

## RESEARCH PAPER

## Optimization of the Process of Gold Leaching from Arsenic-Bearing Gold Ore Using an Oxidizing Agent in Heap Leaching

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Received: 04.09.2025

Accepted: 08.09.2025

## ABSTRACT

The results of laboratory studies for gold recovery from sulfide and oxidized ores under percolation (heap) leaching are presented in this article. The results of chemical elemental analysis, X-ray phase, and mineralogical analyses for the forms of gold deportment in ore are also presented herein. The percolation heap leaching process of low-grade ore in percolation columns was simulated. The efficiency of cyanide leaching and leaching with the use of an oxidizing agent in percolation columns was compared. The initial sulfide ore is refractory for processing by the agitation leaching method. Gold recovery under standard cyanidation of 0.1–0.3% sulfide ore with 90% particle size of -0.071 mm averages 32.0/47.0% (the gold content in the leaching residue is 1.36–1.05 g/t, respectively). In comparison, it is 60.0% in agitation mode with the use of the oxidizing agent (TCCA). The results showed that direct cyanidation at various concentrations recovers 45.0–75.0% from oxidized ore, with the presence of the oxidizing agent trichloroisocyanuric acid (TCCA) at the rate of 76.67%. Percolation leaching of oxidized ore conducted under optimal conditions at a concentration of 0.3% CN<sup>-</sup> with the use of TCCA, with an irrigation pause of two days, at an irrigation rate of 20–30 dm<sup>3</sup>/t, allowed to recover 53–62% of gold into solution within 30 days, respectively.

**Keywords:** arsenic-bearing gold ore, trichloroisocyanuric acid oxidizer, gold recovery, optimization, leaching

## INTRODUCTION

Modern hydrometallurgical production is an important part of the solution for the issue of rational processing of complex ores. The main directions in modern hydrometallurgy studies are recycling technologies, the complete and comprehensive recovery of all valuable components from processed raw materials, and effective methods intended to isolate valuable components from solutions [1]. Today, cyanide leaching is the main gold recovery method from ores. The cyanidation process for gold ores and concentrates has been extensively studied. In particular, the rate of gold dissolution can be controlled by the concentration of either NaCN or oxygen.

The gold form in ore raw materials (free or chemically bound), the size and aggregate state of gold grains, the presence of passivating films, the genesis of ore-bearing rocks (altered or unaltered) and their structural characteristics (porosity, fracturing) determine the feasibility of a particular method intended to process gold-bearing raw materials depending on the initial content of noble metal and mineralogical composition [1-6].

Hydrometallurgical extraction of nonferrous and noble metals from ores, concentrates, and by-products by leaching with solvents [1–3] represents a complex heterogeneous process providing for the transfer of gold and silver into solution in the form of soluble salts or complexes [4–6]. The rate of this process is determined by the chemical nature of the solvent, its composition, as well as the composition and chemical properties of the minerals of nonferrous and noble metals [7]. Leaching gold from low-grade ores is an urgent problem for many regions of the world. This is because reserves of high-grade ores are gradually being depleted, and it is necessary to process lower-grade ores to maintain gold production volumes. This process is generally more complex and costly than the processing of high-grade ores.

The most important problem of gold hydrometallurgy is the search for rational methods of extracting it from low-grade off-balance and refractory ores, which is becoming increasingly urgent as new deposits are discovered and exploited, allowing an increase in the gold reserves of the Republic of Kazakhstan. In world practice, the process of leaching heap gold with alkali metal cyanide solutions has been widely used for the processing of low-concentration gold-bearing ores, in recent decades, expanding the raw material base and improving the technical

and economic performance of both existing and new gold mining enterprises without significant capital expenditures. Geotechnological processes in the mining industry of the Republic of Kazakhstan, in particular heap leaching, have developed relatively recently. Therefore, the advantages of these processing methods have not been fully identified.

In works [8], gold minerals are often covered with rather dense films consisting of argentite, arsenopyrite, galena, oxides and iron, etc., which are difficult to process. The method of its recovery is determined depending on the deportment and concentration of gold in ores. Geotechnological methods (heap leaching) are currently successfully applied for the processing of low-grade ores and small deposits with gold content of 0.6 - 4.0 g/t. This process began to be used in the 1960s in the USA.

