Revista Minelor – Mining Revue
ISSN-L 1220-2053 / ISSN 2247-8590
vol. 30, issue 4 / 2024, pp. 32-43

TECHNOLOGIES AND TECHNICAL MEANS FOR ELECTROSORPTION LEACHING OF GOLD FROM FLOTATION TAILINGS OF RESISTING SULFIDE RAW MATERIALS

Vasyl LYASHENKO[1], Tamara DUDAR[2],Tatiana OLIYNIK[3],Viktor SHAPOVALOV[4]*

[1]Ukrainian Research and Design-Intelligence Institute of Industrial Technology, Zhovti Vody, Ukraine
vilyashenko2017@gmail.com
[2]National Aviation University 03058, Kyiv, Ukraine, e-mail: dudar@nau.edu.ua
[3]Kryvyi Rih National University, 50000, Kryvyi Rih, Ukraine, e -mail: taoliynik@gmail.com
[4]Kryvyi Rih National University, Kryvyi Rih, Ukraine, shapovalov@knu.edu.ua

DOI: 10.2478/minrv-2024-0060

Abstract: ***Relevance.*** *The problem of expanding the raw material base of the gold mining industry is becoming more pressing due to the depletion of explored reserves, rising production costs and the costs of minimizing the man-made impact on the environment. With the depletion of oxidized gold-bearing ores, finely disseminated ores are increasingly being involved in processing. An increase in gold production volumes can be achieved by improving the beneficiation process. An alternative to traditional beneficiation technologies is electrotechnologies that use the phenomenon of energy impact on mineral raw materials. Among them, the range of application of the resin-in-pulp electrosorption leaching technology is expanding.*
Objective. *Justification of technologies and technical means for electrosorption leaching of gold from flotation tailings of refractory sulfide raw materials. This will increase metal production and strengthen the mineral resource base of gold mining enterprises and reduce damage to the environment.*
Methodology. *A comprehensive method was applied, including analytical studies using the fundamentals of system analysis and mathematical statistics, technological experimentation using mathematical planning of experiments, economic and mathematical modeling, technical and economic calculations and pilot industrial implementation. Laboratory studies were modeled on the tailings of flotation enrichment of gold from the flotation tailings of refractory sulfide raw materials. The application of electric fields was provided by two parallel electrodes.*
Scientific novelty. *Theoretical and technological experimentation, substantiation of fundamentally new technologies and technical means of electrosorption leaching of gold from flotation tailings of refractory sulfide raw materials.*
Results. *The efficiency of using technogenic resources is achieved by combining traditional enrichment technologies with the capabilities of hydrometallurgy and electrochemistry. Flotation tailings of ores with gold content from 1.0-1.5 g/t are leached according to the scheme: granulation to a size of 15-30 mm with the addition of 1 g/l of cyanide, sulfuric acid removal of metals, alkaline treatment to pH 10-11, cyanidation with an irrigation density of 20 l/m^2 per hour, gold sorption on anion exchanger, anion exchanger regeneration and regenerate electrolysis. Gold leaching from refractory sulfide raw materials is possible after the destruction of sulfides upon reaching an oxidation potential of 1000 mV, it effectively proceeds in a solution of 20-30% sodium chloride upon application of direct electric current with a density of 800-1200 A/m^2, pH of the medium 2.0-4.0 and a temperature of 60-800 C with the extraction of up to 70-80% of gold into the solution with an electric power consumption of 120-220 kW/t. The results of the experiment confirm the efficiency of the technology of electrosorption leaching of gold from gold-bearing pulps. The leaching rate increases by 25-30%, the sorption capacity of the anionite AM-2B increases by 2.5-3 times. An increase in the capacity of the sorbent and a decrease in the amount of gold in the liquid phase shifts the equilibrium of the system towards gold dissolution and intensifies the volume and completeness of its extraction.*

[*] Corresponding author: Prof. eng. V.I. Lyashenko, Ph.D., Ukrainian Research and Design-Intelligence Institute of Industrial Technology, Zhovti Vody, Ukraine, vilyashenko2017@gmail.com

vol. 30, issue 4 / 2024
pp. 32-43

Implementation. *The technologies of electrosorption and electrochemical leaching of gold from ore flotation tailings have been tested and recommended for industrial development at the Aksu, Bestobe, Zholymbet deposits and implemented in the practice of ABS-Balkhash, Kazakhaltyn JSC (Republic of Kazakhstan) and can be recommended for other developed mining and gold mining countries of the world.*
Keywords: *gold-bearing ores, enrichment, electro-sorption leaching, resin in pulp, ecology, efficiency*

1. Introduction

In the context of continuous increase in production and consumption of metals, the problem of expanding the raw material base of the gold mining industry is of particular importance [1]. Increasing the efficiency of mining production based on the use of waste from the extraction and processing of gold ore raw materials, ensuring environmental safety, taking into account the electrosorption leaching of gold from pulp, improving the beneficiation process, using electrical technology and the phenomenon of energy impact on mineral raw materials, solves important scientific, practical and social problems [2]. The authors have carried out a study and definition of an effective technology for the use of technogenic resources while combining traditional processing with the capabilities of hydrometallurgy and electrochemistry, as well as laboratory and production experiments, physical modeling using standard and new methods of leading specialists from developed mining countries of the world with the participation of the authors [3].

The purpose of the work is to substantiate technologies and technical means for electrosorption leaching of gold from flotation tailings of refractory sulfide raw materials. This will ensure an increase in metal production and strengthening the mineral resource base of gold mining enterprises and reduce damage to the environment. To achieve the set goal, the following tasks are solved:

– analyze the experience of using technologies and technical means for gold mining;

– propose effective technologies and technical means for extracting gold into solution, as well as processing solutions and pulps;

– assess the environmental safety of the proposed nature- and resource-saving technologies and promising areas for further research.

Research methods. The work uses a comprehensive method, including analytical studies using the fundamentals of system analysis and mathematical statistics, technological experimentation using mathematical planning of experiments, economic and mathematical modeling, technical and economic calculations and pilot implementation. Five series of studies were carried out in stages: identification of input parameters; sorption leaching with the imposition of an electric field. Samples were collected according to the scheme: before the start of the experiment, the initial gold content in the solid and liquid phase and the sodium cyanide content were determined in the pulp. The current at a voltage of 36 V increased from experiment to experiment within 20...80 A. Laboratory studies were conducted in a column, the volume of which ensured the possibility of cyanidation of pulp up to 0.5 kg at a solid to liquid ratio of 1:1. Compressed air consumption during the study was 0.5 l / s.

