International Journal of Mechatronics and Applied Mechanics
2025, Issue 22, Vol. II

SELECTIVE RECOVERY OF AU AND CU FROM OXIDIZED KALMAKYR ORES VIA GRAVITY CONCENTRATION

Doniyor Kholikulov[1,[0000-0001-6968-9297]], Ruslan Normurotov[2, [0009-0001-5889-7418]], Uktam Rakhmonov[1, [0009-0007-6327-5123]], Bakhtiyor Niyazmetov[3, [0009-0003-0672-7200]], Abdulaziz Yusupov[1, [0000-0002-7378-0023]]
[1]Almalyk branch of Tashkent State Technical University, 110100 Almalyk, 45 M.Ulugbek str., Uzbekistan
[2]JSC Navoi Mining and Metallurgy Company, Navoi, Republic of Uzbekistan
[3]JSC "Almalyk Mining and Metallurgical Plant" Republic of Uzbekistan, Almalyk, Republic of Uzbekistan
Email: kholikulov.d@tdtuof.uz

Abstract—This paper presents the results of research aimed at assessing the technological feasibility of extracting precious metals from oxidized copper ores from dump No. 39 at the Kalmakyr deposit. The total volume of these ores is 74.5 million tons, containing 171,000 tons of copper (average concentration of 0.23%), 31.6 tons of gold (grade 0.424 g/t), and 132.2 tons of silver (grade 1.77 g/t). The distribution of gold particles of varying sizes was studied, and the mineralogical forms of its occurrence were determined. The dependence of the content of the fraction smaller than 0.074 mm on the duration of grinding was established, which allowed for clarification of the specific features of ore preparation for enrichment. Gravity tests performed on a Knelson MD3 concentrator allowed us to determine the optimal parameters for centrifugal enrichment of oxidized ores: water consumption for fluidization varied from 1 to 5 l/min, the rotor speed was maintained at 1200 rpm, the duration of each test was 3 min, and the solid-to-liquid phase ratio was 1:3. Under these optimal conditions, the yield of the finished grade was 7.8%. Gold extraction reached 52.2%, copper – 12.45%, and silver – 6%. The study's results on the efficiency of gold extraction from cooling copper ore using Knelson centrifugal concentrators. The resulting concentrate can be used as a flux for smelting copper concentrates. The novelty of the study lies in its comprehensive assessment of the processability of oxidized ores from the Kalmakyr deposit, substantiating the effectiveness of their enrichment using centrifugal separation, and clarifying the relationships between the degree of grinding and gold distribution. Based on the results of the work, a technological scheme was proposed aimed at increasing the extraction of metals from oxidized copper ores. The implementation of this technology allows not only the creation of valuable components but also the creation of a product with additional value, contributing to the sustainable development of science.

Keywords: Oxidized copper ore, Kalmakir deposits, Mineralogical analysis, Ore crushing and grinding, Gravity concentration, Gold-bearing concentrate, Concentration tailings, Gold and silver recovery, Knelson centrifugal concentrator, Size class, Product yield.

1. Introduction

The Republic of Uzbekistan has significant mineral reserves: about 6 thousand tons of gold [1-3] and 40 million tons of copper. This allows the country to occupy leading positions in the world in terms of the volume of these resources, namely fourth and eleventh places, respectively. The Kyzylkum and Tashkent regions concentrate the bulk of gold deposits, while the Almalyk region primarily hosts copper deposits. The annual production volume in the country exceeds 100 tons of gold and 150 thousand tons of cathode copper. In the period from 2010 to 2019, Uzbekistan exported 687 tons of non-monetary gold, and in 2020, 100 tons.

The Government of Uzbekistan [4] forecasts that by 2026, the total annual gold production at the Navoi and Almalyk Mining and Metallurgical Plants (MMC) will exceed 155 t. At the same time, copper production at the Almalyk MMC is expected to increase to 150 thousand tons per year. In the future, the Tashkent region will become a key center of gold mining in Uzbekistan. Recent geological studies have confirmed the presence of new gold deposits in the

https://doi.org/10.17683/ijomam/issue22.v2.23

Tashkent region [1]. Currently, the Almalyk MMC primarily processes sulfide copper ores. Oxidized copper ores from the Kalmakyr deposit, both compliant and substandard, serve as an additional source for extracting copper, gold, and other valuable elements.

In copper-molybdenum ores of the Erdenetiin-Ovoo (Mongolia) and Kalmakyr (Uzbekistan) deposits, copper minerals demonstrate a tendency to oxidation processes, unlike molybdenite, which has increased resistance to external influences [5-6]. In the process of enrichment of complex ores of the Kalmakyr deposit, characterized by a high content of oxidized copper, flotation requires the use of special collecting reagents at the cleaning stage, as well as xanthates [7]. The developed process flow chart [8], based on the separation of copper concentrate and separate enrichment of sand and sludge fractions, is the basis for the creation of cost-effective unified methods for processing mining waste.

The use of gravitational separation of gold under centrifugal field conditions is a promising method for the enrichment of complex copper-bearing ores [9]. Considering the significant content of oxidized copper compounds in such ores, scientific works [10-12] often turn to hydrometallurgical extraction methods. However, studies [13-17] demonstrate the low economic efficiency of hydrometallurgy, due to the low yield of copper and increased consumption of sulfuric acid, in connection with which flotation enrichment is proposed. The use of complexing collectors, such as dithiocarbamates (sodium DEDTC and DBDTC), helps to increase the degree of metal extraction to 4.5% [18-20].

