ISSN 2518-170X (Online)
ISSN 2224-5278 (Print)

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

ХАБАРЛАРЫ

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»

NEWS

OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN

SERIES

OF GEOLOGY AND TECHNICAL SCIENCES

3 (471)

MAY – JUNE 2025

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).
The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.
Thematic scope: *geology, hydrogeology, geography, mining and chemical technologies of oil, gas and metals*
Periodicity: 6 times a year.
http://www.geolog-technical.kz/index.php/en/

«ҚР ҰҒА» РҚБ Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *Геология, гидрогеология, география, тау-кен ісі, мұнай, газ және металдардың химиялық технологиялары*

Мерзімділігі: жылына 6 рет.

http://www.geolog-technical.kz/index.php/en/

«Известия РОО «НАН РК». Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, гидрогеология, география, горное дело и химические технологии нефти, газа и металлов*

Периодичность: 6 раз в год.

http://www.geolog-technical.kz/index.php/en/

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NEWS of the National Academy of Sciences of the Republic of Kazakhstan
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224–5278
Volume 3. Number 471 (2025), 83–95

https://doi.org/10.32014/2025.2518-170X.462

UDC 681.518.5

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ANALYSIS OF THE INTERACTION OF TRADITIONAL AND NEW TECHNOLOGIES FOR THE EXTRACTION OF METALS FROM SUBSTANDARD RAW MATERIALS

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Abstract: *The relevance* of the work lies in the need to increase the volume of metal mining to meet the ever-increasing demands of the population. This need leads to the need to develop existing and create new innovative technologies for the extraction of natural resources. The purpose of the work is to optimize the interaction of technological approaches and technical means to increase the efficiency of extraction and processing of metal-containing raw materials. *Methodology.* The basis of the approach to achieving the goal is the search for an algorithm for the interaction of methods for managing the efficiency of mining in the metal mining process. The possibilities of organizing work using traditional technologies with filling the developed space with hardening mixtures and new technologies with leaching are being investigated so that the combined technologies improve each other's performance. *Results.* It is shown that the depletion of the mineral resource base requires the creation of innovative technologies for the exploitation of natural and man-made deposits. A methodology has been developed and the results of studies on the completeness of metal extraction from nonconditional ores and processing tailings, depending on the degree of their preparation, are presented.

Conclusions. The formation of man-made mineral reserves with the depletion of the mineral resource base of Russia determines the priority of creating extraction and processing technologies with permanent optimization of technological processes of extraction and processing according to the criterion of minimizing production waste.

Keywords: Mining, processing, ore, metal, leaching, array, analysis

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СТАНДАРТТЫ ЕМЕС ШИКІЗАТТАН МЕТАЛЛ ӨНДІРУДІҢ ДӘСТҮРЛІ ЖӘНЕ ЖАҢА ТЕХНОЛОГИЯЛАРЫНЫҢ ӨЗАРА ӘРЕКЕТТЕСУІН ТАЛДАУ