The host rock is quartz, SiO<sub>2</sub>, which is a typical oxide, one of the most widespread minerals in the Earth's crust. It is present in significant quantities in numerous hydrothermal deposits in association with various minerals: pyrite, chalcopyrite, tourmaline, calcite, chlorites, etc. The gold in quartz is generally larger than that in other minerals of the same ore. Large and medium-sized gold is relatively easily freed from the mineral associated with it during the crushing and grinding of ore and is then successfully cyanided. Fine gold contained in quartz is practically not leached.

The size of the gold grains has a decisive effect on the gold recovery process contained in these minerals. Ore containing relatively coarse gold in sulfides can, in principle, be easily processed using heap leaching technology. Gold with a particle size of less than 10 microns, "sealed" in pyrite and arsenopyrite, as a rule, cannot be recovered by heap leaching due to the impermeability of cyanide solutions into sulfide grains [9].

Gold ores can be considered refractory if the gold recovery from them with traditional cyanidation technology fluctuates within 80%. The presence of finely disseminated gold in mineral raw materials is one of the main reasons for the technological resistance of raw materials. The combination of two factors - the dense structure of mineral grains, impenetrable to cyanide solutions, and the dispersion of gold contained in minerals determines the resistance of gold ores in the leaching process. The combination of these factors is most characteristic of gold-bearing sulfides and partly quartz. The leading place among sulfides, both in

abundance and practical significance, belongs to pyrite, FeS<sub>2</sub>, and arsenopyrite, FeAsS.

Therefore, a preparatory stage is required. It improves recovery to acceptable values, or an increase in gold recovery can be achieved with various reagents. Preparation involves dispersing the gold inclusion in a manner that provides access to the cyanide solution. For sulfides and arsenopyrite, which are the main carriers of gold, the preparation typically involves oxidising the sulfide or arsenide matrix.

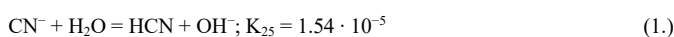
The correct choice of a particular process intended to leach gold-containing raw materials, as well as the selection of the grinding degree required to open minerals, can be made and convincingly justified only by taking into account the results of a detailed study of the material composition and structure of the mineral [10].

Not all ores are suitable for heap leaching. Gold and silver are most effectively extracted from silicified and calcareous sedimentary rocks, sandy dolomites and shales, quartz and volcanic rocks [11, 12]. The process of cyanide heap leaching is complicated by the presence in the ore of partially oxidised sulfides of antimony, zinc, iron, copper, arsenic, carbonaceous materials, acid-forming compounds, as well as the presence of gold and silver with passivated surfaces. The presence of clay fractions in the ore makes percolation of the solution in the heap difficult or even prevents it, and they also significantly sorb dissolved gold. Therefore, leaching is advisable to conduct on ores with low gold and silver content.

Most heap leaching plants in the world (in the USA, more than 30) operate on cyanide solutions [13-19]. Gold and silver recovery by this method ranges from 50 to 95%, in most cases 50 – 70%, which, on average, is lower than by tank leaching.

More than 20 gold solvents are known: cyanides, hydrochlorides, thiocarbamides, etc. However, not all of them are of technological interest, i.e. they must simultaneously meet requirements such as non-toxicity, kinetic activity, selectivity with respect to noble metals, moderate cost, and feasibility of industrial-scale production.

There is a significant number of gold solvents. Thiosulfates of alkali and alkaline-earth metals: Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>, K<sub>2</sub>S<sub>2</sub>O<sub>3</sub>, CaS<sub>2</sub>O<sub>3</sub>, etc., effectively dissolve gold in the presence of oxygen, high temperatures, and pressure. Inorganic acids: a hot mixture of HNO<sub>3</sub> and HCl dissolves gold somewhat better than NaCN. Hydrochloric, sulfuric, and phosphoric acids, under special conditions (oxygen pressure, presence of O<sub>3</sub>, CuCl<sub>2</sub>, C<sub>2</sub>H<sub>5</sub>OH), are also capable of dissolving gold. Salts of CuCl<sub>2</sub>, FeCl<sub>3</sub>, and Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub> dissolve gold quite easily at 200°C. Gold dissolves well in cyanides, humic compounds, amino acids, halogens, and thiourea [20]. Under current conditions, alkali metal cyanides [21] have become the most widely used gold solvents; to prevent their hydrolysis with the formation of volatile hydrocyanic acid, the process is performed in an alkaline medium (pH = 11).



