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MINERAL DRESSING

Dressability of Old Gold-Bearing Tailings by Flotation

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Abstract—The research results on floatability of old gold-bearing tailings are presented. The complex material composition and process features of processing waste are governed by difference in treatment of various ore types (sulfide, oxidized and mixed) at processing plant, as well as with supergene processes in the tailings pond. Feasibility of re-flotation of tailings is discussed. It is found that short-term mechanical activation of tailings in a mill with the subsequent flotation (at the adjusted reagent mode as against the current technology) results in gold recovery of 29.0 to 45.4% in flotation concentrate at the residue content of metal in rejects at the level of 0.2–0.3 g/t.

Keywords: Flotation, old tailings, mining waste, reagent mode, recovery, tailings pond, dressability study.

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INTRODUCTION

The mining industry of Russia holds more than 12 billion tons of wastes. The wastes from iron and nonferrous industries in terms of volume estimate more than 210 Mm^3 per year of hard rock materials and more than 140 Mm^3 of tailings per year [1]. The matter of mining waste material reprocessing requires consideration not only due to the expansion of the enterprises' mineral resource base, but it is also important for the environmental safety of the country [2, 5].

The examples of mining waste stockpiling are represented by the tailings ponds Musin Log of Artem Plant (Plast); Artemovskaya Gold Recovery Plant (GRP) (Kasnoyarsk Territory); Polyarninsky Mining And Processing Plant (MPP) (Chukotka); Belov Plant (Magadan Region); Balakhchin Plant (Khakassia), etc.

For more than 20 years one of the processing plants has been stockpiling flotation and hydrometallurgy tailings produced in the course of processing of different types of gold ores, both primary and oxidized ones (from several deposits). The average gold content in the tailings for different years ranges from 1.2 to 0.4 g/t.

Today the tailings pond represents the largest gold-containing man-made formation with reserves of more than 76 mln t comparable to an average gold ore deposit. Except for gold the tailings of this enterprise also contain silver, antimony, and tungsten.

1. MATERIALS AND EQUIPMENT

The objective of this research is to study the composition and physical properties of tailings, as well as dressability study performed in the course of flotation using small technological samples collected by core sampling from bund wall of the tailings pond.

For the analysis of gold content in the old tailings, the fire assay with atomic absorption spectrophotometry (AAS) was used. The study of the material composition was conducted by X-ray diffraction analysis in conjunction with the data of X-ray fluorescence analysis. For X-ray diffraction analysis XRD-6000 (Shimadzu) diffractometer was used, X-ray fluorescence analysis was carried out by means of MobiLAB X-50 (Olympus Innov-X). The data interpretation was performed with the help of the Joint Committee on Powder Diffraction Standards (JCPDS) database.

Microscopic examinations were performed by means of Axioscope 40A Pol (Carl Zeiss) polarization microscope. The samples prepared by extraction of a heavy fraction from the tailing on the concentration table Gemeni GT60 were analyzed.

For preparation of polished transparent sections the following materials and equipment were used: EpoFix epoxy resin for the samples impregnation, TegraPol-15 (Struers) polishing machine.

Dressability studies by flotation method were carried out according to the flowsheet including rougher, scavenger and recleaner flotation operations. The processing was performed in a mechanical flotation cell (240 FL-A) with capacity of 3 l during rougher and scavenger operations to obtain the amounts of froth products enough for gold assay performance (solid to liquid ratio of 1:2). The cleaner flotation was performed in 237 FL-A flotation cells with capacity of 0.5 l. Flotation process was conducted until froth bed exhaustion.

2. RESULTS AND DISCUSSION

According to the results of fire assay tests and assessment of gold distribution throughout the tailings core samples collected from bund wall of the tailings pond, comparatively low gold contents (0.2–0.4 g/t) were detected in the bottom part of the tailings and higher contents (0.70–1.13 g/t) were found in the top part of the section—in the tailings of mixed and sulfide ores processing. To carry out the dressability studies three process samples have been prepared: sample 1—sulfide (with gold content of 0.57 g/t), sample 2—mixed (0.61 g/t), sample 3—oxidized (0.30 g/t).

