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Development of mining technologies of underground block leaching of metals from the ores off-balanced in terms of useful component[1]

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Abstract
Purpose. The main scientific and practical results of the development of mining technologies for underground block leaching (hereinafter UBL) of metals from the ores off-balanced in terms of useful component achieved due to the introduction of a comprehensive technology that includes a traditional chamber system with a solid stowing and underground block leaching of metal from the ores stored in the chamber providing increase in efficiency of development of complex-structure deposits reserves are given in the article.
Methodology. The methods of complex generalization, analysis and evaluation of practical experience and scientific achievements in the field of geotechnology, theory and practice of blasting destruction of solid media, continuum mechanics, mathematical statistics as well as methods of wave processes research using standard and new methods of leading experts in this field are described.
Results. Factors determining the effectiveness of UBL of metals from rocky ores are established and the parameters of the blasting are justified taking into account the average linear size of the lump of blasted ore mass and the seismic safety of the protected objects.
Scientific novelty. It has been proved that when developing deposits of poor rocky ores in Ukraine, introduction of UBL should be considered as a promising area. Percent of metal recovery ξ greatly depends on the average linear size of the lump of blasted ore d_{av} and with a high degree of reliability (R^2=0.97) is described by the following ratio $\xi=11.817d_{av}^{-0.4501}$.
Practical significance. Development of the test block 5-86 at the Ingulskaya mine of SE "VostGOK" (8248 tons of low-grade ore have been breaking) has confirmed the possibility of UBL of the rocky ores as well as the justification of the preparation scheme (the maximum deviation of the actually measured class–25+0 is 7.2 %). When involving in the production of below-standard ore deposits, their raw materials base at the operating mines can be increased by 1.4-1.6 times.
Key words: MINING-ENGINEERING TECHNOLOGIES, UNDERGROUND MINING, BLOCK LEACHING, METAL RECOVERY.

Introduction

The national uranium producer in Ukraine is SE "Eastern Mining and Processing Plant" (SE "VostGOK"), which in August 2016 turned 65 years old. The mines of this plant develop the deposits of rocky ores with a low content of useful component using chamber systems with stowing of the developed area. Successful operation of the plant in the market economy conditions is impossible without the introduction of new technological solutions for the recovery and processing of uranium raw materials.

World experience in the use of mining and chemical technology for uranium recovery by an underground method from rocky ores is still insufficient [1-4].

Therefore, the development of mining-engineering technologies of underground block leaching (UBL) of metals from ores off-balanced in terms of useful ore components based on the substantiation of the parameters of underground mining and the introduction of integrated technology including a traditional chamber system with a solid stowing and underground block leaching of metal from the ores stored in the chamber providing rational use and protection of subsoil, increase in their efficiency while developing the stocks by geotechnological methods is an important scientific, practical and social task.

Discussion of research results

During the research, the authors have been using the method of complex generalization, analysis and evaluation of practical experience and scientific achievements in the field of geotechnology, theory and practice of blasting destruction of solid media, continuum mechanics, mathematical statistics and research methods of wave processes using standard techniques of leading experts in this field [5–7]. It has been established that the effectiveness of different options for technology of leaching metal from the ore is determined by the completeness of its recovery. The experience accumulated in the world practice shows that with other conditions being equal such as the nature of the mineralization, the structure, the porosity of the ore, the diffusion coefficient, the temperature, the concentration of working solutions, etc., the leaching completeness is directly dependent on the quality of ore crushing, uniformity and density distribution in the stored state. As a result of the research it has been established that mining and chemical technologies can be used for the development of low-graded and off-graded ores of domestic deposits which during recovery by traditional technologies are considered to be unprofitable. Due to the involvement in the production of off-grade ores, the uranium resource base in operating mines can be increased by 1.4-1.6 times.