The study [19] proposed a technology for enriching mixed copper ores that allows obtaining a gravity concentrate with a gold content of 50.5 g/t with an extraction of 23.57%, as well as a copper concentrate containing 19.06% copper with an extraction of 66.7%. Copper-containing waste is often characterized by a high content of gold and silver, which makes it an additional source for the extraction of valuable metals. There are various technological processes for processing such materials [21—28].

2. Materials and Methods

To assess the effectiveness of gravity enrichment of gold-bearing ore, the GRG analysis method was used in [29-31]. The total gold extraction level exceeded 41%. The best extraction results were observed at the beginning of the process, when the particle size reached 1.6 mm, and at the end, with a particle size of 0.071 mm.

Researchers have developed a method for processing polymetallic ores that uses gravity concentration to recover gold [32-34]. When using the gravity method, gold recovery into the initial gravity concentrate varied from 27.57% to 36.48%, and silver—from 14.79% to 22%. The data obtained indicate the prospects of using the processing technology with preliminary gold separation by the gravity method.

Research object. The object of study was ores located in dumps №39 of the Kalmakyr deposit, located within 2-4.5 km from copper processing plant No. 2 (CPP-2). The total volume of these ores is 74.5 million tons, containing 171 thousand tons of copper (average concentration of 0.23%), 31.6 tons of gold (content of 0.424 g/t) and 132.2 tons of silver (concentration of 1.77 g/t). The dumps with oxidized ore are located at a distance of 2 to 20 km (Figure 1).

The presented work is devoted to the study of various forms of gold occurrence in oxidized copper ores mined at the Kalmakyr deposit. The main objective is to determine the possibilities of extracting copper compounds and precious metals using gravity concentration to process samples extracted from dump No. 39, whose confirmed reserves are estimated at 1.5 million tons of ore.

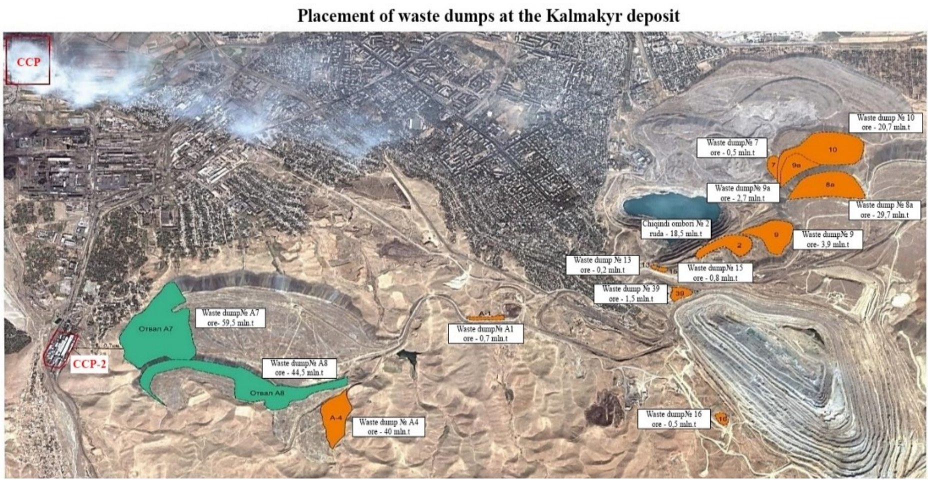


Figure 1: Location of dumps of the Kalmakyr deposit

3. Results and Discussion

The study of gold occurrence forms and phase analysis allowed us to determine the type of gold in oxidized copper ores of the Kalmakyr deposit using an electron microscope and the method of rational analysis. Electron microscopy revealed the presence of native gold, electrum, kuestellite, and petzite. Gold in the sample is mainly presented in the form of nuggets with a fineness varying from 700 to 1000 units, which characterizes it as low, medium, high, and very high purity gold. The average gold fineness is about 890 units. The main impurity is silver; sometimes tellurium is found. In addition to native gold, petzite and, less commonly, electrum and kuestellite were found in the oxidized ore. Most grains are small particles ranging in size from 0 to 2 µm (51.6%) (Figure 2). Grains ranging in size from 2 to 8 µm account for 18.56%. The maximum size of gold particles reaches 20 µm. "Large" metal particles, ranging in size from 15 to 20 µm, account for 29.84%. Free gold accounts for 13.86%.

Most of the valuable metal is in the form of completely closed inclusions (55.85%). Gold particles with an open surface or a degree of disclosure from 30 to 60% were not found. A significant proportion (29.84%) falls to rich, practically disclosed gold particles. In other categories, the content of noble metal particles ranges from 0.19 to 0.25%.

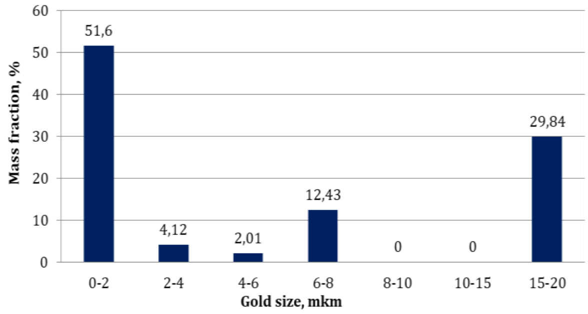
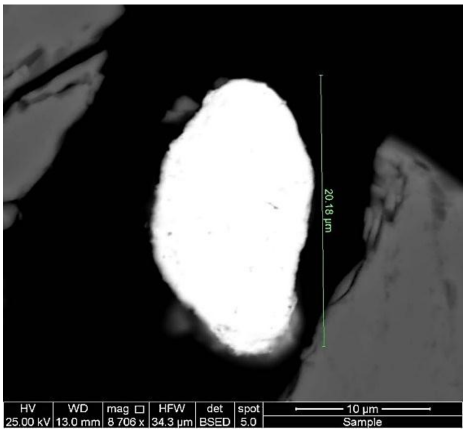
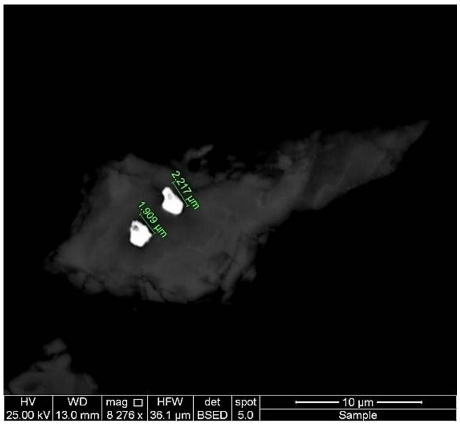