The scientific novelty of the work lies in the theoretical and technological experimentation of the substantiation of fundamentally new technologies and technical means of electrosorption leaching of gold from flotation tailings of refractory sulfide raw materials.

Object of study and its technological audit. The object was the flotation tailings of the Aksu mine (Republic of Kazakhstan). The electric field was created by two parallel stainless steel electrodes with a diameter of 3 mm and a distance between the electrodes of 40 mm (Fig. 1).

A rectangular pulse generator was used as a power source, providing the possibility of varying the signal frequency within 10–20,000 Hz and the duty cycle within 2.5–45.0 μs, a stabilized DC source of the type and an autotransformer. The sample is characterized by a quartz-silicate composition with a small amount of sulfur and carbon dioxide, the presence of arsenic, copper sulfides, iron and carbonates, clay and mica. The results of processing gold-bearing sulfide are systematized, and the variables affecting enrichment are ranked. Using regression analysis in the Maple environment, the proportion of gold recovery into the solution during pulp disintegration is determined depending on the time of exposure to electrical pulses. A rectangular pulse generator was used as a power source, providing the possibility of varying the signal frequency within 10–20,000 Hz and the duty cycle within 2.5–45.0 μs, a stabilized DC source of the type and an autotransformer. The sample is characterized by a quartz-silicate composition with a small amount of sulfur and carbon dioxide, the presence of arsenic, copper sulfides, iron and carbonates, clay and mica. The results of processing gold-bearing sulfide are systematized, and the variables affecting enrichment are ranked. Using regression analysis in the Maple environment, the proportion of gold recovery into the solution during pulp disintegration is determined depending on the time of exposure to electrical pulses.

vol. 30, issue 4 / 2024
pp. 32-43

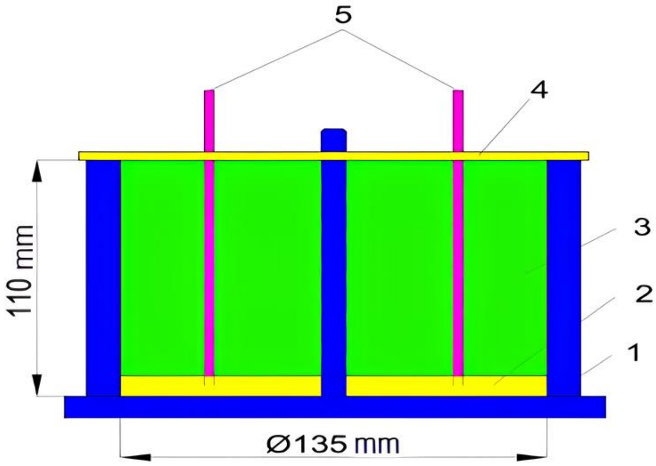

Fig. 1. Potentials of the electric field in the cell: 1-frame; 2-polyurethane foam fixing pad; 3-working container; 4-cover with holes at the nodal points; 5-potential-setting movable electrodes

2. Researching existing solutions to the problem

The urgency of the problem of providing industry with metals is further increasing due to the depletion of reserves suitable for development, the rise in the cost of mining mineral resources and the need to minimize the negative impact of ore beneficiation tailings on the environment [4]. A significant share of reserves is lost during the extraction and beneficiation of raw materials extracted from the subsoil. With the depletion of reserves of oxidized gold-bearing ores, finely disseminated ores are increasingly involved in processing. In the context of changing economic systems, the urgency of finding fundamentally new technologies for gold extraction and processing is increasing [5], [6]. Due to losses from 10 to more than 30% of gold during extraction and beneficiation, its reserves in technogenic deposits reach 2 thousand tons. Using the capabilities of geotechnology, hydrometallurgy and electrochemistry makes it possible to significantly increase the volume of gold production, reduce the number and duration of operations and increase the lifespan of enterprises [7], [8]. The increase in gold production volumes is ensured by activating the beneficiation process under the influence of energy flows [9], [10]. The main methods of ore enrichment are gravity and flotation. Of these, gravity methods are the most common. The capabilities of gravity enrichment and its efficiency depend on the morphometric parameters of gold and the nature of its mineral bonds. The lower limit of grains for effective gravity separation varies in the range from 500 to 40 μm. Centrifugal enrichment of raw materials with fine gold in intergrowths ensures the extraction of 40–70% of gold. Thus, during gravity enrichment of stale tailings with a gold content of 0.6–0.8 g/t in a centrifugal concentrator, gold recovery after three separation stages ranged from 4.8 to 43%. From the current flotation tailings of the enrichment plant, after centrifugal enrichment, 40% of gold was extracted into a gold-bearing product. Gravity methods are promising for the recovery of fine gold using centrifugal concentrators and concentration tables, but in most cases this method does not provide high gold recovery and is only applicable in combination with flotation and hydrometallurgy.

Flotation and gravity-flotation technologies are the most common method of enrichment of non-ferrous and precious metal ores [11], [12]. Their efficiency is affected by the size and degree of grain opening, the presence of coating films, isomorphic impurities and associations with ore and rock minerals. During flotation of sulphide ores, gold recovery does not exceed 60–70%. The least efficient is flotation extraction of gold from finely dispersed tailings. The developed product is resistant to cyanidation due to the fine dissemination of gold in sulphides. Combined gravity-flotation schemes include additional grinding of waste, flotation classification of hydrocyclone discharge and copper flotation of the froth product. When using butyl xanthate, mercaptobenzothiazole and their mixtures as collectors in sulfide concentrate, gold extraction was 56%, and silver extraction was 52% [13], [14]. An alternative to common technologies are electrotechnologies that use the phenomenon of the impact of energy flows on mineral raw materials. Among them, the range of application of the resin-in-pulp electrosorption leaching technology is expanding [15], [16].