At the Michurinskoe deposit of SE "VostGOK" (Ukraine), large-scale research has been carried out to recover metal from a fragmented and fractionated ore mass, which allowed us to establish quantitative parameters of the leaching process (Fig. 1). Figure 1

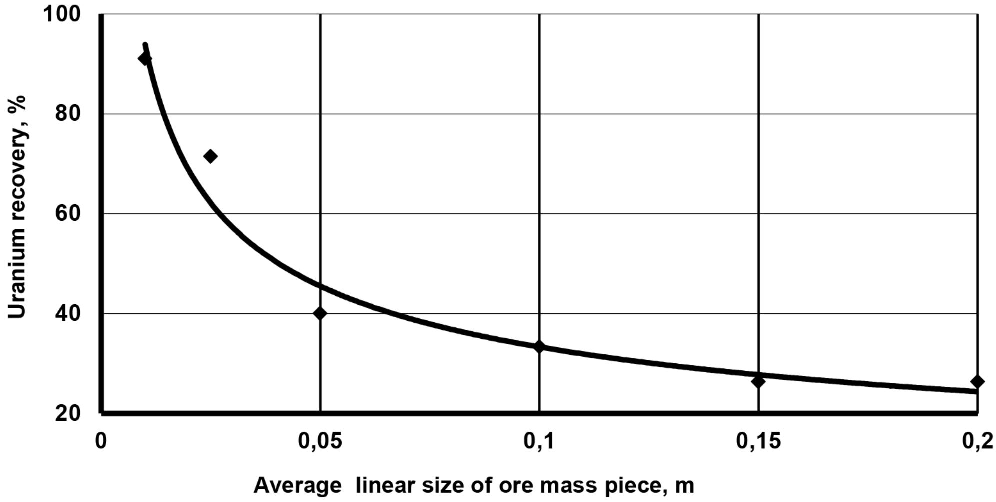


Figure 1. Dependence of metal recovery on the average linear size of the ore mass crushed by the blast

shows that percentage of metal recovery ξ greatly depends on the average linear size of the lump of the blasted ore d_{av} and with a high degree of reliability (R^2 = 0,97) is described by the following ratio:

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

Finding the required blasting energy taking into account the limiting energy intensity of crushing rock is a distinctive feature of the methodology for determining the parameters of destruction of rocky ores with a given quality of crushing for leaching. Knowing the specific consumption of the explosive (E), it is possible to determine the charge mass per one well and the geometric parameters of the location of the wells in the blasted block.

From the analysis of expression (1), it can be concluded that it is advisable to reduce the weighted average linear size of the freed ore lump as well as to re-crush the components of the leached media in order to increase the contact surfaces. The described regularity is also of great importance in the control of the subsequent parameters of the leaching process. One of these methods which allows us to reduce the average linear size of a lump and increase the newly formed area of the rock mass to be destroyed is the preparation of the ore mass for leaching using the kinetic energy of the flying apart lumps of rock mass followed by the breaking of the ores in the clamp.

The near-surface reserves of the Michurinskoe deposit, a significant part of which lies beneath the Ingul River, industrial and civil buildings and structures, are represented by steeply pitching ore bodies of various capacities. The length of the ore bodies along the strike varies from 600 to 700 m (predominantly is 100-250 m), after the fall it ranges from 150 to 400 m. The ores and their host rocks are hard (the coefficient of strength on the scale of Professor M. M. Protodyakonov is f = 14÷18), massive rocks have unstratified structure. In the direction towards the surface, the quantitative and qualitative characteristics of the jointing are deteriorated significantly both for individual deposits and for the deposit in general. On the upper horizons of the rock are eroded, the coefficient f is reduced to 6. The deposit is developed by the chamber development system with filling of mined-out space with the hardening mixture. Depending on the mining and geological conditions, the development is carried out by chambers located both along the strike and across the strike of the ore deposits, which in general mining are 37.9% and 62.1% respectively. Mining works are carried out at a depth of 40 to 350 m. The chambers are worked out by sublevels 10-15 m high. The ore is broken down with wells with diameter of 57 mm and 65 mm which are drilled by the machines NT-2 and PK-75. Parallel down wells with diameters of 85 mm and 105 mm to form cut-off slots are drilled by NKR-100 M machines [8].

