIMCA, Krasnokamensk, Russian Federation), mining systems with solidifying backfill and metal leaching from ores stored in the chamber are most widespread (Fig. 3) [17, 18].

Uranium UBL method is used for ores with uranium content less than 0.15 %. The ore stored in the chamber is irrigated with a sulfuric acid solution according to the infiltration scheme of uranium leaching. In the lower part of the chamber there is a drainage drift for collecting productive solutions, from which they are pumped through a pipeline to a surface processing unit for primary processing. The resulting semi-finished uranium is transported by trucks to the hydrometallurgical plant (HMP). Losses of uranium at UL do not exceed 30–35 %.

The main disadvantages of the existing technologies of PMB of metals from the metals stored in the chamber are:

- labor intensity of the technological process to create conditions for effective leaching;
- the need to transport rock mass and fill the worked-out space with a hardening mixture, the formation of an artificial bottom;
- lack of justified parameters of drilling and blasting operations that ensure the specified quality of ore crushing and technological conditions, and short-delay blasting in a clamped environment;

- the stable parameters of the blocks have not been determined either, which, without taking into account the energy control of explosive destruction, can lead to the collapse of the structural elements of the blocks;
- the effective height of leaching of metals and the coefficient of loosening of broken ores have not been substantiated, taking into account the control of the energy of explosive destruction.

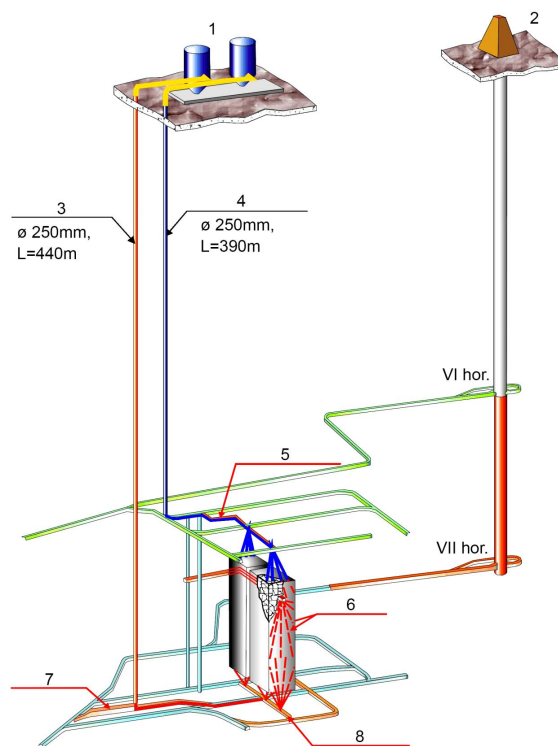


Fig. 3. Scheme of underground block leaching of metal from ores stored in chambers at the Glubokiy mine: 1 – UL unit; 2 – Barrel No. 3B; 3 – Well for produce of productive solutions; 4 – Well for the supply of productive solutions; 5 – Irrigation drift; 6 – Camera; 7 – Pump chamber; 8 – Drainage drift

5. Methods of research

In the course of the study, methods of complex generalization, analysis and evaluation of practical experience and scientific achievements in the field were used:

- technologies and technical means of underground mining of ores in energy-disturbed massifs of complex structure;
- underground geotechnology;
- complex technology, including a traditional chamber system with solidifying backfill and UBL of metals from rock ores;
- theory and practice of explosive destruction of solid media.

Let's also use the methods of continuum mechanics, mathematical statistics and methods of studying wave processes according to standard and new methods of leading specialists of developed mining countries of the world with the participation of authors in this area, in particular, the authors of works.

6. Research results

6.1. Study of the dependence of metal recovery on the average linear size of a piece of ore. The technical problem

for the solution of which the proposed combined technology is aimed is to increase the efficiency of the process of developing ore deposits in combination with UBL, by optimizing the parameters of production blocks and creating conditions for controlling the energy of explosive destruction. This ensures the optimal granulometric composition of the rock mass of a given crushing quality, as well as the coefficient of metal leaching from ores and a decrease in the consumption of technological solutions when leaching useful components.

At the operating mines of Ukraine, the combined method of metal extraction is recommended for use as the most effective. It includes traditional mining technologies and technical means in combination with UBL of metals from rock ores with their preliminary crushing by explosives in installations mounted in mine workings. This will allow, through the modernization of fixed assets and technical re-equipment of production, to involve the reserves of poor, as well as substandard ores in the development, and thus extend the life of the existing mines.