3. Research results

Theory of the issue. Electrical action on the system "crushed ore - leaching solution - sorbent" is accompanied by a number of effects that contribute to an increase in the capacity of the sorbent, a more complete dissolution of gold and intensification of mass transfer. Full-scale studies of the distribution of the electric field in the working volume of an industrial column at different distances between the electrodes allow us to draw a conclusion about the acceptable distance between the electrodes with their length corresponding to the total power of the working layer. The effect of electrical treatment is characterized by the value of excess of the sorption capacity parameter relative to the control one at the achieved degree of leaching. The confidence interval is described by a model of the type:

$$\left[\bar{x}-1{,}64\frac{\delta}{\sqrt{n}};\bar{x}+1{,}64\frac{\delta}{\sqrt{n}}\right], \quad (1)$$

where $\bar{x}$ – average value of the indicator; δ – standard deviation; n – sample size of observations; 1.64 – Student's distribution coefficient.

Laboratory studies. As a result of laboratory work it was established: An electric field intensifies the process of sorption leaching of gold by 25-30%. The sorption capacity of the ion exchanger increases by 2.2 times during electrical treatment. The "resin in pulp" technology includes the preparation of ore pulp, cyanidation, sorption leaching of gold on ion-exchange resin, gold desorption, resin regeneration and electrolysis. The most complete extraction of gold from the liquid phase of the pulp is achieved by ensuring optimal pulp-resin counterflow, pulp viscosity, temperature and intensity of mixing of the resin-pulp mixture. At the gold recovery plant of the Kyzylkumredmetzoloto concern (Republic of Uzbekistan), the technology of sorption leaching of gold is used to process ore from the Muruntau deposit (Republic of Uzbekistan).

Sorption leaching is carried out continuously in a cascade of several sequentially connected devices, observing the counter-current principle. The pulp is fed into the first device (pachuca) and removed from the last pachuca. Fresh anionite is loaded into the next device in the direction of pulp movement, and the gold-saturated resin is removed from the first. The pulp is separated on the pachuca screens. The pulp passes through the screen and enters the next pachuca via a chute. The resin rolls into the same pachuca, and from the two outer screens it enters the resin flow and is removed to the next pachuca. Slide distribution of the resin is carried out upon reaching the equilibrium capacity of the resin at a given stage of sorption [17], [18]. The saturated resin is fed to a drum screen to wash the resin from the pulp and then to a jigging machine to separate it from sand.

After jigging, the resin is pumped to the resin preparation unit, where the resin and chips are separated and the resin is dehydrated on drum screens. After dehydration, the resin is fed for regeneration. The spent pulp is separated from the pulp through drum screens and sent to the tailings storage facility. Disadvantages of the multi-stage resin regeneration scheme: long process duration - more than 300 hours; loss of silver at the cyanide treatment stage; low gold concentration in the regenerate when the solution is saturated with sodium sulfate. At the stage of cyanide purification of the resin from impurities on it, desorption occurs: iron - 43%, copper - 96%, silver - 47%, gold - 10%.

Desorption of nickel, zinc, cobalt at this stage is insignificant. Most of the impurities are removed at the stage of sulfuric acid treatment of the resin. The regenerated sorbent has a residual capacity for gold of 0.08 mg/g and for the sum of impurities less than 0.7 mg/g. The resin sorbs gold from solutions contaminated with impurities of non-ferrous metals and iron, which reduces its sorption-volume capacity for gold. The depressant effect is determined by the nature of the depressants and the ratio between the components of the solution.

The main task of increasing the efficiency of sorption leaching is to prevent the extraction of impurities into the solution during leaching. To intensify the sorption leaching of gold by suppressing impurities, electrical methods of activating gold ions are used, for example, applying an electric current to the process. Electrical methods of intensifying chemical and technological processes for extracting metals from ores are aimed mainly at intensifying the desorption process. Solutions are known for using electric current to intensify the sorption process and intensify leaching. Sorption is carried out with the application of an alternating electric field with a frequency of 5-40 Hz. High frequency does not cause pulsation of the solution in the capillaries due to inertial forces and insufficient polarization. At low frequencies of about 1-2 Hz, the effect is also not great.

White mud from the Pavlodar Aluminum Plant containing zeolites is used as a sorbent. In the process, 1 g of the sorbent is mixed with 1 l of calcium hydroxide solution while passing an electric current of 0.6 A, 35 V, and 16 Hz for 30 min. Calcium sorption from the calcium hydroxide solution increases to 300 versus 58 mg/g without applying current. Sorption on ion exchangers in a constant magnetic field is carried out within the framework of the ion-exchange process in a column with a suspended layer of finely dispersed ion exchangers. The liquid flow rate in this case is 8-10 times higher than the filtration rate. An increase in the sorbent capacity in the "raw material - sorbent - solution" system shifts the equilibrium towards gold dissolution and intensifies its extraction.

Gold sorption from pulps is a process in which the forces of electrical action between the ions of the solution and the active centers of the crushed ore and sorbent prevail. If the sorbent charge is higher than that of the crushed ore pulp, complex ions settle on the sorbent. The process of gold dissolution in cyanide solutions has an electrochemical nature. The mechanism of action of electric fields is characterized by a number of effects. In external electric fields, layers of hydrated ions are set in motion, attracted by the force of the uncompensated electric charge of the surface. This effect, or electroosmosis, occurs at an electric field strength of about 0.1 V/cm. The destruction of layers of hydrated counterions facilitates the access of complex gold ions to the active centers of the sorbent and solvent ions. White mud from the Pavlodar Aluminum Plant containing zeolites is used as a sorbent. In the process, 1 g of the sorbent is mixed with 1 l of calcium hydroxide solution while passing an electric current of 0.6 A, 35 V, and 16 Hz for 30 min. Calcium sorption from the calcium hydroxide solution increases to 300 versus 58 mg/g without applying current.

Sorption on ion exchangers in a constant magnetic field is carried out within the framework of the ion-exchange process in a column with a suspended layer of finely dispersed ion exchangers. The liquid flow rate in this case is 8-10 times higher than the filtration rate. An increase in the sorbent capacity in the "raw material - sorbent - solution" system shifts the equilibrium towards gold dissolution and intensifies its extraction.