At the operating mines of Ukraine, the combined method of metal mining is recommended for use as the most effective. It has been established that the volume of preparatory mining operations in the combined mining method directly depends on the completeness of the use of previously passed (existing) mine workings and the adopted UBL scheme (Fig. 2).

According to the research, despite the discrepancy in the scheme options for the preparation of blocks for leaching, the common feature is the high requirements to the quality of drilling and blasting operations (DBO) as the main technological process that provides ore preparation for the subsequent effective recovery of metal from the stored ores. On the example of conducting blasting operations to provide mining, their results have been analyzed and the corresponding ratios have been built (Fig. 3).

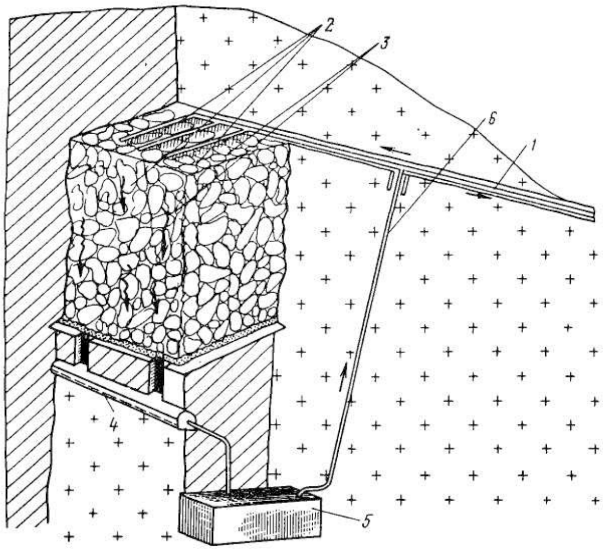


Figure 2. Scheme of underground leaching with the use of mine workings: 1 - pipeline for working agents; 2 - pipeline for the ore massif moistening; 3 – blasted ore block; 4- intake basin for PR solution; 5 - common intake basin; 6 - pipeline for PR solution lifting

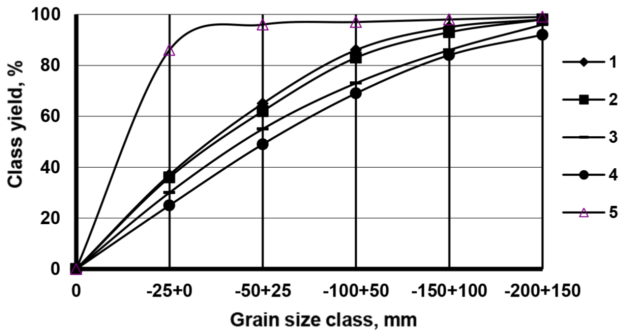


Figure 3. Yield of the appropriate grain size classes for different well diameters d and specific explosive consumptions q for the blast: Michurinskoe deposit (block 5-86, Ingulskaya mine): 1 – specified crushing quality (d = 67 mm, q = 2.5 kg/m^3); 2 – actual crushing quality (d = 67 mm, q = 3.6 kg/m^3); 3 – specified crushing quality (d = 85 mm, q = 2.34 kg/m^3); Bikogorskoye deposit (Republic of North Ossetia - Alania): 4 - specified crushing quality (d = 100 mm, q = 1.1 kg/m^3); 5 – actual crushing quality (d = 100 mm, q = 5 kg/m^3)