Other oxidizers, such as BrCN, Na<sub>2</sub>O<sub>2</sub>, BaO<sub>2</sub> etc., in addition to oxygen, can be used to accelerate cyanidation. Thus, BrCN is used in the bromcyanidation process; Na<sub>2</sub>O<sub>2</sub> was used in some cyanide gold extraction plants in Canada and gave positive results; BaO<sub>2</sub> is used in laboratory studies of cyanidation processes. Intensification of gold leaching by cyanide-containing solvents is performed in two ways: 1 – improvement of equipment (reactors) for agitation leaching and creation of special hydro- and aerodynamic conditions; 2 – preliminary treatment with various reagents and the use of oxidizers. It has been proposed to pretreat the ore with an aqueous solution containing transition metal ions – V(V), Co(III), Mn(VII), to increase the degree of gold recovery from poor sulfide ores by cyanidation [16-21].

Silicate minerals mainly represent sulfide ores: albite (Na[AlSi<sub>3</sub>O<sub>8</sub>]), microcline (K[AlSi<sub>3</sub>O<sub>8</sub>]), quartz (SiO<sub>2</sub>), kaolinite (Al<sub>4</sub>(OH)<sub>8</sub>[Si<sub>4</sub>O<sub>2</sub>]), biotite (K(MgFe)<sub>3</sub>(OH, F)<sub>2</sub>[AlSi<sub>3</sub>O<sub>10</sub>]), hornblende (Na<sub>3</sub>Fe<sub>3</sub>Fe<sub>2</sub>Si<sub>8</sub>O<sub>23</sub>(OH)). Ore minerals present include arsenopyrite (FeAsS), pyrite (FeS<sub>2</sub>), marcasite (FeS<sub>2</sub>), chalcopyrite (CuFeS<sub>2</sub>), hematite (Fe<sub>2</sub>O<sub>3</sub>), bismuthinite (B<sub>2</sub>S<sub>3</sub>), and native bismuth (Bi) (Fig. 2), which are evenly distributed in quartz veins. The gold content in them is 1.5 - 4 g/t.

Native gold is confined to quartz-arsenopyrite veins and veinlets, as well as to quartzified zones of host rocks with disseminated arsenopyrite. Isolated gold inclusions or their nest-like clusters, containing up to 15 - 20 grains, are confined either to microfractures in quartz and arsenopyrite, to the interstices of arsenopyrite aggregates, or to fractures in dark-colored minerals of altered host rocks. Gold grains quite often form close intergrowths with bismuthinite. Their

form is irregular, platy, hair-like, i.e. xenomorphic. Sometimes crystals and droplet-like formations of gold are observed in bismuthinite. Their sizes range from 0.0005 to 0.53 mm, with 79% of the measured grains having a size from 0.0008 to 0.008 mm.

For the first time, a comprehensive comparison of leaching of gold-arsenic sulfide and oxidized ores using trichloroisocyanuric acid (TCCA) as an oxidizing agent was performed for the ores of the Vasilkovskoye deposit, which made it possible to increase gold recovery compared to traditional cyanidation. A technological model of controlled flows in heap leaching was developed and tested, including double perforated pipe systems with water-permeable inert fillers, ensuring uniform distribution of the solution inside the heap and year-round operation of the process.

The modern mining industry of the Republic of Kazakhstan is focused on the processing of mineral raw materials with a complex material composition, including refractory, finely disseminated, low-grade, and oxidized ores. Due to the depletion of easily accessible and high-grade gold ores, the requirements for the development of new technological solutions that allow efficient extraction of gold from low-grade and refractory raw materials are increasing. This problem is especially relevant for Kazakhstani gold deposits, such as Vasilkovskoye, where a significant volume of reserves is represented by sulfide and oxidized ores with finely dispersed or sulfide-encapsulated gold.

The Vasilkovskoye gold deposit, located in the Akmola region, is the largest in Kazakhstan in terms of balance gold reserves. Its exploitation is performed by open-pit mining at significant depths, which requires the use of energy-efficient and environmentally safe processing technologies. The main types of ores are gold-arsenic sulfide and oxidized rocks, characterized by a high content of quartz, microcline, albite, pyrite, and arsenopyrite. In such ores, gold is often present in finely dispersed or associated form, which determines their high technological refractoriness. Classical gold extraction schemes based on direct cyanidation do not allow achieving high recovery rates from refractory ores. The main reason lies in the presence of a dense mineral matrix impermeable to the solution, as well as in the encapsulation of gold within sulfide minerals. For effective gold recovery, it is necessary to apply preliminary methods of opening gold-bearing minerals or to use additional oxidizing reagents that promote the breakdown of the sulfide phase and increase the accessibility of gold to reagents.