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Аннотация. Жұмыстың өзектілігі халықтың үнемі өсіп келе жатқан сұраныстарын қанағаттандыру үшін металл өндіру көлемін ұлғайту қажеттілігі. Бұл қажеттілік табиғи ресурстарды өндірудің қолданыстағы және жаңа инновациялық технологияларын жасау қажеттілігіне әкеледі. Бұл әсіресе құрамында металы бар кендерді өндіруге, оның ішінде осы кендерді таусылған кен орындарынан алуға қатысты. Жұмыстың мақсаты құрамында металл бар шикізатты өндіру мен өңдеудің тиімділігін арттыру үшін технологиялық әдістер мен техникалық құралдардың өзара іс-қимылын оңтайландыру. Әдістеме. Мақсатқа жету тәсілінің негізі металдарды өндіру процесінде тау-кен өндірісінің тиімділігін басқару әдістерінің өзара әрекеттесу алгоритмін іздеу. Өндірілген кеңістікті қатайтатын қоспалармен толтыра отырып, дәстүрлі технологияларды және біріктірілген технологиялар бір-бірінің көрсеткіштерін жақсартатындай жаңа шаймалау технологияларын қолдана отырып, жұмыстарды ұйымдастыру мүмкіндіктері зерттеледі. Зерттеулер қатайтатын қоспалар мен шаймалау құйрықтарының массивтерін біріктіруге баса назар аудара отырып, жалпы қабылданған әдістермен жүзеге асырылады. Нәтижелер. Минералды-шикізат базасының сарқылуы табиғи және техногендік кен орындарын пайдаланудың инновациялық технологияларын құруды талап ететіні көрсетілген. Металдарды кондиционерленбеген кендерден және қайта өңдеу қалдықтарынан олардың дайындалу дәрежесіне қарай алу толықтығын зерттеу әдістемесі әзірленді және нәтижелері келтірілді. Кондициялық емес кендерден және байыту қалдықтарынан металдарды алу технологиясы, оның ішінде процестің механохимиялық активациясы бар ыдыратқыштың жұмыс камерасында егжей-тегжейлі көрсетілген. *Қорытындылар.* Ресейдің минералды-шикізат базасының сарқылуымен минералдардың техногендік қорларының қалыптасуы Өндіріс қалдықтарын азайту критерийі бойынша өндіру мен өңдеудің технологиялық процестерін тұрақты оңтайландырумен өндіру және өңдеу технологияларын құрудың басымдылығын анықтайды. Алынған нәтижелер тау-кен өндіру салаларының жаңа кәсіпорындарын салу және жұмыс істеп тұрғандарын жаңғырту кезінде, сондай-ақ қызметкерлер мен білім алушылардың біліктілігін арттыру үшін пайдаланылуы мүмкін.

Түйін сөздер: өндіру, өңдеу, кен, металл, шаймалау, массив, зерттеу

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АНАЛИЗ ВЗАИМОДЕЙСТВИЯ ТРАДИЦИОННЫХ И НОВЫХ ТЕХНОЛОГИЙ ДОБЫЧИ МЕТАЛЛОВ ИЗ НЕКОНДИЦИОННОГО СЫРЬЯ

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Аннотация. Актуальность работы состоит в необходимости увеличения объема добычи металлов для удовлетворения постоянно увеличивающихся запросов населения. Эта потребность приводит к необходимости развития существующих и создания новых инновационных технологий извлечения природных ресурсов. Особенно это касается добычи металлосодержащих руд, в том числе и добычи этих руд из обедненных месторождений. Цель работы заключается в оптимизации взаимодействия технологических приемов и технических средств для повышения эффективности добычи и переработки металлосодержащего сырья. Методология. Основу подхода к достижению цели составляет поиск алгоритма взаимодействия методов управления эффективностью горного производства в процессе добычи металлов. Исследуются возможности организации работ при использовании традиционных технологий с заполнением выработанного пространства твердеющими смесями и новых технологий с выщелачиванием так, чтобы комбинируемые технологии улучшали показатели друг друга. Исследования осуществляются общепринятыми методами с акцентированием на комбинировании массивов из твердеющих смесей и из хвостов выщелачивания. Результаты. Показано, что истощение минерально-сырьевой базы требует создания инновационных технологий эксплуатации природных и техногенных месторождений. Разработана методика и приведены результаты исследований полноты извлечения металлов из некондиционных руд и хвостов переработки в зависимости от степени их подготовки. Детализирована технология извлечения металлов из некондиционных руд и хвостов обогащения, в том числе в рабочей камере дезинтегратора с механохимической активацией процесса. Выводы. Формирование техногенных запасов минералов при истощении минерально-сырьевой базы России обусловливает приоритетность создания технологий добычи и переработки с перманентной оптимизацией технологических процессов добычи и переработки по критерию минимизации отходов производства. Полученные результаты могут быть использованы при строительстве новых и модернизации действующих предприятий горнодобывающих отраслей, а также для повышения квалификации работников и обучающихся.

Ключевые слова:добыча, переработка, руда, металл, выщелачивание, массив, исследование

Introduction. Metal leaching is a technology that allows transferring metal from mineral to solution and extracting it from solution, bypassing a number of processes of traditional technology. According to the technological features, the technology options are divided into borehole, shaft, heap and combined, combining the capabilities of all types (Malozyomov, et. al., 2024; Konstantinova, et. al., 2021). Depending on the place of leaching, in-situ leaching and heap leaching are distinguished. Leaching on an industrial scale is used in technologically developed countries (Nussipali, et.al., 2024).