The analysis of the curves (ref. Fig. 3) shows that the increase in the specific flow rate of explosives above the limit value q = 3 kg/m^3 does not lead to a significant improvement in the quality of crushing (curves *1* and *2*). The consequence of the increase in the value of q up to 5 kg/m^3 is an improved crushing of ore and increasing the yield of very small fractions (curve 5). The breaking of wells with a diameter of 85 mm and 100 mm is characterized by almost the same grain size composition as well as the breaking with the diameter of 67 mm (curves *3* and *4*). However, the specific consumption of explosives when using bore wells of a larger diameter is much less. Proceeding from this, with the further development of UBL technology of stored ores, the transition to drilling out the ore massif with the wells 85 mm in diameter is recommended. When calculating the parameters of blasting destruction of ores with a given quality of crushing to provide block leaching (hereinafter BL), it is recommended to follow the established ratios. Formation of the ore mass store for UBL shall be done with the use of kinetic energy of flying pieces with the subsequent crushing of ore in the clamp. The proposed new mining technology allows us to ensure optimal costs for the preparation of the block for leaching and explosive preparation of the ore with a specified quality. Studies have established that in order to achieve an effective metal recovery from the stored ore, considerable attention should be paid both to the technology of forming cut-off slots and compensation spaces, and to ensuring optimum fragmentation of the ore store under the condition of effective leaching (fragmentation coefficient $k_f \leq 1,2$), which is regulated by the volume of ore released from the block. With the joint underground mining operations using traditional methods and UBL method one of the ways to increase the efficiency of mining and chemical technology is the fuller application of existing mine workings. The height of the store of ore mass prepared for leaching is proposed to be corrected on the basis of an analysis of the mining situation created at the area of a particular deposit recovery and assumed equal to 50 m.

According to the research, mineralization of the deposit is localized in the highly fragile “lamellar” albitites, which were formed during the metasomatic substitution of migmatites. Morphologically mineralization of the deposit is a complex metasomatic formation of a lenticular form with an incidence angle of 55–60^o. The ores within the deposit are represented by alkaline-amphibole albitites and migmatites. In their composition, albite is predominant – 93–98%, acid-intensive minerals (carbonate and phlogopite) are 2-7%. Ores are characterized by impregnated, less often vein-expressed textures.

Geological structure contains (downward) the soil-vegetation layer, loess loam, sandy loam and loam, small medium-grained sands of the Buchak Stage. The total thickness of the sedimentary rocks is 12-14 m. Sedimentary rocks are found everywhere along the eluvium of the weathering crust of crystalline Proterozoic rocks. The weathering crust is composed of clay-clastic material, namely primary kaolin, gum and sandy-argillaceous depending on the composition of the crystalline rocks. The crystalline rocks of the foundation up to 60 m are represented by the albitites of a massive medium-strength texture, intensely cataclazed and crumbling. Rocks in the area of preparation of the experimental block for BL are represented by gray biotite adergneisses, medium grained with porphyritic feldspar crystals sorting. There are shale rocks of silicified biotite gneisses.

When preparing blocks for leaching, a slot with a cross-sectional area of 12 m^2 is cut off, for this purpose parallel wells are drilled. After the completion of their drilling and explosives blasting, a cut-off slot is formed. Raise wells are drilled from top to bottom. The main preparation of ore in the block begins with a short-delayed blasting of wells with a specified sequence. To ensure the blast in the clamped environment, a compensation space is formed by the batch discharge of the break down rock. To ensure the necessary delay intervals including inside well one, the use of initiation systems based on low-energy waveguides is recommended.

Parameters of drilling and blasting operations. *When the compensation space is formed:*

- the width of the cut off slot is not less than 4 m;
- well diameter is 85 mm; number of wells in the row is 4; the distance between rows of wells is 1.5 m.

When breaking the ore mass in the chambers:

- optimal specific consumption for breaking, kg/m^3;
- distribution of the explosives concentration over the ore massif (uniform or nonuniform).

Uniform distribution of the explosives mass along the massif is possible under the condition of a parallel arrangement of column loads, which is impossible with a complex morphology of ore bodies with low ore mineralization. When a fan pattern of charges, a uniform energy distribution in the massif is not feasible.

