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Research article

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Evaluation of the efficiency and environmental impact (on subsoil and groundwater) of underground block leaching (UBL) of metals from ores

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Abstract

One of the most problematic aspects of underground block leaching (UBL) of metals from ores is the possibility of pollution of water and air in the affected zone. Therefore, proving the possibility of mitigating environmental impact of metal leaching from ores by managing production processes with the implementation of nature- and resource-saving technologies is an important objective. The purpose of this study is to justify underground development effectiveness of ore deposits by traditional and integrated methods with leaching of metals from substandard and off-balance ores. This will allow the raw material base for extraction of metals from off-balance ores to be expanded and the environmental impact on subsoil and groundwater (hydrogeological systems) to be mitigated. A distinctive feature of a UBL (underground site for leaching of metals from shrunk ores) is that leaching solutions are supplied from sorption column placed in mining workings of the leaching level in the immediate vicinity of the extracting block. The pregnant solutions in the form of resin are discharged from the sorption column, placed in the leaching level mine workings, then winded in mine cars and further supplied to hydrometallurgical plant in tanks. A still rare attempt to justify the efficiency and environmental safety of underground metal leaching (UBL) from off-balance and substandard rock ores in installations mounted in mine workings, on the basis of monitoring and evaluation of subsoil and groundwater conditions was investigated. The average value of uranium concentration by level was established: 210 m – 3.6 mg/L; 225 m – 3.58 mg/L; 280 m – 0.91 mg/L. At the same time no contamination of underground mine waters was detected. Levels of sulfuric acid aerosols and radon decomposition products did not exceed the maximum allowable concentration (MAC) values. It is recommended that the hydrogeological environment be protected through silting the bottom of the stope for collection of pregnant solutions with clay mud and construct semi-active water-permeable chemically active barriers. The mentioned BIL process was implemented during the development of pilot block 5-86 and recommended for blocks 5-84-86 and 5-88-90 of Michurinskoye deposit of SE VostGOK, Ukraine, as well as during for development of ore deposits in Russia, Kazakhstan, and other developed mining countries.

Keywords

ore deposits, underground block leaching (UBL), installations, mine workings, monitoring, hydrogeological systems and environment, groundwater, performance

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РАЗРАБОТКА МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Научная статья

Оценка эффективности гидрогеологической и окружающей среды при подземном блочном выщелачивании металлов из руд

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Аннотация

Одним из самых проблемных мест подземного блочного выщелачивания (ПБВ) металлов из руд является возможность загрязнения водной и воздушной среды в зоне их влияния. Поэтому доказательство возможности минимизации последствий ПБВ металлов из руд путем управления технологическими процессами в рамках реализации природо- и ресурсосберегающих технологий актуально. Цель исследования – обоснование эффективности подземной разработки рудных месторождений традиционными и комбинированными технологиями с выщелачиванием металлов из скальных некондиционных и забалансовых руд. Это обеспечит повышение сырьевой базы добычи металлов из забалансовых руд и улучшит охрану недр, гидрогеологической и окружающей среды. Отличительной особенностью ПБВ (подземного участка по выщелачиванию металлов из замагазинированных руд) является то, что выщелачивающие растворы подают из сорбционной колонны, размещенной в горных выработках горизонта орошения в непосредственной близости от эксплуатационного блока. Выдачу продуктивных растворов в виде смолы осуществляют из сорбционной колонны, размещенной в горных выработках горизонта орошения, в вагонетках на дневную поверхность и далее в цистернах на гидрометаллургический завод. Исследованию подвергается пока еще редкий опыт обоснования эффективности и экологической безопасности ПБВ металлов из забалансовых и некондиционных скальных руд в установках, смонтированных в горных выработках, на основании мониторинга и оценки охраны недр, гидрогеологической и окружающей среды. Выявлено усредненное значение концентрации урана по горизонтам: 210 м – 3,6 мг/л; 225 м – 3,58 мг/л; 280 м – 0,91 мг/л. При этом загрязнения подземных шахтных вод не обнаружено. Уровень аэрозолей серной кислоты и продуктов распада радона не превышал значений предельно-допустимой концентрации. Рекомендовано охрану гидрогеологической среды производить заиливанием глинистым раствором днища камеры по сбору продуктивных растворов, сооружать полуактивные водопроницаемые химически активные барьеры. Указанная технология ПБВ внедрена при отработке опытного блока 5–86 и рекомендована для блоков 5–84–86 и 5–88–90 Мичуринского месторождения ГП «ВостГОК», Украина, а также при разработке рудных месторождений Российской Федерации, Республики Казахстан.