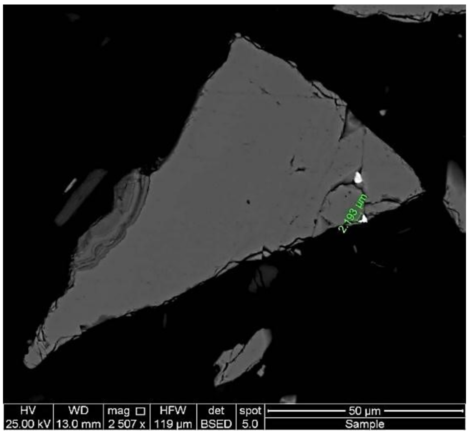
Figure 2: Distribution of gold particles by size in a sample of oxidized copper ore, dump No. 39



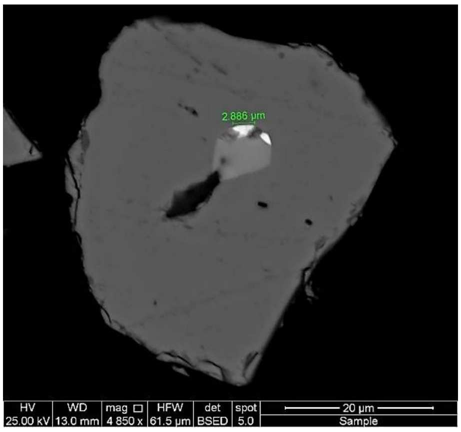
Free Au (gd), partially intergrown with $CuFeS_2$ (chp)



Inclusion of Au(gd) in Ag_3AuTe_2(pz)



Inclusions of Au (gd) and PbS (gn) in FeS_2 (py). FeS_2 in intergrowth with iron oxides (hox Fe)



Au (gd) in association with PbS (gn) and Cu_5FeS_4 (bo) as an inclusion in FeS_2 (py)

Figure 3: Forms of gold occurrence in minerals

In the studied sample, gold is present in the form of individual elements and granules with a partially exposed surface; about 26.71% of gold particles are capable of interacting with various solutions and chemical compounds. The main mineral accompanying gold is pyrite. A significant proportion of gold (50.36%) was found in the form of conglomerates with pyrite. Complexes of gold with chalcopyrite and iron oxides make up 10.34% and 6.29%, respectively. An insignificant amount of gold is found in compounds with other minerals. Electron microscopic analysis established the most typical examples of gold grains' relationship with various minerals (Figure 3). A detailed phase analysis of gold in an averaged sample was carried out to clarify the various forms of gold occurrence and how it interacts with ore minerals and host rocks. Rational analysis was carried out on a representative sample of material with a particle size of less than 2.0 mm. To more accurately determine the degree of gold extraction, the analysis included a step-by-step amalgamation, starting with the initial particle size, with further grinding of the material until the content of the -0.071 mm class was reached in 60% and 95%, respectively. Gold in minerals occurs in various forms: in native form (extracted by amalgamation), as visible inclusions, in a form accessible for cyanidation after preliminary treatment with hydrochloric acid, in combination with sulfides, and as minerals and quartz resistant to the effects of aqua regia (Table 1).

Amalgamation of material with a particle size of up to -2 mm ensures the extraction of only 5.88% of native gold present in the ore. Finer grinding, in which 60% of the particles are smaller than 0.071 mm, allows for an additional extraction of 7.84% of the valuable metal. A further increase in the degree of grinding to 95% of the -0.071 mm class significantly increases the extraction of native gold—by 17.65%. Thus, the total amount of native gold in a mixed sample of oxidized ore with a particle size of 95% of the -0.071 mm class does not exceed 31.37%. Gold in the form of open intergrowths makes up a significant part - 56.86% of the total content. It was found that a total of 88.24% of the precious metal is in a form that can be directly cyanided. Hard-to-recover gold in the ore, which is difficult to process with cyanides, is mainly in the form of acid-soluble layers (5.88%). The amount of gold contained in minerals and quartz resistant to the effects of aqua regia is estimated at 3.92%. Small gold particles enclosed within sulfide compounds make up 1.96% of the total volume. Consequently, the total share of "refractory" gold, which cannot be directly extracted by cyanidation, reaches 11.76%, which is equivalent to a gold content of 0.06 g / t.