For the cost-effective development of such reserves, there is a need to apply new technologies, including options for processing by leaching metals from ores and ore dressing wastes that are substandard in terms of metal content. The use of such technologies, in particular physical and chemical methods, is complicated by the complexity of the structure of the polymetallic, copper and tungsten and molybdenum deposits being mined, as well as by the multi-type and multi-grade nature of the ores (Batuhtin, et.al., 2016; Kondrakhin, et.al., 2023; Malozyomov, et.al., 2023). The priority direction of increasing the efficiency of mining enterprises in the operation of underground deposits is the involvement in the processing of poor and lost ores, as well as tailings of enrichment and metallurgy. It is realistic to do this, as the waste of enterprises are technogenic deposits ready for metal extraction by new methods (Kravtsov, et.al., 2023; Kondratyev, et.al., 2020; Gozbenko, et.al., 2016).

Recent studies have laid the foundations for the concept of rational environmental management, including the application of geoinformation technologies in solving three-dimensional geo-ecological problems, predicting the geomechanical state of the massif when mining deposits, and studying the impact of improving the quality of enrichment waste in the utilisation of primary processing tailings (Adigamov, et.al., 2022; Martyushev, et.al., 2023; Golik, et.al., 2023). The direction of activation of metal-containing raw materials during leaching in disintegrators is being developed. A number of works establish regularities of changes in geomechanical conditions under changing conditions of mining operations, regularities of influence of mechanical activation on structural characteristics of materials and others (Semernik, et.al., 2023; Tynchenko, et.al., 2024; Konyuhov, et.al., 2020).

The considered problem is given attention in foreign literature, for example, increasing the efficiency of copper leaching by mechanochemical activation of ores, extraction of uranium and molybdenum from copper leaching solutions using ion exchange, extraction of uranium from sandstones by acid in-situ leaching, the influence of force on the efficiency of metal leaching, etc.

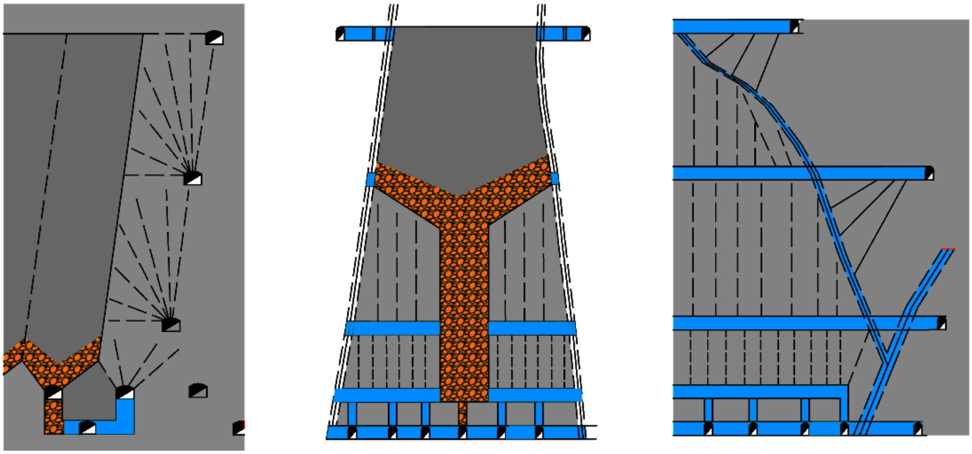
Materials and methods. Comprehensive study of gold extraction technologies from substandard raw materials includes the study of leaching regularities, establishment of relationships between the parameters of raw material extraction and gold recovery, and justification of effective options for metal extraction. Based on the research results, the concept of gold leaching from substandard mineral raw materials is formed.

Results and discussion. Massif condition management. The most common technologies used in the development of valuable ore deposits are characterised by filling the excavated space with materials. The ore body is divided into chambers and pillars excavated at different times. Layer systems differ in the direction of layer excavation: upward and downward (Khekert, et.al., 2021; Brigida, et.al., 2024; Zaalishvili, et.al., 2024). If a layer of wedged structural blocks is created above the excavated space, mixtures of reduced strength can be used. In case of downward excavation by horizontal excavation, the strength of the concrete slab is set by directive: not less than 1.5 MPa. Indicators of ore-bearing massif condition management are improved when conditions of volumetric compression are created. Variants of transferring the embedding massifs into the volumetric compression mode are presented in Table 1.