Ключевые слова

рудные месторождения, подземное блочное выщелачивание, установки, горные выработки, мониторинг, гидрогеологическая и окружающая среда, эффективность

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Для цитирования

Lyashenko V.I., Golik V.I., Kluev R.V. Evaluation of the efficiency and environmental impact (on subsoil and ground-water) of underground block leaching (UBL) of metals from ores. *Mining Science and Technology (Russia)*. 2022;7(1):5–17. https://doi.org/10.17073/2500-0632-2022-1-5-17

Introduction

With the increase in the volume of underground ore mining, the volume of waste on the surface and in underground workings increases, enhancing environmental pollution [1, 2]. Many areas of operating deposits are a fragmented rock mass, forming the basis for uncontrolled process of natural leaching [3, 4]. Therefore, proving the possibility of minimizing the consequences of natural leaching by managing technological processes as part of the implementation of resource-saving technologies is relevant. Therefore, proving the possibility of mitigating environmental impact of natural metal leaching from ores through managing production processes as part of the implementation of resource-saving technologies is an important objective [5, 6]. The main scientific and practical results of the studies of integrated methods for development of ore deposits, relating to both processes of beneficiation and hydrometallurgy, and methods of underground mining of minerals (physical-and-chemical geotechnologies), are presented below [7, 8]. This work is a continuation of the authors' research, the main scientific and practical findings of which are most fully presented in [9, 10–12].

Goal of research

The purpose of the study is to justify underground development effectiveness of ore deposit by traditional and integrated methods with leaching of metals from substandard and off-balance ores. This will allow expanding raw material base for extraction of metals from off-balance ores and mitigating environmental impact on subsoil and groundwater (hydrogeological systems).

In order to achieve this goal, the following tasks need to be undertaken:

1. To analyze the factors affecting the performance and environmental safety of underground development of ore deposits with metal leaching.

2. To identify the conditions and sources of possible pollution of water and air in the in the block in-situ leaching affected zone.

3. To develop measures for mitigating the adverse environmental impact of block in-situ leaching of metals from ores.

4. To outline promising areas of study aimed at increasing performance and environmental safety of underground block leaching of metals from ores.

Research Methods

Continuum mechanics, mathematical statistics, and wave processes research using standard and new techniques were used to summarize, critically analyze, and outline promising areas of scientific advances in the methods and technical means of underground ore mining, underground geotechnology, and blasting rupture of solid media.

Findings Discussion

Technology audit of block in-situ leaching

The known methods of extracting metals from ores are not waste-free. More and more money and energy are being spent in fully utilizing the tailings. These methods produce obvious environmental impact, since secondary tailings are activated and migrate into the environment during storage and processing. Significant economic efficiency distinguishes new method from known ones by the fact that there is no need to wind ore to the surface [11, 12].

Underground block leaching (UBL) has been carried out at the Gumeshevskoye deposit since 2005. The mines of the Priargunsky Industrial Mining and Chemical Association (Krasnokamensk, Russia) use mining methods involving metal leaching from shrinked (in stopes) ores on industrial scale. Geotechnological methods of metal production in RNO-Alania have been known since the second half of the last century [13, 14].

The environmental impact of ore natural leaching was studied based on the experience of enterprises in the North Caucasus. Here the contents of products of natural leaching of ores exceed the sanitary norms by 2-3 orders of magnitude. For instance, the Baksan River (Kabardino-Balkaria) at the Tyrnyauz deposit site receives effluents from the tungsten-molybdenum complex, containing tungsten and molybdenum. In the Alagirsky District of the Republic of North Osetia-Alania, the Ardon River is polluted with copper, lead, and zinc at the Sadon deposit site [15, 16].

The process of in situ dissolution of ore with transfer of useful components to the solution is an alternative to the traditional methods of development of these deposits The ore is shrunk into blocks. After percolating through the ore mass the pregnant solution of reagents is collected in the bottom, and from there directed to processing facilities (Fig. 1).

During block in-situ leaching of ores with grades of lead of 0.99 %, and zinc, 0.71 % at Kakadurskoye deposit (North Osetia), a method for development of the whole deposit (instead of development of a separate area of substandard (for conventional methods) reserves) was proposed. Professor I.A. Ostroushko proved its feasibility and achieved its implementation. The new method of mineral leaching in a disintegrator is based on the fact that at an impact velocity of 250 m/s their processing properties change. The processing of tailings of Sadon ores in the disintegrator allowed extraction of 22 % of lead and 76 % of zinc (from their initial content in the primary tailings). By means of multiple processing, the ultimate content was brought to the required level [17, 18]. The content of metals in natural leaching solutions corresponds to the content of the process accelerants, iron-bearing minerals, and retarders, calcium and magnesium minerals. In order to evaluate the characteristics of mine drainage in the Ardon River, its water samples were examined (Fig. 2).