Gold sorption from pulps is a process in which the forces of electrical action between the ions of the solution and the active centers of the crushed ore and sorbent prevail. If the sorbent charge is higher than that of the crushed ore pulp, complex ions settle on the sorbent. The process of gold dissolution in cyanide solutions has an electrochemical nature. The mechanism of action of electric fields is characterized by a number of effects. In external electric fields, layers of hydrated ions are set in motion, attracted by the force of the uncompensated electric charge of the surface. This effect, or electroosmosis, occurs at an electric field strength of about 0.1 V/cm. The destruction of layers of hydrated counterions facilitates the access of complex gold ions to the active centers of the sorbent and solvent ions.

The electrochemical effect is created by the formation of a short-circuited galvanic cell, one of the electrodes of which is a gold particle, and the other is an electrically conductive mineral. The electrochemical nature of gold dissolution is that on the surface of the gold electrode, as a result of gold oxidation, electrons are released, the removal of which is carried out by oxygen. When an electric field is applied, the reactions are activated. The percolation effect occurs when, when an electric current passes through rock particles in the pulp, energy is released in the pores, capillaries and microcracks, in places of their narrowing. The growth of cracks and capillaries facilitates the access of the solvent to gold. At a current density of about 5-10 A / m^2, several hours are enough for the permeability in the rock to change. The effect of sorbent polarization in a constant electric field increases its activity and capacity with different areas of electrodes and the pachuca body.

The system also experiences secondary effects: piezoelectric, magnetostriction, thermal, thermomechanical, etc. The input power of the electric current source is estimated by the activation energy of ions on the ion exchanger. According to research, 4.5 mg of gold is sorbed from the flotation tailings leaching solution per 1 g of AM-2B ion exchanger. Since gold precipitates in the ion exchanger as a complex ion, the calculation is performed for 1 mole of this substance. The weight of 1 mole of the complex gold cyanide ion is 249, including 197 pure gold. This amount of gold is sorbed on 43.8 kg of ion exchanger or on 0.31 m^3 of resin. With a sorption column volume of about 50 m^3, there will be 128 mol of gold in the column. The required amount of energy to activate gold ions will be 4.8x 106 J. Knowing the sorption time (10 h), the specific input power per column will be 133 W.

About 90% of the energy passes between the ion exchanger grains, therefore the power of the current source is taken as 1–3 kW per column. The parameters of the change in the energy characteristics of the electric field for different electrode configurations were determined in a steel cuvette with a diameter of 135 mm and a height of 110 mm. A stainless steel rod with a diameter of 3 mm was used as an electrode. A caustic soda solution with a pH of 9 served as the working medium. A potential of 18 V was applied to the electrodes, and the voltage drop relative to the grounded mass of the cuvette was measured in a section with a step of 1 cm along the x and y axes. A three-electrode power input scheme with a symmetrical arrangement of electrodes relative to the central compressor pipe was used in a cyanidation pachuca with a diameter of 5.6 m and a height of 24 m.

The distance from the electrode to the pachuca wall is 0.7; 0.9; and 1.0 m, to the compressor pipe - from 1.9 to 2.2 m. To increase the representativeness of the experiment, we tested schemes with two, three and four electrodes. Laboratory studies were carried out in a column, the volume of which ensured the possibility of cyanidation of pulp up to 0.5 kg at a solid to liquid ratio of 1: 1. Compressed air consumption during the study was 0.5 l / s. The application of an electric field was ensured by two parallel stainless steel electrodes with a diameter of 3 mm and a distance between the electrodes of 40 mm. A rectangular pulse generator was used as a source of electricity, providing the ability to vary the signal frequency in the range of 10-20000 Hz

vol. 30, issue 4 / 2024
pp. 32-43

and the duty cycle in the range of 2.5-45 m / ks, a stabilized DC source of the type and an autotransformer. The sample is characterized by a quartz-silicate composition with a small amount of sulfur and carbon dioxide, the presence of arsenic, copper sulfides, iron and carbonates, clay and mica. The results of experiments with changing the modes (R) of electrical action, sorption capacity for gold and copper concentration on the leaching process are given in Table 1.

Table 1. Modes of electro-impact, sorption capacity for gold and zinc concentrations

Mode	**R_1**	**R_2**	**R_3**	**R_4**	**R_5**	**R_6**	**R_7**	
Modes of electrical action								
Voltage, V	15-18	15-18	15-18	15-18	15-18	15-18	15-18	
Current, A	0.5	0,.	0.5	0.2	0.2	0.2	0.5	
Field frequency, Hz	20000	20	10000	10	10000	20000	10000	
Sorption capacity for gold								
Sorbent capacity, mg/g	4.5	12.8	6.2	11.7	4.9	10.3	11.0	10.4
Zinc concentrations								
Concentration in the process, mg/dm^3	2.9	1.42	2.8	1.33	1.37	2.61	2.61	1.52
Residual concentration, mg/dm^3	0.97	0.09	-	0.73	0.99	0.68	1.37	0.35

One of the pachucas was equipped with a system of electrodes and connected to an electric current generator, the second pachuca was intended for control observations. The duration of the stage was 9 hours. The following were monitored: voltage, frequency and density of electric current, as well as the concentration of gold in the sorbent and solution. The electrosorption leaching operations are characterized by Table 2. The data of chemical analyses and the dynamics of the gold leaching-sorption processes are presented in Table 3 (series 2 at a current of 20-25 A) and (series 5 at a current of about 60-80 A). The specific input power in the last experiments is given as 12 W per 1 m^3 of pulp. Information on the test complex is presented in Table 4.

Table 2. Sequence of the experiment

Name of operations	**Process technology indicators**
The tailings are dried, mixed and placed in a container	–
The sorbent is soaked in distilled water	–
Tailings and sorbent are weighed	200 mg tailings, 5 g sorbent (2.5%)
Sodium cyanide solution is prepared	C=180 mg/dm3 (water, pH adjustment with sodium per 10 l of water - 1 g Na OH and 6 g 30% Na CN)
The compressor is started, equal volumes of tailings and solution are introduced into the column	Cyanidation duration
The compressor is switched off, the tailings are soaked for 15 minutes.	– 2 h
The sorbent is introduced into the column, current is applied to the electrodes, the compressor is started	Sample volume – 5 ml
The compressor and electrodes are switched off, the pulp is settled for 15 minutes	Sorption duration – 1 h
Samples of the solution and sorbent are taken	– 15 ml solution, 1.5 g sorbent
The pulp is neutralized	–

