SCIENTIFIC ARTICLE
UDC 622.765.063
DOI: 10.56195/20793332_2024_6_125_131

НАУЧНАЯ СТАТЬЯ
УДК 622.765.063

DETERMINATION OF CONDITIONS FOR DIRECT CYANIDATION OF FLOTATION CONCENTRATES WITH DIFFERENT QUALITY CHARACTERISTICS

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Abstract: The study has established that flotation concentrates with different gold content obtained by processing iron-oxidized low-sulfide gold-copper ore have an almost identical chemical composition with the rock-forming elements. Changes in gold content correlate with changes in the concentrations of Cu, Pb, Zn, S, As, C – there is an increase in the content of these components from a flotation concentrate poor in gold to a flotation concentrate with a higher gold content. The main minerals of copper and iron have been determined, the main part of which is oxidized. Phase analysis showed that the main part of gold in concentrates is in free form, and intergrown with copper minerals as well. Laboratory studies determined equal optimum time for leaching gold with cyanide for all flotation concentrates, regardless of gold content. At the same time, the extraction of copper into the solution is about 13-20 %. Optimum concentrations of sodium cyanide have been determined. It is recommended to continue research for reducing the consumption of sodium cyanide and releasing by-products in the form of high-quality copper concentrate.

Keywords: flotation concentrate, extraction, cyanidation, concentration, leaching, kinetics

For citation: Nogaeva K. A., Myrzaliev B. M., Molmakova M. S., Turarbek A. Determination of conditions for direct cyanidation of flotation concentrates with different quality characteristics. *Mine Surveying and Subsurface Use*. 2024;(6):125-131. (In Russ.). https://doi.org/10.56195/20793332_2024_6_125_131.

ОПРЕДЕЛЕНИЕ УСЛОВИЙ ПРЯМОГО ЦИАНИРОВАНИЯ ФЛОТАЦИОННЫХ КОНЦЕНТРАТОВ С РАЗЛИЧНЫМИ КАЧЕСТВЕННЫМИ ХАРАКТЕРИСТИКАМИ

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Аннотация: Исследованиями определено, что флотоконцентраты с различным содержанием золота, полученные при переработке железоокисленной малосульфидной золото-медной руды, имеют практически идентичный химический состав породообразующих элементов. Выявлена корреляция между изменениями содержания золота и изменением концентраций Cu, Pb, Zn, S, As, C - увеличение содержаний этих компонентов от флотоконцентрата бедного по золоту к флотоконцентрату с более высоким содержанием золота. Установлены основные минералы меди, железа из которых основная часть находится в окисленной форме. Фазовым анализом определено, что основная часть золота в концентратах находится в свободной форме, также в сростках с минералами меди. Лабораторными исследованиями определено одинаковое оптимальное время выщелачивания золота цианидом для всех флотационных концентратов независимо от содержания золота. При этом извлечение меди в раствор порядка 13-20 %. Определены оптимальные концентрации цианида натрия. Для снижения расхода цианида натрия и выделения попутной продукции в виде высококачественного медного концентрата, рекомендуется проведение дополнительных исследований.

Ключевые слова: флотоконцентрат, извлечение, цианирование, концентрация, выщелачивание, кинетика

Для цитирования: Ногаева К. А., Мырзалиев Б. М., Молмакова М. С., Турарбек А. Определение условий прямого цианирования флотационных концентратов с различными качественными характеристиками. *Маркшейдерия и недропользование*. 2024;(6):125-131. https://doi.org/10.56195/20793332_2024_6_125_131.

Introduction

Gold is known to be an inert metal. Utilization of oxygen in gold cyanide leaching produces a water -soluble cyanide complex, therefore the amount of cyaniding reagent is a determining factor in gold leaching. To ensure optimal gold leaching, a certain amount of free cyanide in the pulp is necessary, which depends on the nature of the gold –bearing rock.

Gold cyanidation is slow, the leaching rate increases with time, but after reaching a certain value, its increase will slow down. The optimum leaching time and the reaction rate of gold with cyanide also depend on the nature of the gold-bearing rock [1-6].