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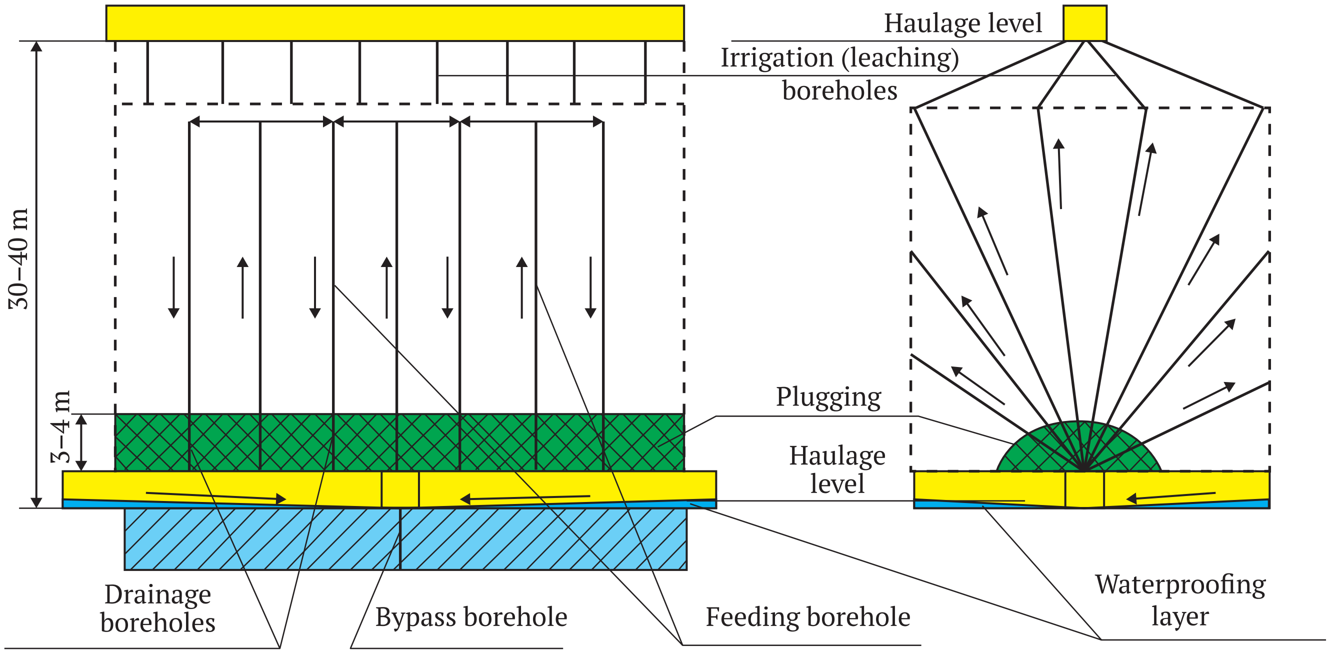

