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INFLUENCE OF ORE PROCESSING BEHAVIOR ON HEAP-LEACH CYANIDATION AND AGITATION LEACHING EFFICIENCY

The study addresses efficiency of heap-leach cyanidation as function of processing properties of ore. The grain size composition, chemistry and mineralogy represent the main ore properties. The test ore samples contain up to 76% of aluminum and silicon oxides. The ore features a few impurities and a moderate amount of sulfide sulfur (0.6%). Assaying after preliminary gravity separation of gold shows that average Au content is 1.74 g/t (site 1) and 1.43 g/t (site 2). This research aims to analyze the processing properties of ore and assess expediency of heap-leach cyanidation of this ore. The representative samples for the heap leach tests are the primary sulfide ore. The lab-scale tests of agitation cyanidation of ore samples from different sites were carried out using bottle agitator. The scope of the analysis also embraced the influence of the ore size and cyanide concentration on the leaching efficiency. Furthermore, adsorption of gold from cyanidation solutions was also tested. The cyanidation products were subjected to atomic adsorption spectroscopy (solution) and assaying (cake).

Keywords: *gold, ore, cyanidation, extraction, heap leaching, production research*
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Introduction

The present-day gold deposits are mostly composed of small ore bodies with low content of the useful component and are located in hard-to-reach areas. The cost of the detailed exploration and full-scale processability research of such deposits, considering the required time and labor input, may be higher than the cost of the metal produced. In this regard, it is of the current concern to find effective technologies of mineral processing at low capital expenditures.

One of such technologies is the heap-leach cyanidation which enjoys increasingly wider application in the last decade.

In 1887 in Glasgow, John Steward McArthur first proposed to extract gold from ore using cyanide solutions [1]. Cyanidation process introduced in gold mining enabled a jump in the gold production. The first application of the heap leach method at a commercial scale was undertaken by Carlin Gold Mining Company in 1969 in the north of Nevada. After that, many universities initiated studies into the technology.

The first research papers covered by global citation databases appeared in 1974 [2] and mostly addressed gold and silver hydrometallurgy [3].

The advancement in science and technology spurred a breakthrough in this trend. Heap leaching is in acute demand in the modern geotechnology [4]. For another thing, heap leaching needs to be environmentally safe. The impact of heap-leach cyanidation on the wildlife has been studied [5]. The scientific centers in Great Britain [6], Mexico [7], China [8] and in other countries are engaged in development of alternative technologies for extraction of valuable components, including gold [9], from ore.

The ample research into the process of raw material preparation for heap leaching discuss application of HPGR technology to enhance leaching efficiency [10–11].

Much attention is paid today to the computer technologies and advanced software [12]. Both are applicable in prediction of metal recovery in heap leaching. Nonetheless, the modeling results sometimes disagree with the experimental data, which eventually may affect profitability of production.

Despite a variety of studies dealing with heap leaching, the basic industrial trend is the classic hydrometallurgy using cyanide solutions to extract valuable components [13–16].

This study aims to analyze processing properties of ore and to assess practicability of heap-leach cyanidation and agitation leaching. The heap leach testing included representative samples of primary sulfide ore taken in two different sites of one and the same deposit.

Research

The chemical composition of the test ore samples was determined from the silica content analysis of ore (**Fig. 1**). The content of noble metals was found from assaying.

The test ore composition represents aluminum and silicon oxides up to 76%. The moderate content of sulfide sulfur (0.6%) means that this is the lean sulfide ore. The total content of MnO, P_2O_5, TiO_2, Cd, Cu, Pb, Zn, Ba, Ni, Co, V_2O_5, Cr_2O_3 is less than 1%. The semiquantitative spectral analysis reveals no traces of such elements as Nb, Ta, Pt, Au, Te, Tl, Gd, Sb, As, Ce, Cd, U, Th, Hg and In.

The assaying shows a nonuniform distribution of gold in the test ore. The average gold content of the samples is 1.68 g/t (Eastern site) and 1.34% (Western site). The content of silver is less than 2 g/t.

The size grading and gold distribution per size grades are determined from the screen analysis of each site ore crushed to the size of –15, –10 and –5 mm. The results of the analysis are depicted in Fig. 1, where blocks 1 and 2 stand for the Eastern and Western sites, respectively.