Gold in ores is associated with iron-bearing minerals, which must be decomposed before leaching. The rate of gold dissolution depends on the rate of liberation of gold-bearing minerals. Dissolution of sulfide minerals in alkaline cyanide solutions proceeds in stages [22-28].

One of the promising solutions is the use of trichloroisocyanuric acid (TCCA) — a chlorine-containing organic compound with pronounced oxidizing properties capable of effectively destroying the sulfide shell and releasing encapsulated gold. Unlike traditional oxidizers (oxygen, hydrogen peroxide, hypochlorite, etc.), TCCA has high stability, low toxicity, ease of transportation and storage. In addition, when dissolved in an aqueous medium, it provides the release of active chlorine, which participates in the formation of soluble gold chloro-complexes.

Previous studies have shown the prospects of using chlorine-containing reagents in leaching schemes of refractory ores. However, the use of TCCA in heap or percolation leaching under industrial conditions in Kazakhstan has not been considered to date. This reagent may become a cost-effective alternative to more expensive and toxic oxidants, especially in combination with conventional sodium cyanide solutions.

In addition to selecting the reagent composition, an important direction in improving gold recovery efficiency is the improvement of the leaching scheme itself. Traditional heap irrigation methods have several disadvantages, including uneven distribution of the solution, evaporation, and seasonal limitations. In this regard, particular interest is attracted by the technology of controlled flows, based on the supply of the leaching solution through a double system of perforated pipes, ensuring uniform infiltration of the solution into the deeper layers of the ore and the possibility of year-round operation of the unit. Such a system makes it possible to significantly increase the degree of coverage of the ore mass, reduce solution losses, and stabilise process parameters.

The controlled flow technology can be used as the basis to build an innovative heap leaching scheme for sulfide and oxidized ores in combination with the use of TCCA and optimisation of irrigation parameters (reagent concentration, feed density, pause duration). Thus, the methodology proposed in this paper is aimed at solving three key tasks: increasing the efficiency of exposing gold-bearing minerals through the use of a chlorine-containing oxidizer (TCCA); developing a scheme for year-round leaching with uniform distribution of the solution inside

the ore mass; establishing optimal technological parameters (pH, concentration, duration, irrigation density) based on experimental data.

The scientific and practical significance of these studies lies in their potential implementation in technological schemes for processing refractory and low-grade ores, including operating enterprises with existing heap leaching infrastructure. This is especially important in the context of the transition of the Kazakhstani mining and metallurgical industry to the principles of sustainable development, resource conservation, and minimization of environmental impact.

The technological novelty consists of the use of trichloroisocyanuric acid as an oxidiser, which will significantly increase the degree of gold extraction into the pregnant solution.

The purpose of this paper is to optimize the process of gold leaching from gold-arsenic ore using an oxidizer in heap leaching and to compare the efficiency of leaching by the controlled flow method with vertically perforated pipes.

To achieve this goal, the following tasks were solved: a comprehensive study of the material composition and forms of occurrence of gold in initial samples of sulfide and oxidized ores; conducting agitation and percolation leaching with various concentrations of sodium cyanide and TCCA; and determining the influence of leaching duration and irrigation mode on gold recovery.

## MATERIAL AND METHODS

The object of the study was gold-arsenic ores of the Vasilkovskoye deposit: sulfide and oxidized samples. The study of the ore material composition included: X-ray fluorescence multi-element analysis, X-ray phase qualitative and quantitative analysis of the main components, chemical analysis of copper content. The chemical composition of ore samples from various horizons was determined using a Shimadzu 7000 atomic absorption spectrometer. X-ray fluorescence elemental analysis was performed using a combined Axios "PANalytical" wavelength dispersive spectrometer (Netherlands). X-ray phase analysis was performed on a D8-ADVANCE diffractometer manufactured by Bruker Elemental GmbH (Germany). Electron microscopic analysis was performed using a JEOL JXA-8230 microprobe analyzer manufactured by JEOL (Japan). Mineralogical analysis was performed using an Olympus BX 51 optical microscope.