Fig. 1. Preparation of ore bodies for leaching without ore crushing

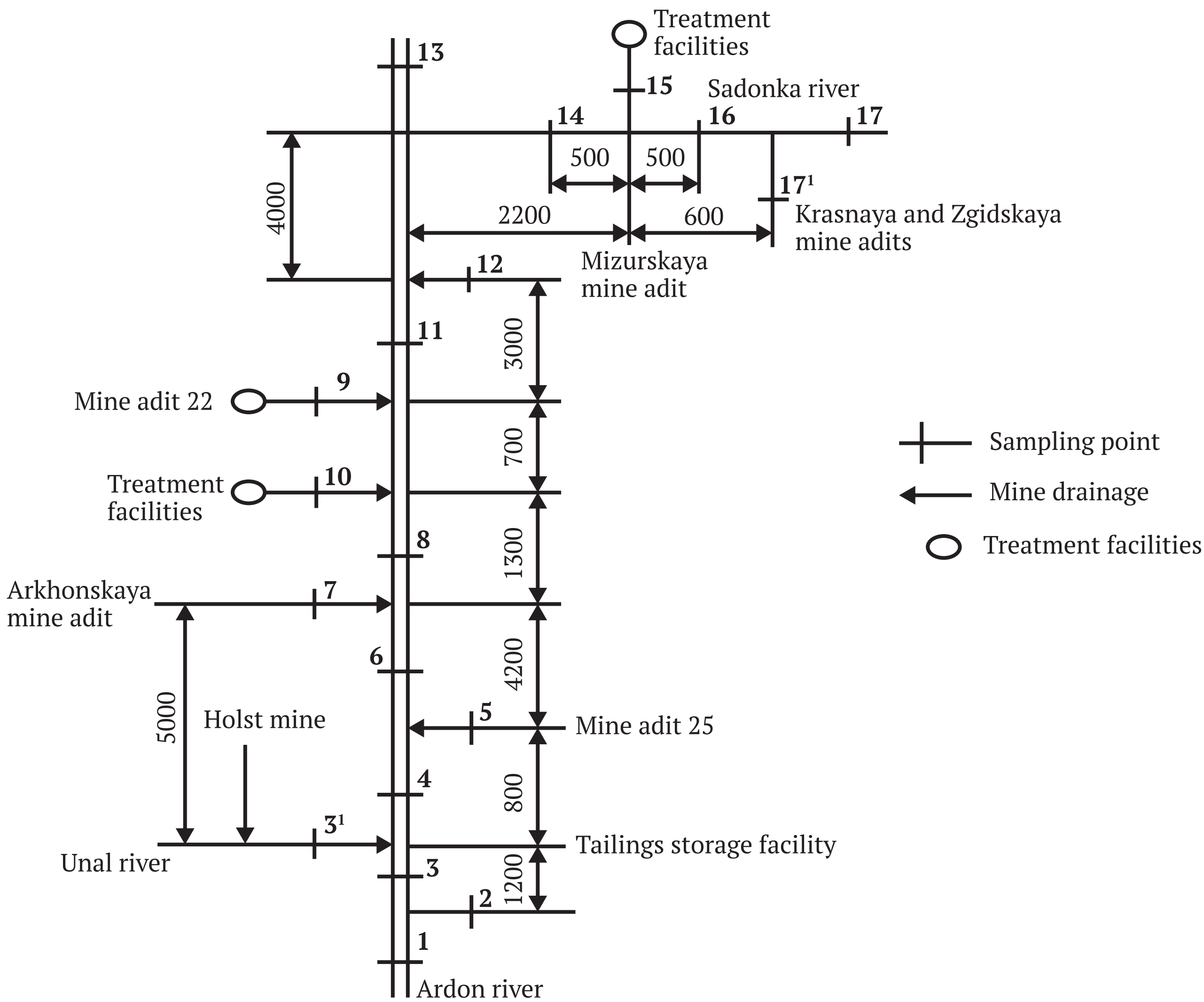

Fig. 2. The Ardon river sampling schematic

Combining the activities of enterprises, for example, the lead-zinc complex and JSC "Kavdolomit" (RNO-Alania, Russia) allows for the environmental impact to be mitigated. This includes backfilling of the mined-out space with backfilling mixture on the basis of dolomite-based binders to reduce losses of ores in the course of breaking. In order to produce the dolomite binder fraction, mills are used. They allow the dolomite specific surface to be increased up to 3000 cm^2/g thus raising the activity of binding additives by 20–30 % [19, 20]. Underground block leaching of metals from the broken ores is one of the best ways to reduce the amount of radioactive waste on the surface, decrease the backfill volume and increase the enterprise performance in the production process (Fig. 3).

Process flow sheet for metal leaching from ores in the installations placed in mine workings is illustrated in Fig. 4.

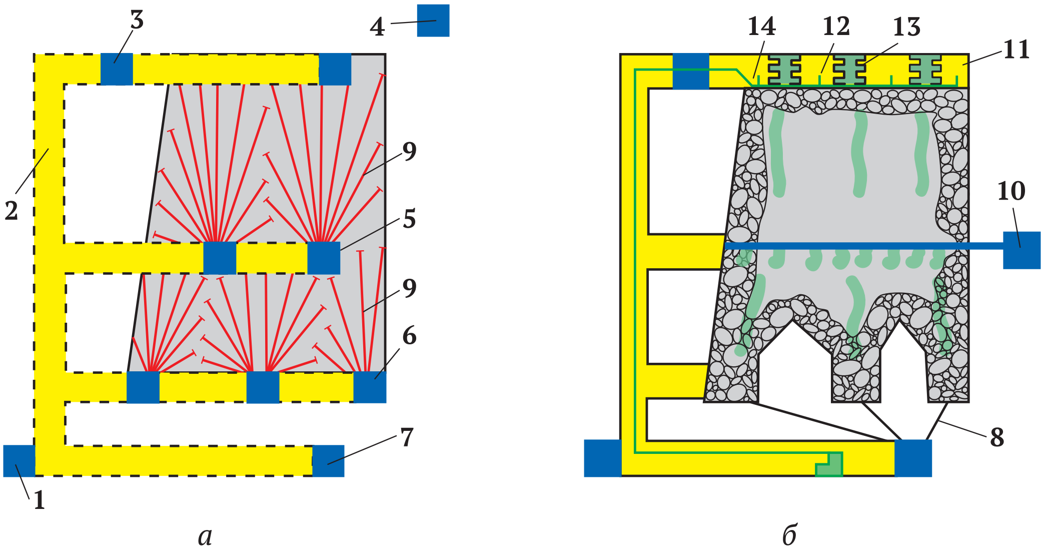

Fig. 3. Method of underground block leaching of metals from broken ores:
a and *b* – drilling and leaching of shrinked ores in a block:
1 – drift; *2* – raise; *3* – drift for leaching; *4* – drift; *5* – drill drifts; *6* – drill drifts; *7* – drainage drift; *8* – drainage boreholes; *9* – intermediate leaching level; *10* – intermediate leaching level; *11* – drift for leaching; *12* – top undercut; *13* – cribwork; *14* – leaching system

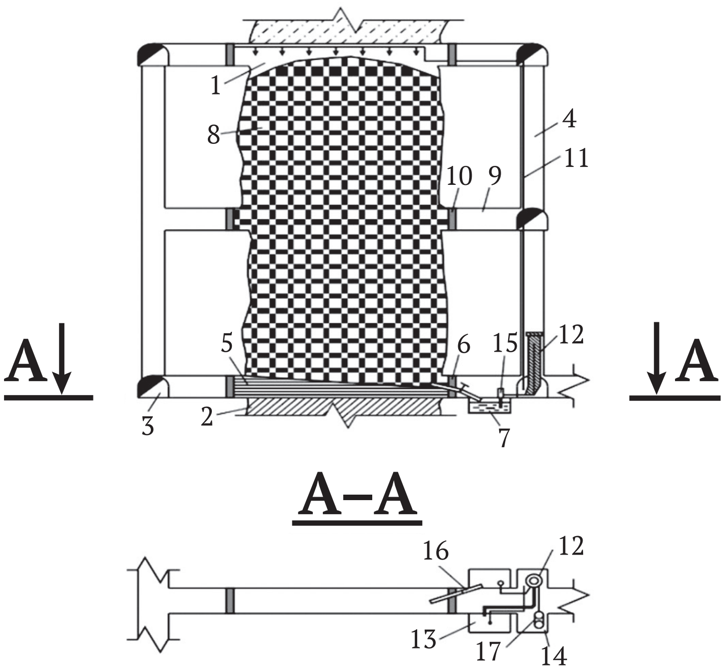

Fig. 4. Process flow sheet for metal leaching from ores in underground installations:
1 – stope; *2* – ore body; *3, 4* – horizontal and vertical workings; *5* – liner; *6* – stopping; *7* – tank; *8* – shrunk ore; *9* – working; *10* – stopping; *11* – pipeline; *12* – pregnant solution processing sorption units; *13* – tank for preparation of leaching solution; *14* – niches; *15* – pumps; *16* – pipe; *17* – metal desorption unit