Based on the size grading of the Eastern site ore, the maximum yield is shown by the size –5+2 mm and is 49.69%, the least yield is the size – 0.045 + 0 (2.1%). Regarding the Western site ore, the maximum yield is also in the size –5+2 mm and equals 47.12%, and the least yield is in the size –0.2+0.074 (2.18%). So, we can state that at the size of –5 mm, the yield of sizes capable to affect permeability of a heap leach pile (smaller than 0.2 mm) is insignificant, less than 7% in case of the Eastern site ore and is 10.6% in case of the Western site ore.

It is typical of the test samples that gold concentrates in the sizes of +0.2 mm. These sizes contain more than 90% of the whole metal. Accordingly, the leaching efficiency directly depends on the ore fragmentation size.

The occurrence forms of gold are found from the phase analysis of ore samples –2 mm in size and at the content of 95% of the size of –0.074 mm. Percentage of free gold in the Eastern site ore at the size of –2 mm and at the content of 95%

of the size of –0.074 mm is 42.76 and 77.05%, and percentage of leach-suitable gold is 76.7 and 94.53%, respectively. The minerals and quartz undissolved in the chlorazotic acid contain less than 4% of the metal. When the size of particles is decreased from –2 mm to the size of –0.074 mm at the content of 95%, percentage of free gold grows owing to dissociation of concretions and extra dissociation of gold. Percentage of free gold in the Western site ore at the size of –2 mm and at the content of 95% of the size of –0.074 mm is 61.15 and 78.01%, respectively, and the leach-suitable gold percentage is 74.1 and 92.9%. The minerals and quartz undissolved in the chlorazotic acid contain less than 7% of the metal. In both sites, when the size of particles is decreased from –2 mm to the size of –0.074 mm at the content of 95%, the increment in cyanidable gold results from the decrease in the gold content of films and sulfide associates.

The ore features a few impurities and a moderate amount of sulfide sulfur, which favors efficient application of heap-leach cyanidation of gold [17–18].

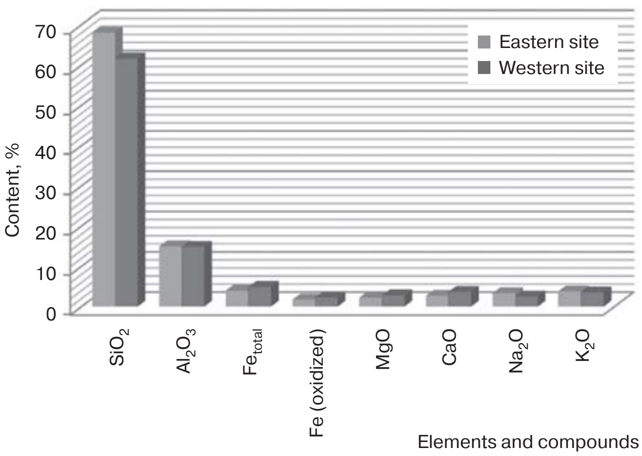

Fig. 1. Silica content analysis of ore

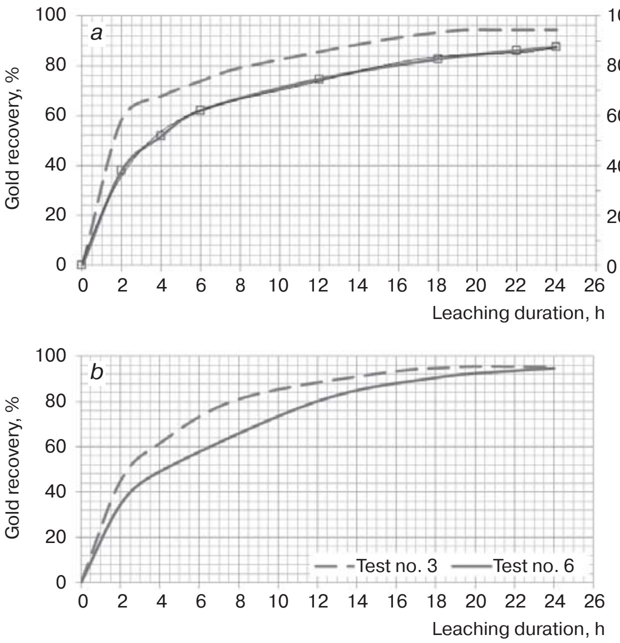

Fig. 2. Agitation leaching of ore

a—Eastern site; *b*—Western site

Agitation leaching of Eastern site ore

The processing property tests of the Eastern site ore included agitation leaching of particles –2 mm in size and particle of the size of –0.074 mm at the content of 95%, in the solution with cyanide concentration of 0.05%, 0.1% and 0.2%. Furthermore, adsorption of gold from cyanide leaching solution at coal feed of 10% of the liquid phase volume was tested.

