

Developing ways to reduce the consumption of reagent collectors during the flotation of gold-containing ores

Dilmurod Makhmarejabov^{1*}, Siyuan Yang², Sokhibjon Matkarimov^{1, 3}, Bakhridin Berdiyarov¹, Difuza Yavkochiva¹ and Zaynobiddin Matkarimov⁴

Department of Metallurgy, Tashkent State Technical University, University Street 2, Almazar District, Tashkent, 100095, Uzbekistan¹

School of Resources and Environmental Engineering, Wuhan University of Technology, Wuhan 430070, China²

Laboratory of Mining and Deep Processing of Mineral Resources, Uzbek-Japan Innovation Center of Youth, 2b, Almazar District, Tashkent, 100011, Uzbekistan³

Department of Technology of Silicate Materials and Rare, Noble Metals, Tashkent Institute of Chemical Technology, 32 Navoi Street, Tashkent, 100011, Uzbekistan⁴

Received: 10-August-2023; Revised: 13-February-2024; Accepted: 15-February-2024

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Abstract

Due to shortages, high costs, and the necessity to import, there arose a need to substitute imported reagents with locally produced ones from Uzbek enterprises. This substitution could decrease the cost of reagent procurement, reduce expenses in copper and gold production, and aid in the development of waste-free manufacturing. The material composition of gold-bearing ores is characterized by their complex nature, low concentration of nonferrous metals, and the fine intermingling of valuable components with their host rocks. In our research, the gold-bearing ore from the Amantaytau deposit was selected as the study subject. Gold is a key component of the ore. The primary ore minerals in the sample are pyrite, arsenopyrite, iron hydroxides, and parasites. The non-metallic portion is mainly composed of quartz, sericite, feldspars (albite, orthoclase), carbonates, chlorites, and kaolinite. There is a consistent presence of carbonaceous matter and graphite. The reliability of the research findings was ensured through well-defined objectives. These results emerged from laboratory and semi-industrial scale studies, comparing technological processes for treating difficult-to-enrich gold ores. These processes involved the use of synthesized reagents from local industrial waste, either directly or through electrochemical activation, and combined beneficiation and metallurgical methods. This approach resulted in a notable increase in gold extraction from the Amantaytau deposit ores, ranging from 0.75 to 1.74%. This finding indicates the potential efficacy of electrochemical treatment in the flotation of gold-bearing ores. The results, validated through comprehensive research, demonstrate the successful achievement of the desired outcomes.

Keywords

Material composition, Reagent, flotation scheme, Extraction, Electrochemical treatment, Installation, Result.

1. Introduction

Among the countries in the world, Uzbekistan is one of the leading countries in terms of the production of precious metals. Along with the increase in production, the reduction in reserves of rich and easy-to-enrich gold ores allows for the attraction of gold ores that are difficult to enrich for production [1]. Many scientific and practical results have been achieved in the development of beneficiation schemes using traditional and new local reagents for the beneficiation of ores from existing mines in our republic.

However, the development of various methods for beneficiating and processing gold ore that are difficult to beneficiate, the search for ways to increase the efficiency of beneficiation in beneficiation factories, which are difficult to beneficiate, and a number of scientific and practical results are being achieved by introducing advanced scientific measures for the introduction of innovative technologies for the processing of gold ore using traditional reagents. Large golden particles [1] are freed from dusted minerals (free gold) when burning ore and easily differ when enriched by the gravitational method; however, they float poorly and slowly dissolve in a cyane solution. Small golden

*Author for correspondence

particles are found in burning ore that is partially free and partially glued to other minerals. Free fine golden particles float well and dissolve rapidly in cyanide solution but are difficult to enrich by the gravitational method.

It dissolves well in golden cyan solutions associated with plants, and its flotation ability is determined by the ability to float related minerals. During flotation with the help of sulfide hydride accumulators [2], gold associated with sulfide plants floats well, floating well within a certain ratio of gold, the open surface of gold and the associated mineral surface.

Primary and secondary oxidized gold ores [3] typically contain large gold particles. Coarse and fine gold are found in uranium ores. As the number of sulfides in ores increases, the proportion of copper-dispersed gold usually increases. In gold-pyrite ores, the amount of such gold is on average 10-15%; in golden-copper, gold-limestone and gold-resource ores, it is 30-50%; and in some gold-polycomponent ores, almost all gold particles are found in the form of fatty dispersed particles. Therefore, the use of flotation, calcination, and dissolution processes in the processing of such ores has increased, and the use of gravitational and cyanization methods has decreased [3].

Due to these problems, the development of technological schemes for the processing of difficult-to-enrich gold ores using reagents synthesized from local industrial wastes and the processing of ores containing precious metals are of great scientific and practical importance. The structure of the paper is outlined as follows: section 2 provides the details of related work carried out for this paper. Section 3 covers the methodology and details of the proposed methods of flotation of gold-containing ores. The dataset used in this paper and different evaluation metrics are discussed in section 3 also. Experiments and results are discussed in section 4, and the conclusion and future work are discussed in section 5.

2.Literature review

This section proffers to the review of conventional processing of gold ore mainly includes two-stage technological processes, i.e., beneficiation and metallurgical processes. Ore beneficiation includes crushing, screening, screening, gravity, flotation, etc., and methods are performed repeatedly. Hydrometallurgical methods for ore removal and enrichment processing include cyanide removal,

amalgamation, incineration, sorption, oxidation, biotechnology and other methods. In the following years, selective melting of gold with the help of reagents of different compositions was included as an independent technological direction in hydrometallurgical methods [4].

There are three successive technological processes:

- Traditional enrichment of metal from ore (gravity and flotation methods); as a result, gold-rich products, enrichment products and waste are obtained;
- primary metallurgical processing of concentrates (cyanidation, sorption selective smelting);
- processing (refining) of raw metal to obtain a finished product.

The choice of gold ore processing scheme depends on several factors, the main of which are the technological properties of the ore. Due to its chemical inertness, gold is mostly found in free form in ores. Typical additives-silver, copper, iron, a small amount of arsenic, tellurium, selenium and other elements-can be found in native gold particles. The amount of gold in the pure gold particles is 75-90%, the silver content is up to 1-10%, and the copper content is up to 1%. The forms of gold particles in ore are different and include hook-shaped, wire-shaped, small-veined, granular, bubble-like, dendritic and other forms [5].

The material compositions of gold ores differ. Some ores contain up to 50-70% quartz, others contain up to 50-60% barite quartz, 20-30% carbonates, up to 25% iron oxides, and up to 50% tourmaline. The amount of sulfides (mainly pyrite, arsenopyrite, and pyrrhotite) can vary from 0 to 40%.

Currently, primary ores are of increased industrial importance. The amount of sulfides in these samples ranges from one tenth to 80-90%. In some ores, oxidized minerals are also involved, and they practically do not affect the processing technology. A distinctive feature of oxidized ores is the presence of iron oxides. Some ores retain oxidized minerals of other metals as well as silty components. In ores, sulfides are found in very small quantities, as they do not react or affect the technology [6].

Oxidized ores with sulfides of iron and preserved oxidized minerals of other metals. Some components of the ore, which are not of industrial importance, complicate the processing technique, regardless of their low chemical content or specific properties.

These components include copper (in addition to chalcopyrite and chrysocolla), antimony, pyrrhotite, elemental selenium, selenates, carbonaceous matter, tellurium, and easily soluble minerals. During cyanizing, such gold ground passes through the dog with difficulty, which forces telluride ores to work via special methods. The presence of sludge-forming components (talc, clay minerals, shale, etc.) in the ore slows the processes of crushing, condensation, flotation and filtration. Therefore, these ores are processed using special methods [7, 8].