The ore body 2 is divided into extraction blocks, then secondary development and face-entry drivage are performed. Drilling of 50–85 mm (in diameter) boreholes from sub-level workings 9 is carried out. Partial shrunk ore drawing 8 is performed to the haulage level. The leaching system consisting of pipes 11 and nozzles is mounted in the upper part of stope 1. Workings 7 for collecting of pregnant solutions are prepared in the lower part [21, 22].

A process flow diagram of the underground block leaching commercial implementation is shown in Fig. 5. It includes: railway tank; pumps F430 PP-50/38, X 80-50-250 E, PR63, AX 125-100-400E, and X50-32-125 types; tank for low-quality acid; discharge device; road tanker and tank for resin; submersible pump of F-706 PP-185 type; sump for pregnant, neutralization, and leaching solutions; hydraulic hoist; 0.4 and 0.8 m^3 tanks; SNK-type sorption column; pipeline; ejector; free tanks; tanks for acidizing and neutralization; hand hoist with load-carrying capacity up to 1 ton.

Leaching and pregnant solutions are pumped from the lower to the upper levels without the solutions winding to the day surface. At the day surface, the products are wound as resin for further processing at the hydrometallurgical plant. In fact, an underground area for the leaching of metals from ores in UBL blocks with processing of solutions in units is placed in the underground workings. The authors point out that this method allows for a significant reduction in the list of operations required, when compared with the traditional mining methods [23, 24] (except for such operations as: creation of compensation space, drawing and delivery of up to 30 % of the shrunk ore from the UBL stope, etc.).

Hydrogeological and environmental monitoring

The system of environmental monitoring includes three-step control and allows the following tasks to be resolved: monitoring of the conditions of the mine waters; determining zones of mine air pollution; detecting emergency environment pollution; providing company management with necessary information.

a *b* *c* *d*

Fig. 5. Process equipment for UBL at Ingulskaya mine of SE VostGOK (photo):
a and *b* – sorption columns of SNK type; *c* – pump room with a 0.4 m^3 tank and AX pump;
d – train of tanks with ion exchange resin and diluted sulfuric acid

Research Findings

In order to monitor possible migration from the stope of the block and sump towards the block bottom, six rising observation boreholes were drilled (Fig. 6). The first level of water environment monitoring was implemented on a monthly basis. This requires measuring the hydrogen index (pH) of the mine water in observation boreholes by the staff of the pilot block.

During the testing 18,630 water pH measurements were performed. The observation boreholes remained dry during the testing. The water pH was practically neutral of 6.5–7.5, and only in 5 cases pH was measured at 1.5–2.0, which was explained by pipeline failures and stop valve wear. The halo of spreading the process solutions was local and neutralized by lime milk.

The second level of the monitoring aquatic environment included measuring the following indicators: uranium concentration; alkalinity; and hydrogen index (pH). During the block development, 882 samples of mine water were taken. Table 1 shows the monitoring results averaged on quarterly basis. The analyses show the average uranium concentrations of 3.6 mg/L at 210 m level; 3.58 mg/L at 225 m level; 0.91 mg/L at 280 m level. The water pH was neutral. The observations indicate no negative impact of the testing block on mine water quality, and the observation boreholes remained completely dry [25, 26].

The third level also included air monitoring. Full chemical analysis of the mine water samples for calcium, magnesium, sodium, potassium, total iron, carbonates, bicarbonates, sulfates, chlorides, nitrates, nitrites, ammonium, dry residue, uranium was carried out on monthly basis, and radiochemical analysis for radium-226, thorium-230, polonium-210, lead-210, uranium was performed on quarterly basis (Table 1).

Table 1

The third level monitoring results for mine water

Designation	Sample Location	Control parameters		
		Alkalinity, mg-eq/L	pH	Uranium, mg/L
Pre-testing	P – 1 P – 2 P – 3 P – 4 p – 5 P – 6	2.70 0.50 5.75	7.8 7.8 7.9	6.7 0.64 1.32
Averaged value for 3 years of testing	P – 1 P – 2 P – 3 P – 4 P – 5 P – 6	2.60 3.21 5.37	7.3 7.5 7.7	3.60 3.58 0.91

During the testing, 210 samples of mine water for ultimate analysis and 60 samples for radiochemical analysis were taken and analyzed. The results of the chemical and radiochemical analysis of the mine water, as well as those of the mine water immediately before the mine water treatment (in the unit at 210 m level) are given in Table 2.