The Eastern site ore may contain coarse gold such that its dissolution requires longer and more intense leaching. For proving effect of coarse gold on its extractability, the intense cyanidation tests were performed. The intense cyanidation regime ensures complete dissolving of coarse gold potentially present in the ore. By comparing the outcomes of the direct and intense regime leaching, it is possible to describe the influence exerted by gold coarseness on the leaching duration and on the gold recoverability.

Initial gold content of ore was determined in each test using the data of the agitation leaching balance. The leaching regime was the same in all tests: pulp density—40% of solid; pH pulp—10.5; cyanidation duration—24 h; particle size of –0.074 mm at the content of 95%. **Figure 2*a*** shows the ore cyanidation curves.

The agitation leaching results show that the Eastern site ore is suitable for leaching: gold recovery is more than 90% in case of the particle size of –0.074 mm at the content of 95%; the cyanide consumption ranges as 0.1–0.45 kg/t (considering the agent residue), and the lime consumption is around 1 kg/t.

The cyanidation tests at different concentrations of the solvent show that the gold recovery is independent of the cyanide concentration in the liquid phase of the pulp. The comparison of the direct leaching results and the data of adsorption of gold from the cyanide leach solution yields that the Eastern site ore has no adsorption activity.

The gold recovery in cyanidation of ore –2 mm in size is 72.07%, which is less by 4.63% than percentage of cyanidable metal from the phase analysis. This discrepancy is explained by the fact that coarse free gold undissolved in the agitation leaching is removed from the analysis at the stage of the metallurgical processing.

The gold recovery variation range of 87.33–95.69% is reflective of the presence of the coarse metal in the ore and points at the insufficient duration of leaching. This fact is also proved by the intense cyanidation tests. The curves in Fig. 2 illustrate the difference in the required duration of leaching for two similar samples. In test no. 3, the required leaching duration is 19 h, while in test no. 6, gold recovery in solution keeps active 24 h after agitation.

Agitation leaching of Western site ore

The agitation leaching tests of the Western site ore used the size grades of –2, –1 and of –0.074 mm at the content of 95%, the cyanide concentrations in the solution were 0.05, 0.1 and 0.2%. Furthermore, adsorption of gold from cyanide leaching solution at coal feed of 10% of the liquid phase volume was tested.

The Western site ore features a uniform distribution of gold, and the intense regime leaching is rejected therefore, and the initial gold content is assumed from the results of the gravity separation.

The agitation leaching tests of the Western site ore show that gold recovery in case of the particle size of –0.074 mm at the content of 95% is more than 93% at the consumption of cyanide of 0.1 kg/t (considering the residue) and lime of 0.97 kg/t.

At the cyanide concentrations in the range of 0.05–0.2%, gold recovery is the same. **Figure 2*b*** depicts gold recovery in cyanidation at the cyanide concentrations of 0.2% and 0.1% in tests nos. 3 and 6, respectively.

It follows from Fig. 2 that the cyanide concentration only influences the leaching dynamics while the gold recovery after 24 h of agitation is the same in both tests.

The hydrophysical characteristic of the test samples shows that the water content of ore lowers with the decreasing size of the particles. This is explained by the larger surface area in case of the decreased coarseness of the material and, accordingly, by much water consumed to moist the particle surface. The maximal velocity of leach solution permeation in ore decreases with the decreasing size of the material as many fine particles impede normal seepage of the solutions through the piles. Aimed to improve permeability of the piles, pelletizing of ore –5 mm in size was carried out in a dish-type pelletizer with addition of a binder. Adjustment of the pelletizing process parameters needs additional research using a larger ore sample from column leaching.

Ore leaching in columns 1.5 m high

The percolation-based leaching of ore was carried out in lab-scale columns 1.5 m high with a diameter of 150 mm. The test ore samples had weights of 40–50 kg. The test ore sizes were –5, –10 and –15 mm (for samples from both sites). The ore samples –10 and –15 mm in size were subjected to two parallel tests.

From practice and based on experimental sprinkling, the optimal sprinkling density is assumed as 200–250 l/(m^2×day). The test concentrations of cyanide in the sprinkling solution ranged as 0.05–0.1%. Caustic soda was used as an alkali protection at the concentration of 0.02%.