Trichloroisocyanuric acid (TCCA) is an organic compound with the formula:  $C_3Cl_3N_3O_3$ . The main active ingredient in trichloroisocyanuric acid is chlorine. It makes up more than 90% of the total specific gravity of the finished product. When it is used as a leaching or oxidizing agent, chlorine promotes the transfer of gold into a productive solution to produce a water-soluble complex [11-13].



A study was performed to examine the effect of cyanide concentration in the solution and leaching duration on the main process parameters (gold recovery, reagent consumption) on the initial samples of sulfide and oxidized ore.

## RESULTS AND DISCUSSION

To determine the intensity of gold leaching, experiments were conducted at cyanide concentrations of 0.2% and 0.24%. The content of precious metals in the sulfide ore was Au – 2.0 g/t; Ag – 0.04 g/t, and in the oxidized ore: Au – 0.6 g/t; Ag – 0.16 g/t. According to mineralogical analysis, the main ore minerals are pyrite, and in the oxidized sample, also pyrite and iron hydroxides. The results of X-ray fluorescence analysis are presented in **Table 1**.

The results of X-ray fluorescence analysis (**Table 1**) indicate that the main elements are silicon, oxygen, aluminum, and sodium. They form the basis of quartz and albite. This is confirmed by the X-ray phase analysis (**Table 2**).

**Table 1** Results of X-ray fluorescence analysis of the initial ore sample

Element name															
O	F	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Cu	As
<i>sulfide</i>															
50,760	0,124	1,083	0,521	7,005	30,626	0,074	0,109	0,043	3,046	0,469	0,266	0,013	1,371	0,014	0,442
<i>oxidized</i>															
52,215	-	0,812	0,607	8,805	27,315	0,062	0,069	0,032	2,717	0,366	0,307	0,025	1,857	0,020	0,416

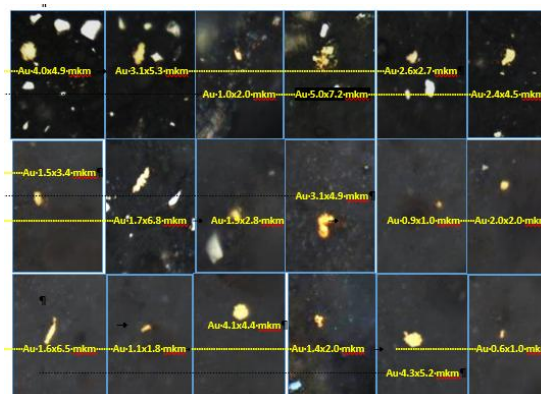
**Table 2** Results of X-ray phase analysis of initial ore samples

Component	Formula	Content, %	
		<i>sulfide</i>	<i>oxidized</i>
Quartz	SiO <sub>2</sub>	51,9	58,4
Microcline	KAlSi <sub>3</sub> O <sub>8</sub>	30,8	22,2
Albite	NaAlSi <sub>3</sub> O <sub>8</sub>	9,0	10,5
Muscovite	H <sub>2</sub> KAl <sub>3</sub> (SiO <sub>4</sub> ) <sub>3</sub>	7,0	6,5
Kaolinite	Al <sub>2</sub> (Si <sub>2</sub> O <sub>5</sub> )(OH) <sub>4</sub>	-	2,3
Grunerite	(Fe <sub>0.9</sub> Mg <sub>0.1</sub> ) <sub>7</sub> Si <sub>8</sub> O <sub>22</sub> (OH) <sub>2</sub>	1,3	-

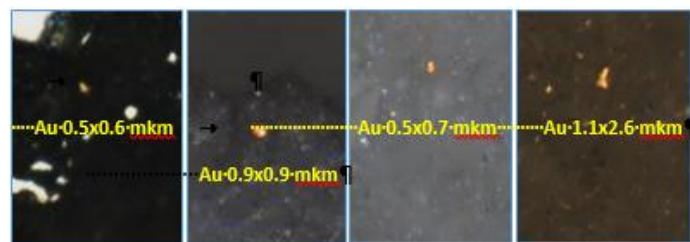
The data of **Table 2** show that sulfide and oxidized ores are mainly represented by silicate minerals: albite, microcline, quartz, kaolinite, muscovite.

A mineralogical analysis of sulfide and oxidized ore samples with an initial particle size of 89% – 10 μm (-0.01 mm) was performed to determine the forms of gold.