Currently, gold recovery plants have methods and techniques that allow direct cyanidation of gold-containing concentrate with copper, iron, etc. minerals. The capabilities of such technologies are determined by the nature and magnitude of the depressant effect of copper minerals on the cyanidation process. The depressant property is characterized by: "cyanidity" and the reducing capacity of the studied material entering cyanidation process. Cyanidity also depends on the concentration of active (free) cyanide and the duration of leaching [7-10].

Studies have shown that cyanidation process at low sodium cyanide concentrations requires a longer leaching time, but ensures high gold extraction rates with lower total solvent consumption. Gold recovery plants when processing ores (concentrates) with cyanide properties, such as oxidized copper ores [11-14], use this method.

Research objective: to determine the conditions for cyanidation of flotation concentrates with different gold content, ensuring its maximum extraction.

Research object: flotation concentrates of enrichment of iron-oxidized low-sulfide gold-copper ores.

Research methods and materials

An Olympus BX51 microscope equipped with a SIMAGIS 2P-3C digital camera and specialized Mineral C7 software were used for a mineragraphic description of concentrates in briquetted and polished samples. The material and mineral composition was studied using the analytical complex of IVS JSC, equipped with a VEGA 3 LMU (TESCAN) scanning electron microscope with an INCA X-MAX energy-dispersive microanalysis system, as well as using a D2 PHASER X-ray diffractometer.

Fire assay and fire assay-atomic absorption analysis was performed to establish the gold content in the initial flotation concentrates.

In order to study the size-classification of gold, the studied products were sifted and the content of noble metals in each class was established.

Cyanidation of each type of concentrate was carried out in two parallel experiments under the following conditions: cyanidation time 72 hours; solid content in the pulp 25% by weight; sodium cyanide concentration 2 g/l; pH=10.5-11.5.

During the leaching process, the specified NaCN concentration was maintained by adding a concentrated sodium cyanide solution, and the pH was maintained by adding lime milk to the pulp. At the end of the experiment, the sodium cyanide consumption was calculated per ton of the initial material.

To record the kinetics of gold leaching during the experiment, intermediate samples of the solution were taken after 2, 4, 6, 8, 12, 18, 24, 36, 48 and 72 hours. The solutions were analyzed for gold and copper content. The optimum leaching time was determined based on the kinetics data.

After the end of the experiment, the solid precipitate was separated on a vacuum Nutsche filter, washed three times with fresh water until a neutral reaction, dried to a constant weight at a temperature of 105-110 °C and analyzed for residual gold content.

Discussion

The chemical composition of the flotation concentrates obtained from the original ore sample is presented in Table 1.

Table 1 / Таблица 1

The chemical composition of the flotation concentrates / Химический состав флотоконцентратов

Element / Элемент	Content, % / Содержание, %			
	Concentrate № 1 / Концентрат № 1	Concentrate № 2 / Концентрат № 2	Concentrate № 3 / Концентрат № 3	Concentrate № 4 / Концентрат № 4
Cu	1,32	1,35	1,17	1,12
Pb	0,1	0,06	0,04	0,024
Zn	0,19	0,07	0,051	0,025
Fe	28,5	28,5	29	28,7
S	0,67	0,3	0,23	0,12
Co	< 0,001	< 0,001	< 0,001	< 0,001
Ni	< 0,001	< 0,001	< 0,001	< 0,001
Mn	4,51	4,47	4,44	4,24
SiO_2	27,9	28,5	29,5	31,7
Al_2O_3	6,55	6,71	6,49	5,98
CaO	1,18	1,12	1,14	1,09
K_2O	2,07	1,98	2,03	1,95
Na_2O	0,38	0,35	0,36	0,38
MgO	0,65	0,3	0,27	0,26
Mo	0,0029	0,0021	< 0,002	< 0,002
As	0,032	0,022	0,013	0,004
Sb	0,0019	< 0,002	< 0,002	< 0,002
Hg	0,00012	0,00008	0,00004	0,000009
C	0,38	0,28	0,24	0,15
	Content, g/t / Содержание, г/т			
Au	42,3	33,1	22,5	8,79

Concentrates with different gold content have similar chemical composition of rock-forming elements. Thus, the SiO_2 content varies within 27.9 to 31.7%; Al_2O_3 5,98-6,55 %; K_2O 1,95-2,07 %; CaO 1,09-1,18 %. The iron and manganese content in the samples is practically equal: Fe (28.5-29.0%); Mn (4.24-4.51%).