The Western site ore –5 mm in size was subjected to pelletizing. The additives were Portland cement and lime at the consumptions of 10 kg/t and 2 kg/t, respectively. The pellets were aged for 3 days. The tests were carried out on 10 lab-scale plants for heap leaching.

Crushed ore was placed in the columns and sprinkled with the solutions using the dozing pumps. The pregnant solution was collected at the column bottom and analyzed (gold, cyanide, pH). The leaching duration was from 50 to 75 days. The metal balance was estimated in each test from the data of tailings assaying and from the atomic adsorption spectroscopy of the solutions. Assaying of cyanidation cakes in all 10 tests shows an essential discrepancy between the parallel estimates. The bulk of gold was extracted, but some metal escaped dissolving yet. This mean that some gold (especially coarse particles) is insusceptible to heap leaching, including particles –5 mm in size. The gold content of the cakes was determined from assaying after preliminary concentration of gold by gravity.

Figure 3 illustrates leaching of ore from the Eastern and Western sites. **Figure 4** gives the bar charts of increment in gold recovery in sprinkling periods of 5 days.

The highest gold recovery is reached with the particle size of –5 mm: *81.99%* (Eastern site ore) and *80.99* (Western site ore). This size ore also features the highest leaching kinetics which is proved by the curves in Fig. 2. On the whole, the curves exhibit the same behavior in all tests, without jumps or drops, which means the ore possesses no adsorption activity.

The maximum Au concentration in the leaching solutions was 3.63 mg/l (test no. 10) and it drops after 6 days of sprinkling (down to 1 mg/l and lower). After 49–51 days of leaching, gold concentration is not higher than 0.036–0.073 mg/l in all test solutions.

The cyanide consumption was 0.29–1.07 kg/t, and the caustic soda consumption was 0.9 kg/t. The increased consumption of cyanide in test no. 1 (1.07 kg/t) is connected with water pre-sprinkling of the leach pile for the analysis of the hydrophysical characteristics and with lower pH as a consequence. The decelerated rate of gold recovery (as compared with test no. 2) is also the after-effect of water pre-sprinkling.

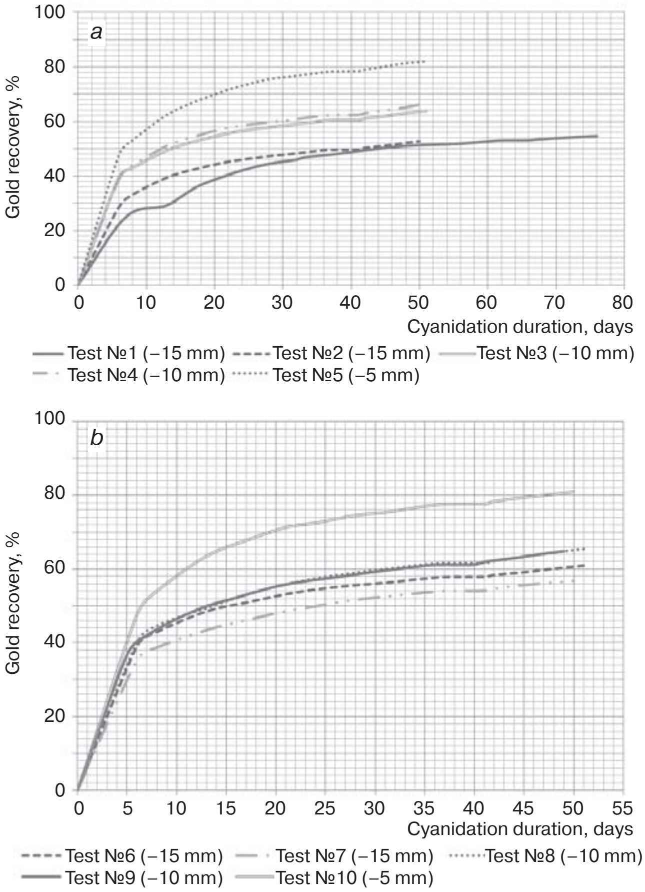

Fig. 3. History of leaching of ore from Eastern (*a*) and Western (*b*) sites

It follows from Fig. 4 that after 30 days of leaching the increment in the daily gold recovery is 0.28–0.38% and remains the same up to the end of the tests. After 36–37 days of sprinkling (62 days in test no. 1), leaching was stopped and was resumed in 2 days at the cyanide concentration of 0.1% in the sprinkling solution. This approach allows saturation of the ore pile with oxygen from air, which increases the gold recovery by a few per cent.