Table 3. Results of experimental work

Time from the beginning of the experiment, h.	**Sorbent capacity, mg/g**	
	electrical processing	**control mode**
Basic Contents	0.08	0.08
Episode 2		
0.5	1.1	0.6
1	2.1	1.1
1.5	2.5	1.4
5	11.5	3.1
9	12.7	4.4
Episode 5		
0.5	2.6	0.9
1	3.9	1.3
1.5	11.5	3.2
5	13.2	4.3
9	14.2	4.7

vol. 30, issue 4 / 2024
pp. 32-43

Table 4. Results of a set of 5 experiments

Duration of leaching, hours	**Gold concentration, mg/dm^3 under the conditions**		**Sorbent capacity, mg/g under the conditions**	
	impact	control	impact	
Initial content	1.28	1.28	0.08	0.08
0.5	0.95	1.10	1.85	0.75
1.0	0.82	0.92	3.0	1.2
1.5	0.70	0.81	7.5	2.3
5.0	0.39	0.52	12.35	3.7
9.0	0.31	0.42	13.45	4.55

4. Efficiency of the research

Technological efficiency. Electrical impact on the process of sorption leaching intensifies the dissolution of gold by sodium cyanide, which at the cyanidation stage increases the concentration of gold in the solution due to the shift of the chemical equilibrium in the "pulp-sorbent" system towards sorption with an increase in the capacity of the anion exchanger for gold [19], [20]. According to research data, the concentration of gold on the sorbent increases, and in the solution it decreases, which leads to a shift in the equilibrium and intensification of the process of sorption leaching of gold. With an increase in the input power, an increase in the concentration of gold was noted, both in the resin and in the leaching solution. The studies substantiated the feasibility of involving gold-containing waste in the processing with an increase in gold production and a decrease in damage to the environment. The efficiency of resource use is achieved by combining traditional enrichment technologies with the capabilities of hydrometallurgy and electrochemistry.

The suitability of enrichment tailings for leaching is determined by a probabilistic recognition algorithm based on a set of attributes, the scope of application is the reaction of profit to the ratio of gold production volumes using new and traditional technologies. Flotation tailings of ores with a gold content of 1.0–1.5 g/t are leached according to the following scheme: granulation to a size of 15–30 mm with the addition of 1 g/l of cyanide, sulfuric acid removal of non-ferrous metals, alkaline treatment to pH 10–11, cyanidation with an irrigation density of 20 l/m^2 per hour, gold sorption on anion exchanger AM–2B, anion exchanger regeneration, and regenerate electrolysis. Gold leaching from refractory sulfide raw materials is possible after the destruction of sulfides upon reaching an oxidation potential of 1000 mV. It proceeds effectively in a 20–30% sodium chloride solution with the application of direct electric current with a density of 800–1200 A/m^2, pH of the medium of 2.0–4.0 and a temperature of 60–800 C with the extraction of up to 70–80% of gold into the solution with an electric power consumption of 120–220 kW/t. The experimental results confirm the efficiency of the technology of electrosorption leaching of gold from gold-bearing pulps [21]. The leaching rate increases by 25–30%, and the sorption capacity of the AM-2B anion exchanger increases by 2.5–3 times. When combining the processes of gold leaching from ores and their processing products and sorption, activated, for example, by the application of electric fields, the reactions are enhanced due to the occurrence of a synergistic effect. An increase in the capacity of the sorbent and a decrease in the amount of gold in the liquid phase shifts the equilibrium of the system towards gold dissolution and intensifies the volume and completeness of its extraction (Fig. 2).

Electrical impact on the process of sorption leaching intensifies the dissolution of gold by sodium cyanide, which at the cyanidation stage increases the concentration of gold in the solution due to the shift of the chemical equilibrium in the "pulp-sorbent" system towards sorption with an increase in the capacity of the anionite for gold.

Economic efficiency. The starting material for the experiment was sulfide-containing raw materials from the Aksu, Bestobe and Zholymbet deposits of Kazakhaltyn JSC. Capital investments in the construction of a pilot industrial complex for electrochemical leaching of gold, thousand dollars: total estimated cost - 830; construction and installation work - 383; equipment - 420; other - 27 thousand dollars. Specific capital investments: per 1 ton of processed raw materials - 16.6 dollars; per 1 gr. gold obtained from raw materials - $ 2.96. Estimated annual operating costs: $ 920 thousand, including electricity - $ 414 thousand - 45%. For 1 g of gold leached from sulfide raw materials containing 7 g / t of gold, the annual productivity of the pilot industrial complex for raw materials is 50 thousand tons, operating costs are $ 3.28. The cost of electrochemical leaching of 1 g of gold from sulfide raw materials is at the level of heap leaching technology from oxidized raw materials. The costs of sorption, desorption and refining (3.28 x 0.85 = $ 2.79 / t). The cost of production of 1 g of gold (in finished products) - ≈ $ 6 /g. With the selling price of 1 gram of gold being $ 12, the profit is $ 6/g.

vol. 30, issue 4 / 2024
pp. 32-43

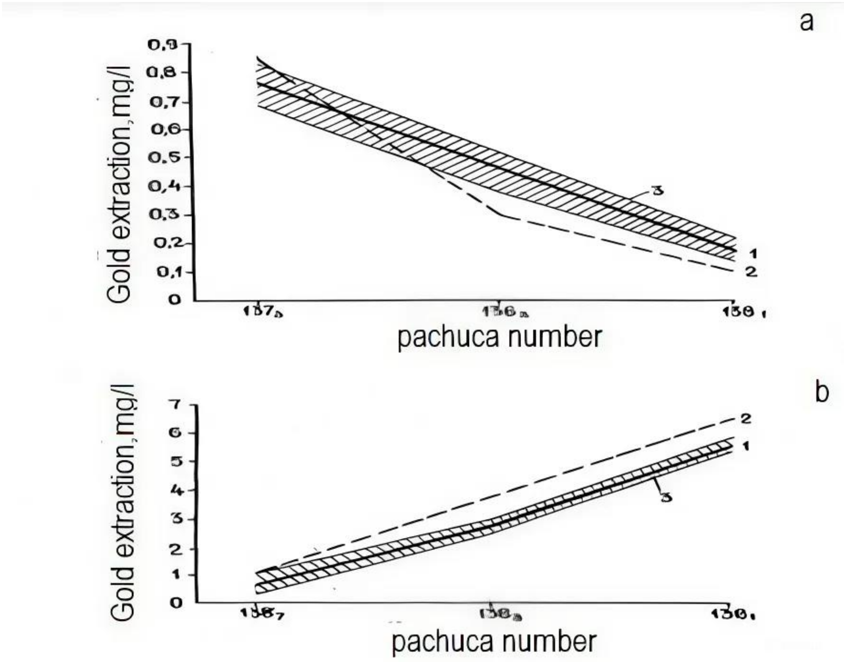

Fig. 2. Change in gold concentration in solution (a) and sorbent (b) during cyanidation: 1 – control mode, 2 – experimental mode, 3 – 90% confidence interval region