Table 1. Methods of converting arrays to compression mode

Exposure time	Option	Terms of use
Preliminarily	Anchors in lateral rocks	Unstable host rocks
At the same time	Feeding the mixture to the ore	No restrictions
	The inclination of the walls of the chambers	Unstable ores
	Creating a shielding gap	Unstable rocks
	The survey	Unstable ores and rocks
With a lag	Differentiation of the strength of the mixture	Depending on the conditions

The array hardening methods are illustrated in Figure 1.



a b c

Fig. 1. Methods of solidification of the array: a – the inclination of the walls of the chambers to the ore; b – the supply of the mixture to the ore; b – anchoring

The works of I.V. Baklashov, V.I. Borsch-Kompaniyts, M.A. Iofis, D.M. Kazikaev, L.A. Krupnik, M.V. Kurleni, etc. proved that the load-bearing capacity of a material under volumetric compression increases significantly (Golik, et.al., 2023; Akzharkyn, et.al., 2024; Kheker, et.al.,2023). The failure of the specimen in compression occurs due to the development of shear stress at an angle to its axis. Lateral pressure increases the strength of rocks, which explains the prevalence of technologies with embedding with solidifying mixtures. At the Cobar mine (Australia), with 10 tons of volumetric compression on a press and 0.1 MPa lateral pressure, the compressive strength was 0.7 after 7 days and 1.2 MPa after 80 days.

Classification of hardening mixture components increases the strength of hardening mixtures in 1.2...1.5 times, and cohesion in 1.2...2.5 times. The efficiency of chamber mining by alternative variants: continuous and two-stage excavation is evaluated by comparing the present costs:

$$\acute{Y} = \left[\left(\tilde{N}_1 + \mathring{A}_i \hat{E}_1\right) - \left(\tilde{N}_2 + \mathring{A}_i \hat{E}_2\right)\right]\grave{A}$$

where Э - economic effect, rub.; $E_н$ - discount factor; K_1 - capital investment in two-stage excavation, rub.; K_2 - capital investment in continuous excavation, rub.; C_1 - unit cost of production in two-stage excavation, rub.; C_2 - unit cost of production in continuous excavation, rub.; A - annual volume of concentrate production in continuous excavation of chambers, tons.

The results of evaluation of chamber mining options are given in Table 2

Table 2. Indicators of ore extraction options

Indicators	Units	Two-studio	Solid		
			The slope of the walls	Protective array	Feeding the mixture to the ore
Contents in balance sheet stocks	%	0,2	0,2	0,2	0,2
Dilution of ore	%	15,7	11,4	12,6	9,1
Ore losses	%	6,7	5,6	5,9	6,5
Extraction into concentrate	%	86,1	88,6	88,1	89,6
Content in the concentrate	%	59,2	59,2	59,2	59,2
The cost of processing 1t of ore	rub.	42,72	42,72	42,72	2,72
Cost of extraction of 1t of ore	rub.	152,6	146,3	145,5	147,8
The cost of 1t of metal in concentrate	rub.	85374	75502	78525	74053
Economic efficiency of 1t of metal	rub.	-	9871	6848	11321
Savings from mining 1t of ore	rub.	-	24,71	16,76	29,12

The methods of determining the allowable exposed roof spans differ (Table 3). Combination of mining technologies with filling the mined-out space with solidifying mixtures and leaching tailings contributes to the creation of the condition of volumetric stress state of rocks. In order to ensure the effectiveness of combined technologies, mine fields are divided into areas safe in terms of stresses. Combined technology is recommended for mining gold, uranium and copper ores, which are united by common origin, dispersion, presence of iron sulfides and uneven distribution in the ore body (Podoprigora, et.al., 2024; Shutaleva, et.al., 2022).

Leaching of metals in blocks. The block is prepared by a system. The upper part of the chamber is equipped with an irrigation system, and in the lower part - excavations for collection of production solutions. Optimization of intensification processes, improving the quality of extracted metals and reducing energy costs allows the use of pulse currents. Mixing of the raw material crushed to a coarseness of 0.2 mm with solvent also contributes to this.