An increase in gold content noticeably correlates with the changes in the concentrations of Cu, Pb, Zn, S, As, C - the content of these components increases with the increase of gold in the concentrate from poor to a concentrate with a higher gold content.

According to the granulometric composition (Table 2), more than 90% of the concentrates are represented by a size of less than 45 microns.

Table 2 / Таблица 2

Granulometric composition of flotation concentrates / Гранулометрический состав флотоконцентратов, полученных из исходной пробы, исследуемой руды

Grain size, mm / Классы крупности, мм	Concentrate № 1 / Концентрат № 1	Concentrate № 2 / Концентрат № 2	Concentrate № 3 / Концентрат № 3	Concentrate №4 / Концентрат №4
	Recovery, % / Выход, %			
0,071	2,89	0,93	2,81	6,90
-0,071+0,045	2,58	1,78	2,78	5,17
-0,045	94,53	97,28	94,42	87,92
Initial	100,00	100,00	100,00	100,00

Gold classification by size (Table 3) shows a high concentration of gold in the +45 microns class, which indicates the presence of large gold (more than 70 microns) in these products. The main part of gold is concentrated in the -45 microns class, its distribution in this product is 60-70%.

The results of X-ray phase analysis are presented in graphical form (Fig. 1) (See the color insert on page 66) as diffraction patterns where the main mineral phases are marked. The main mineral phases of the concentrates are quartz, clay-micaceous minerals, iron oxides (goethite, hematite), and minerals of the feldspar group. Sulfide minerals are represented by chalcopyrite, pyrite (marcasite), covellite, and less often bornite. Sphalerite, galena, bornite, and minerals of the fahl ore group are found as occasional particles. The total share of sulfide minerals decreases from the concentrate with a higher gold content (No. 1, 42.3 g / t) to a lower one (No. 4, 8.79 g / t) and is from 1.5% abs. (concentrate No. 1) to 0.4% abs. (concentrate No. 2). Graphite grains occurred as occasional particles.

The results of studies of copper phase composition (Table 4) show that the content of copper in the oxidized form is (80.3-85.2% rel.) and is represented by copper carbonates: malachite, azurite and a small amount of chrysocolla.

Primary copper sulfide (chalcopyrite) is 13.3-16.7% (rel.). Secondary sulfides are presented by covellite, chalcocite (Fig. 2, 3), less often bornite and are 1.3-3% (rel.).

Phase analysis of gold in concentrates is presented in Table 5.

As can be seen from the table, the main part of gold is in free form and intergrown with minerals (74.4 -78.9% rel.), 19.4-22.8% (rel.) of gold is associated with copper minerals.

The results of mineragraphic studies of concentrates showed that the size of free gold particles fluctuates within 100-120 microns, but the majority of the detected gold particles are 20 to 70 microns in size. Free gold particles are mostly of a dendritic shape, often elongated in one direction or, on the contrary, almost isometric (Fig. 2).

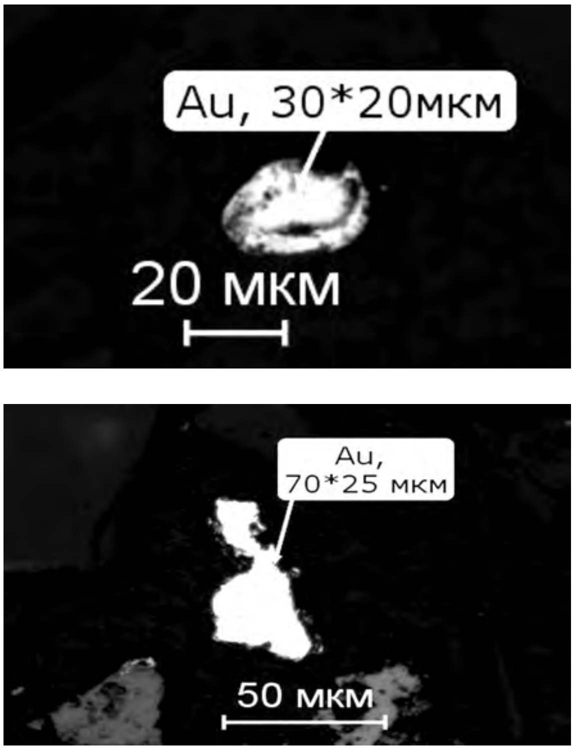


Fig. 2. Free gold particles in flotation concentrates. (Reflected light) /
Рис. 2. Свободные золотины в флотоконцентратах. (Отраженный свет)