In all tests, the break in the sprinkling process positively influences Au recovery which increases by 0.64% on the average.

Consumption of NaOH in leaching is not higher than 0.28 kg/t in most tests. In test no. 10, in ore pelletizing, the batch mixture was added with CaO at the amount of 2 kg/t, and the estimate of the caustic soda consumption was complicated because of the simultaneous presence of lime in the solution. This test also features the least consumption of cyanide, i.e. it is expedient to add lime to ore before leaching.

From the analysis of gold distribution per size grades in leach cakes, gold mostly concentrates in the coarse sizes of cakes in case of both test sites. For the Eastern site ore –5 mm in size, the gold recovery from the size of +2 mm is not higher than 75%, while the recovery of gold from the size grades less than 2 mm exceeds 90%.

On the whole, the lab-scale investigations imply that the test ore is suitable for heap leaching to extract gold. The test ore features a nonuniform distribution of gold, which complicates the test data analysis and the circuit inventory composition, while the low permeability of the ore conditions preliminary fine milling.

Conclusions

The agitation leach tests of the Eastern site ore prove the ore suitability for cyanidation: gold recovery exceeds 90% at the ore size of –0.074 mm at the content of 95%, and the consumptions of cyanide and lime are 0.1–0.45 kg/t (with regard to the residue) and around 1 kg/t, respectively. The gold recovery in cyanidation of ore –2 mm in size is 72.07%.

Regarding the agitation leach tests of the Western site ore, gold recovery exceeds 93% at the ore size of –0.074 mm at the content of 95%, and the consumptions of cyanide and lime are 0.1 kg/t (with regard to the residue) and around 0.97 kg/t, respectively.

The ore samples from both sites feature varied results of agitation leaching even in case of the finely milled material, which is a consequence of the nonuniform distribution of gold in ore and because of the coarse particles yet left. In the intense cyanidation, the difference of the results vanishes, which also is reflective of the presence of difficult coarse gold. The nonuniform gold distribution in ore complicates both the test data analysis and the metal inventory composition in actual production.

The tests of leaching in the columns 1.5 m high show that the maximum gold recovery is reached with the ore size of –5 mm and in leaching for 50 days. The maximum gold recovery from the ore from the Eastern and Western sites totaled 81.99% and 80.99%, respectively.

The level of gold recovery from the ore size of –5 mm (81–82%) is sufficiently high for the practice of heap leaching. In this respect, the feasibility of the mixed-type processing technology (with gravity separation or agitation cyanidation of fine ore sizes) should undergo detailed evaluation as the increment in gold recovery may be insufficient, while the process circuit complication may entail higher capital and operating costs.

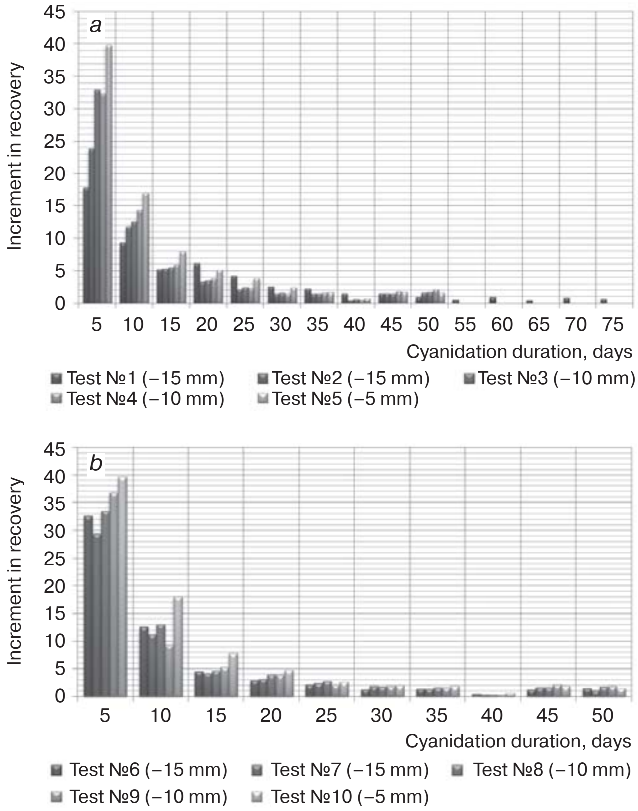

Fig. 4. Increment in gold recovery from ore of Eastern (*a*) and Western (*b*) sites