Table 1. Results of phase analysis of gold in a sample of oxidized copper ore from dump № 39

Forms of gold occurrence and the nature of its connection with ore and rock-forming minerals	Distribution of gold	
	g/t	%
In the form of open intergrowths with ore and rock-forming components	0,29	56,86
Total in cyanidable form	0,45	88,24
Free, extractable by amalgamation at a size of -2.0 mm	0,03	5,88
Free, extractable by amalgamation with regrinding to a size of 60% -0.071 mm	0,04	7,84
Free, extractable by amalgamation with regrinding to a size of 95% -0.071 mm	0,09	17,65
Total free gold with a clean surface	0,16	31,37
In acid-soluble films	0,03	5,88
Finely disseminated in sulfides	0,01	1,96
Finely disseminated in minerals insoluble in aqua regia and quartz	0,02	3,92
Total	**0,51**	**100,00**

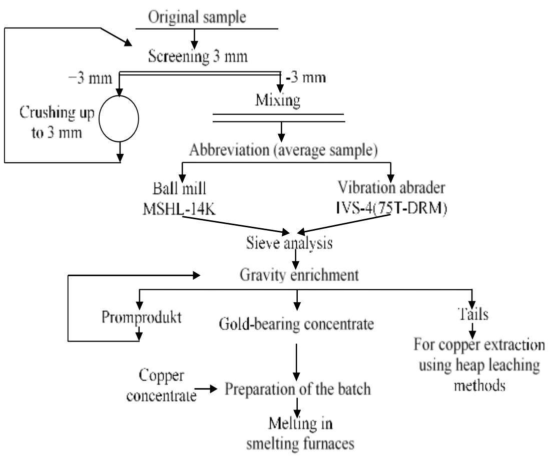


Figure. 4. Technological scheme of metal extraction from oxidized copper ores of the Kalmakyr deposit

Based on these data, it can be stated that oxidized copper ore from dump No. 39 of the Kalmakyr deposit (Almalyk MMC JSC) is of interest for gravity enrichment. However, the increased copper concentration (0.47%) may complicate the use of this technology.

Experimental methodology. The gravity concentration method is widely used in the mining industry worldwide to extract useful minerals and components from ores and their processing products. Before conducting gravity studies using screw and centrifugal separators, the parameters of the corresponding equipment were carefully analyzed [35-38]. The standard methodology [39-43] was used to study the possibility of extracting metals from process samples of dump No. 39 of oxidized copper ores of the Kalmakyr deposit using the gravity concentration method. Laboratory experiments were carried out using the process flow chart developed for extracting metals from oxidized copper ores of the Kalmakyr deposit (Figure 4).

To prepare for analysis, 100 kg samples were selected, which were then crushed to achieve a fraction with a particle size of 70% less than 0.074 mm (200 mesh). Grinding was carried out using a ball mill MShL-14K, and the duration of each experiment was from 4 to 6 min. After gravitational enrichment in a screw separator, the obtained products were separated by sedimentation and filtration. The liquid component was dried in a laboratory drying cabinet SNOL-3.5.3-I41 at a temperature of 105-110 °C. After drying, the residues were manually crushed in a porcelain mortar. Then, abbreviated analytical samples weighing 100 g were collected, which were subsequently crushed in a vibratory grinder IVS-4 (75T-DRM) and hermetically packed for subsequent analysis.

The elemental composition of the samples was determined by chemical analysis, in accordance with the MVI O‘z O‘U 0501:2010 method, using an Analyst 200 spectrometer. In addition, semi-quantitative spectral analysis was performed with the BRA-135F X-ray fluorescence spectrometer.

Knelson equipment is highly respected among mining enterprises due to its durability, ease of use, and noticeable improvements in metallurgical processes. Knelson concentrators, operating in a periodic unloading mode, are leaders among centrifugal gravity devices used in this area. Feed fluidization creates optimal conditions for material separation, ensuring process stability and reducing equipment wear from abrasive particles. Continuous discharge concentrators effectively separate a significant portion of fine particles from the incoming material and are not subject to clogging, which distinguishes them from other centrifugal concentrators.

Knelson concentrators are recognized worldwide and have been installed on more than eight types of processed ores (gold-bearing sulfides, tin, tungsten, talc, scrap metal, ferrochrome, copper, and chromite). Their advantages include low energy consumption, low capital and operating costs, and a small footprint, allowing the technology to be integrated into existing systems to improve recovery.

Such concentrators are integrated into existing production lines and are characterized by high productivity relative to the occupied volume. The concentration unit can be implemented in a unique dual design, allowing two different concentrate streams to be obtained simultaneously. Separation of primary and secondary concentrates allows for individual processing of each of them to achieve maximum process efficiency.

In laboratory conditions, gravity enrichment experiments were conducted on a Knelson MD3 concentrator with various process parameters. To optimize the fluidization water consumption based on the analysis of the target component content in the enrichment products, experiments were conducted under the following conditions: the water consumption for fluidization varied from 1 to 5 l/min, the rotor speed was maintained at 1200 rpm, and the duration of each test was 3 min (Figure 5). The best indicators were recorded at a water consumption rate of 3 l/min.

Water for fluidization creates a "pseudoiquidized layer" in the concentrator bowl. At low water consumption, light minerals are not washed out, and the concentrator begins to take in a lot of foreign material. At a water consumption of 2.5-3.0 l/min, the concentrate yield is 4.8% and the Au content in the concentrate reaches 2.5 g/t. A further increase in water consumption leads to an increase in the product yield, but selectivity decreases, and some heavy minerals are carried away to the tail.

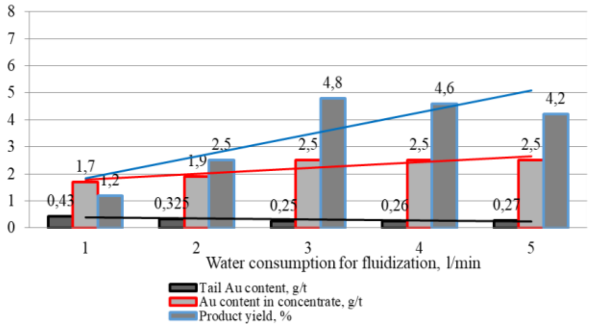


Figure 5: Results of determining the optimal water flow rate for fluidization

The obtained analysis results (Figure 6, 7) were subjected to analytical processing. Optimum indicators were observed with the following parameters: the volume of water used for fluidization was within 3.0 l/min, the rotor speed was half of the maximum (50%), and the solid-to-liquid phase ratio was 1:3. Under these optimal conditions, the yield of the finished class was 7.8%. At the same time, gold extraction reached 52.2%, copper—12.45%, and silver—6%.