Large gold particles are freed from the minerals attached to them when the ore is crushed (free gold) and easily separated by gravity enrichment, but poor flotation slowly dissolves in cyanide solution. Fine gold particles are found in crushed ore that is partly free and partly attached to other minerals. Free small gold particles are well flattened and dissolve quickly in cyanide solution but are difficult to concentrate by the gravity method.

When associated with plants, gold dissolves well in cyanide solutions, and flotation is determined by the flotation ability of the minerals associated with the solution [9]. The gold associated with nonsulfide mineral growth floats well at a certain ratio of the exposed surface of gold to the surface of the mineral associated with it [10].

The surface of finely dispersed gold is imperceptibly exposed during the crushing of the ore, and its main mass remains in minerals, often pyrite and arsenopyrite. In some pyrites, the amount of finely dispersed gold reaches up to one hundred grams/ton. During beneficiation by gravity and flotation, such gold particles are separated from the carrier minerals. If gold is contained in sulfides, it is separated only by dissolution in cyanide solutions after disintegration of the sulfides. In some ores, finely dispersed gold pores are located within nonsulfide minerals, iron hydroxides and carbonates. In this case, gold can be dissolved using cyanide solutions even from coarsely ground products.

Primary and secondary oxidized gold ores usually contain large gold particles. Large and small gold grains are found in gold-uranium ores. As the content of sulfides in ores increases, the proportion of finely dispersed gold usually increases. The amount of such gold in gold-pyrite ores is on average 10-15%; in gold-copper, gold-arsenic and gold-antimony ores, 30-50%; and in some gold-polycomponent ores, practically all gold particles are found in the form of

finely dispersed particles. Therefore, the role of flotation, incineration, and melting processes is increasing in the processing of such ores, the importance of gravity and cyan ash methods is decreasing, and the structure of gold particles affects their behaviour in some technological operations. In gravity enrichment, isometric and monolithic particles are better separated than particles with a branched surface and sponge-like particles, while in cyanidation, gold particles with a porous surface dissolve faster, and flat and granular particles undergo better flotation [11–13].

Naturally, gold contains dozens of additional elements, such as silver, copper, lead, iron, tellurium, arsenic, and mercury. From a tenth of a percentage of silver to 50% or more, the total amount of other additives is less than 0.1%, sometimes up to 0.5%. The properties of gold with additives differ from those of pure gold: additives reduce the density of gold particles and change their structure. Chemically less rare. Iron additions give gold its magnetic properties. The difference in the composition of gold particles is especially noticeable during flotation and when cyanide is used. Additives impair the flotation ability of gold. With the increase in the amount of silver and copper, the rate of gold dissolution in cyanide decreases, and the presence of copper slows the dissolution more than the presence of silver [14]. The condition of the gold surface is highly important for technology. Gold particles often have a surface coating consisting of oxides of iron, argentite, cobalt, galena, kaolinite and other minerals. In addition to their natural origin, coatings are also formed as a result of the mechanical friction of the gold surface with solid particles during burning [15].

Native gold particles and their forms, other metals, tellurides, antimonides, selenides and minerals consisting of intermetallic compounds are found in the ore. In carbonaceous ores containing humic acids and bitumen-type organic compounds, gold is located in the form of little-studied organic compounds, and when the ore decomposes to form metal and is oxidized, it is finely dispersed [16].

The variety of properties of gold ores causes difficulties in studying the material composition of these ores and in developing technologies for extracting valuable components from them. This situation is further complicated by the presence of silver, which has a more diverse mineral form, in industrial concentrations in addition to gold in most ores.

2.1 Peculiarities in processing gold ores that are difficult to enrich

Due to the impossibility of directly extracting gold from gold-bearing ores that are difficult to enrich, they are reprocessed by gravity-flotation methods of enrichment and hydrometallurgical and hydrometallurgical extraction of gold from the obtained enrichments extracted by pyrometallurgical or other methods. The latter methods, as a rule, require special emphasis on the high separation of metals due to their high complexity and high operational and capital costs.

Another characteristic of gold-arsenic ores, which are difficult to enrich, is the presence of coal shale, which consists of fine-grained silt-shale aggregates saturated with carbon.

When potassium butyl xanthate (PBX) and a foaming agent are added, the shales are converted to carbonaceous products. Fine fractions of shale (-20 μm) have good flotation properties and float only when a foaming agent is added. The carbonaceous material absorbs the xanthogenate and foaming agent from the bottom, increasing the consumption of these reagents and requiring them to be fed into the process in portions. An increase in the consumption of reagents leads to contamination of the enrichment with loose rocks [17].

During the processing of partially oxidized sulfide-bearing ores, the selection process is more strongly disturbed. To separate them, the concentration of xanthogenate should be high, and the flotation time should be longer. Complete separation of sulfides can be achieved only after separating the carbon retainers into foam. In this case, the output of the foam product is very high (45-50%).

Selective flotation is usually used in the beneficiation of complex gold-arsenic ores that contain valuable components other than gold, and it is difficult to obtain the benefits of nonferrous and rare metals that meet the requirements for the amount of arsenic. Carbon gold-arsenic enrichments are a special type of product of difficult-to-enrich gold deposits. These products are the soft state of gold in sulfides that are technologically difficult to enrich (mainly in arsenopyrite) and active carbon storage with the ability to sorb a large amount of gold to the cyanide complex. Gold-bearing sulfide ores expose the surface of hard-to-be-enriched gold that cannot be extracted by direct cyanidation of the ore.

The hard-to-enrich gold class primarily includes the following:

- tightly bound with sulfides;
- covered with oxide films of iron and other compounds;
- fine spot in quartz spotty.

The other forms of hard gold in normal sulfide enrichments are very low in quantity and do not significantly affect the total metal balance.

2.2 Separation of gold from hard-to-enrich ores by the flotation method

In the processing of coal-bearing gold ores, separation using the carbon flotation method is important. One example of this process is the kerosene flotation of coal shales, which can remove much of the graphite from the carnation cycle. This technology was implemented at a factory in Montana (USA) [18]. Processing of carbon-retaining gold ore (45 thousand t/day, gold content 5 g/t) at the "Kumtor" factory of Kyrgyzstan, flotation-selective dissolution of the product by initial cyanidation sorption (CIP)-enrichment cyanide and sorptive selective dissolution of the product without preliminary cyanidation (CIL)-flotation waste, depending on the amount of carbon, produced 76-80% [18].

Flotation can also be used to separate more difficult enrichment fractions. In this case, the obtained flotoprint can be burned or sent to melt [19]. The Royal Mountain King (USA) plant processes two types of ore: 1% carbon-retaining and carbon-free. The amount of gold in the ore is 2-2.2 g/t. the scheme used in the factory allows for the processing of both types of ores using gravity-flotation methods of beneficiation and CIP-cyanidation. Separation of the remaining carbon by flotation in the apparatus is considered the optimal method, and the obtained coal enrichment is dismantled by the CIL method and sent to the landfill [20]. At the Queiroz Mine (Brazil), flotation of 3% carbon is separated into flotation beneficiation by 88%, gold separation is 47%, reagent consumption is methyl-isobutyl-carbonyl and aeroflot mixture in a ratio of 3:1, and copper sulfate (CuSO_4) is used as an activator of sulfides.

Patent [21] recommended using the coal substance present in the original ore as a sorbent (absorber) for gold. In this case, 1% activated carbon is placed in a cyanide or thiourea solution on the soft ore. The molten gold is absorbed by the carbonaceous material in the ore and then separated by bubble flotation

while still. The obtained enrichment is processed by metallurgical methods; depending on the content of flotation waste, the waste is sent to a landfill or for further treatment by the CIP method at a temperature of 50-60°C.