Leaching in the disintegrator forms microdefects both on undisturbed areas of the mineral and near crystal clusters, and inside the host gold minerals - develops channels for access of the leaching solution to metal particles. During long-term storage of tailings, oxidation of sulfides in areas with limited oxygen access is slow, while in the beach part of the tailings pond it is faster. Enrichment processes are being modernized through the use of hydrometallurgical processing operations. Leaching alone does not ensure the reliability of the process, as it takes a long time for reagents to penetrate deep into the mineral particle, so leaching processes are intensified.

Extraction of metals from solutions is carried out on ion exchange resin. After removal of impurities and metals the sorbent has residual capacity: for gold (up to 0.08 mg/g), for the sum of impurities (up to 0.7 mg/g). At electrosorption leaching metal concentration in the liquid phase increases by 11 %, concentration in solution decreases by 15 %, and sorption capacity of resin increases by 12 %.

Sorption leaching is carried out in a cascade of several apparatuses (pachukes), following the principle of counterflow. The pulp is fed into the first unit and discharged from the last pachuk. Fresh anionite is loaded into the next unit along the pulp flow, and saturated resin is removed from the first unit. After cyanidation, the slurry enters the first sorption pile, is pumped to the twelfth pile by elevators, and the resin moves from the twelfth to the first pile. Pulp separation takes place on screens installed in the head of the pachuca. The pulp passes through the screens and flows through a chute into the next packhouse. The resin is rolled into the same pachuca, from the two outermost nets it enters the resin stream and is discharged into the next pachuca. Schiber distribution of resin through the chain is carried out when the equilibrium capacity of resin at a given sorption stage is reached. After dewatering, the resin is fed for regeneration and the spent pulp is directed to the tailings pond.

At the stage of cyanide treatment of the resin from the impurities on it desorption occurs, for example, for Sadon conditions: iron - 43 %, copper - 96 %, silver - 47 %, gold - 10 %. Increasing the intensity of leaching makes it economically feasible to use it for tailings processing with an additive effect - increasing the efficiency of ore dressing. Directions for using the phenomenon of metal leaching to manage stresses in the array:

- in the block with the formation of leaching tailings;
- in heaps and percolators with the formation of raw materials for the manufacture of solidifying mixtures;
- in disintegrators with activation of raw materials for the production of solidifying mixtures.

The peculiarity of the technology is that the same extraction of metals in the disintegrator is achieved in seconds, and in the agitator in 15-60 minutes, or 2 orders of magnitude more. The loosening factor of the ore mass in the block is 1.15-1.20. At diameter of blast holes 100 mm ore yield from 1 m of hole is 6-7 m3. When using AC-8 granulite, the consumption of explosives is 1.3 kg/m3 of rock mass. The leaching process includes the following stages:

- movement of solvent to the surface and within the pores of minerals;
- chemical reaction of ore and solution;
- displacement of the metal-bearing solution into the solvent.

Sulfide minerals interact with solvents according to the scheme:

$$Me\,S + 2NaCl + H_2SO_4 + 0{,}5O^2 = MeCl_2 + S0_3 + Na_2SO_4 + H_2O$$

In the separation of metals from chloride solutions, the best precipitant is caustic soda, the cheapest reagent is calcium hydroxide, and the most suitable reagent is soda ash. Metal transfer within the block occurs due to the difference in metal concentration in solution and on the mineral surface. Leaching in film-drop mode is preferred over leaching in flood mode. The application of the technology is limited by the ore's ability to slump. The ore is irrigated through perforated pipes. A spreading zone is formed around the wells when solutions are delivered, and area spreading occurs when large volumes of solutions are delivered. The solution can be fed through horizontal wells drilled in the roof of the destroyed interstorey pillar. In order to wet the ore in the dead zone, large portions of solutions are periodically fed between the wells, creating a hydraulic flow regime.