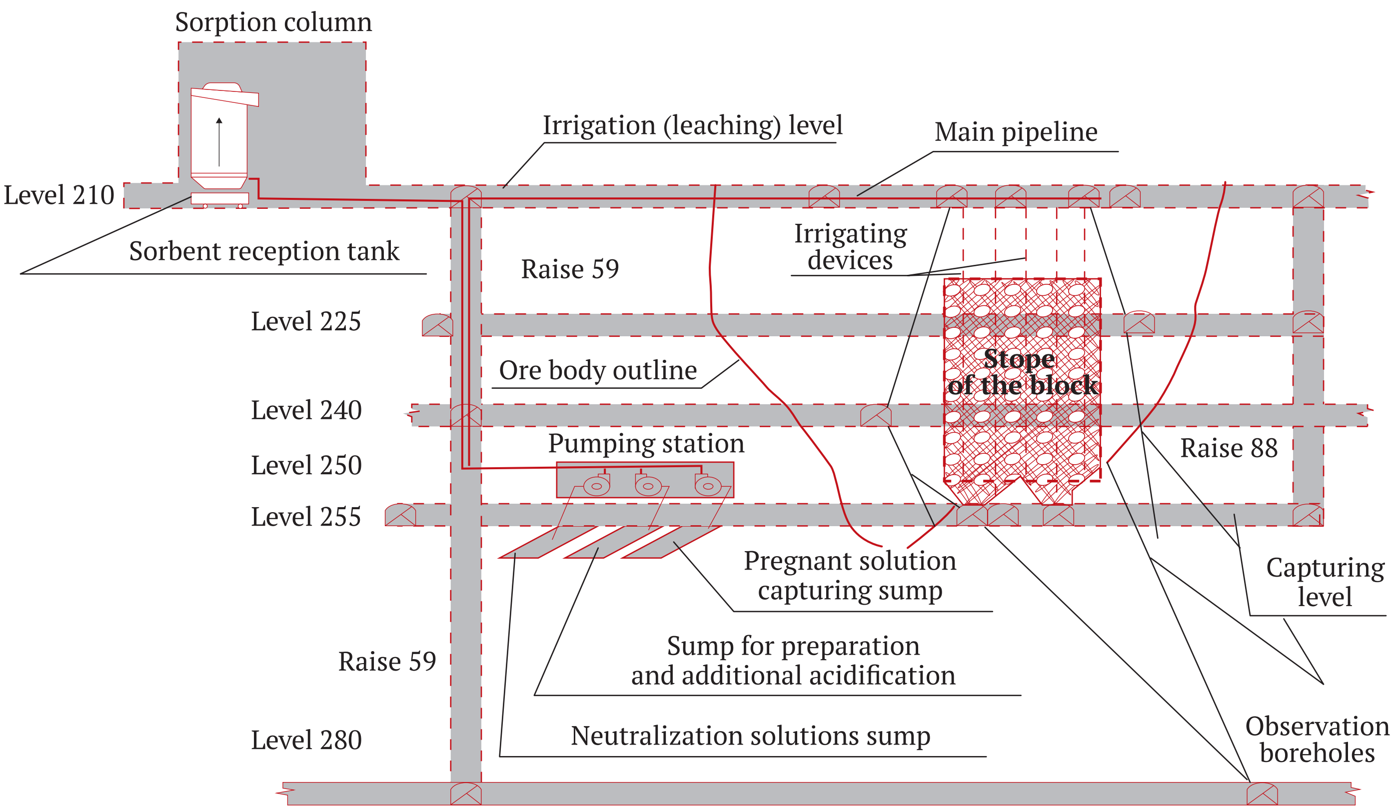

Fig. 6. Process flow diagram of block preparation for leaching:
Pc.59 – ore chute of 59-th axis; Raise 59, Raise 88 – ventilation and manway raise of 59-th and 88-th axis, respectively

Data on the chemical composition of the mine water samples showed that up to the moment of block acidification the mine water, the chemical composition varied considerably both spatially and depending on time of sampling. For example, sulfate ion concentration varied from 403.0 to 998.0 mg/L, that of uranium, from 0.35 to 7.30 mg/L. Comparing the water analysis data, it can be concluded that the average concentrations of sulfate-ion, chloride-ion, uranium, pH, dry residue in the samples taken during the UBL testing did not exceed those in the samples taken before the acidizing (leaching) of the shrunk ore. No essential changes in composition and concentrations of elements in mine water discharged into Ingul River during UBL operation (blocks 5-86; 5-84-86; 5-88-90) were observed. Samples were collected once a month for the following parameters: sulfuric acid aerosols; radon concentration; gamma exposure rate. Since the beginning of block 5-86 operation only, 576 samples were collected. Review of the data presented in Table 3 showed that the determined indicators did not exceed those of the samples taken before the testing [27, 28].

Review of Findings

Initial findings of the study showed significant dependence of the leaching process performance (based on time factor) on the working volume of the sump for pregnant solutions. Optimal volume was found to be 70–80 m^3, while design volume was 20 m^3 only. The