The results of mineralogical analysis revealed that gold forms the main intergrowths with Fe hydroxides and, less frequently, with chalcopyrite.

Gold intergrown with iron hydroxides has a wide range of sizes: from fine inclusions measuring 2-3 µm to oval and dendritic ones measuring 20-50 µm (Fig. 3).

The results of phase analysis show that about 20% of gold is associated with copper minerals. Gold particles in the form of in-

Table 3 / Таблица 3

Gold classification by flotation concentrates Grain-size / Распределение золота по классам крупности флотационных концентратов, полученных из исходной пробы

Size, mm / Крупность, мм	Concentrate №1 / Концентрат №1		Concentrate №2 / Концентрат №2		Concentrate №3 / Концентрат №3		Concentrate №4 / Концентрат №4	
	Recovery, % / Выход, %	Au, g/t / г/т	Recovery, % / Выход, %	Au, g/t / г/т	Recovery, % / Выход, %	Au, g/t / г/т	Recovery, % / Выход, %	Au, g/t / г/т
+0.045	5.5	211.1*	2.7	402.1*	5.6	136.5*	12.1	28.8*
-0.045	94.5	32.54	97.3	22.8	94.4	15.76	87.9	6.04
Initial / Исходная	100.0	42.3	100.0	33.1	100.0	22.5	100.0	8.79
		Recovery, % / Выход, %		Recovery, % / Выход, %		Recovery, % / Выход, %		Recovery, % / Выход, %
+0.045		27.28		32.99		33.87		39.58
-0.045		72.72		67.01		66.13		60.42
Initial / Исходная		100.00		100.00		100.00		100.00

Note: *Au content is pre-calculated / Примечание: *содержание Au – расчетное

Table 4 / Таблица 4

Phase analysis of copper in flotation concentrates / Фазовый анализ меди в флотационных концентратах

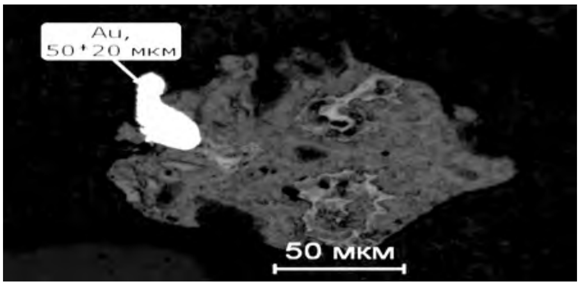
Metal speciation in the sample / Форма нахождения металла в пробе	Concentrate №1		Concentrate №2		Concentrate №3		Concentrate №4	
	Mass fraction, % / Массовая доля, %	Rel.% / Отн.%	Mass fraction, % / Массовая доля, %	Rel.% / Отн.%	Mass fraction, % / Массовая доля, %	Rel.% / Отн.%	Mass fraction, % / Массовая доля, %	Rel.% / Отн.%
Copper content in free oxidized minerals / Сод. меди в свободных окисленных минералах	0.71	53.8	0.70	53	0.62	52.9	6.15	54.9
Copper content in associated oxidized minerals / Сод. меди в связанных окисленных минералах	0.35	26.5	0.43	31.8	0.36	30.7	3.40	30.3
Copper content in secondary sulfides / Сод. меди во вторичных сульфидах	0.04	3,0	0.03	2.0	0.02	2.0	0.15	1.3
Copper content in primary sulfides	0.22	16.7	0.18	13.3	0.17	14,5	1.51	13.5
Initial / Исходная	1.32	100.0	1.35	100.0	1.17	100.0	1.12	100.0