In some factories, the gold separation process is limited by flotation technologies. At the Austin Gold Venture (USA), 150-170 g/t of gold and 20% flotation were extracted from 6 g/t gold ore and subsequently sent to the Noranda copper smelter. First, the flotation waste CIL was used in this enterprise. However, flotation can also result in damage to activated organics remaining in the effluent, which drastically reduces the sorption capacity of the effluent and redissolved gold from saturated coal [20]. The Kidd Creek (Canada) factory processes two ores with graphite retention and gold contents of 15 and 4 g/t according to the gravity-flotation scheme. The sludge waste was floated in "Denver-18 and -24" chambers. The flotation mixture is then melted together with the waste from the concentration table [17].

The Penjom (Malaysia) enterprise processes 600,000 tons of ore with a gold content of 6-10 g/t per year. This ore is characterized by the presence of 0.2-0.5% organic carbon, which is considered to cause serious prerobbing problems. Cyanidation during flotation was carried out according to technology of cyanidation of flotation effluents (RIL) technology by adding Minix tar kerosene and diesel fuel [22]. The Barbrook Gold Mine (South Africa) factory sorbent active carbon ore flotation waste cyanide was processed according to RIL technology [23].

Macraes Gold (New Zealand) processes ore containing 1.6 g/t gold and a high carbon content. The resulting film was ground to 18 µm, oxidized in an autoclave at a temperature of 225°C, and subsequently placed in the CIL cascade. The separation of gold in the sorption stage is 95%, and the total separation from the ore is 84% [24].

In the case of gold-bearing coal beneficiation, successive flotation of coal material and sulfides and subsequent combination with sulfides for coprocessing are also of interest. In this case, a reduction in the overall beneficiation output occurs by carefully selecting the flotation beneficiation procedure at each stage. An example of an industrial application of sequential flotation is Cannon Mine (USA), which processes 2.2 thousand tons of ore per day.

A deposit containing 8 g/t gold and 12 g/t silver is floated after crushing in stage I, and a grade of 60-150 g/t gold is obtained. In stage II, after crushing, the ore is subjected to sulfide flotation. The total grade is 155 g/t gold and 220 g/t silver.

The separation of metals ranged from 85-92%, and this enrichment was performed with a smelter in Germany.

2.3 Combined use of collecting reagents in gold ore flotation

The enrichment efficiency of the flotation method is determined by the correct selection of reagents. Currently, most factories use potassium and sodium butyl xanthate, methyl isobutyl carbinol, amyl and isobutyl xanthate, lime, cyanides, zinc sulfate, etc., as flotation reagents. Aerofot-25 and propylene glycol are used as foaming agents. In some factories (Echo Bay, Silver Bear (Canada)), sodium isopropyl xanthate (consumption 13 g/t) and PBX (consumption 45 g/t) are used in cleaning flotation to obtain richer oil [25].

CuSO₄ silicate is used to activate sulfides, and dextrin (JAR) is used to quench mud rocks. At the Morro do Ouro (Brazil) plant, potassium amyl xanthate was used as a collecting reagent during the processing of 0.6 g/t gold ore, and 4-Methyl-2-pentanol (MIBC) was used as a foaming agent (consumption of 30 g/t). A flash-flotation gold concentration of 500-600 g/t was obtained [26].

New collection reagents have been investigated for the flotation of quartz-sulfide gold ores and gravity tailings. The selectivity of the nitrogen-saving reagent (NSR) and phosphorus-saving reagent (PSR) against gold was determined [27].

Currently, one of the main ways to improve the technological parameters of the flotation process is to improve the composition of the reagent [28-35]. According to the results of the experiments and flotation practices presented in the literature, it was determined that it is possible to increase metal separation or reduce the cost of reagents by using two or more collectors together.

For flotation of gold ores or cyanidated tailings, an effective collector containing 5-20% xanthogenate and 80-95% fatty acids has been recommended. In this case, 4.8-7.2 g/t of gold was obtained from the product containing 0.6-1.0 g/t of gold at potential of

hydrogen (pH) 5-8, and the separation of gold into the beneficiation was 89% [36].

According to Patent [37], the combined use of petrochemical residue (KOH-92) and PBX reagents leads to an increase in gold recovery of 4.9% and a reduction in flotation time compared to the flotation of gold ore from the Nejdamin mine with PBX alone. The results of using a mixture of PBX and isobutyl dithiophosphate (DTF) with isopropyl-ON-methylthiourea to increase the selective flotation carried out in the monomineral fraction of pyrite and chalcopyrite [38] have been described. The combined use of sulfhydryl ionogenic (strong) and nonogel (weak) collectors allows a change in the composition of surface compounds in the sulfide minerals of the collectors, which leads to a change in the degree of hydrophobicity of the surface and an increase in the flotation selectivity.

In recent years, a mixture of effective reagents for the flotation of gold-bearing sulfide minerals has been found: mercaptan, imidazoline and foaming agents; wolfene and their hydrocarbinol derivatives; a penflout (TM)-3 (dodecyl mercaptan) mixture of alkylthiocarbamate and aliphatic aldoxime; quaternary ammonium chlorides; methylisobutylcarbinol; ethylxantylformate; and mixtures of elemental sulfur with hydrocarbons. Additionally, reagents such as mercaptobenzothiazole (MBT), DTF, and Hostafлот M-91, which have specific collecting effects on rare metals, have been recommended [39].

The effectiveness of using the "Ofom" reagent for the separation of gold has been noted. As a result of the use of the "Ofom S-800" reagent in several copper beneficiation plants, including those in the USA, Canada, and the Philippines, the separation of gold as a satellite element increased by 14% [40].

The method of flotation of rare metals using a thermomorphic polymer with a phosphine or aminosulfide functional group as an additional collector to the main collector capable of forming a strong complex compound with rare metals is recommended [40]. The use of this method allows an increase in the separation of rare metals from 84 to 92%.

A combination of xanthogenate, diethyldithiocarbamic acid 2-oxypropyl ether and oak bark extract was used for the selective separation of gold-bearing pyrite flotation into a frothy product.

This reagent can form a complex with respect to gold [41].

The choice of the optimal option for the processing of coal-bearing ores depends on the mineral content of the ore being enriched, the amount of gold, the proportion of sulfides, the nature of gold binding to ore and rock-forming components, the granulometric characteristics of the ore, and the level of sorption activity of coal. For the beneficiation of complex ores, flotation with cyanide and metallurgical processing of the resulting flotation can be used in a separate cycle.

The difference in the content of gold particles is especially noticeable during the flotation and cyanization processes. Additives facilitate the flotation ability of gold. With an increase in the amount of silver and copper during cyanidation, the gold dissolution rate decreases, and the participation of copper slows compared to the participation of silver [42-47].

The state of the gold surface is highly important for this technology. The gold particles have a surface coating consisting of oxides of iron, argentite, covellite, galenite, kaolinite and other minerals. In addition to the natural origin of the coatings, the surface of gold during combustion is formed as a result of mechanical moistening with solid particles [48].

As a rule, the gold surface covered with the coating does not float well compared to gold. When enriched by gravity, coarse gold with a coating becomes enriched, but such gold is more difficult to extract from enrichment using conventional technology. Gold is not dissolved in the cyano solution if the coating is integral and dense (in a nonconductive solution). If the coating is partially covered with leather or gold, the melting process is slow.

In ore, in addition to particles of generic gold and its manifestations, minerals consist of intermetallic compounds of gold with other metals, tellurides, antimonides and selenides. In carbon ores containing organic compounds in the form of humic acids and bitumen, gold is placed in the form of poorly studied organic compounds; when the ore is oxidized, it disintegrates in the form of a metal with an oil dispersion [49]. A number of storage reagents are known to be used in the flotation of hard-to-recover gold-bearing ores, including BCC (potassium buty l xanthate) and other storage reagents [50]. The

disadvantages of these reagents include their high price, low selectivity and unexplored possibilities for increasing their activity.