At low rotor speeds (g-force), heavy ore grains go into tails, and lighter minerals are drawn into the concentrate. At too high a speed, concentrate quality improves, but the equipment becomes clogged, and losses in the drain increase. G-force 800 rpm is optimal for most oxidized ores, while the maximum gold is extracted into concentrate.

The results of the conducted studies confirm the efficient extraction of gold from oxidized copper ores using centrifugal concentrators. When designing a technological process for processing such ores, it is recommended to include gravity enrichment carried out on Knelson MD3 concentrators.

An alternative method of processing oxidized copper ores based on gravity enrichment allows obtaining a product containing gold and copper suitable for further use. Recently, the issue of processing gravity concentrates directly on site has become acute.

This phenomenon is due to the following: the cost of transporting raw materials containing precious metals has increased significantly, and existing hydrometallurgical methods of processing concentrates do not extract precious metals.

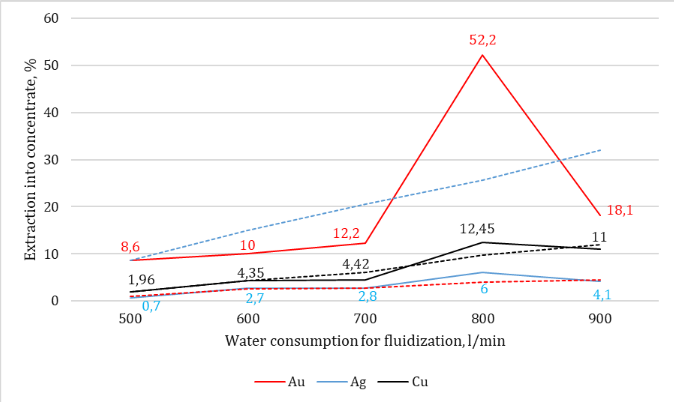


Figure 6: Dependence of gold, silver, and copper extraction into finished concentrate on the rotation speed of the Knelson MD3 concentrator rotor

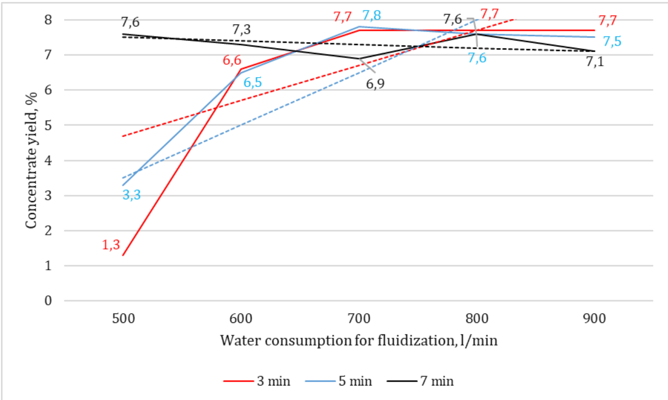


Figure 7: Dependence of concentrate yield on the duration of the process

It is a mistake to assume that the higher the G-force value, the more effective the apparatus is for extracting fine minerals. All this leads to an increase in the cost of gold production and a decrease in profits. Of all the known methods for processing concentrates containing precious metals, the pyrometallurgical method is the most suitable. The essence of this method is the collection of precious metals in a collector. This method allows, with a minimum of costs, to obtain a product with a gold content of 70-90%, in which gold and silver are concentrated. As a rule, this product can serve as a collector (flux) during the smelting of copper concentrates in the furnaces of JSC Almalyk MMC [44-49]. The use of this process flow chart will lead to an increase in gold production volumes. The product of gravity enrichment containing gold and copper during the smelting of copper concentrates will completely pass into matte and be further extracted.

The test for each parameter was carried out in 5-6 experiments, and the obtained data showed that the error of the experiments does not exceed 1%. In most cases, Student's t-test is used to determine the statistical significance of differences in average values. It is usually used both in cases of comparing independent samples and when comparing related populations [50-53]. For statistical processing of the obtained results, the following main numerical characteristics were calculated.

- arithmetic mean value of parameters [54]:

$$\mu = \overline{a} = \frac{1}{n}\sum_{i=1}^{n} a_i ;$$

- deviation of individual measurements:

$$\Delta a = \overline{a} - a_i ;$$

- dispersion:

$$D_a = \sigma^2 = \frac{1}{n-1}\sum_{i-1}^{n}(a_i - \overline{a})^2 ;$$

- standard deviation:

$$\sigma = \sqrt{D_a} ;$$

- variation coefficient:

$$\upsilon = \frac{\sigma \times 100\%}{\mu} ;$$

From the results of the dispersion analysis of the metal extraction value (Table 2), it was established that when extracting metals from oxidized copper ores, with a probability of 0.9-0.999, deviations from the basic value of gold extraction of 52.2% can be obtained within ±1.21%, copper 12.45.3 ±8.41%.