As a result, 36 gold particles were found in sulfide ore (**Fig. 1**), of which 30 particles were in free form – 83.33%, with Au sizes from 0.5 to 18.8 μm; in oxidized ore (**Figure 2**), four particles were in intergrowths with gangue – 11.11%, with Au sizes from 0.7 to 7.4 μm. The particle size is within: Au (0.5–18.8 μm), i.e. ultrafine-dispersed (0.1–1.0 μm) fine-dispersed gold (1.0–10.0 μm) and visible dusty gold (10.0–50.0 μm), (according to Petrovskaya's classification "Native gold").



**Fig. 1** Free gold particles in polystyrene



**Fig. 2** Gold particles in free state, covered with oxidation films, possibly of a goethite-limonite composition

Experiments on agitation leaching of gold-bearing ores were performed at a temperature of 25°C at an S:L ratio of 1:3, with ore samples of 200 g, a leaching time of 24 hours, with the addition of NaCN at concentrations of 1 g/L and 3 g/L and with preliminary oxidation by TCCA for 3 hours. The results of the experiments are shown in **Table 3**.

**Table 3** Results of chemical analysis of solutions after agitation leaching

№	Sample/Method	Au mg/l	Au cake, g/t	Au recovery, %
1	Oxidized ore 0,1% CN <sup>-</sup>	1,05	0,33	45,00
2	Oxidized ore 0,3% CN <sup>-</sup>	1,78	0,15	75,00
3	Sulfide ore 0,1% CN <sup>-</sup>	1,84	1,36	32,0
4	Sulfide ore 0,3% CN <sup>-</sup>	3,2	1,05	47,5
5	Oxidized + TCCA + CN <sup>-</sup> - 0,3%	1,78	0,14	76,67
6	Sulfide + TCCA + CN <sup>-</sup> - 0,3%	3,8	0,80	60,0

Thus, the studies conducted on the selection of sodium cyanide and oxidizer concentrations showed high efficiency both for cyanidation and with the use of the TCCA oxidizer.

Studies on percolation leaching of sulfide and oxidized gold-bearing ore were performed using perforated pipes on a laboratory unit of IMOB JSC with samples of a certain particle size, each weighing 14.8–18 kg. The percolators were equipped with false bottoms and polyethylene vessels to collect the solutions after irrigation. Alkaline NaCN solutions (pH = 10) and 0.1% sodium cyanide were used as gold solvents to conduct experiments.

The optimal parameters of percolation (heap) leaching of ores, such as solvent concentration, irrigation density, and irrigation pauses, depend on the chemical and mineralogical compositions of the ore and are determined experimentally. The ore was crushed before loading into the percolator with the following fraction yields obtained, wt. %: - 50+30 - 9.3, -30+10 - 2.20; -10+5 - 3.75; 5+0 - 2.75. Tests were performed in two percolators. In the first one, the sulfide ore was treated before leaching with alkaline-cyanide solutions with a concentration of 0.3% CN<sup>-</sup> in the presence of an oxidizer at pH=10. In the second one, the oxidized ore was irrigated with alkaline-cyanide solutions with a concentration of 0.3% CN<sup>-</sup> in the presence of an oxidizer at pH=10.

The leaching solution was fed into the percolator from above and, after passing through the ore mass via perforated pipes, was collected in a storage tank. The leaching solutions were prepared in a receiving tank with a capacity of 5 m<sup>3</sup> and then pumped into perforated pipes with a capacity of about 10.0 m<sup>3</sup>, from which, through sprinkler devices (polyethylene perforated pipes) installed in the percolators, they flowed by gravity. The irrigation solution passed through the ore mass and accumulated in the receiving tank. Tail solutions, fully or partially replenished with solvent and made up with water to the required volume, were directed for repeated irrigation. The acidity adjustment was performed using a pH meter. The ore was saturated with moisture (water washing) for 24 hours before the start of leaching. The effect of cyanide concentration at constant irrigation density and pauses between irrigations on process indicators was studied in the initial stage of the process.

Clarified, pregnant process solutions were recycled for leaching after replenishment with reagent and make-up water or sent for further processing. The irrigation regime was as follows: five irrigations without solution discharge and a two-day pause.

The results (**Table 4**) show that, with increasing irrigation density, the leaching indicators improve by increasing leaching duration up to the extraction of 5–10% of gold: the Au concentration in the solution increases, and sodium cyanide consumption decreases. After that, the indicators deteriorate, the gold content in the solution decreases, and sodium cyanide consumption increases.