The purpose of this work was to find ways to partially replace flotation reagents in the flotation of gold-bearing ores using a new locally produced reagent, polybutene-1 (PB-1), synthesized in the laboratory "Organic Chemistry". This is achieved by chemical modification of the fuel oil "Tashvinzavod" instead of the traditional reagent PBX, as well as the use of electrochemical processing reagents to increase flotation activity.

3. Materials and methods

This section gives an idea of the methodology and structure of the proposed hybrid model which the combined use of beneficiation and metallurgical methods. In the process of research, using modern theoretical and experimental, static and analytical methods summarizing the practice of processing gold ores that are difficult to be enriched, conducting theoretical studies, laboratory studies, experiments on a semi-industrial scale, checking the developed methods in the production process of industrial enterprises, analyzing spectral, chemical, comparison of results obtained from rational, granulometric, mineralogical, phase and other methods and analytical processing methods were used (Figure 1).

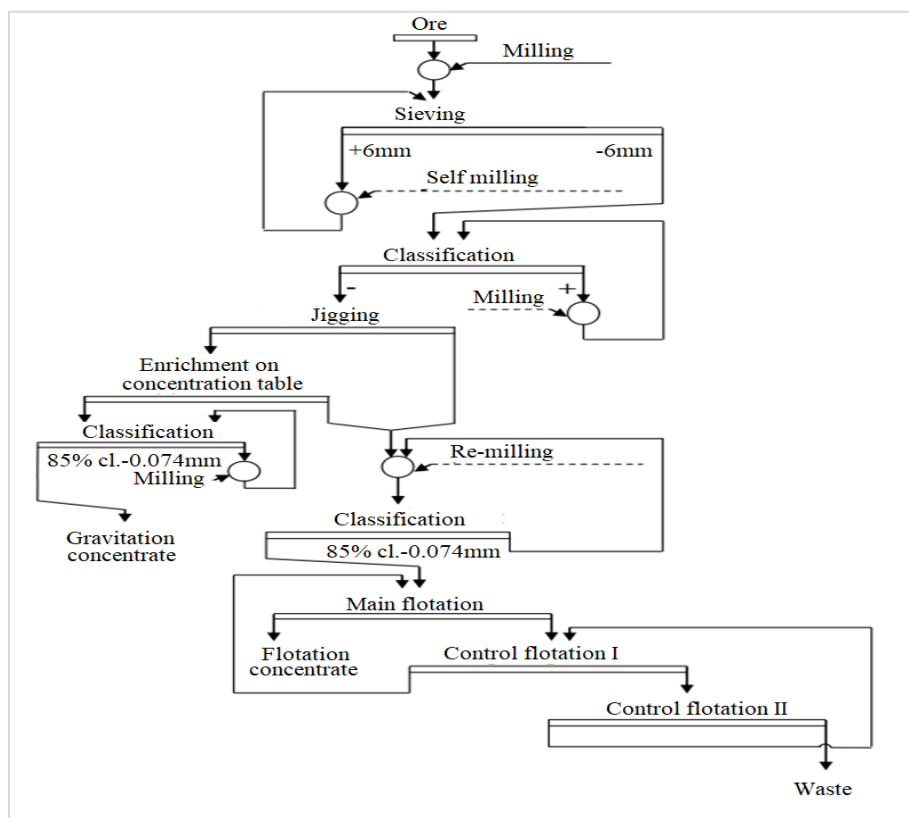


Figure 1 Recommended scheme of ore beneficiation of Amantaytau deposit

3.1 Preparation of ore for studying its material composition

The study of the chemical and material composition of gold ores includes the arrangement of gold and other precious components, the texture and structural characteristics of the ore, the granulometric composition and the ratio between the free particles and growths of minerals of different sizes, the determination of some physical properties of

minerals and their aggregates, and the study of the surface conditions of minerals. Chemical, mineralogical and physical methods of analysis are used to solve these problems. Technological experiments are highly important for determining the material composition of ore. Therefore, various specialists, benefactors, chemists, mineralogists and physicists participate in determining the material composition. The experiential methods used mainly

by enrichers are defined, and the issues to be solved by other specialists are indicated. For the purpose of complex use of mineral raw materials, it is necessary for enrichers to play an active role in determining the material composition, content and size through careful study of both useful and harmful components. For example, clay minerals in slurry ores should be studied especially carefully because they can complicate processing methods or be considered industrially useful components that can be isolated along the way. Telluride, selenium, carbon ores, and ores with large amounts of quartz and feldspar deserve a similar approach [49].

In this article, “Auminzo-Amantoy” gold-arsenic ore samples were selected as the objects of research. General methods for studying gold ores can be used to study the material composition of difficult-to-enrich gold-arsenic ores [14]. However, it is necessary to take into account some specific

characteristics of difficult-to-enrich gold ores: gold is found in the form of fine particles; high contents of arsenic and antimony; coal retainers; and other impurities.

The material composition of the ore is rational, and average samples were separated for study by chemical, spectral, granulomere, mineralogical and other methods of analysis.

3.2 Spectral analysis

Spectral analysis of the gold ores obtained for the study was carried out on a spectral analysis instrument (STE-1). The STE-1 instrument is equipped with a photoelectronic attachment (FEA-9), which allows us to immediately display the results obtained during the process of burning a sample with a spectrogram [49]. The results of the spectral analysis of the ore sample are presented in *Table 1*.

Table 1 Spectral analysis results of the ore sample

Elements	Quantity, %	Elements	Quantity, %	Elements	Quantity, %
Si	>1	Cu	0.027	Ga	0.017
Al	>1	Pb	0.062	R	0.121
Mg	>1	Ag	0.001	Sn	–
Ca	>1	Ace	0.661	Be	0.0001
Fe	>1	Ms	0.012	Nb	–
Mr	0.021	No	0.221	Sat	–
Ni	0.012	Y	–	Sr	–
Co	0.018	Yb	–	In	–
Ti	0.511	Mo	0.002	Aw	0.015
V	0.012	Ba	0.051	Cd	–
Cr	0.002	Bi	–	–	–
Zr	–	Sc	–	–	–

3.3 Chemical analysis

The gold ores taken for research were analysed by chemical analysis, and *Table 2* shows the results of the chemical analysis of the average ore sample.

According to the data presented in *Table 2*, the main industrially valuable components of the ore are gold and silver, and their amounts are 6, 7 and 3.04 g/t, respectively.

Table 2 Results of chemical analysis of the average ore sample

Components	Quantity, %	Components	Quantity, %	Components	Quantity, %
SiO ₂	43.0	Na ₂ O	0.44	p.p.p.	10.37
Fe ₂ O ₃	13.0	K ₂ O	2.89	Au, g/t	6, 7
FeO	1.98	C _{general}	9.99	Ag, g/t	3.04
TiO ₂	0.71	C _{sulfide}	9.53	Pt, g/t	0.065
MnO	0.04	SO ₃	1.07	Pd, g/t	0.12
Al ₂ O ₃	13.21	R ₂ O ₅	0.16	As	0.21
CaO	2.32	SO ₂	3.52	-	-
MgO	2.43	-N ₂ O	0.72	-	-

3.4 Rational analysis

The location patterns of rare metals in different ore samples were studied based on the results of rational analysis. Rational analysis was carried out by selective melting of the ore crushed to 85% - 0.074 mm in a sequential cyanide solution after separating gold and silver from other ore and rock-forming components.

The following steps were used in the analysis: cyanidation of ore, treatment of I-cyanide waste in alkali buffer, treatment of II-cyanide waste in hydrochloric acid, treatment of III-cyanide waste, treatment of III-cyanide waste in nitric acid, and treatment of cyanide in insoluble residue. *Table 3* shows the results of the rational analysis for gold.