Table 5 / Таблица 5

Phase analysis of gold in flotation concentrates / Фазовый анализ золота в флотационных концентратах

Form of gold occurrence / Форма нахождения золота	Conc. №1 / К-т №1		Conc. №2 / К-т №2		Conc. №3 / К-т №3		Conc. №4 / К-т №4	
	g/t / г/т	%	g/t / г/т	%	g/t / г/т	%	g/t / г/т	%
Free gold and gold in aggregates / Золото свободное и золото в сростках	29.85	74.6	21.94	74.4	15.28	76,0	5.43	78.9
Gold associated with copper / Золото ассоциированное с минералами меди	9.15	22.8	6.61	22.4	4.14	20.6	1.33	19.4
Gold coated with films and minerals soluble in hydrochloric acid / Золото, покрытое пленками и в минералах, растворимых в соляной кислоте	1.07	2.67	0.94	3.18	0.69	3.43	0.12	1.74
Initial / Исходная	40.0		29.5		20.1		6.88	

clusions in chalcopyrite have drop-shaped forms of precipitation and small sizes (5-10 μm) (Fig. 4). According to the electron microscopic study, native gold signs in concentrates have a constant silver admixture from 7.4 to 29.5%, which averages 13.6% Ag [15-16].



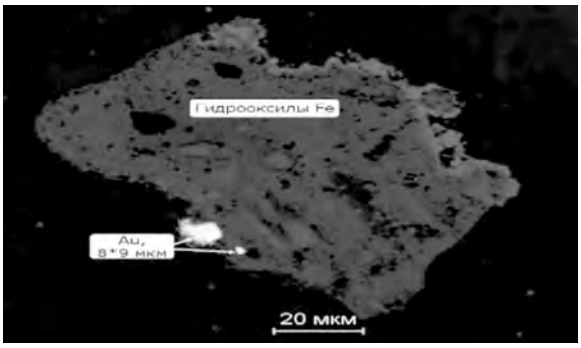


Fig. 3. Gold intergrown with iron hydroxides in flotation concentrates. Reflected light, nicols /
Рис. 3. Золото в сростках с гидрооксидами железа в флотоконцентратах. Отраженный свет, николи

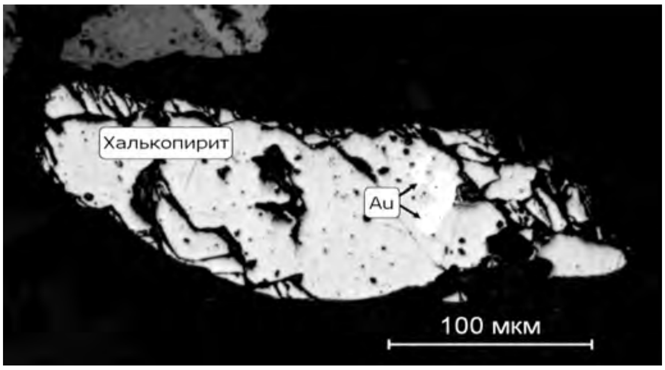


Fig. 4. Gold inclusions in chalcopyrite. Concentrate No. 1 (42.3 g/t), obtained from the original sample. Reflected light, nicol. /
Рис. 4. Включения золота в халькопирите. Концентрат №1 (42,3г/т), полученный из исходной пробы. Отраженный свет, николи

The results of studies of the optimum time for leaching gold from flotation concentrates with different gold contents are presented in Fig. 5 (See the color insert on page 66).

Gold leaching kinetics for each type of concentrate (average values from 2 parallel experiments (fig.6) (See the color insert on page 66) shows that copper extraction into the leaching solution varies from 13 % to 20 % (table 6).

According to the kinetic curves of cyanidation of concentrates with different gold content, the optimum leaching time for all products is 24 hours. The kinetics of copper leaching from concentrates with different gold content shows a constant increase in copper concentrations in the solution for each product during the entire leaching process. When cyanidating concentrates with different gold content, the copper concentration in the solution correlates with the copper content in the initial product. The maximum copper recovery into the solution is (19.63%), which corresponds to cyanidation of the concentrate with the maximum gold content (42.3 g/t).