In order to achieve a higher quality of crushing than during a bulk mining, it is necessary to increase the specific consumption of explosives for breaking by varying DBO parameters, which include the following points:

- diameter of the charges located in the fan wells;
- line of least resistance, m;
- distance between the ends of the wells, m.

According to the works of professor V.N. Mosinets, specific consumption of explosives *q,* kg/m^3 for the destruction and movement of the ore mass depending on the conditions for providing a specified degree of crushing is determined by the formula [5,6]:

$$q \cong \frac{0.085}{K_j \cdot A_{ex}} \cdot f, \text{ kg/m}^3, \qquad (2)$$

where K_j – coefficient that takes into account jointing of the rock massif (varies from 0.95 to 1.1); A_{ex} – complete perfect work of the blast with the use of explosives (grammonite 79/21, granulite AC-4, AC-4B, AC-8, AS-8B, rock ammonite No. 1, etc.).

When breaking of the ore mass in the chambers, the optimum specific consumption of explosives is set and distributed over an ore massif (uniform or nonuniform). Uniform distribution is possible under the condition of parallel arrangement of column loads, which is impossible in the case of complex morphology of ore bodies with low ore mineralization. When a fan pattern of charges, a uniform energy distribution in the massif is impossible. In order to achieve a higher quality of crushing than during a bulk mining, it is necessary to increase the specific consumption of explosives for breaking by varying DBO parameters (diameter of the charges located in the fan wells, line of least resistance, distance between the ends of the wells).

An increase in the specific consumption of explosives for breaking is possible due to an increase in the diameter of the wells of the column loads from 85 to 105 mm and is relevant for drilling circular or descending fans, which makes it possible to obtain the grain size composition of the specified parameters during the massive crushing (Table 1).

The use of wells with small diameters (57, 67 mm) for these purposes is ineffective due to the need to reduce the line of least resistance and take the distance between the ends of the wells less than 1.3 m, which is unsafe and is confirmed by the practice of ore deposits development. The complex of works in preparation for BL included the following operations: breakoffs and drilling rooms, drilling of wells, driving of cut-off rises, formation of cut off slots and compensation space, breaking the ores with well charges and their subsequent storage.

In each specific case, the schemes for preparing blocks with their generality have their own specifics. Block 5-86 had the following parameters: height - 20 m, width - 16 m, length - 24 m. Blast holes with a diameter of 67 mm were drilled with a machine tool NT-2 and cut off slot wells with a diameter of 85 mm have been drilled with a machine tool NKR-100 M. The specific consumption of explosives for breaking off the chamber reserves for technological leaching is justified by earlier conducted pilot industrial works and averages 3 kg/m^3 (designed) and 3.6 kg/m^3 (actual).

When preparing the research block 5-86 for leaching, the candidate for a degree has justified his own recommendation for maximum use of previously worked out mine workings. This approach has been carried out in preparation for leaching of operational blocks 5-86, 5-84-86, 5-88-90 and 1-75-79. To obtain a given quality of crushing in the test block 5-86, the blasting operations have been performed into a formed

Table 1. DBO parameters of block 5–84–86 for chamber stocks breaking

Sequence of blasting	Horizon or sublevel (fan wells)	DBO parameters				
		d_w, mm	W, m	well spacing a, m	coefficient of wells approach m	specific consumption of explosive q, t/m^3,(kg/m^3)
1st blast	–260 m (1′–5′, 1–8)	85	1.8	1.9	1.06	1.160 (3.07)
	–240 m (1, b–6, b)	85	1.8	1.9	1.06	1.080 (2.88)
	–240 m (1′–5′, 6)	67	1.2	1.2	1.00	1.080 (2.88)
2nd blast	–225 m (1′–3′, 1–7)	105	2.0	2.2	1.10	0.945 (2.50)
3d blast	–210 m (1, 2, 3, 1A–4A)	105	2.0	2.2	1.10	1.280 (3.39)
4th blast	–210 m (1A′–3A′, 4–10, 5A–10A)	105	2.0	2.2	1.10	1.280 (3.39)

compensation space. For the qualitative crushing, the kinetic energy of the ore lumps, which have been scattering, colliding and additionally crushing as well as the properties of stress waves during blast in the clamp have been used. The calculated and actual parameters of the blast breakdown of ores are quite similar (Table 2), which indicates the high reliability of the method for calculating the DBO parameters during the blasting preparation of ore for leaching with a specified degree of crushing taking into account the ultimate energy intensity of destruction.