Table 3 Results of the rational analysis

The form of placement of gold and the nature of bonding with other components	Distribution			
	Aw g/t	%	Ag g/t	%
Fine spot - gold in spot sulfides (pyrite and arsenopyrite).	3.48	57.10	1.65	52.40
Gold combined with chemical compounds and minerals of antimony and arsenic (except for arsenopyrite and 5-valent compounds of antimony)	–	–	–	–
Gold associated with acid-soluble minerals, oxidized minerals (carbonates, oxides, and hydroxides) of iron and manganese	0.20	3.32	0.30	9.47
Native Au and Ag; growing with other minerals, chlorides, sulfides associated with simple sulfides of silver (cyanidable)	2.31	37.80	1.15	36.53
Gold in quartz, aluminosilicates and other rock-forming minerals	0.11	1.78	0.05	1.60
In total ore:	6.10	100	3.15	100

The amount of pure gold and its amount during growth with minerals are determined by cyanidation. The amount of gold associated with various veils and sulfides is determined by cyanidation after working in hydrochloric acid and nitric acid.

According to the data presented in *Table 3*, native gold is in cyanidable form and associated with sulfides 3 (7.8%), pyrite and arsenopyrite (57.1%, associated with iron and manganese oxides 3.32%, quartz), for a total of 1.78%.

3.5 Granulometric composition of ore

Mineral raw materials (ore, rocks) and products processed at the processing plant consist of a mixture of particles of various sizes and irregular shapes. The sieving method was used to determine the granulometric content.

For sieve analysis, the material was divided into different size classes using a series of sieves. The analysis of grinding and crushing products of large grains was carried out manually or via automatic vibrating granulometry using a series of sieves, and the analysis of fine grains was carried out by sieving through a mechanical analyser-titrator.

To determine the distribution of the main valuable components by size class, the ore was analysed by sieving after grinding to -3+0 mm, after which the amount of valuable components in each class was determined. The results of the granulometric analysis are presented in *Table 4*. *Table 4* shows that the amount of gold in small classes increases with gold separation, but the output of large classes is much greater than that of small classes, so the main parts of gold and silver are located within them.

Table 4 Results of granulometric analysis of crushed ore

Size classes, mm	Output, %		Amount, g/t		Distribution by classes, %	
	Private	Common	Au	Ag	Aw	Ag
-3.0+2.5	8.46	8.46	5.71	2.33	7.32	6.67
-2.5+1.5	22.64	31.10	6.85	3.11	23.50	23.83
-1.5+1.0	11.19	42.29	6.76	3.36	11.46	12.76
-1.0+0.5	18.90	61.19	7.04	2.85	20.16	18.23
-0.5+0.25	17.16	78.39	6.41	2.59	16.66	15.05
-0.25+0.1	14.43	92.78	6.19	2.85	13.54	13.92
-0.1+0.074	6.22	99.00	6.79	3.87	6.40	8.17
-0.074+0	1.00	100.00	6.34	4.04	0.96	1.37
Ore	100		6.60	2.95	100	100

3.6 Mineralogical analysis of the sample

Mineralogical analysis of the ore from the “Auminzo-Amantou” mine was carried out using chemical, atomic absorption, and spectral analysis methods on the average sample of the ore, its enrichment products and flotation waste [23].

Based on the analysis, it was determined that the sample used was a gold-sulfide-quartz ore. The sample was partially oxidized.

It consists of fragments of ore kolche, carbon-graphite shales, siltstone and granitoid R (with quartz-feldspar composition). Barite-celestine veins are found in these veins. The added rocks have undergone hydrothermal changes—beresited. Products in the zone of oxidation and weathering are porous, friable and strongly altered—argillized and limonitized. The sulfides in the sample form a large, flat, linear-layered, small-veined, porous and hollow

structure. More than 42 different minerals are found in the studied sample, but only some of them are of industrial importance.

The main valuable component in the ore is pure gold, and the main ore minerals in the sample are pyrite, arsenopyrite, iron hydroxides and jarosite. The mineral part of the sample consists mainly of quartz, sericite, feldspar, carbonates, chlorites, and kaolinites. Carbonaceous matter and graphite have been found to be involved. Accessory minerals include monazite, zircon, xenotime, corundum, sphene, and epidote. They form splices and inclusions with hypogene and hypergene minerals. The rest of the ore-forming and ore-incorporated minerals are present in very small amounts. The list of ore-forming minerals, their quantitatively estimated proportions, the sizes of the particles and monomineral aggregates, the gravio- and floto-weights, and the gravity waste are given in *Table 5*.

Table 5 Estimated amount and grain size of minerals found in ore samples of "Auminzo-Amantou" deposits

Naming of minerals	Amount, % Sample average	Grain size, mm			
		Available		In use	
		from	up to	from	up to
Gold	Less	0.001	0.06	0.005	0.02
Pyrite	17.8	0.005	3.0	0, 1	0, 3
Arsenopyrite	~0.5	0.001	0.5	0.005	0, 1
Sphalerite	Less	0.005	0.3	0.01	0.05
Galena	Less	0.001	0.3	0.01	0.02
Chalcopyrite	Less	0.001	0.2	0.01	0.1
Pyrrhotin	Less	0.001	0.05	0.01	0.0 5
Jamesonite and head.	Less	0.001	0.15	0.005	0.02
Pb , Cu , Fe sulfosol	Less	0.001	0.01		
Yarosit	1.5	thin crystals and other formation			
Scorodite	Less	thin crystals			
Covellin, chalcozin	Less	thin crystals			
Beidellite	Less	Thin crystals in the form of complex mixtures			
Halothrichitis	Less				
Ferrimolybdate	Less				
Wulfenite	Less				
Anglesite	Less	thin crystals			
Lead silicates (almozite, barycilitis)	Less	thin crystals			
Magnetite	Less	thin crystals			
Goethite , hydrogethite and Mn oxide	~2.0-3.0	0.001	2.0	Pseudomorphoses and other formation	
Ilmenite, ilmeno-rutile and rutile	~1.0	0.001	0.02	0.005	0.01
Sheelite	Less	0.01	0.05	0.01	0.05
Quartz	24.4	0.01	3.0	0.1	0.5
Sericite	20.0	thinly coated			
Plagioclase (albite+oliclease)	5.0	0.005	0.3	0.05	0.1
Orthoclase	2.0	0.005	0.4	0.05	0.2
Amphiboles _	Less	0.001	0.2		
Chlorites _	2.5-3.0	thinly coated			

Naming of minerals	Amount, % Sample average	Grain size, mm			
		Available		In use	
		from	up to	from	up to
Carbonates (dolomite + calcite)	7.5	0.001	1.0	0.01	0.05
Biotite	<0.5	0.01	0.2	0.01	0.1
Celestine	1.0	0.01	0.1	0.01	0.1
Barite		0.01	0.2	0.01	0.1
Plaster	0.4	0.01	0.5	0.1	0.2
Apatite	<0.4	0.01	0.1	0.01	0.05
Corundum	Less	0.001	0.1	0.001	0.05
Kaolinite	8.5	coated			
carbon and graphite	<1.0	thin crystals			
Epidote	Less	0.005	0.1	0.01	0.05
Monazite	Less	0.001	0.05	0.005	0.01
Xenothyme	Less	0.001	0.05	0.005	0.01
Sphene	Less	0.001	0.01	0.001	0.01
Zircon	Less	0.005	0.02	0.01	0.02

3.7 Flotation tests of the sample

Flotation tests were carried out in laboratory flotation machines with chamber volumes of 1.0, 0.5, and 0.25 l. The crushing of ore for flotation experiments was carried out in mills in an aqueous medium at a ratio of S:L: W=1:0.5:6. The following reagents were used as flotation reagents: collectors—spindle oil, PBX and PB-1; activator—CuSO₄; medium regulator—soda; and foaming agent (T-80). The reagents used in

the process were fed in the following sequence: reagent regulators, activators, collectors, and foaming agents. In flotation experiments, the mass fraction of solids in the pulp ranged from 15 to 40%. The main and control flotations were carried out on dense pulp, and cleaning was performed on more liquefied pulp. Flotation experiments were carried out according to the scheme shown in Figure 2. Table 6 shows the flotation of gravity waste with conventional reagents.