It has been established that the volume of preparatory mining operations with a combined mining method directly depends on the completeness of the use of previously passed (existing) mine workings and the adopted UBL scheme.

In the conditions of the Michurynske deposit of the SE «VostGOK» (Ukraine), large-scale studies of the dependence of metal recovery from crushed and fractionated ore mass were carried out, which made it possible to establish the quantitative parameters of the leaching process (Fig. 4).

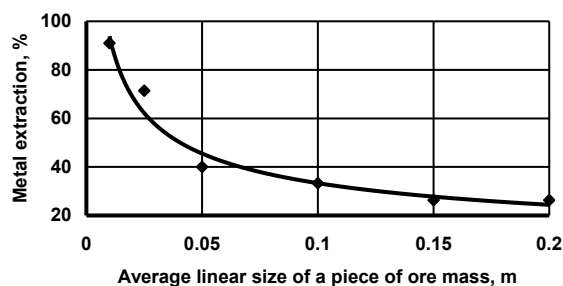


Fig. 4. Graph of the dependence of metal recovery on the average linear size of the ore mass crushed by the explosion of explosives

In Fig. 4 dots show the actual indicators of metal extraction during its leaching from the corresponding fractions of ores of the Michurynske rock deposit. As can be seen from the graph in Fig. 4, metal recovery ξ , %, significantly depends on the average linear size of a piece of blasted ore d_{av} and with a high degree of reliability ($R^2=0.97$) is described by the expression:

$$\xi = 11.817 d_{av}^{-0.4501}. \quad (1)$$

A distinctive feature of the methodology for determining the parameters of the destruction of rock ores, with a given crushing quality for leaching, is the finding of the required explosion energy, taking into account the limiting energy consumption of rock crushing.

Knowing the specific consumption of explosives, it is possible to determine the mass of the charge per one well and the geometrical parameters of the location of the wells

in the blasted block. From the analysis of the expression, it follows that it is advisable to reduce the average diameter of pieces of chipped ore, as well as crushing the components of the leached media in order to increase the contact surfaces. The regularity described by expression (1) is important in the control of the subsequent parameters of the leaching process.

One of these methods, allowing to reduce the average linear size of the piece and increase the newly formed area of the destroyed rock mass, is the preparation of the ore mass for leaching using the kinetic energy of the scattering rock lumps, followed by breaking the ores in the clamp [19, 20].

6.2. Combined technology of ore mining and metal leaching. Mining technology. The reserves of the Michurynske deposit, a significant part of which lies under the Ingul river, industrial and civil buildings (Kizelgur village of Kropyvnytskyi city, Ukraine) and structures are represented by steeply dipping ore bodies of various capacities. The deposit is being developed by a chamber mining system with backfilling of the goaf with a hardening mixture of various composition and strength.

Mining operations are developing at a depth of 40 to 350 m. The chambers are mined at sublevels of 10–15 m. Ore breaking is performed with borehole charges 57 and 65 mm in diameter drilled with NT-2 and PK-75 machines (Ukraine). Parallel down-wells with a diameter of 85 and 105 mm are drilled with NKR-100 M machines (Ukraine) to form cutting slots. The main features and effectiveness of the UBL use is achieved with the following main mining-geological and mining-technical characteristics of ore deposits [21, 22]:

- stable and medium stability steeply dipping ore bodies occurring in rocky acid-water-resistant enclosing rocks;
- by the quality of ores – these are balance, poor and off-balance;
- by the content of the useful component;
- fracture zones in the block space are poorly developed, and the presence of carbonates is not more than 2–4 %;
- ore deposits have significant off-balance halos in the absence of clay inclusions.

The technological scheme of metal leaching during underground ore mining is shown in Fig. 5.

6.3. Theory of drilling and blasting ore preparation for underground metal leaching. In the process of developing rocky, poorly permeable ore massifs, they carry out driving of preparatory and grooved mine workings, cutting slots and their expansion [23, 24]. Drilling of wells and charging of explosive, its short-delayed blasting in a compressed environment is carried out. The irrigation horizon and the bottom are drilled to collect productive solutions, and the ore is partially discharged to the cut-off slot.

Based on the results of many years of research on a complex of scientific research work in underground mining in energy disturbed massifs, the authors propose calculation formulas to substantiate the stable parameters of the chambers (Table 1).