As studies have shown, the grain size composition of the ores after leaching has been changed. Their lumpiness has differed both from the parameters specified in the calculation and from the values obtained after breaking in the block (Table 3).

Analysis of the data indicates a high accuracy of the forecasted quality of uranium ore crushing (the maximum deviation of the actual composition of ore grade -25 + 0 is 7.2%).

In particular, when a metal is leached out of stored rocky ores, its recovery value is in a power-law dependence on the average linear dimension of the lump of blasted ore mass and reaches its maximum values for its size class –25+0 mm, that allows to select rational parameters of blast preparation of uranium ores with specified quality of crushing, to increase infiltration of productive solutions and to recover more than 70% of useful components.

The ratio of the average linear size of the lump of blasted ore mass to the well diameter required according to the maximum condition of uranium recovery is determined by matching the energy of the blast with the kinetic energy of the flying lumps of rock mass and is a logarithmic function of the explosives specific consumption for primary crushing, which ensures the adequacy of the technological parameters of well breaking to the conditions of leaching and seismic safety [9-11].

The use of stopes with a width of 20 m and a length of 35 m is recommended for UBL based on the advisability of a more complete use of existing mine workings. The peculiarity of the block preparation for BL is freedom from undercut level, drainage wells, from the design of the block bottom by blasting the fans of downward wells. Required inclination of the block bottom is provided by reducing the length of the corresponding blast holes in circular fans. Studies have shown that, in the case of UBL, high demands are placed on the quality of DBO as the main technological process for the subsequent effective extraction of uranium from the stored ores. A new mining technology (Fig. 4) and technological equipment for its implementation are proposed (Fig. 5).

Directions for Future Research

The uranium recovery from the subsoil by the method of underground leaching is a highly effective environmental safety technology and allows reducing by 70% the winding to the mining mass surface of mining resources, as a result, the volume of solid waste from the processing of radioactive raw materials is correspondingly reduced, for example at Priargunsky

Table 2. The content and recovery of metal by the size classes in the leached ore

Indicators	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
Uranium content according to size class, %	0.038	0.038	0.030	0.025	0.014
Uranium recovery according to size class, %	26.3	26.3	33.3	40.0	71.4

Table 3. Grain size composition of the rock mass (calculated and after breaking)

Size class, mm	–200+150	–150+100	–100+50	–50+25	–25+0
Calculated yield of a specified size class, %	3.0	7.0	35.0	15.0	40
Yield of size class after breaking, %	4.0	12.0	30.4	20.8	32.8