The profit from the involvement of substandard useful components and reserves in production due to the increase in production volumes, growth in production and increased return on capital for combined leaching technologies is determined according to a mathematical model of the type [22]:

$$P = \sum_1^n \left[\left(C_{ore}^b - C_{ext}^b - C_{enr}^b - C_{met}^b \right) V^b + \left(C_{ore}^c - C_{ext}^c - C_{enr}^c - C_{met}^c \right) - D_{total} \right] V^c, \qquad (2)$$

where P – annual profit from combining technologies, monetary units; C_{ore}^b, C_{ore}^c– accordingly, the cost of selling metals from balance and combined ore reserves, monetary units/t; C_{ext}^b, C_{enr}^b, C_{met}^b – accordingly, the costs of extraction, enrichment and metallurgical processing of balance ores, monetary units/t; C_{ext}^c, C_{enr}^c, C_{met}^c – accordingly, the costs of extraction, enrichment and metallurgical processing of combined ore reserves, monetary units/t; V^b, V^c – respectively, the volume of selectively mined balance and combined ores, t; n – nomenclature of extractable metals; D_{total} – total damage (economic consequences) caused (–) to the environment or prevented (+) taking into account the costs of storing pollutants and protecting the population living in the area of influence of mountain objects, monetary units.

Implementation of new technologies. In general, the technology of electrosorption leaching of metal from ore flotation tailings allows extracting, for example, gold without their agglomeration, intensifies the leaching process and increases the capacity of the sorbent for the corresponding metal. Theoretical and methodological developments have been used in the practice of scientific research work at JSC CGCC (Stepnogorsk, Republic of Kazakhstan) and the D.A. Kunayev Institute of Mining (Republic of Kazakhstan), the State Company Kyzylkumredmetzoloto (Navoi, Republic of Uzbekistan), JSC SredazNIPI Promtekhnologii (Tashkent, Republic of Uzbekistan), as well as in the educational process of KazNTU named after K.I. Satpayev (Almaty, Republic of Kazakhstan).

Methodological recommendations for heap leaching of gold form the basis for the technological complex developed by JSC SredazNIPIpromtekhnologii (Tashkent, Republic of Uzbekistan) for the Globa-Kazakhstan corporation (Republic of Kazakhstan).

Technologies of electrosorption and electrochemical leaching of gold have been tested at the production base of the Central Scientific Research Laboratory of the Joint-Stock Company "Tselinny Mining and Chemical Combine" (Stepnogorsk, Republic of Kazakhstan) and the hydrometallurgical plant ("Kyzylkumredmetzoloto" (Navoi, Republic of Uzbekistan). They are also recommended for industrial development of gold mining from flotation tailings of ores of the Aksu, Bestobe, Zholymbet deposits and have been introduced into the practice of the ABS-Balkhash company, JSC "Kazakhaltyn" (Republic of Kazakhstan).

vol. 30, issue 4 / 2024
pp. 32-43

5. Perspective research directions

Processing of technogenic waste (ore beneficiation tailings) requires technologies based on the latest achievements of science and technology. Implementation of effective methods for extracting metals from such waste will improve the environmental situation in the areas of their storage and will ensure an increase in the mineral resource base of the mining industry. Involvement in the production of technogenic reserves of ore beneficiation tailings, as well as processing of dumps of ores with substandard content of useful components in modular units helps to obtain additional metal, as well as reduce environmental pollution in developed mining countries [23], [24].

To prevent dust transfer of contaminated material beyond the mining facilities, sanitary protection zones and strips around them should be planted with tall trees, which will restrain the wind speed over the specified facilities. These include mines, waste rock dumps and off-balance, in terms of useful component content, ores, stowage complexes, sites for preliminary concentration and heap leaching of metals from substandard ore raw materials, tailings storage facilities, etc. Dust will settle without entering populated areas. New scientific and methodological foundations, technologies and technical means are needed to improve the efficiency of soil use in industrial zones of mining facilities, as well as to assess their impact on the environment [25], [26].

It is necessary to separately note the need to create protective forest belts along the perimeter of tailings storage facilities, as well as along transport routes (roads, railways, pulp pipelines, etc.). Territories where the maximum permissible concentration (MPC) of pollution is exceeded should be converted to sowing industrial crops, in water bodies - prohibit fishing, swimming and other environmental protection measures [27], [28].

Territories of gold ore mining and processing should be considered taking into account man-made sources of natural radioactivity, as well as environmental pollution with heavy metals and implement appropriate measures to identify uranium and gold ore legacy sites [29].

Also relevant are rehabilitation projects that involve at least partial restoration of landscapes at the site of former uranium production facilities to a socially acceptable level of comfort for the population living in the adjacent territories. For example, during the rehabilitation of the facilities of the Wismut enterprise in Germany, the task was not only to bring the uranium production waste storage sites into a safe condition, close old mines and clean up the territories, but also to almost completely restore all man-made landscapes [30]. Today, this program is almost complete. According to various estimates, € 3-5 billion were invested in it, with a significant share of the funds spent on social payments and restoration of the aesthetics of the environment, harmoniously fitting into the landscape of the adjacent territories (Fig. 3). And also the still rare experience of strengthening radiation and social protection of the population of Zhovti Vody, Ukraine, which is forced (since the 50-s of the last century) to live in the zone of influence of uranium industry facilities. Rehabilitation and social activities are carried out at the expense of the central and local authorities, as well as the enterprise in accordance with the special state "Program of activities for radiation and social protection of the population of the city of Zhovti Vody", Ukraine [1**],** [2], [27]. Mining and technical reclamation of the tailings storage facility in the quarry of brown iron ore presented at (Fig. 4).