The tailings material under investigation represented fine fraction with fragments of rocks, mostly shales. Single garnet grains were detected. In some cases, secondary aggregations of sand grains bonded by gypsum or hydrous iron oxides (tailings samples of primary and oxidized ores processing, respectively) were found. Visual inspection of the samples revealed some differences: ochre color and brown shades were common for the tailings of oxidized ores processing.

Ore mineralization of the tailings samples is represented by magnetite, pyrite pyrrhotine, arsenopyrite, antimonite. The presence of galena and antimony primary minerals (jamesonite, gudmundite, berthierite and ullmannite) was detected in the tailings samples of sulfide ores processing. Limonite prevailed in the oxidized tailings material. Among nonmetallic minerals the most common are quartz (its content is from 50.28 to 80.45%, depending on the sample), calcite and clinochlore; clay bond is present.

Chemical analysis showed that the material of the samples differs in gold, calcium and carbon content. For instance, the chemical composition of sample 1 revealed the presence of: Au—0.56 g/t, Ag $<$ 0.1 g/t, As—0.18%, Sb—0.11%, S_{total}—0.73%, Fe—3.46%, Ca—6.88%, C—2.48%. The content of the same elements in Sample 3 is 0.34 g/t, 0.12 g/t, 0.16%, 0.14%, 0.83%, 3.00%, 1.35%, 0.50%, respectively.

Native gold was found in the samples in the form of individual occurrences with a size of less than 0.1 mm in the placer material and in the intergrowths with arsenopyrite, pyrrhotine and zirconium. Free gold found in the tailings' heavy fraction during binocular examination is notable for its light-yellow color and hooked shape.

A specific feature of gold-bearing arsenopyrite is the replacement by pyrrhotine: apparently, in the line of replacement the cumulation of indiscernible gold occurs in arsenopyrite and larger grains can be formed. The fineness of gold varies from high (934) to low (693), the major impurity is mercury, silver is practically absent.

Rational analysis of the tailings' process samples showed that the maximum metal content (56.25%) in a cyanidable form is found in Sample 1. In the sample representing complex raw material the cyanidable gold content is around 50%. Among all three samples the most rebellious is sample 3, where the cyanidable gold content is merely 33%. By processing practice it was found [6–12] that gold recovery from tailings by cyanidation did not exceed 30–40%, by re-flotation—20–60%, by gravity method—10–20%.

The tailings of dressing plants are a complex object for flotation processing. Technological refractoriness during old tailings processing is connected with significant content of water-soluble salts, flotation agents, lube oils etc. However, the processing of tailings by flotation, as well as ore processing, concerns the necessity in froth recovery both of native gold and sulfides containing noble metals which become greatly depressed in lime-cyanide medium. In a number of researches it was noted, that in the course of storage the particles became consolidated [13].

Notwithstanding the above-mentioned, the processing of old tailings by flotation method makes it possible to achieve high technological performance, moreover, in flotation of gold-bearing ores and old tailings a wide variety of agents are used [14]. For hydrophobization of minerals it is recommended to use short-chain xanthates, dialkyl dithiophosphates, amines, mercaptobenzothiazole and its derivatives, individually and in various combinations. In Russia the most common agent used in flotation processing of gold-bearing raw material is butyl xanthate. There is a positive experience of re-flotation of the tailings containing noble metals in our country and abroad [3, 15–18].

To perform flotation processing of cyanidation tailings two cases were proposed—flotation in alkaline and in acidic conditions [7]. In the first case the tailings are thoroughly washed free from cyanide and lime, sulfides are activated by copper (II) sulfate and flotation is performed in alkaline conditions using xanthates and frothers. The flotation usually proceeds slowly, because after cyanidation the flotability of sulfides cannot be completely regained.

Acidic conditions can be created by treatment of the pulp with sulfur dioxide. The treatment time and gas flow rate per unit of time are adjusted by experiment, it often takes several hours. The restriction for this method is a long period of pulp contact with sulfur dioxide.

The recovery of gold by flotation is performed after activation of gold-containing sulfides by copper (II) sulfate, where optimal duration of mixing the pulp with this agent may reach 30–40 min. the reagent consumption is 20–100 g/t. The collectors are represented by sulfhydryl agents, the frothers—pine oil or oxal.