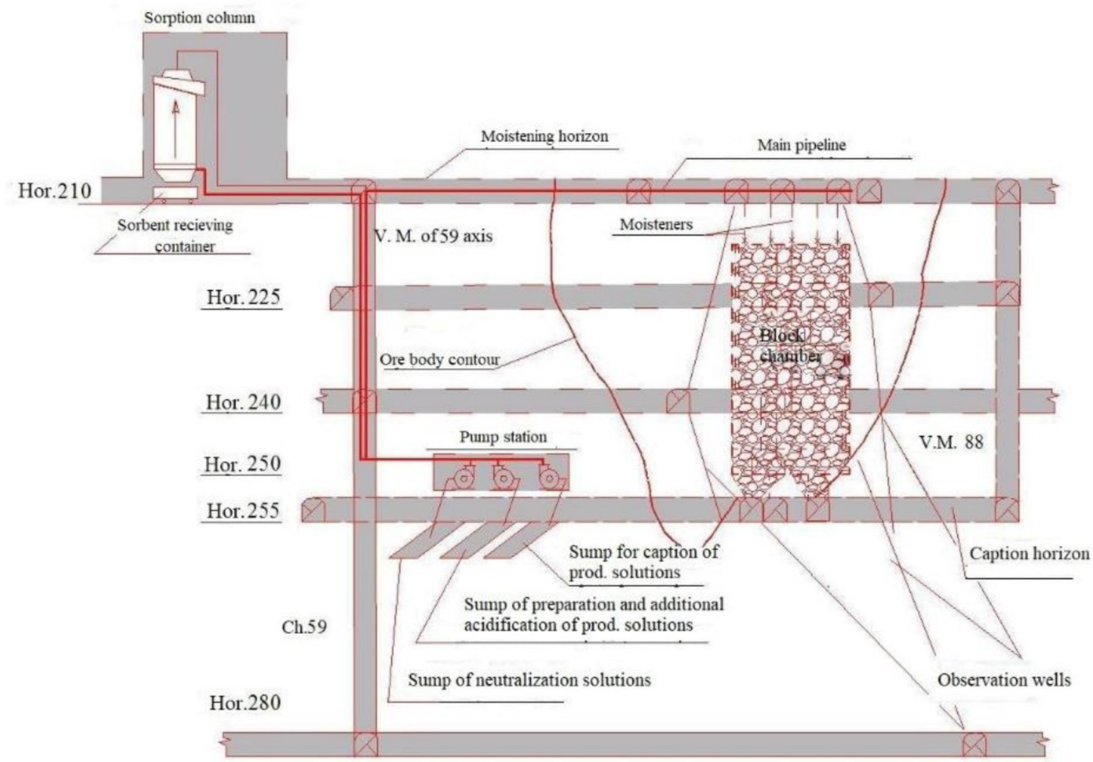
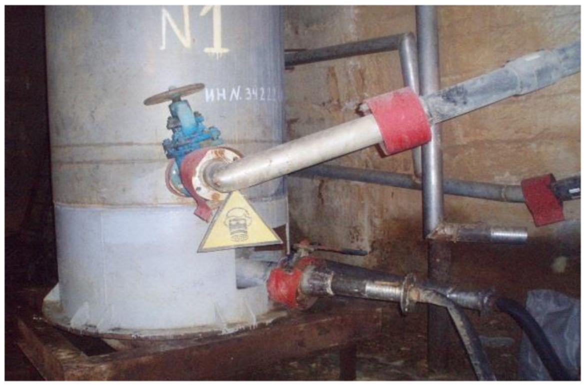


Figure 4. Technological scheme of preparation of the block for leaching: Ch 59-ore chute of 59 axis; V. M 59, V. M 88-ventilation and manway raise of 59 and 88 axes respectively

a



b

c

d

Figure 5. Technological equipment for leaching ore at the Ingulskaya mine of the SE "Vost GOK" (photo): a and b - sorption columns of SNK type; c - pumping station with a capacity of 0.4 m^3 and pump AX; d - composition of tanks with ion exchange resin and dilute spirit of alum

mining and chemical association of the uranium holding M/s ARMZ, which is currently the largest uranium mining enterprise of the Russian Federation (Fig. 6) [14].

Thus, the introduction on an industrial scale of a combined system incorporating BL will not only significantly improve economic performance, but also increase the recovery of stocks of low-grade and non-grade ores and expand the existing resource base of the mining industry [15,16].

Conclusions

1. It is justified that when developing deposits of low-graded uranium ores in Ukraine, the introduction of UBL shall be considering a promising area. Percent of metal recovery ξ significantly depends on the average linear dimension of the blasted ore piece d_{av} and with a high degree of reliability (R^2=0.97) is described by the following dependence $\xi = 11.817 d_{av}^{-0.4501}$.