Table 2. Results of dispersion analysis of metal extraction value

Indicators	Variance σ2	Standard σ	Student's coefficients, t_α						Variation coefficient, υ
			0,900	0,95	0,98	0,99	0,998	0,999	
Au recovery	1,21	1,1	1,71	2,06	2,49	2,78	3,45	3,72	1,15
Cu recovery	8,41	2,9	1,7	2,04	2,46	2,75	3,39	3,43	5,94

The obtained data indicate the potential of using a centrifugal concentrator for oxidized copper ores. The implementation of this technology at enterprises such as JSC Almalyk MMC can lead to a significant reduction in copper production costs by reducing the need for purchased fluxes. In addition, an increase in gold extraction volumes will increase the profitability of ore processing and strengthen the company's position in the precious metals market.

The Knelson MD3 concentrator is a laboratory model, and the obtained results are used to justify the technological scheme of processing oxidized copper ores, select parameters, evaluate metal extraction, and prepare for the transition to industrial concentrators. On an industrial scale, the Knelson KC-XD (Extra Duty) or Concentrator CVD (Continuous Variable Discharge) is used, with a capacity of 300-6000 t/min and higher.

4. Conclusions

The results of the conducted studies showed the possibility of gold extraction from oxidized copper ore using Knelson centrifugal concentrators. The optimal process parameters are fluidization water consumption - 2.5-3 l/min, rotor speed - 800 rpm, process duration - 5 min, and solid-to-liquid phase ratio - 1:3. Under these optimal conditions, the yield of the finished class was 7.8%. Gold extraction into concentrate will be 52.2%. The resulting concentrate contains 2.87 g/t of gold and can be used as a flux in the smelting of copper concentrates.

Thus, the proposed method of processing oxidized copper ores using gravity concentration is a promising direction for increasing the efficiency and profitability of mining and metallurgical enterprises. The implementation of this technology will allow not only the extraction of valuable components but also the creation of a product with additional value, contributing to the sustainable development of the industry.

References

[1] Doniyor, K., Shokhrukh, K., Khaydaraliev, K., Olmos, B., Tuymurod, K., Orif, A., & Abdulaziz, Y. (2025). Application of ozone for the treatment of process solutions and wastewater in copper production. *International Journal of Mechatronics and Applied Mechanics*, *1*(19), 193–197. https://doi.org/10.17683/ijomam/issue19.22

[2] Kholikulov, D. B., Yakubov, M. M., Mukhametdzhanova, Sh. A., & Bekbutaev, A. N. (2022). Development of technology for extracting metals from process solutions by ion flotation. Tsvetnye Metally, 2022(6), 19–24. https://doi.org/10.17580/tsm.2022.06.01

[3] Ganbaatar Z., Zimin A. V., Solovieva L. M., Nazarov Yu. P. Improvement of copper-molybdenum ore enrichment technology at the Erdenetiyn-Ovoo deposit. Mining Journal 2010, No. 10. P. 34-37. https://www.rudmet.ru/journal/451/article/3950/

[4] Nakhaei F., Iranmajad M. Investigation of effective parameter's for molybdenite recovery from porphyry copper ores in industrial flotation circuit // Physicochemical Problems of Mineral Processing. 2014. Vol. 50(2). P. 477–491.

[5] Nazarov, Yu. P. Finding ways to improve the quality of copper concentrates during the enrichment of copper-molybdenum ores at existing plants. Mining Journal 2014, No. 11. P. 49-55. https://www.rudmet.ru/journal/1360/article/23340/

[6] Qiao Chena, Hong-ying Yanga, Lin-lin Tonga, Hui-qun Niua, Fu-sheng Zhang, and Gui-min Chen. Research and application of a Knelson concentrator. A review // Minerals Engineering. 2020, vol. 152, article 106339. DOI: https://doi.org/10.1016/j.mineng.2020.106339

[7] Morozov, Yu. P. Increasing the complexity of using sulphide ores based on additional gold extraction. – Ekaterinburg: Fort Dialog-Iset, 2015. – 61 p.

[8] Senchenko A. Y., Fedotov K. V., Chanturiya V. A. Process flowsheet for Udokan copper ores // Proceedings of the XXIX International Mineral Processing Congress. – Moscow, 2018. P. 2113–2121.

[9] Sundar S. Sombhatla, Ashish Kumar, Kiran Kr. Rokkam, Sheeba M., Akhilesh Shukla. In-house copper sulphate extraction from gold purification cake at Hindustan Zinc refineries // Proceedings of the XXIX International Mineral Processing Congress. – Moscow, 2018. P. 2876–2886.

[10] Yang Li, Yaping Liu, Yuhui Fu, Ziliang Liu, Peilong Wang, Jun Yin, Jue Kou, Chunbao Sun, Wanxiang Liu. Enhanced leaching of copper from refractory oxidized copper ore by calcium fluoride: Behavior and mechanism, Green and Smart Mining Engineering, Volume 1, Issue 1,

2024, Pages 85-95, https://doi.org/10.1016/j.gsme.2024.03.006

[11] Karnaukhov S. N., Plyasovitsa S. S., Ivanova N. V. Study of flotation technology of copper ores from a skarn deposit // Ore dressing. 2018. No. 2. P. 19–22. DOI: https://doi.org/10.17580/or.2018.02.04

[12] Yufan Mu, Yongjun Peng. The effect of saline water on copper activation of pyrite in chalcopyrite flotation // Minerals Engineering. 2019. Vol. 131. P. 336–341.

[13] Chipfunhu D., Bournival G., Dickie S., Ata S. Performance characterization of new frothers for sulfide mineral flotation // Minerals Engineering. 2019. Vol. 131. P. 272–279.