References

1. McArthur J. C., Forrest R., Forrest W. Process obtaining gold and silver from ores. US Patent 403. 1889. 202 p.
2. Potter G. M., Salisbury H. P. Innovations in gold metallurgy. *Mining Congress Joumall*. 1974. Vol. 60. pp. 54–57.
3. Heinen H. J., McClelland G. E., Lindstrom R. E. Enhancing percolation rates in heap leaching of gold-silver ores. *Report of Investigations—United States, Bureau of Mines*. Washington, DC. : U.S. Dept. of the Interior, Bureau of Mines, 1979. 20 p.
4. Rasskazova A. V., Sekisov A. G., Kirilchu M. S. et al. Stage-activation leaching of oxidized copper–gold ore: Theory and technology. *Eurasian Mining*. 2020. No. 1. pp. 52–55. DOI: 10.17580/em.2020.01.10
5. Donato D. B., Madden-Hallett D. M., Smith G. B. et al. Heap leach cyanide irrigation and risk to wildlife: Ramifications for the international cyanide management code. *Ecotoxicology Environmental Safety.* 2017. Vol. 140. pp. 271–278.
6. Adams C. R., Porter C. P., Robshaw T. J. et al. An alternative to cyanide leaching of waste activated carbon ash for gold and silver recovery via synergistic dual-lixiviant treatment. *Journal of Industrial and Engineering Chemistry*. 2020. No. 8. pp. 120–130. DOI: 10.1016/j.jiec.2020.08.031
7. Torres R., Lapidus G. T. Base metal citrate pretreatment of complex ores to improve gold and silver leaching with thiourea. *Hydrometallurgy.* 2020. Vol. 197. DOI: 10.1016/j.hydromet.2020.105461
8. Qin H., Guo X., Tian Q. et al. Pyrite enhanced chlorination roasting and its efficacy in gold and silver recovery from gold tailing. *Separation and Purification Technology*. 2020. Vol. 250(9). DOI: 10.1016/j.seppur.2020.117168
9. Prokhorov K. V., Burdonov A. E. Chloride-hypochlorite leaching of gold from oxidized ores of the Malmyzh field. *Gornyi Zhurnal*. 2018. No. 10. pp. 62–66. DOI: 10.17580/gzh.2018.10.12
10. Tang Y., Yin W., Huang S. et al. Enhancement of gold agitation leaching by HPGR comminution via microstructural modification of gold ore particles. *Minerals Engineering*. Vol. 159(6). 2020. DOI: 10.1016/j.mineng.2020.106639
11. Tang Y., Yin W., Wang J. et al. Effect of HPGR comminution scheme on particle properties and heap leaching of gold. *Canadian Metallurgical Quarterly*. 2020. Vol. 59(3). DOI:10.10 80/00084433.2020.1769365
12. Botz M., Marsden J. Heap Leach Production Modeling: A Spreadsheet-Based Technique. *Mining Metallurgy and Exploration*. 2019. Vol. 36(2). pp. 1041–1052.
13. Burdonov A. E., Kovalev E. V., Prokhorov K. V. et al. A study on the use of pelletization in the processing of argil-laceous gold-bearing ores. *Obogashchenie Rud*. 2020. No. 3. pp. 31–37. DOI: 10.17580/or.2020.03.06
14. Eksteen J. J., Oraby E. A., Tanda B. C. et al. Towards industrial implementation of glycine-based leach and adsorption technologies for gold-copper ores. *Canadian Metallurgical Quarterly*. 2018. Vol. 57(4). pp. 390–398.
15. Fedotov P. K., Senchenko A. E., Fedotov K. V. et al. Concentration studies for low sulfide ores. *Obogashchenie Rud.* 2020. No. 1. pp. 15–21. DOI: 10.17580/or.2020.01.03
16. Hedjazi F., Monhemius A. J. Industrial application of ammonia-assisted cyanide leaching for copper-gold ores. *Minerals Engineering*. 2018. Vol. 126. pp. 123–129.
17. Cao P., Zhang S. H., Zheng Y. J. Effects of iron, arsenic and carbon removal from a dust of refractory gold concentrates on cyanide leaching. Zhongguo Youse Jinshu Xuebao. *Chinese Journal of Nonferrous Metals.* 2020. Vol. 30. pp. 1142–1152.
18. Fedotov P. K., Senchenko A. E., Fedotov K.V. et al. Hydrometallurgical Processing of Gold-Containing Ore and its Enrichment Products. *Metallurgist*. 2021. Vol. 65(3). pp. 214–227.