2. Development of the test block 5-86 at the Ingulskaya mine of the SE “VostGOK” (8248 tons of off-grade ore have been broken down) has confirmed the possibility of UBL of rocky ores, as well as the validity of the preparation scheme (maximum deviation of the actually measured class –25+0 is 7.2 %).

3. It has been established that the most intensive infiltration leaching occurs at a size class of ore chunks of 100+0 mm. For the Michurinsky deposit during leaching, the yield of such a fraction in the breaking ore is recommended to be about 90%. Metals from the fractions -200 + 100 mm are recovered less intensively and for a longer time. The recommended yield of ore of this size class is 10%.

4. It is proved that during UBL, explosive preparation of the ore shall be at the main place, which ensures the effective recovery of uranium from the stored ores. Technological operations to create cut-off slots and compensation spaces as well as to ensure the optimal loosening of the stored ore for test leaching of uranium (a loosening factor $k_1 \leq 1.2$) are not less responsible.

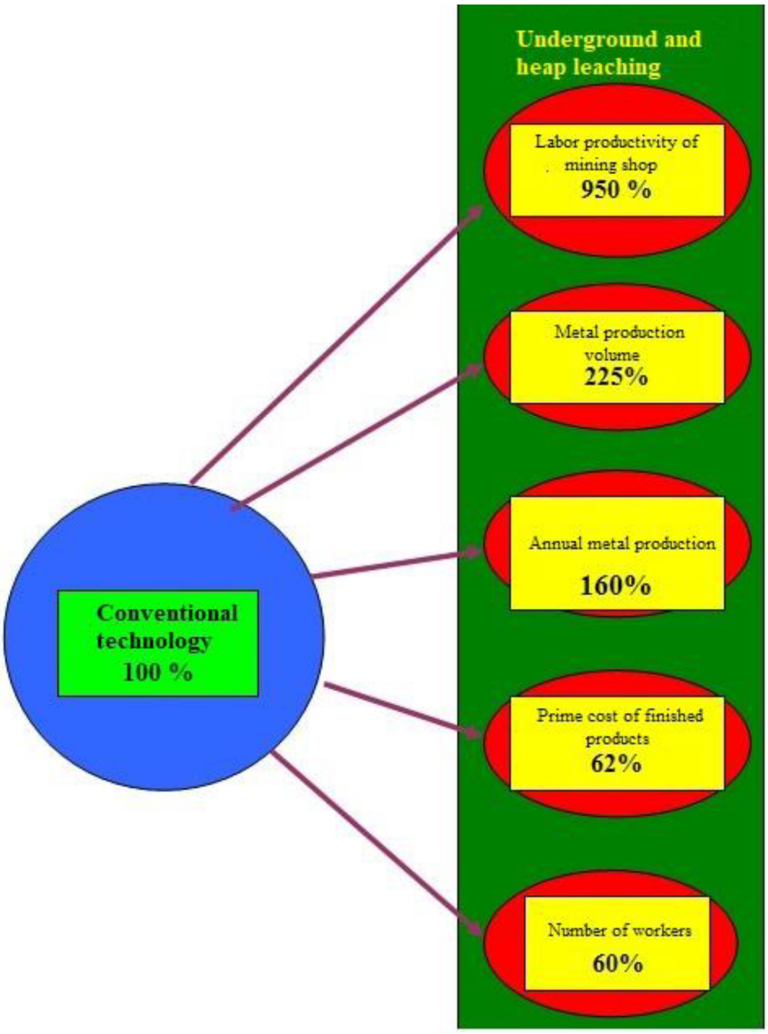


Figure 6. Scheme of determining the efficiency of uranium leaching in comparison with conventional technology

5. It is determined that the breaking of the ore by wells with a diameter of 85 mm and 105 mm is characterized by almost the same grain size composition as with a well diameter of 67 mm, but with a lower specific consumption of explosives. With the further development of UBL technology, it is recommended to switch to the drilling of wells with a diameter of 85 mm in the ore massif. The designed specific consumption of explosives during their blasting is 2.2 kg/m³.

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