Solutions are captured at the base of the blocks, where metal-containing solutions are transferred through mine workings or boreholes. To prevent migration of solutions outside the block contour, impervious curtains are created or solidifying mixtures and resins are injected. The peculiarity of leaching in the disintegrator is that a portion of the reagent solution is fed into the mechanical working body, where the extraction of metals occurs simultaneously with the destruction of crystals. Solid particles of tailings are an additional abrasive, facilitating the process of conversion of insoluble natural compounds into soluble ones. Fine grinding reveals the binding properties of minerals, reducing cement consumption. Under the same conditions, the strength of concrete set in activated water at the age of 28 days increases by 30-40 % (Fig. 2).

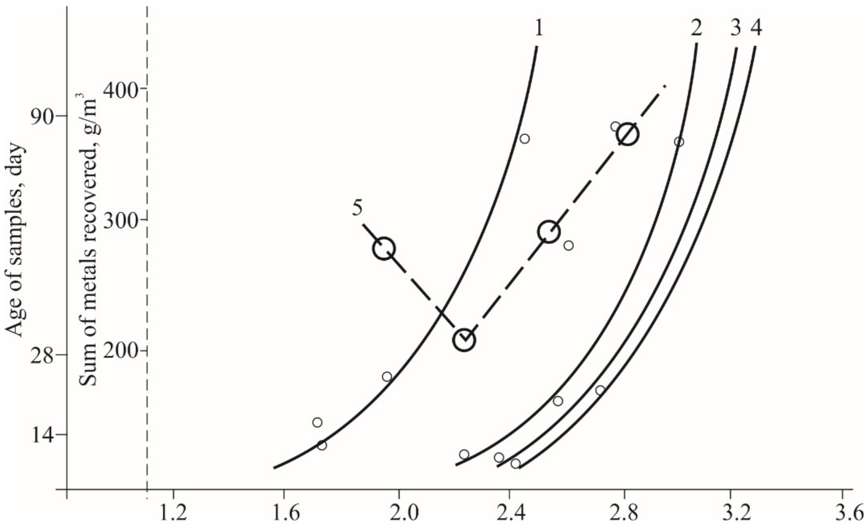


Fig. 2. Dependence of concrete strength on reagents: 1 – hydrochloric acid; 2 – chloric acid; 3-anolyte by irrigation; 4 – anolyte in a disintegrator; 5 – average results

Grinding ores before leaching to 0.1-0.2 mm is not always sufficient to open them. Therefore, the leaching efficiency is increased by activation of the process. In the layer adjacent to the solid phase, the working solution moves slowly.

The connection between the upper layers and the inner layers of the mineral is weakened, metal-containing particles separate and increase the concentration of matter in the boundary layer. The throughput of the layer is reduced by the presence of small mineral particles. The leaching rate is increased by the vortex motion of the solution created by the disintegrator. Mechanochemical treatment affects the metal deposition parameters. Management of metal leaching efficiency is reduced to creation of conditions for mineral opening on the contacts of aggregation and minimisation of losses of valuable components.

The degree of ore opening in the process of preparation varies within 54...80 %. Mineral activation model in the disintegrator:

$$A = f\ (E,\ t,\ Q,\ K_{\grave{a}}, r)$$

where E - energy input; t - processing time; Q - disintegrator productivity; K_a - activation coefficient; r - radius of mineral particles.

When choosing the design of a disintegrator, the criterion of optimality is not crushing, but destruction along the surfaces of cleavage. The most mastered method of curing metals from solutions is electrodialysis. Indices of electrodialysis deteriorate at increase of hardness of solutions, therefore solutions are preliminary softened and desalted. The plant includes electrolysis units with ion exchange membranes and electrodialysis units. The solution with mineralisation up to 3 g/dm3 is released from the slurry and demineralised in cathode chambers. Two-stage treatment of the anolyte at each treatment stage reduces the salt concentration by about 50 %.The indicators of physical and electrical treatment are given in Table 3.

Table 3. Indicators of the technological regime

Processes	Capacity, m^3/h	Pressure, MPa	Temperature, °T	Current strength, A	Voltage, V	Current density, A/m^2
Softening	30	0,1	+40	600	30	300–500
Desalination	25	0,25–0,35	+40	200	300	100-200

The processes are characterised by parameters (Table 4).