Table 2

The third level monitoring results for mine water

Subject of research and measurement component	Mine water	Average Value		
		pre-testing	testing	post-testing
Uranium, mg/L	90	6.7	6.2	4.4
Ra – 226 × 10^{-11}, Ci/L	20	8.37	6.24	6.7
Th – 230 × 10^{-11}, Ci/L	20	3.03	2.46	2.2
Pb – 210 × 10^{-11}, Ci/L	20	32.05	9.53	10.4
Po – 210 × 10^{-11}, Ci/L	20	2.5	1.18	2.8
$SO^{2-}{}_4$, mg/L	70	614	659	691
CI, mg/L	70	172	166	142
PH, unit	70	7.6	7.7	8.2
Ca^{2f}, mg/L	70	145	133	124
Md^{2f}, mg/L	70	41.3	62.8	52
Na^{f}, mg/L	70	235	229	220
K^{f}, mg/L	70	15.5	13,2	12
Fe_{tot}, mg/L	70	0.05	0.05	0,05
NH_4, mg/L	70	1.1	0.15	0.1
NO_3, mg/L	70	40	15	9
NO_2, mg/L	70	26	0.2	0.1
HCO_3, mg/L	70	92	157	132
Dry residue, mg/L	70	1588	1560	1366

Table 3

The third level monitoring results for air

Subject of research and measurement component	Air	Average Value		
		pre-testing	testing	post-testing
Level 210 m				
Sulfuric acid aerosols, mg/m^3	640	–	0.5	–
Radon, Bq/m^3	64	580	645	110
EDR, μR/hr (gamma radiation exposure dose)	64	146	206	227
Level 240 m				
Sulfuric acid aerosols, mg/m^3	128	–	0.26	–
Radon, Bq/m^3	128	513	490	439
EDR, μR/hr (gamma radiation exposure dose)	128	454	331	312

initial operating experience revealed a negative factor in terms of a significant amount of sand and debris in the regenerated resin at the hydrometallurgical plant. Subsequently the decision was taken to install an autonomous resin regeneration unit at the plant for the UBL pilot areas [29, 30].

During development of block 5-86, in accordance with the recommendations issued, the previously driven workings were used as much as possible. The same approach was used at preparation of pilot blocks 5-84-86 and 5-88-90, as well as pilot-commercial block 1-75-79, for UBL at Michurinskoye deposit. The required volume of remedial work as in previously driven mine workings was carried out. At the same time the issues of stability of mine workings of the leaching level located in the area of intensive influence of worked-out blocks require special attention. The ore mass in level 197–210 m was already weakened by the development workings and stopes, constructed before the preparation of blocks for UBL, as well as by the network of boreholes of the leaching system currently being created. In these workings, a systematic monitoring of their stability and the stress-strain state of the near-contour rock mass was organized (geotechnical and seismic monitoring). The results of UBL commercial testing showed that the system of stockpile preparation for extraction existing at VostGOK only change in the drilling while blasting parameters allowed ores of optimal granulometric composition to be produced in the pilot block. During the testing, about 54 % of the metal reserves in the block were transferred into the solution at an acid consumption rate of 36 % of the design value. Thus, extraction and processing of ores with the use of traditional methods under current economic conditions is inexpedient if the metal content in the extracted ordinary ore is less than 0.070 c.u. (Table 4).

Advantages of block leaching

There are no costs for individual operations as compared with the traditional ore mining and processing methods, namely:

Mining: secondary crushing and drawing of ore; in-mine transportation of ore; ore winding to the surface; crushing and beneficiation of ore; backfilling of mined-out space; loading into rail cars and transportation of ore to hydrometallurgical plant;

Table 4

Main indicators of metal block leaching

Designation	Value
Volume of ore being leached, kt	8.248
Grade of metal, c.u.	0.065
Acid H_2SO_4 used, t	231.1
Acid specific consumption, kg/t	28.0
Acid consumption for acidizing, t	27.8
Oxidant specific consumption, kg/t	3.3
Acidification time, day	40
Volume of solutions fed to leaching, m^3	66106
Density of leaching, L/m^2 x hr	9.6
L/S ratio, units	8:1
Leaching time, day	166
Sorption duration, day	398
Volume of solutions for sorption, m^3	25756
Characteristics of pregnant solutions: a) metal concentration, average, mg/L b) average acidity, g/L	 220 13.5
Characteristics of irrigation solutions: Fe^{+3} /Fe^{+2}, concentration, g/l Mineralization (dry residue), g/l	 1.9/0.38 43.2
Volume of metal-saturated anionite, m^3	101.3
Average capacity of saturated sorbent, kg/m^3	27.3
Residual capacity of regenerated sorbent for metal, kg/m^3	0.66
Tailings washing in block: duration, days	65
Washing water volume, m^3	5775
Specific water consumption for washing, m^3/t	0.7

Processing at hydrometallurgical plant: ore rehandling; ore crushing; leaching; sorption; resin regeneration; tailings storage.

The phenomenon of natural leaching is a consequence of the insufficient sophistication of mining methods used. The mechanism of the natural metal leaching processes is known and controllable/applicable. The radical approach to the mitigation of the environmental impact of natural leaching is the complete utilization of metal-containing raw materials. The concept of environmental protection of subsoil use provides for the replacement of uncontrolled natural leaching with artificial leaching in a controlled workspace. The level of knowledge on the theory and practice of metal extraction from metal ores allows the methods with leaching to restore the previous potential of mining industries [31, 32].