Substantiation of an effective loosening factor allows increasing the extraction of useful components from ores to economically feasible limits [25, 26].

perforated polyethylene pipes with a diameter of 16 mm. The pipes are inserted into 48 wells drilled from the 210 m horizon down into the block chamber. The total length of these wells is 309.2 m, the network of irrigation points has reached 2×2 m. Irrigation is carried out periodically for 30 minutes with pauses of 2–3 hours. During the pauses, favorable conditions are created for aeration of the ore material and the development of oxidative processes that contribute to the transition of the metal from the hardly soluble tetravalent form to the readily soluble hexavalent one. The irrigation density during the experiment varied from 9 l/m²·hour to 16 l/m²·hour, which ensured the infiltration regime of irrigation.

The technology of the experimental section of the UBL includes the following operations:

- acidification of the broken-off ore in the experimental block;
- irrigation of stored ore with sulfuric acid solutions;
- sorption of metal from productive solutions onto resin (regenerated anionite grade AMP);
- intensification of leaching processes by shaking explosions;
- pumping out, through the main drainage of the mine, excess solutions after sorption to the mine water treatment plant (MWTP);
- neutralization and washing of the spent ore mass with lime solution and mine water [27, 28].

Technological equipment for leaching metal from ore installed in underground workings at the Ingul mine of the State Enterprise «VostGOK» consists of:

- sorption columns of SNK type (Ukraine);
- pumping station with a capacity of 0.4 m³ and an AX pump (Ukraine);
- the composition of containers with ion exchange resin and diluted sulfuric acid.

Leaching process maintenance is provided by technological equipment, including: surface unit; technical complex for receiving and dispensing acid and resin; underground node; technological complex for leaching and sorption. Sulfuric acid from a railway tank car, used as a consumable tank, is periodically pumped through a beetroot (tank) and a drain device into a transport tank car. A tank car with acid is lowered down the shaft to a horizon of 210 m. Acid, in accordance with the technological regulations, is dosed at a horizon of 240 m into a sump of productive solutions for the preparation of a leaching solution [29, 30].

Periodically saturated resin, from the sorption column, is unloaded into a special tank car and rises to the surface, where, with the help of «transport» water from the pump, it is loaded by gravity into a tank truck with a volume of 6.4 m³ and transported for regeneration to a hydrometallurgical plant. The regenerated resin is loaded into the trolley from a tank truck by gravity – with the help of circulating water, which, during loading, drains from the truck or tank truck through a cartridge filter. On the haulage horizon, the resin is fed from the tank car into the sorption column by airlift.

After the completion of leaching, flushing and neutralization of the block, insulating and ventilation bridges are constructed in all adjacent workings of horizons 280, 240 and 210 m to prevent the emanation of radon and other harmful substances. Studies have established that after leaching, there was a change in the granulometric composition of the ores. The leached ore, after being delivered from the block to wagons and transported to the

surface, was carefully screened through changing sieves at an ore processing plant (OPP), collected and weighed fractionally. Their lumpiness began to differ both from the parameters set by the calculation and from the values obtained after breaking off in the block (Table 2).

Table 2

Content and recovery of metal by size classes in leached ore

Size class, mm	–200+150	–150+100	–100+50	–50+25	–25+0
Class yield, %	8.8	17.0	27.0	35.3	11.9
Metal content by class, %	0.038	0.038	0.030	0.025	0.014
Metal recovery by class, %	26.3	26.3	33.3	40.0	71.4

6.5. Effectiveness of the results. The profit from the involvement of substandard reserves in terms of the content of useful components in production is provided by increasing production volumes, increasing production and increasing the return on capital for combined leaching technologies [31, 32]. The study of the processes of sorption purification of contaminated water was carried out using solutions, the composition of which, in terms of the main anionic components, corresponded to the composition of underground waters of the storage facility for liquid waste of uranium ore processing at the State Enterprise VostGOK (Zhovti Vody, Ukraine) [33]. This ensures a decrease in the degree of metal contamination of ground and surface waters, soils and sediments, including the main Michurynske fault and an anti-seepage curtain (constructed using technology, for example, a «wall in the ground») [34, 35].

Thus, the UBL implementation on an industrial scale will significantly improve the economic and environmental performance of production. As a result of the studies, it was found that mining and chemical technologies can be used for the development of poor and substandard ores of rocky deposits, and thus, increase their profitability [36, 37].