To determine the optimal concentration of sodium cyanide when leaching flotation concentrates with different gold content the above method was used for cyanidation under the same conditions, except for the concentration of sodium cyanide (g/l: 0.5, 0.75, 1.0, 1.5). To record the kinetics of gold leaching, samples of the solution were taken in 2, 4, 6, 8, 12, 18 hours.

Table 6 / Таблица 6

Extraction of copper into the solution when leaching flotation concentrates with different gold content / Извлечение меди в раствор при выщелачивании флотоконцентратов с различным содержанием золота

Experiment code / Шифр опыта	Content of gold in the initial concentrate, g/t / Содержание золота в исходном концентрате, г/т	Content of copper in the initiate concentrate, % / Содержание меди в исходном концентрате, %	Extraction of copper into the solution, % / Извлечение меди в раствор, %
Ш 1	8,79	1,12	13,04
Ш 2	22,5	1,17	15,11
Ш 3	33,1	1,35	15,43
Ш 4	42,3	1,32	19,63

The optimum concentration of sodium cyanide for leaching flotation concentrates was chosen according to the data on the residual gold content in cyanidation tailings and the specific consumption of cyanide.

Fig. 7 - 10 graphically present combined diagrams of the dependence of gold extraction and sodium cyanide consumption on the specified concentration of NaCN for each concentrate. The histogram columns show gold extraction, and the graph shows the specific consumption of sodium cyanide per gram of gold.

The graphs show the expected trend towards increasing NaCN concentration required to achieve maximum gold extraction with increasing gold content in the initial concentrate.

The optimum cyanide concentrations were established based on the results of the studies presented in the diagrams of dependence of gold extraction into solution and sodium cyanide consumption on a given NaCN concentration for each concentrate.

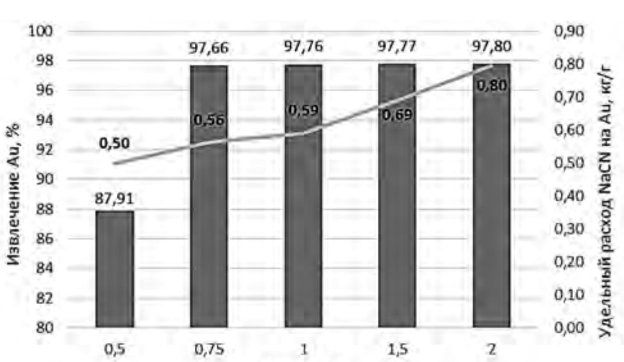


Fig. 7. Gold extraction into solution and sodium cyanide consumption depending on NaCN concentration for concentrate with Au content of 8.79 g/t /
Рис. 7. Извлечение золота в раствор и расход цианида натрия в зависимости от концентрации NaCN для концентрата с содержанием Au-8,79 г/т

The optimum sodium cyanide concentration for achieving maximum gold extraction when leaching flotation concentrates obtained from processing a complex iron-oxidized low-sulfide gold-copper ore is:

- 0.75 g/l for a concentrate with a gold content of 8.79 g/t;
- 1 g/l for concentrates with a gold content of 22.5 g/t and 33.1 g/t;
- 2.0 g/l for a concentrate with a content of 42.3 g/t.

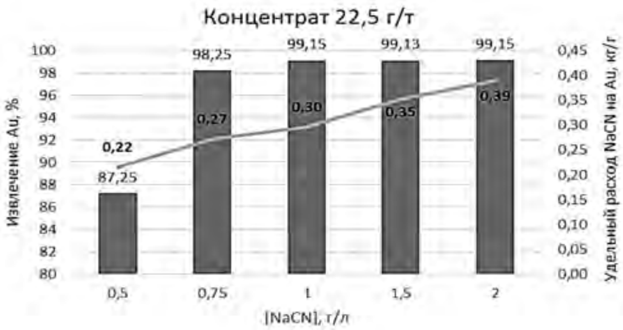


Fig. 8. Gold extraction into solution and sodium cyanide consumption depending on NaCN concentration for concentrate with Au content of -22,5 g/t /
Рис. 8. Извлечение золота в раствор и расход цианида натрия в зависимости от концентрации NaCN для концентрата с содержанием Au-22,5 г/т