The application of phosphates (polyphosphates, hexamataphosphates) in sulfide ores processing intensifies the flotation due to their depressive effect on silicates and the increase in flotation response of sulfide minerals [19]. Different salts of phosphoric and polyphosphoric acids exhibit ion-exchange properties, bind ions of calcium and magnesium and also promote suspension peptization, which is of great importance when it concerns the tailings treated by lime during cyanidation. In [9] it was noted that the efficiency of extra-fine particles processing by flotation using hydrocarbon oils increases after the pulp treatment with peptizing agents (sodium silicate, cellulose sulfate, sodium hexametaphosphate (SHMP)).

Exploratory experiments in processing of the tailings by flotation conducted in the plant mode (copper (II) sulfate—60 g/t, butyl xanthate (total in the primary and check-out operation)—153 g/t, Flotanol (total quantity)—10.2 g/t) did not provide acceptable process parameters. Further researches were carried out with the same agents in various quantities. Flotation process was conducted under neutral conditions (pH 7) on the basis of recommendations [2]. Taking into consideration the fact, that to obtain residue content of metal in tailings the increased dosages of collector were needed, the consumption of the agent in some of the experiments reached 500 g/t.

Flotanol agent was fed to the pulp in the form of 0.1% solution, xanthate and copper (II) sulfate were used in the form of 1% solutions. Agitation duration with each agent was 2 min. Flotation duration was 8, 5, 6 min for the rougher, cleaner and scavenger flotation, respectively. Depending on the experiment conditions the drip feed of kerosene was provided, as well as SHMP (dispersant). The feed of kerosene was provided due to the assumption, that microscopic particles of the valuable element were adsorbed on mineral grains, particularly on carbon-bearing constituents (the presence of carbonaceous shale in the primary ore). The consumption of kerosene was 100 g/t, because this agent in high dosages can have a defrothing effect.

To demonstrate the dispersant efficiency the preliminary tailings processing tests using SHMP agent were conducted. For this purpose the sample material of sulfide tailings (500 g) was soaked in a solution with 500 g of the agent for 20 min by intermittent stirring. After that screen sizing was performed according to the scheme in Fig. 1. Size characteristics in minus grade with and without SHMP application are given in Fig. 2.

It is determined that with additional treatment of the samples with SHMP agent the grain size distribution changes, the most critical changes could be observed in size yield of –40+20 μm, –20+10 μm being the most productive, considering the experience of researches. Only preliminary pulp dispergation in the presence of SHMP in the dose of 500 g/t and the use of kerosene as an apolar collecting agent in addition to the variety of previously tested agents resulted in the increase of gold recovery in the concentrate (probably, because of the increased product yield from 1.5 to 5.0%). Despite loss reduction of the metal by 14.9%, the residue content of gold was not achieved: the content of gold in the tailings decreased from 0.46 to 0.37 g/t.