It should be noted that the degree of gold recovery per one irrigation and its overall extraction at the same number of irrigations increase with an increase in irrigation duration (**Table 4**). The gold concentration in the solution after leaching, however, decreases.

Percolation leaching, performed under optimal conditions at a concentration of 0.3% CN<sup>-</sup> in the presence of the TCCA oxidizer, with a two-day irrigation pause and an irrigation density of 20–30 dm<sup>3</sup>/t, made it possible to extract 53–62% of gold into solution within 30 days, respectively.

**Table 4** Effect of irrigation pause duration on the indicators of percolation gold leaching

τ leaching, days	τ irrigation pause, dm <sup>3</sup> /t	C <sub>Au</sub> in solution, mg/dm <sup>3</sup>		Gold recovery, %		Consumption NaCN, t/kg Au	
		sulfide	oxidize	sulfide	oxidize	sulfide	oxidize
5	2	0,57	0,30	7,0	8,5	1,75	3,33
10	2	0,635	0,486	15,0	27,0	1,57	2,06
15	2	0,745	0,729	17,12	40,5	1,34	1,37
20	2	0,878	0,88	20,18	48,99	1,14	1,14
25	2	1,08	0,96	24,83	53,33	0,93	1,04
30	2	1,25	1,12	28,74	62,2	0,80	0,89

Thus, the results of laboratory experiments demonstrated the efficiency of gold leaching from gold-arsenic ore with the use of an oxidizer compared to the chemical method. In terms of its material composition, the ore of the Vasilkovskoye deposit is a favourable raw material for the hydrometallurgical method. The use of trichloroisocyanuric acid (TCCA) as an oxidizer made it possible to modify the structure of the ore material. The introduction of active chlorine ensures the destruction of sulfide minerals and improves the gold extraction, as confirmed by an increase in the recovery of the precious metal.

The initial sulfide ore is refractory for processing by the agitation leaching method. Gold recovery during cyanidation of 0.1–0.3% of ore at a particle size of 90% -0.071 mm averages 32.0/47.0% (the gold content in the leaching cake is 1.36–1.05 g/t, respectively), and with the use of the oxidizer (TCCA), 60.0%.

The results showed that direct cyanidation at various concentrations extracts 45.0–75.0% of gold from oxidized ore, while in the presence of the oxidizer (TCCA), 76.67%.

Percolation leaching, performed under optimal conditions at a concentration of 0.3% CN<sup>-</sup> in the presence of the TCCA oxidizer, with a two-day irrigation pause and an irrigation density of 20–30 dm<sup>3</sup>/t, made it possible to extract 53–62% of gold into solution within 30 days, respectively. The development of a unit with a double system of perforated pipes, an inert substrate, and irrigation density control ensured uniform solution distribution and stability of the leaching process. Such a design is particularly effective when working with poorly filterable ores.

Thus, the developed approach using TCCA as an oxidizing agent in combination with cyanide leaching showed efficiency and technological feasibility. It can be adapted to different types of refractory ores, ensuring stable gold recovery rates and process stability.

## CONCLUSION

The results of laboratory experiments demonstrated the efficiency of gold leaching from gold-arsenic ore with the use of an oxidizer compared to the conventional chemical method. The introduction of trichloroisocyanuric acid (TCCA) ensured the destruction of sulfide minerals and improved gold extraction, as confirmed by higher recovery rates.

Experimental results showed that the application of TCCA increased gold recovery from refractory sulfide ores up to 60.0%, compared to 32.0–47.0% under standard cyanidation. For oxidized ore, direct cyanidation achieved 45.0–75.0% recovery, while the use of TCCA increased this value to 76.67%.

Percolation leaching under optimal conditions (0.3% CN<sup>-</sup> concentration, two-day irrigation pause, irrigation density of 20–30 dm<sup>3</sup>/t) with the addition of TCCA allowed the extraction of 53–62% of gold into solution within 30 days. The developed leaching unit with a dual pipe system and controlled irrigation density ensured uniform solution distribution and stable process performance.

Thus, the proposed approach using TCCA as an oxidizing agent in combination with cyanide leaching proved to be effective and technologically feasible. It can be adapted to various types of refractory ores, providing stable gold recovery and process sustainability.

**Acknowledgements:** This research was supported by a grant project of the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan, project AP22682778.

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