Fig. 3. Modern view of the areas where the waste heaps of depleted ores and tailings of the Wismut enterprise were previously located (photographs by Ch.Kunze, Wisutek, Germany)

Fig. 4. Mining and technical reclamation of the tailings storage facility in the quarry of brown iron ore (photo, Zhovti Vody, Ukraine)

To protect the hydrogeological environment from heavy metal pollution, ensuring increased efficiency of gold mining in the zone of influence of its tailings, the construction of semi-active permeable chemically active barriers (SPACB) and biological technologies is very relevant [31], [32]. In this case, the length of the SPACB should be at least 100 m, the minimum depth 6.0 m. To monitor the efficiency of its operation, it is necessary to construct an observation network of wells monitoring the input and output flows of groundwater into the hydrogeological environment, consisting of three profiles and four wells with a total drilling volume of up to 120 m.

In our opinion, the following new scientific and methodological provisions deserve attention:

Methodological principles for choosing production development options, in particular gold and technologies for its repeated extraction from ore enrichment waste, have been developed. They allow increasing the completeness of the use of natural mineral resources and reducing the negative impact of waste on the environment.

Detailing of the theoretical foundations and methodological base for gold mining from ore enrichment waste has been completed electrosorption leaching. The obtained results of the study can be used in the development of gold-bearing deposits in developed mining countries of the world.

The technologies of electrosorption leaching of gold from ore flotation tailings are recommended, which allows extracting gold without their agglomeration, intensifies the leaching process and increases the capacity of the sorbent for gold. The proposed technology is recommended both for the repeated extraction of gold from ore flotation tailings and for leaching gold from low-grade gold-bearing raw materials.

6. Conclusions

The efficiency indices of gold leaching in the liquid phase have been established, which increase by 11% during cyanidation, and decrease by an average of 15% during electro-treatment during sorption, while the sorption capacity of the resin increases by 11%.

The indices of gold leaching from refractory sulfide raw materials after sulfide destruction upon reaching an oxidation potential of 1000 mV have been substantiated. Gold leaching proceeds effectively in a 20–30% sodium chloride solution upon application of direct electric current with a density of 800–1200 A/m^2, pH of the medium of 2.0–4.0, and a temperature of 60–800 C with extraction of up to 70–80% of gold into the solution at an energy consumption of 120–220 kW/t.

The efficiency of using technogenic resources by combining traditional beneficiation technologies with the capabilities of hydrometallurgy and electrochemistry is demonstrated. In this case, flotation tailings of ores with a gold content of 1.0–1.5 g/t are leached according to the following scheme: granulation to a size of 15–30 mm with the addition of 1 g/l of cyanide, sulfuric acid removal of non-ferrous metals, alkaline treatment to pH 10–11, cyanidation with an irrigation density of 20 l/m^2 per hour, gold sorption on anion exchanger, anion exchanger regeneration, and regenerate electrolysis.

The efficiency of the technology of electrosorption leaching of gold from gold-bearing pulps is confirmed: with an increase in the leaching rate, it increases by 25–30%, and the sorption capacity of the AM-2B anion exchanger increases by 2.5–3 times.

Acknowledgments

The authors express their sincere gratitude for valuable constructive comments and recommendations to specialists B. S. Luzin, V. I. Golik, E. A. Khadzaragova (National Engineering Academy of Kazakhstan, Almaty, Republic of Kazakhstan, State Company Kyzylkumredmetzoloto, Navoi, Republic of Uzbekistan), Tarkhin Yu.M., Stepanov V.I., Zelnichenko V.M., Skotarenko A.G. (DP "UkrNDPRIPROMTECHNOLOGIES", Ukraine), Pukhalsky V.M., Kuchi P.M., Kopanev A.V.(DP "SkhidGZK", Ukraine), PJSC Severny GOK and PJSC ArcelorMittal Kryvyi Rih (PJSC AMKR, Ukraine, specialists of the Kryvyi Rih National University and reviewers of the article.

References

[1**] Babak M.I., Koshik Yu.I., Avdeev O.K., et al.,** 2001
Mining and Processing of Uranium Ores in Ukraine. Monograph. Under the general editorship of ***A.P. Chernova****. K.: Adef – Ukraine,* 238 p. (in Ukrainian)

[2] **Serdyuk A.M. Stus V.P., Lyashenko V.I.,** 2011
Ecology and Livelihoods of the Population in the Industrial Regions of Ukraine. Dnipropetrovsk. Vidavnitstvo "Thresholds", 486 p. (in Ukrainian)

[3] **Lyashenko V. I., Dudar T. V., Stus V. P., Shapovalov V. A.**, 2024
Justification of Efficiency and Subsoil Protection during Underground Development of Ore Deposits Using Traditional Technologies in Combination with Metals Leaching // Mineral Resources of Ukraine, No. 2, pp. 69-77. https://doi.org/10.31996/mru.2024.2.69-77, (in Ukrainian)

[4] **Luzin B.S.**, 2003
Methodology for Determining the Parameters of the Sorption Process of Productive Leaching Solutions // Geology and Conservation of Mineral Resources. – Almaty, No. 3 (8), pp. 59-60, (in Kazakhstan)

[5] **Luzin B.S., Golik V.I., Lyashenko V.I.**, 2005
Scientific and Technical Foundations for the Repeated Extraction of Gold from Ore Processing Waste // Scientific and Technical Bulletin of Economics and Information Non-Ferrous Metallurgy, No. 2, pp. 21- 29, (in Russian)

[6] **Luzin B.S., Golik V.I., Lyashenko V.I.**, 2005
Improvement of the Technology of Gold Extraction from Technogenic Deposits // Scientific and Technical Bulletin of Economics and Information Non-Ferrous Metallurgy, No. 6, pp. 2-8, (in Russian)

[7] **Kaplunov D.R., Rylnikova M.V., Radchenko D.N**., 2015
Scientific and Methodological Foundations for Designing an Ecologically Balanced Cycle of Integrated Development and Conservation of the Earth's Bowels. Mining Information and Analytical Bulletin, no 4 (special issue No. 15), pp. 5–11, (in Russian)

[8] **Adibi N., Ataee-pour M., Rahmanpour M.,** 2015
Integration of Sustainable Development Concepts in Open Pit Mine Design // J. Clean. Prod., Vol. 108, pp. 1037–1049