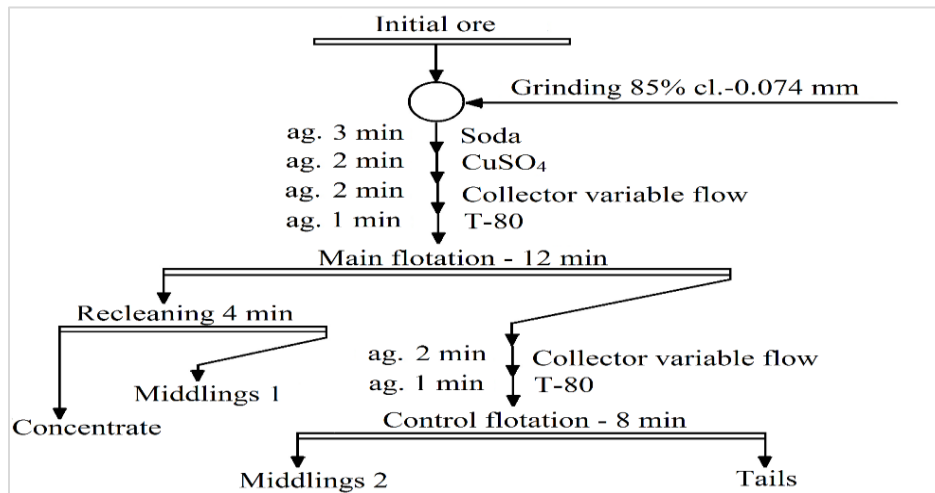


Figure 2 Scheme of flotation experiments

Table 6 Flotation of gravity waste with conventional reagents

Name of products	Output, %	Quantity, g/t		Separation, %		Consumption of reagents, main and control flotation, g/t
		Au	Ag	Au	Ag	
Concentrate 1	7.47	1.90	1.71	13.55	9.25	Soda-1000+500
Concentrate 2	12.30	5.89	6.10	68.94	54.41	Spindle butter -40
Middlings 1	8.01	1.18	1.14	9.00	6.60	CuSO ₄ -300+100+50
Middlings 2	3.13	0.71	0.68	2.12	1.54	PBX 150+50+20
Tail	69.09	0.10	0.56	6.39	28.20	T-80 - 20+60+40+20

Name of products	Output, %	Quantity, g/t		Separation, %		Consumption of reagents, main and control flotation, g/t
		Au	Ag	Au	Ag	
Graviotail	100	1.05	1.38	100	100	

Increasing the capacity of flotation enrichment plants requires reducing the consumption of expensive flotation reagents, replacing them with relatively cheap reagents, increasing the effectiveness of the reagents used, and determining the reagent order of the currently working enrichment plants.

3.8 Electrochemical method technology

Electrochemical technology is sufficiently well developed and has methods recommended for industrial production. Currently, the electrochemical synthesis of organic and inorganic compounds is used in the metallurgy of nonferrous and ferrous metals, petrochemical synthesis, the pharmaceutical industry, etc., and is widely used in three main areas of application of electrochemical technology in flotation processes:

- Electrochemical processing of solutions of flotation reagents and synthesis of new reagents;
- electroreduction and electrooxidation of flotation sludge to change the procedure for the separation of valuable products;
- Electrochemical treatment of technical water to accelerate the flotation process and use a circulating water supply.

Electrochemical processing of solutions of flotation reagents involves changing the state and composition of the reagent solution before it is sent to the flotation process. In the processes of the anode (positive charge on the electrode), electrooxidation reactions occur, and in the cathode (negative charge on the electrode), electroreduction reactions occur. The anode is an acceptor of valence electrons, and the cathode is a donor of valence electrons.

The higher the potential for the release of hydrogen at the cathode and oxygen at the anode is, the more water solutions of reagents can be used for electrochemical processing. The higher the voltage range is. It is recommended that the electrochemical treatment of reagents be carried out directly in the reagent pad, taking into account the pretreatment experiments before feeding the reagent solutions into the process. A special device consisting of an electrochemical cell, a magnetic stirrer, and an electric current control source was created for conducting experiments on the electrochemical processing of reagent solutions (*Figure 3*).

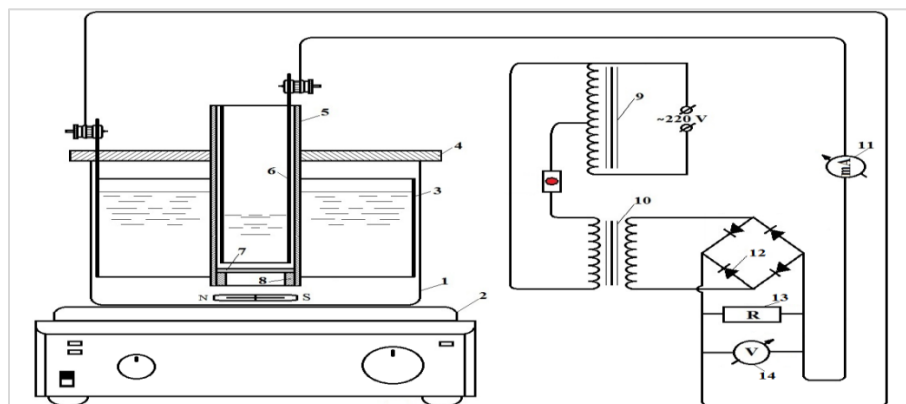
The electrochemical cell consisted of a 500 ml glass crystallizer, and a cylindrical working electrode made of a stainless steel sheet with a thickness of 0.5-0.8 mm was placed along the inner perimeter of the crystallizer. The crystallizer is closed from the top with a round glass cover, and in its centre, it is a limiting glass with an open glass bottom. A circle of filter paper was placed on the bottom of this glass and clamped. An auxiliary electrode made of a 0.5-0.8 mm stainless steel sheet was installed in the limiting cup. The studied reagent solution is poured into the cell such that the concentration in the crystallizer is slightly greater than that in the limiting glass. The difference in levels was created so that the electrooxidation products of the reagent solutions did not interact with the electroreduction products. During the entire experiment, the solution was slowly poured from the crystallizer into the limiting glass. For the experimental study of the process of electrochemical treatment of reagent solutions, a special setup was assembled, consisting of an electrochemical cell, a magnetic stirrer, and an adjustable source of electric current (*Figure 2*).

The electrochemical cell consisted of a glass crystallizer with a capacity of 500 ml and a cylindrical working electrode made of a 0.5-0.8 mm thick stainless steel sheet laid along the inner perimeter of the crystallizer. From above, the mould is closed with a round Plexiglas cover, in the centre of which a restrictive Plexiglas cup is inserted, open from the bottom side. A circle of filter paper was inserted into the lower end of the glass, which was pressed with a Plexiglas clamping ring. An auxiliary electrode 0.5-0.8 mm thick was placed inside the restrictive cup in the form of a cylindrical stainless steel sheet. The studied reagent solution was poured into the cell such that the concentration in the crystallizer was slightly greater than that in the restrictive glass. The difference in levels is created so that the products of the electrooxidation of the reagent solution do not interact with the products of its electroreduction. During the entire experiment, a weak overflow of the solution from the crystallizer into the restrictive glass occurred.