[14] Ghislain Bournival, Yeo Cheon Kim, Imtiaz Shah, Sayed Janishar Anzoom, François Guillard, Seher Ata, Novel application of X-ray characterization techniques in froth flotation for the study of bubble clusters, Minerals Engineering, Volume 215, 2024, 108787, ISSN 0892-6875, https://doi.org/10.1016/j.mineng.2024.108787

[15] Bao Guo, Yongjun Peng, The interaction between copper species and pyrite surfaces in copper cyanide solutions, International Journal of Mineral Processing, Volume 158, 2017, Pages 85-92, ISSN 0301-7516, https://doi.org/10.1016/j.minpro.2016.11.021

[16] Matveeva, T. N., Chanturia, V. A., Gromova, N. K., Lantsova, L. B. New compositions of reagents for the extraction of fine gold from enrichment waste. Mining Journal. 2019, No. 12, 10.17580/gzh.2019.12.10. https://www.rudmet.ru/journal/1885/article/32022/

[17] Matveeva T. N., Ivanova T. A., Getman V. V., Gromova N. K. New flotation reagents for the extraction of micro- and nanoparticles of noble metals from refractory ores // Mining Journal. 2017. No. 11. P. 89–93. DOI: https://doi.org/10.17580/gzh.2017.11.16

[18] Hassan Oumesaoud, Rachid Faouzi, Khalid Naji, Intissar Benzakour, Hakim Faqir, Rachid Oukhrib, and Moulay Abdelazize Aboulhassan. Enhancing flotation of oxidized copper ores through the integration of artificial neural networks and the design of experiments approach for process optimization, Case Studies in Chemical and Environmental Engineering, Volume 11, 2025, 101064, ISSN 2666-0164, https://doi.org/10.1016/j.cscee.2024.101064.

[19] Strizhko L.S., Normurotov R.I., Kholikulov D.B. Study of the process for gold hydrochlorination in gold-containing magnetic fraction processing // Russian Journal of Non-Ferrous Metals. 2009. Vol. 50, Iss. 5. P. 449–451. DOI: https://doi.org/10.3103/S1067821209050046

[20] Abols, J. A., and P. M. Grady. 2006. Maximizing gravity recovery through the application of multiple gravity devices. Accessed December18. 2023. https://citeseerx.ist.psu.edu

[21] Zhang Ch. Experimental and computational insights into the selective adsorption mechanism of a novel flotation reagent 4-amino-5-mercapto-1,2,4-triazole on chalcopyrite surface // Proceedings of XXIX International Mineral Processing Congress. Moscow, 2018.

[22] Surimbayev, B., Bolotova, L., Akcil, A., Yessengarayev, Y., Khumarbekuly, Y., Kanaly, Y., Akzharkenov, M. Gravity Concentration of Gold-Bearing Ores and Processing of Concentrates: A Review. Mineral Processing and Extractive Metallurgy Review. (2024). https://doi.org/10.1080/08827508.2024.2395824

[23] Strizhko L. S., Normurotov R. I., Kholikulov D. B. Investigations into extracting gold from gold-containing magnesium fraction by chlorination // Russian Journal of Non-Ferrous Metals. 2009. Vol. 50, Iss. 4. P. 348–352. DOI: https://doi.org/10.3103/S1067821209040075

[24] Balatovic M. Handbook of Flotation Reagents: Chemistry, Theory, and Practice. Flotation of Sulfide Ores. — Elsevier. 2007. — 445 p.

[25] Kholikulov, D. B., Normurotov, R. I., Shonazarov, M. I. Extraction of precious metals from the magnetic fraction of gold processing plants by chlorination. Tsvetnye Metally, 2025, № 1. Pp. 26-32. DOI: https://doi.org/10.17580/tsm.2025.01.04

[26] Bulut G., Ceylan A., Soylu B., Goktepe F. Role of Starch and Metabisulfite on Pure Pyrite and Pyritic Copper Ore Flotation // Physicochemical Problems of Mineral Processing. 2011. Vol. 48(1). P. 39–48.

[27] Gerasimenko L.A., Logovskaya G.V. Features of the technology for processing off-balance ore of the Kalmakyr deposit. Mining magazine. 2023, No. https://doi.org/10 10.17580/gzh.2023.10.06

[28] Surimbaev B.N., Kanala E.S., Bolotova L.S., Shalgimbaev S.T. Evaluation of gravity enrichment of gold-bearing ore – GRG. Mining sciences and technologies. 2020;5(2):92-103. DOI: https://doi.org/10.17073/2500-0632-2020-2-92-103

[29] Study of pyrite oxidation with chlorine dioxide under mild conditions / Z.Dong, Y.Zhu, Y.Han, X.Gu, K.Jiang // Minerals Engineering. 2019. Vol. 133. P. 106-114. DOI: https://doi.org/10.1016/mineng.2019.01.018

[30] Jones T., Foster A. 25 International Mineral Processing Congress, Brisbane, 6–10 Sept., 2010. Australia Inst. Mining and Met., 2010, c. 859–869.

[31] Yakubov, M.M., Yoqubov, O.M., Kholikulov, D.B., Maksudhodjaeva, M.S. Depletion of converter slags to waste in the Vanyukov furnace during pyrometallurgical copper production at JSC Almalyk MMC, Kompleksnoe ispolzovanie mineralnogo syra, 2024, 331(4), pp. 60-68.

[32] Agorhom, E.A.; Owusu, C. The Effects of pulp rheology on gravity gold recovery in free milling gold ore of the Tarkwaian systems of Ghana. *Miner. Process. Extr. Met. Rev.* 2020, 1-6.

[33] Tursunbayev, S., Turakhodjayev, N., Mardanokulov, S., Zokirov, R., & Odilov, F. (2023). The effect of lithium on the mechanical properties of alloys in the Al-Li system. E3S Web of Conferences, 390. https://doi.org/10.1051/e3sconf/202339005046

[34] Bode, P.; McGrath, T.; Eksteen, J. Characterizing the effect of different modes of particle breakage on coarse gangue rejection for an orogenic gold ore. Miner. Process. Extr. Met. 2020, 129, 35–48.