[9] **Capilla A.V., Delgado A.V.,** 2015
The Destiny of the Earth's Mineral Resources. – London: World Scientific Publishing Co. Pte. Ltd., p. 289

[10] **Doifode S. K., Matani A. G.**, 2015
Effective Industrial Waste Utilization Technologies towards Cleaner Environment // International Journal of Chemical and Physical Sciences, Vol. 4, Special Issue, pp. 536–540

[11] **Jarvie-Eggart M. E.,** 2015
Responsible Mining: Case Studies in Managing Social & Environmental Risks in the Developed World // Englewood, Colorado: Society for Mining. – Metallurgy and Exploration, 804 p

[12] **Wills B. A., Finch J. A.**, 2015
Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery // Oxford: Butterworth-Heinemann, 512 p

[13] **Chipfunhua D., Bournivalc G., Dickieb S., Atac S**., 2019
Performance Characterization of new Frothers for Sulphide Mineral Flotation // Minerals Engineering, Vol. 131, pp. 272–279

[14] **Henckens M. L. C. M., van Ierland E. C., Driessen P. P. J., et al.,** 2016
Mineral Resources: Geological Scarcity, Market Price Trends, and Future Generations // Resources Policy, Vol. 49, pp. 102–111

[15] **Adams M. D.,** 2016
Gold Ore Processing. Project Development and Operations // Amsterdam: Elsevier Science, 980 p

vol. 30, issue 4 / 2024
pp. 32-43

[16] **Canda L., Heput T., Ardelean E.**, 2016
Methods for Recovering Precious Metals from Industrial Waste // IO P Conference Series: Materials Science and Engineering, Vol. 106, No. 1, pp. 12–20

[17] **Lopez F.A., Garcia-Diaz I., Rodriguez Largo O., et al.**, 2018
Recovery and Purification of Tin from Tailings from the Penouta Sn–Ta–Nb Deposit// Minerals, Vol. 8, No. 1, pp. 20

[18] **Schmidt P., Schafer R.**, 2017
Methods in Physical Chemistry // Manchester: John Willey & Sons Limited, 370 p

[19] **Chen T., Lei S., Yan B., Xiao H.,** 2014
Extraction of Metals from Copper Sulfide Tailings Using Leaching and Fractional Ptechnology // Hydrometallurgy, Vol. 147-148, pp. 178-182, (in Russian)

[20] **Zhou C., Gong Z., Hu J., Cao A., Liang H.,** 2015
A Cost-Benefit Analysis of Landfill Mining and Material Recycling in China // Waste Management, Vol. 35, pp. 191–198

[21] **Aben E.,** 2019
Study of Change in the Leaching Solution Activity after Treatment with a Cavitator / E. Aben [and others] // Mining of Mineral Deposits, Vol. 13, No.4, pp. 114-120

[22] **Ya Li, L. Zhuo, Shadrunova I.V., et al.,** 2020
Development of Technologies for Reducing Environmental Risks in Gold Extraction from Refractory Ores// Mining Industry, 2020, pp.143–147, (in Russian)

[23] **Lyashenko V.I., Golik V.I.,** 2017
Scientific and Design-Technological Support for the Development of Uranium Production. Achievements and Tasks // Mining Information and Analytical Bulletin, No. 7, pp. 137-152, (in Russian)

[24] **Samusev A.L., Minenko V.G.,** 2016
Influence of Chemical-Electrochemical Leaching Parameters on Gold Extraction from Refractory Mineral Raw Materials // Mining Information and Analytical Bulletin, No. 5, pp. 134-140, (in Russian)

[25] **Lyashenko V.I., Golik V.I., Dyatchin V.Z.,** 2020
Tailings Storage in Underground Mined-out Space and Tailings Storage Facility in the Form of Hardening Masses//Obogashchenie rud, No. 1, pp. 41-47, (in Russian). DOI: 10.17580/or.2020.01.08

[26] **Golik V.I., Khetagurov V.N., Mikhalchenko S.N.,** 2022
Justification of Technologies for Electrosorption Leaching of Gold from Flotation Tailings of Refractory Sulfide Raw Materials // Bulletin of Tula State University. Earth Sciences, Vol. 1, No. 1, pp. 223-233, (in Russian). DOI 10.46689/2218-5194-2022-1-1-223-233

[27] **Dvoretsky A. I., Lyashenko V. I., Topolny F. P., et al.,** 2018
Influx of Uranium Industry into the Production Plant and Population // Metallurgy and Girnichorud Industry, No. 4, pp. 99–109, (in Ukrainian)

[28] **Dudar T.V.,** 2023
Territories of Mining and Processing of Uranium Ore as a Technogenic-Enhanced Source of Natural Radiation. ISSN 1562-6016. Problems of Atomic Science and Technology, Issue 3 (145, pp. 127-132, (in Ukrainian). DOI 10.46813/2023-145-127

[29] **Kamnev E.N., Karamushka V.P., Seleznev A.V., et al., et al.,** 2020
Environmental Problems and Their Solution during the Closure of Uranium Production (on the Example of Russia, the CIS and Germany) // Mining Information and Analytical Bulletin, No. 5, pp. 26-39, (in Russian). DOI: 10.25018/0236-1493-2020-5-0-26-39

[30] **Lisichenko G.V., Kovach V.E.**, 2013
World Experience in the Rehabilitation of Former Uranium Production // Collection of Scientific Works Technogenic-ecological Safety and Civil Protection, No. 6, pp. 4-12, (in Ukrainian)

[31] **Kovalchuk I., Tobilko V., Kholodko Yu., et al.,** 2020
Purification of Mineralized Waters from U (VI) Compounds Using Bentonite/Iron Oxide Composites. //Technology Audit and Rroduction reserves, T. 3, No. 3 (53), C. 12-18, (in Ukrainian)

[32] **Kovalenko, G., Dudar, T., Iavniuk, A.**, 2023
On the Issue of Radioecological Conditions of Surface Waters and River Sediments in Ukraine. In: Zaporozhets, A., Popov, O. (eds) Systems, Decision and Control in Energy IV. Studies in Systems, Decision and Control, vol. 456, Springer, Cham. https://doi.org/10.1007/978-3-031-22500-0_21