A magnetic stirrer is necessary for mixing the reagent solution during electrochemical treatment to create a uniform mode of electrochemical treatment and

prevent the reaction products from fixing on the

surface of the main electrode.



1-glass mold; 2-magnetic stirrer; 3-working electrode; 4-lid; 5-limiting glass; 6-auxiliary electrode; 7-filter paper; 8-clamping ring; 9-laboratory autotransformer; 10-step-down transformer; 11-diode type D7Zh; 12-voltmeter; 13-milliammeter; 14-resistance.

Figure 3 Scheme of the electrochemical treatment of reagent solutions

4. Results and discussion

Increasing the capacity for flotation production requires reducing the consumption of expensive flotation reagents, replacing them with less expensive reagents, increasing the efficiency of the reagents used, and clarifying the existing reagent regimens at existing enrichment plants.

The following parameters were used in the experiments: 80-85% of the cells were ground. -0.074 mm; costs of activators and regulators of the environment: soda ash, CuSO₄. Most of the attention was given to the new collector PB-1 and the traditional collector PBX. As a result, for each ore sample, the optimal flotation mode was established, as shown in Table 7. As shown in Table 7, the use of the collector reagent together with the traditional reagent gives positive results and even surpasses the use of traditional reagents.

In addition, to reduce the cost of flotation reagents, studies have been carried out on the use of the electrochemical processing of reagents. Electrochemical technology has fairly well-developed and implemented methods in industrial production. Under the electrochemical treatment of flotation reagent solutions, there is a change in the state and composition of the reagent solution based on cathodic or anodic electrical treatment before being fed into the flotation process. Electro-oxidation reactions occur in anodic processes (positive charge on the electrode), and electroreduction reactions occur in cathodic processes (negative charge on the

electrode). The anode electrode was the valence electron acceptor, and the cathode electrode was the valence electron donor. The higher the potential for hydrogen evolution at the cathode and oxygen evolution at the anode are, the greater the voltage range that can be used for the electrochemical treatment of aqueous solutions of reagents.

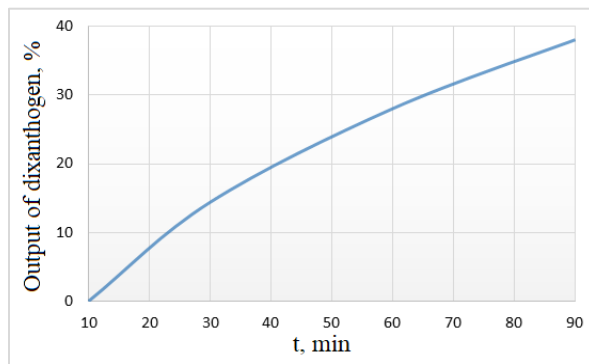
Currently, in the flotation process, three main directions for the use of electrochemical technology have been identified:

- Electrochemical treatment of solutions of flotation reagents and synthesis of new reagents;
- Electroreduction and electrooxidation of the flotation pulp to change the regimes of separation of valuable materials;
- electrochemical treatment of technical water for the intensification of the flotation process and the use of recycled water.

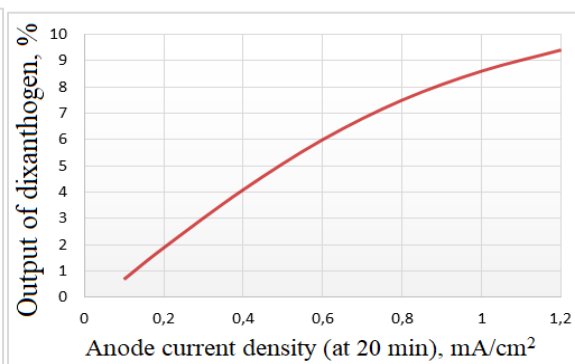
Under the action of an electric current, a fine dispersion of apolar organic substances occurs on the electrode surface. In this case, the formation of an apolar dixanthogen at the anode occurs because of the electrochemical oxidation of xanthate solutions. With an increase in the concentration of the initial xanthate solution and the magnitude of the applied voltage to the electrodes, the yield of the dixanthogen increases. The influence of the electrooxidation time of the xanthate solution on the formation of the dixanthogen was studied. Figure 4 shows the dependence of the yield of dixanthogen during the process of electrochemical treatment with a 3% solution of PBX on time and anodic current density.

Table 7 Results of flotation experiments of samples of gold-bearing ores with PBX and PB-1

Name of products	Output, %	Contents, g t ⁻¹		Extract, %		The consumption of reagents, in the main and control flotation, g t ⁻¹	
		Au	Ag	Au	Ag		
Concentrate	24.41	23.13	6.97	83.04	63.00	Soda-1000+500+250 Spindle butter -40 CuSO ₄ -300+100+50 PBX -150+100+40 T-80-20+80+40+20	
Middlings 1	4.60	12.15	8.46	8.22	14.41		
Middlings 2	3.01	10.48	1.26	4.64	1.41		
Tails	67.98	0.41	0.84	4.10	21.18		
Ore	100	6.80	2.70	100	100		
Concentrate	25.27	22.06	8.34	82.59	74.00	Soda -1000+500+250 Spindle butter -40 CuSO ₄ -300+100+50 PBX -75+50+20 PB-1-75+50+20 T-80-20+80+40+20	
Middlings 1	2.77	22.39	2.26	9.19	2.23		
Middlings 2	3.86	6.78	1.03	3.88	1.41		
Tails	68.10	0.43	0.88	4.34	21.36		
Ore	100.00	6.75	2.81	100.00	100.00		



a) From time to time



b) the density of the anode current

Figure 4 Dependence of the output of dixanthogen on the process of electrochemical treatment of a 3% solution of xanthate

During the flotation of the ore from the Amantaytau deposit, the PBX solution was subjected to electrochemical treatment, as was a mixture of PBX and PB-1 reagents, and the processing time was 20 minutes since approximately 7-8% of the

dixanthogen is formed within 20 minutes, a period that is considered sufficient for surface hydrophobization of arsenopyrite. The flotation experiments were carried out in an open cycle. The consumption of reagents is given in Table 8.

Table 8 Results of flotation experiments of samples of gold-bearing ores with PBX and PB-1 subjected to electrochemical treatment

Name of products	Output, %	Contents, g t ⁻¹		Extract, %		The consumption of reagents, in the main and control flotation, g t ⁻¹	
		Au	Ag	Au	Ag		
Concentrate	24.59	23.60	6.52	83.50	61.00	Soda -1000+500+250 Spindle butter -40 CuSO ₄ -300+100+50 PBX -150+100+40 T-80 - 20+80+40+20	
Middlings 1	3.90	16.77	9.23	9.41	13.68		
Middlings 2	3.91	6.65	1.57	3.74	2.34		
Tails	67.60	0.34	0.89	3.35	22.98		
Ore	100.00	6.95	2.63	100.00	100.00		
Concentrate	25.36	21.73	8.54	83.87	74.71	Soda -1000+500+250 Spindle butter -40 CuSO ₄ -300+100+50 PBX -75+50+20 PB-1 - 75+50+20 T-80 - 20+80+40+20	
Middlings 1	3.47	19.33	2.58	10.21	3.09		
Middlings 2	3.67	5.94	1.07	3.32	1.36		
Tails	67.50	0.25	0.90	2.60	20.84		
Ore	100.00	6.57	2.90	100.00	100.00		

The data given in *Table 7* indicate that the electrochemical treatment of a mixture of PBX and PB-1 contributes to an increase in the extraction of gold from the tested ores. The extraction of gold from the ore of the Amantaytau deposit increases from 0.75 to 1.74%. The results obtained show the potential for the use of electrochemical treatment of xanthate and the reagent PB-1 in the flotation of gold-bearing ores.