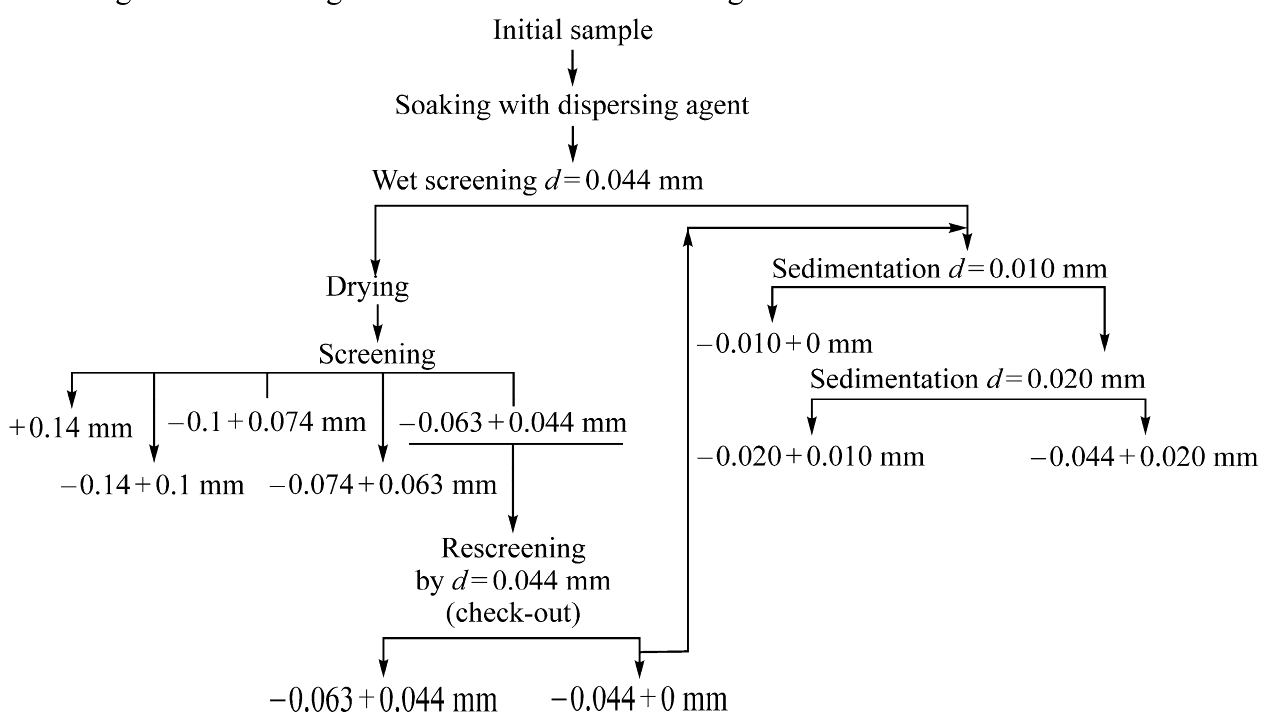

Fig. 1. The scheme of old tailings screen sizing after SHMP agent treatment.

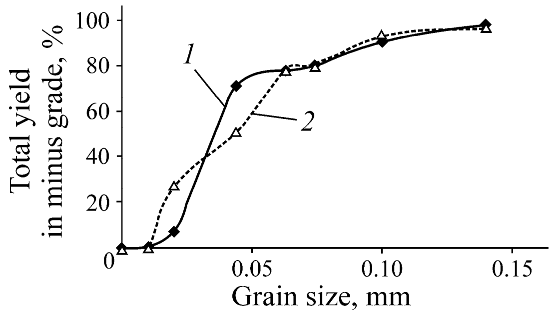

Fig. 2. Size characteristics in minus grade with (*1*) and without (*2*) application of dispersing agent.

The tests were conducted on the tailings of Sample 1 with an aim to determine the efficiency of mechanical activation (surface mechanical attrition treatment)—short-term milling of tailings samples in a ball mill as a way to deal with limed and bonded aggregates of mineral grains. Surface cleaning revealed close results to the ones obtained in the previous experiment with SHMP (with allowance for kerosene feed affected the overall flotation result). The loss of gold with tailings was around 58.5% with the initial tailings gold content of 0.36 g/t.

The efficiency of kerosene addition can be assessed by the results of Sample 1 processing by flotation: gold losses with tailings were reduced by 6%, where gold content in the tailings decreased from 0.36 to 0.34 g/t. The recovery of gold in the concentrate dropped from 29.3 to 32.5%, at the same time the concentration of gold became a bit lower due to the concentrate yield increase from 3.83 to 6.29%.

Further on, after surface mechanical attrition treatment the possibility of flotation in the presence of SHMP dispersant (with constant flow rate of 500 g/t) and with increased consumption of collecting agent varied within the limits of 126–500 g/t was tested. It was found that with the collector dosages increase within the indicated limits the regular increase of gold recovery in the concentrate (from 42.05 to 45.38%) was observed, gold content in the tailings after flotation processing was reduced from 0.32 to 0.27 g/t, the losses with tailings were reduced by 9.3%.

In the dressability studies with the old tailings material of Sample 2 the decision was made to use an apolar collector (kerosene) along with the activator and sulfhydryl collector. Keeping in mind the defrothing properties of kerosene (due to its adsorbtion on the surface of flotation bubbles and the frother molecules displacement to the water layer between them) the dosage of Flotanol agent was increased at least by 3 times during the process (from 8.4 to 25.2 g/t in the rougher flotation, from 1.8 to 5.4 g/t in the scavenger flotation).