Table 4. Process parameters

Parameters	Units	The initial solution	Anolyte	Dilute
The hydrogen index	pH	6-7	7-8,5	6-7
Oxidative potential	mv	100-300	100-150	100
Mineralization	g/dm^3	3	2	1
Rigidity	g-eq/mV	8-2	7	7
Sulfates	mg/dm^3	500-800	300-500	500
Chlorides	mg/dm^3	400-900	300-600	300
Bicarbonates	mg/dm^3	150-250	–	–

Metal ingredients are extracted from brines in the sorption-desorption column SDK. The complete production cycle with tailings utilisation is shown in Fig. 3.

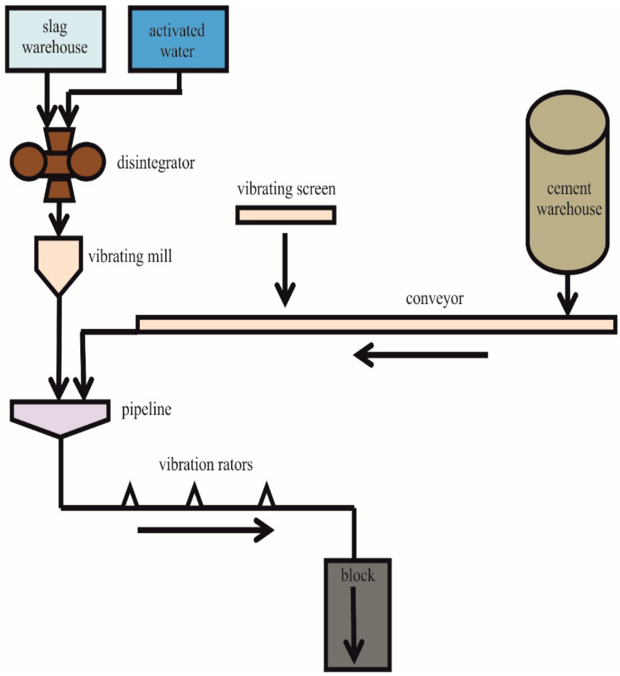


Fig. 3. Scheme of preparation of hardening mixtures with activation of components: 1 – cement warehouse; 2 – vibrating screen; 3 – slag warehouse; 4 – disintegrator; 5 – activated water; 6 – vibrating mill; 7 – conveyor; 8 – pipeline; 9 – vibrationrators; 10 – block

Tailings processing in a disintegrator ensures that the activity of coarse particles is unlocked and the activity of fine mineral particles is enhanced. The raw material base of the North Caucasus mining industry includes more than 560 deposits and ore occurrences, of which the most significant was the Sadonsky ore district. Ore composition of the Sadonskoye deposit, %: galena 1.5; sphalerite 45.5; chalcopyrite 0.5; pyrite 12.015.0; carbonates 46; pyrrhotite 12. The Urupskoye copper-ore deposit is composed of stratified and colonised quartz albitophires and their tuffs with the strength coefficient on the scale of Prof. M.M. Protodyakonov 10...18. About 2/3 of ores of the Urupskoye deposit are disseminated, and the rest are continuous ores (copper-coal, copper-zinc and zinc). The Tyrnyauz tungsten-molybdenum deposit is located in the zone of intersection of the Tyrnyauz fault zone and submeridional structure. Up to half of the reserves are localised in scanned marbles and the rest in biotite hornfels and granitoids. The greatest impact on the performance of underground development of ore deposits in the North Caucasus is caused by poor stability of ores and rocks, abrupt changes in the localisation parameters of ore bodies and intensity of tectonic disturbances.

Conclusion. The studies have substantiated the feasibility of using technologies with metal leaching from metal-containing raw materials. The research results substantiate the possibility of rock massif management by filling the excavated space with the products of enrichment tailings processing and in-situ leaching of metals, as well as combining traditional and innovative technologies with the preservation of the earth's surface as a guarantor of environmental safety. The behaviour of ore-bearing massifs when managing their condition by filling the excavated space with solidifying mixtures and tailings of in-situ metal leaching adequately obeys the laws.

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ISSN 2224-5278 (Print)

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Ж.Ш.Әден*
Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 15.06.2025.
Формат 70x90$^{1}/_{16}$. Бумага офсетная. Печать – ризограф.
14,5 п.л. Заказ 3.

РОО «Национальная академия наук РК»
050010, Алматы, ул. Шевченко, 28, т. 272-13-19