Limitations

Several limitations are acknowledged, including the inability to analyze ores containing gold of varying compositions. It is imperative to determine the technical and economic indicators of their enrichment through hydrometallurgical methods and to develop an effective technological scheme for processing difficult-to-enrich gold ores.

A complete list of abbreviations is summarised in *Appendix 1*.

5. Conclusion and future work

The study on the beneficiation of difficult-to-enrich gold ores yielded several important conclusions. Firstly, a range of research methods, equipment, and directions were selected based on the unique properties of these hard-to-enrich gold ores. During experiments involving gravity fracturing, it was observed that gold ore separation and quantitative indicators were notably superior at a particle size of 0.15 ± 0 mm, compared to other sizes. This study also encompassed an in-depth analysis of the composition, properties, and potential applications of new local reagents. These were recommended as substitutes for traditional reagents in the enrichment of such ores, particularly as collectors of gold-sulfide minerals. The research explored the possibility of using these new reagents alongside traditional ones. Furthermore, the optimal consumption of PBX, a collecting reagent used in the flotation of ore samples from the "Auminzo-Amantou" mine sites, was determined. This was done following the principles of open and continuous processes, including the use of traditional reagents for processing gravity waste. Impressively, a gold recovery rate of up to 93.2% was achieved by utilizing a combination of traditional and new local reagents for the flotation of ore and gravity tailings.

Another significant finding was the practical implementation of electrochemical processing of conventional reagent (collector) solutions. During the flotation of gold and silver ores, this method proved

to enhance the separation of ore components by up to 2.8%. Consequently, these studies indicate that using the new reagent PB-1 and electrochemical treatment of a mixture of PBX and PB-1 can lead to substantial economic benefits. These include reduced production costs and an increase in the extraction of precious metals during the flotation of gold ores. Moreover, this enhanced extraction of gold leads to an increased yield of middling products, which, in turn, boosts the production of finished goods.

In the future research work, processing of gold-containing ores containing various compounds with eco-friendly technologies and the level of extraction of high amounts of gold will be achieved.

Acknowledgment

The authors acknowledge the support of the Agency of Innovative Development under the Ministry of Higher Education, Science and Innovation, a joint scientific-technical project (No. AL-592102410), a research project to be conducted under the MIRAI Fund of Japan for UJICY (No. APPL-02-2022) and the National Key Research and Development Program of China (No. 2022YFE0126800).

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Dilmurod Makhmarejabov: Draft writing, paper framework concept, revision of the paper, conduct the study and results analysis. **Siyuan Yang:** Study conceptualization, supervision of the conducted study and checking the study results. **Sokhibjon Matkarimov:** Study conceptualization, supervised the conducted study and checked the study results. **Bakhriddin Berdiyarov, Dilfuza Yavkochiva and Zaynobiddin Matkarimov:** Study conceptualization, supervised the conducted study and checked the study results.

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Dilmurod Makhmarejabov is an Assistant Professor at the Department of Mining and Metallurgical Engineering, Tashkent State Technical University. His research focuses on Mining Engineering, with skills and expertise in Mining, Rock Mechanics, Mineral Processing, processing of Platinum Group Minerals, Mineral Exploration, and the Extraction and Processing of Arsenic, Copper, Lead, and Gold Mining Industry Leaching Techniques.
Email: dmahmarejabov@mail.ru



Siyuan Yang is an Associate Professor, Doctoral Supervisor, and Vice Chairperson of the Trade Union at Wuhan University of Technology. His research focuses on the development of mineral processing technology and theory. He has received prestigious recognitions, including the Youth Elite

Support Project from the China Association for Science and Technology and the Hundred Talents Program of Hubei Province, China. Yang earned his Bachelor's degree from Wuhan University of Technology, his Master's degree from Central South University, and his Doctorate from the University of Queensland, Australia. He directs several research projects, including those funded by the National Natural Science Foundation of China, the Natural Science Foundation of Hubei Province, the Open Fund Project of the State Key Laboratory, the Open Fund Project of the National Engineering Center, and numerous enterprise-supported projects. He has also contributed to the National Key Project of China and the Joint Key Projects of Australian Universities and Enterprises. Additionally, Yang has organized and participated in many significant academic conferences both in China and internationally.
Email: siyuan.yang@whut.edu.cn



Sokhibjon Matkarimov serves as the Head of the Laboratory for Mining and Deep Processing of Mineral Resources at the Uzbek-Japanese Innovation Center for Youth. He is also a Professor in the Department of Mining and Metallurgy at Tashkent State Technical University. His research interests span a wide range of areas within the field, including Mining and Processing Metallurgy, Leaching, Iron Oxidation, Separation Technology, Carbothermic Reduction, Recycling, Hydrometallurgy, Metal Mining, Flotation, Pyrometallurgy, processing of Steelmaking Slags, Heat Treatment, and Metal Processing, as well as the metallurgy of ferrous and non-ferrous metals.
Email: sohibtm@gmail.com



Bakhridin Berdiyarov, holding the position of Head of the Department of Metallurgy at Tashkent State Technical University, engages in research within the Department of Mining and Metallurgy. His research spans various areas of Mining Engineering and Materials Engineering. Berdiyarov's skills and expertise include Mineral Processing, Engineering Extraction and Processing, Industry Leaching Mining, Solvent Extraction, Hydrometallurgy, Leaching Processes, Extractive Metallurgy, and Pyrometallurgy Smelting.
Email: mr.berdiyarov@gmail.com



Dilfuza Yavkochiva is a PhD student in the Department of Mining at Tashkent State Technical University. Her scientific research focuses on several key areas: studying the geomechanical state of stability of the sides of deep quarries; methods of managing technogenic resources in the open-pit mining of ore deposits; scientific substantiation of the parameters of blasting operations on high ledges of

deep quarries; and the development of technology for processing resistant gold-bearing ores through the combined use of enrichment and hydrometallurgy methods.
Email: d.yavkochiva@tdtu.uz



Zaynobiddin Matkarimov is an Assistant Professor in the Department of Technology of Silicate Materials and Rare, Noble Metals at the Tashkent Chemical-Technological Institute. His primary focus is on studying the laws governing the selection, grinding, mixing, and firing of raw materials in the production of silicate materials. He aims to explore the processes of crystallization and hydration in the production of finished products, emphasizing their theoretical and practical importance for building knowledge, skills, and expertise. His expertise encompasses the main processes involved in the production of silicate materials, the management and acceleration of technological processes, the theoretical foundations of the grinding process, types and theories of mixing and forming processes, and the crystallization process. Matkarimov is dedicated to imparting both theoretical and practical knowledge on the production of silicate materials continuously.
Email: zaynobiddin1986@mail.ru

Appendix I

S. No.	Abbreviation	Description
1	CIP	Selective Dissolution of the Product by Initial Cyanidation Sorption
2	CIL	Sorptive Selective Dissolution of the Product Without Preliminary Cyanidation
3	DTF	Dithiophosphate
4	FEA-9	Photoelectronic Attachment
5	MBT	Mercaptobenzothiazole
6	MIBC	4-Methyl-2-Pentanol
7	NSR	Nitrogen-Saving Reagent
8	PB-1	Polybutene-1
9	PBX	Potassium Butyl Xanthate
10	pH	Potential of Hydrogen
11	PSR	Phosphorus-Saving Reagent
12	RIL	Technology of Cyanidation of Flotation Effluents
13	STE	Spectral Analysis Instrument
14	T-80	Foaming Agent (oxal)
15	TM	Penflout