[35] Pryor, E. Mineral Processing; Elsevier: New York, NY, USA, 1965; p. 488.

[36] Shokhin V.N., Lopatin A.G. Gravity enrichment methods: Textbook for universities. - 2nd ed., revised and additional. - M.: Nedra, 1993. - 350 p.

[37] Marsden, J.; House, D. The Chemistry of Gold Extraction. Society for Mining, Metallurgy, and Exploration Inc.: Littleton, CO, USA, 2006; p. 650.

[38] Knelson T. M. Gravity Concentrator – for maximizing gold recovery. Available from: https://www.flsmidth.com/en-gb/products/precious-metals-recovery/knelson-semi-continuous-gravity-concentrator

[39] S. Sevgü Et Al. , "Concentration of an Oxidized Gold Ore By The Knelson Concentrator," 17th International Mineral Processing Symposium - IMPS 2022 , İstanbul, Turkey, 2022. Pp. 225-231. https://avesis.ogu.edu.tr/yayin/586e80e8-38a4-4f08-9caa-12e0bcb6e75b/concentration-of-an-oxidized-gold-ore-by-the-knelson-concentrator?utm_source=chatgpt.com

[40] Knelson Gravity Concentrators: maximized gold recovery & efficiency. https://im-mining.com/2025/03/26/knelson-gravity-concentrators-maximised-gold-recovery-efficiency/?utm_source=chatgpt.com

[41] Moosavi-Khoonsari, E.; Tripathi, N. Copper Anode Slime Processing with a Focus on Gold Recovery: A Review of Traditional and Recent Technologies. Processes 2024, 12, 2686. https://doi.org/10.3390/pr1212268

[42] Doniyor K., Shokhrukh K., Khaydaraliev K., Olmos B., Tuymurod K., Orif A., Abdulaziz Y. Application of ozone for the treatment of process solutions and wastewater in copper production (2025) International Journal of Mechatronics and Applied Mechanics, 1 (19), pp. 193 - 197, https://doi.org/10.17683/ijomam/issue19.22

[43] Moosavi-Khoonsari, E.; Tripathi, N. Gold Recovery from Smelting Copper Sulfide Concentrate. *Preprints* 2024, 2024091473.

[44] Tomine-Tech-Coperation. Technologies for Copper Anode Slime Treatment (TBRC). Available online: https://topmie.com/solution/technologies-for-copper-anode-slime-treatment-tbrc/

[45] Tursunbaev, S., Turakhodjaev, N., Odilov, F., Mardanokulov, S., & Zokirov, R. (2023). Change in wear resistance of alloy when alloying aluminum alloy with germanium oxide. *E3S Web of Conferences*, *401*. https://doi.org/10.1051/e3sconf/202340105001

[46] Tursunbaev, S., Umarova, D., Kuchkorova, M., & Baydullaev, A. (2022). Study of machining accuracy in ultrasonic elliptical vibration cutting of alloyed iron alloy carbon with germanium. *Journal of Physics: Conference Series*, *2176*(1). https://doi.org/10.1088/1742-6596/2176/1/012053

[47] Fei, C. Study on preparation and luminescence properties ofmonolayer MoS_2. International Journal of Mechatronics and Applied Mechanics, 1(20), pp. 287–294. https://doi.org/10.17683/ijomam/issue20.29

[48] Fan, Y., Chen, Y., Yao, F., Zhuo, H. Key structure optimization of spherical blowout preventer based on multiple regression analysis. International Journal of Mechatronics and Applied Mechanics, 2025(19), pp. 216–224. https://doi.org/10.17683/ijomam/issue19.25

[49] Kudrya, A. V., Sokolovskaya, E. A., Kodirov, D. F., Bosov, E. V., Kotishevskiy, G. V. On the necessity of taking into account the statistical nature of the objects using Big Data in metallurgy. CIS Iron and Steel Review — Vol. 23 (2022), pp. 105–112. DOI: https://doi.org/10.17580/cisisr.2022.01.19

[50] Berdiev, D.M., Yusupov, A.A., Umarova, M.A., Makhmudova, N.A. Decreasing Gear Wear by Improved Thermocyclic Treatment, (2023) *Russian Engineering Research*, 43 (1), pp. 52-54. https://doi.org/10.3103/S1068798X23020065

[51] Berdiev, D., Yusupov, A., Umarova, M., Ibodullaev, T. Improving wear resistance of steel products to unconventional heat treatment methods, (2020) *International Journal of Scientific and Technology Research*, 9 (2), pp. 2504-2509.

[52] Turakhodjaev, N., Akramov, M., Turakhujaeva, S., Tursunbaev, S., Turakhujaeva, A., & Kamalov, J. (2021). Calculation of the heat exchange process for geometric parameters. *International Journal of Mechatronics and Applied Mechanics*, *1*(9), 90–95. https://doi.org/10.17683/IJOMAM/ISSUE9.13

[53] Berdiev, D.M., Yusupov, A.A., Toshmatov, R.K., Abdullaev, A.K. Increasing Die Durability in Cold Stamping by Quenching with Intermediate Tempering, (2022) *Russian Engineering Research*, 42 (10), pp. 1011-1013. https://doi.org/10.3103/S1068798X23020065

[54] Dai, L., Li, B., Li, J., *et al.* A one-step mechanochemical method in preparing graphene materials from spent lithium-ion battery anode graphite for electrochemical application. *Carb Neutrality* 4, 12 (2025). https://doi.org/10.1007/s43979-025-00126-x