Performance

The maximized performance of the integrated method of development with leaching of metals from ores is provided through increasing the extraction of useful components from the subsoil:

$$M' \geq \frac{\varepsilon_n - \varepsilon_T}{\varepsilon_n - \varepsilon_2\varepsilon_3} M, \quad (1)$$

where M – amount of useful component in situ; M' – amount of useful component extracted; ε_n – extraction of metals from ores by the methods with leaching; ε_T – extraction of metals by traditional methods (TS):

$$\varepsilon_T = \frac{M_m}{M} \varepsilon_1\varepsilon_2\varepsilon_3, \quad (2)$$

where M_m – TS quantity of metals; ε_1 – extraction of metals from subsoil by TS; ε_2 – extraction of metals into concentrate; ε_3 – extraction of useful component from concentrate to the final product.

The profit from the use of substandard reserves (low-grade ores) in production at the expense of increasing ore production volumes, output of finished products (metals), and ROI through implementation of integrated methods with leaching is determined according to the following mathematical model:

$$Profit = \sum_1^n \left[\begin{aligned} &\left(C_{ore}^b - C_{ext}^b - C_{enr}^b - C_{met}^b\right) \cdot V_b^{sel} + \\ &+\left(C_{ore}^{comb} - C_{ext}^{comb} - C_{enr}^{comb} - C_{met}^{comb}\right) - D_0 \end{aligned} \right] \cdot V_{comb}^{sel}, \quad (3)$$

where *Profit* is annual profit from combination (integration) of the methods, MU; C_{ore}^b, C_{ore}^{comb} – proceeds from metal sales (produced from balance and combined, respectively, ore reserves, MU/t; C_{ext}^b, C_{enr}^b, C_{met}^b – ccosts of mining, processing, and metallurgical treatment of balance ores, respectively, MU/t; C_{ext}^{comb}, C_{enr}^{comb}, C_{met}^{comb} – costs of mining, processing, and metallurgical treatment of combined ore reserves, respectively, MU/t; V_b^{sel}, V_{comb}^{sel} – volume of selectively extracted balance and combined ores, respectively, tons; n – the mix of extracted metals; D_0 – total damage (economic consequences) to the environment, effected (−), or preventable (+), taking into account the costs of storage of pollutants and protection of the population living in the mining affected zone, MU.

Thus, UBL implementation on commercial scale will significantly improve economic performance of production. Through the modernization of fixed assets, this would allow for the technical re-equipping of production involving reserves of low-grade and substandard ores in production, thus prolonging LoM (for existing mines). The research established that chemical mining methods could be used for development of low-grade and substandard ores, thus increasing profitability. Furthermore, the use of substandard ores could allow the raw-material base of metals at operating mines to be raised 1.4–1.6 times. It was shown that performance of different options of methods for metal leaching from ores was defined in terms of the completeness of its extraction. The experience accumulated in the world practice shows that under other equal conditions, such as mineralization type, structure, porosity of ore, diffusion coefficient, temperature, concentration of process solutions, etc., the completeness of leaching directly depends on the ore crushing quality and uniformity of its density distribution when shrunk. The possibility of underground block leaching of metals from shrunk ores was proved, and the dependence of metal recovery on the average linear size of the blast-crushed ore mass fragments was established [33, 34].

Advanced research directions

In order to prevent groundwater pollution (hydrogeological environment protection) the base of the stope needs to be silted for the collection of pregnant solutions with clay mud. Semi-active water permeable chemically active barriers (VPChAB) need to be constructed and biological technologies in UBL to be used. The main advantages of using iron-oxide composites based on natural clay minerals to clean water from contamination with uranium compounds are their environmental friendliness, cheapness, availability, and manufacturability. This should ensure that the degree of metal contamination of ground and surface waters, soils and sediments, including the main Michurinsky Fault (Kropivnitsky, Ukraine), is reduced. Research needs to be continued to develop such methods that would satisfy both economic and environmental requirements [35, 36].

Conclusions and recommendations

Based on the scientific and practical results of the tests on integrated leaching of metals from off-balance and substandard ores for their subsequent processing at hydrometallurgical plant, the following conclusions were made.

1. Semi-commercial (pilot-plant) testing on leaching of metals from ores of operational block 5-86 of Michurinskoye deposit (Ukraine) was implemented with observations at three levels: 210; 225; and 280 meters. In the tests, the pH of water was at a neutral level of 6.5–7.5, and only in 5 cases were its values 1.5-2.0. This was explained by pipeline failures and stop valve wear and tear. The halo of spreading the process solutions was local and neutralized by lime milk.

2. Environmental monitoring with water analysis showed the average uranium concentrations of 3.6 mg/L at 210 m level, 3.58 mg/L at 225 m level, 0.91 mg/L at 280 m level. No contamination of underground mine waters was detected. The levels of sulfuric acid aerosols and radon decomposition products did not exceed the maximum allowable concentration (MAC) values.

3. It is recommended that the worked-out ore mass be treated with lime milk and mine water through the boreholes for feeding leaching solutions (leaching system), in order to neutralize and wash it. The hydrogeological environment (groundwater) should be protected through silting the bottom of the stope for collection of pregnant solutions with clay mud. Groundwater monitoring should be performed in observation boreholes drilled in the bottom of the production block and at contacts with the ore body, as well as in zones of fracturing and hydraulic fracturing of rocks.

4. The phenomenon of natural leaching of metals from crude ore is a consequence of the insufficient sophistication of mining methods used and can be minimized. This will provide increased financial viability, the rational use of subsoil, groundwater and environmental protection, and increase raw material base for metals production by 1.4–1.6 times.

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