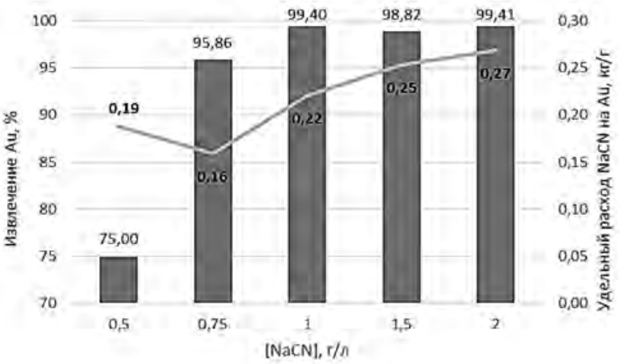


Fig. 9. Gold extraction into solution and sodium cyanide consumption depending on NaCN concentration for concentrate with Au content of -33,1 g/t /
Рис. 9. Извлечение золота в раствор и расход цианида натрия в зависимости от концентрации NaCN для концентрата с содержанием Au-33,1 г/т

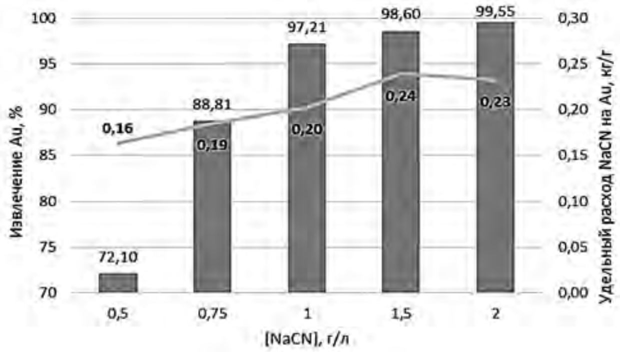


Fig. 10. Gold extraction into solution and sodium cyanide consumption depending on NaCN concentration for concentrate with Au content of 42,3 g/t /
Рис. 10. Извлечение золота в раствор и расход цианида натрия в зависимости от концентрации NaCN для концентрата с содержанием Au-42,3 г/т

Conclusion

1. The objects of the study are flotation concentrates with different gold content obtained during the processing of iron-oxidized low-sulfide gold-copper ore, they have almost identical chemical composition of rock-forming elements. An increase in the gold content noticeably correlates with the change in the concentrations of Cu, Pb, Zn, S, As, C – there is an increase in the contents of these components from a gold-poor flotation concentrate to a flotation concentrate with a higher gold content. The copper content varying from 1.12-1.35% is critical for the subsequent cyanidation of flotation concentrates. Phase chemical analysis shows that the main part of the copper is in the oxidized form (80.3-85.2% rel.)

2. According to the granulometric composition more than 90% of the concentrates are smaller than 45 microns. Gold classification by size shows a high concentration of gold in the +45 micron class, which indicates the presence of large gold (more than 70 microns) in these products. The main part of the gold is concentrated in the -45 micron class, its distribution in this product is 60-70%.

3. The results of phase analysis show that the main part of gold in concentrates (74.4 -78.9% rel.) is in free form and in aggregates, 19.4-22.8% (rel.) of gold is associated with copper minerals.

4. The optimal leaching time for all concentrates was determined. It is 24 hours regardless of the gold content.

5. The optimum concentrations of sodium cyanide were determined to be:

- 0.75 g/l for concentrates with a gold content of 8.79 g/t;
- 1 g/l for concentrates with a gold content of 22.5 g/t and 33.1 g/t;
- 2.0 g/l for concentrates with a content of 42.3 g/t.

6. To reduce sodium cyanide consumption and to isolate by-products in the form of high-quality copper concentrate, additional studies are recommended.

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Критерии авторства / Contribution:
Авторы заявляют о равном вкладе каждого в работу над статьей. / The authors participated equally in the writing and collection oh the material, as well as its processing.

Конфликт интересов / Conflict of interest:
Авторы заявляют об отсутствии конфликта интересов / The authors declare no conflict of interest.