6.6. Promising areas of research. Continue research on the quality of the hydrogeological environment in the zone of influence of the UBL based on the data of hydrogeological monitoring of groundwater pollution [38]. The authors consider it expedient to construct semi-active water-permeable chemically active barriers (WPAB) and biological technologies for UBL by silting the bottom of the chamber for collecting productive solutions with clay solution [39, 40].

7. SWOT analysis of research results

Strengths. On the basis of research and assessment of technology and technical means for underground leaching of metals from rock ores, the parameters were substantiated and rational schemes for the preparation of treatment blocks for combined ore mining by the traditional method and leaching of UBL metals were selected. This will ensure the protection and rational use of the subsoil, and an increase in economic efficiency. The results of the work showed a significant dependence of the leaching process (in terms of the time factor) on the working volume of the sump of productive solutions. The most optimal volume is 70–80 m³, although the design is 20 m³.

Advantages of block leaching: There are no costs for separate operations in comparison with traditional technology of ore mining and processing, namely:

- 1) when mining:
 - secondary crushing and release of ore;
 - intra-mine transportation of ore;
 - delivery of ore to the surface;
 - crushing and beneficiation of ore;
 - backfilling of the worked-out area;
 - loading into railway wagons and transportation of ore to the OPP;
- 2) during processing at OPP:
 - reloading of ore;
 - grinding of ore;
 - leaching;
 - sorption;
 - resin regeneration;
 - storage of tailings.

Weaknesses. Pollution of the hydrogeological environment with leaching and productive solutions in the zone of UBL influence. To neutralize and reduce pollution of the hydrogeological environment with heavy metals, it is recommended to flush the spent ore mass and treat it with lime solution and mine water through wells for supplying leaching solutions (irrigation system). To solve hydroecological problems, it is recommended to organize continuous monitoring of groundwater contamination in the zone of UBL influence through observation wells drilled in the bottom of the production block and to the contacts with the ore body, as well as zones of fracturing and hydrogeological fracturing of rocks.

Opportunities. The issues of sustainability of the workings of the irrigation horizon, located in the area of intense influence of the worked-out blocks, require special attention. The ore massif at the 197–210 m floor has been weakened by the grooved and stope workings that exist before the blocks are prepared for UBL, as well as the network of wells of the irrigation system being created. In these workings, a systematic monitoring of their stability and the nature of the stress-strain state of the near-contour massif (geo-mechanical monitoring) was organized. A negative factor is the presence of a significant amount of sand and debris in the regenerated resin at the OPP. Subsequently, it was decided to install an autonomous resin regeneration unit at the OPP for pilot sites of UBL.

Threats. During the experiment, about 54 % of the metal reserves in the block were transferred to the solution at an acid consumption of 36 % of the design. By attracting substandard ores to production, the raw material base for metal extraction at operating mines can be increased by 1.4–1.6 times. It has been established that the effectiveness of various options for the technology of metal leaching from ores is determined by the completeness of its extraction by the mining and chemical process. The experience accumulated in the world practice shows that the completeness of metal leaching depends directly on the quality of ore crushing and the uniformity of its density distribution in the magnetized state. These conditions include mineralization, structure, porosity of ore, diffusion coefficient, temperature, concentration of working solutions, etc. The possibility of metal leaching from mined deposits has been proved and the dependence of metal extraction on the average linear size of the ore mass crushed by an explosion has been established [12, 29, 30].

8. Conclusions

1. The analysis of the theory and practice of drilling and blasting preparation and breaking of large volumes of ore masses for UBL of metals from rock ores has been carried out. On its basis, the State Enterprise «Ukrainian Research and Design Institute of Industrial Technology» (Zhovti Vody, Ukraine) was recommended and carried out scientific support for the development of UBL experimental blocks at Michurynske deposit of SE «VostGOK» 5–86, 5–84–86 and 5–88–90, as well as industrial experimental block 1–75–79.

2. Technological operations for the formation of cutting slots and compensation spaces were recommended to ensure optimal loosening of the gagged ore according to the condition of ore leaching and the stability of the outcrops of the massifs. This is ensured with a loosening factor of $1.15 > Kp < 1.2$ and structural stable parameters of the chambers: the height of the stored ore – 20 m; width – 16 m; length – 24 m.

3. On the basis of pilot tests at the Ingul mine of the VostGOK State Enterprise of the Michurynske deposit of development of pilot block 5–86, it was shown that the most intensive infiltration leaching occurs when the size class of ore lumps is –100+0 mm. It is recommended that the yield of this fraction in the broken ore is about 90 %. Metals are extracted from fractions – 200+100 mm less intensively and for a longer time.

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