It had been observed that in comparison with Sample 1 the yield of the concentrate in flotation tests with Sample 2 was not less than 4%. In plant modes with activator and sulfhydryl collector the metal loss with tailings ranged between 55–64%, and the metal content in the tailings was not less than 0.44–0.38 g/t. The use of SHMP collector increased the metal recovery in the concentrate by 11.7% with a slight increase in the product yield, reduced the metal loss with tailings by 7.7%, however, this did not provide residue content of metal in tailings.

Similarly to the analysis of the previous sample the best results were obtained by surface mechanical attrition treatment of the sample material, using the dispersing agent SHMP 500 g/t and with the increased collector dosages from 126 to 500 g/t. It was found out that the metal recovery in the concentrate regularly increased from 42.55 to 43.72%, gold content in the tailings was reduced from 0.33 to 0.31 g/t, and the loss of gold with tailings decreased by 5.42%.

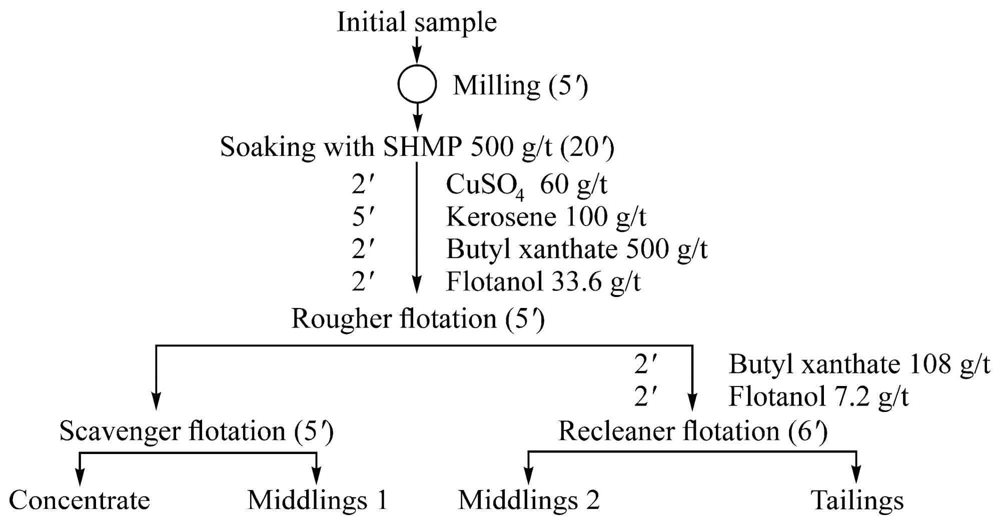

Fig. 3. The scheme of additional extraction of the metal from old tailings.

The most difficult material in terms of processing was Sample 3. At the plant reagent mode the lowest metal recovery in the concentrate was obtained (3.5), the metal loss was 73.63%. The largest fluctuations of gold content (of Sample 2) and generally low content of gold were observed during flotation tests.

In comparison with the plant mode, the tailings conditioning of Sample 3 with 500 g/t of SHMP agent and apolar collector (kerosene) addition has resulted in an increase of gold recovery in the concentrate after the rougher flotation by 3% with constant concentration yield (7.5%), however, after implementation of the entire scheme the residue content of metal in the tailings was not achieved (gold content in the tailings was reduced from 0.24 to 0.23 g/t), the metal loss was reduced by 1.6%.

Much better productivity was observed during the surface mechanical attrition treatment of tailings in a ball mill (5 min) with subsequent flotation at plant mode and additional feed of kerosene. These procedures have provided the increase in recovery by 8.5%, the reduction of gold loss with tailings by 8.32% and the decrease of gold content in the tailings from 0.24 (plant mode) to 0.22 g/t.

Given the positive experience of the suggested processing solutions (Fig. 3) the studies were performed using the surface mechanical attrition treatment together with dispersing agent SHMP and kerosene addition, besides, the effect of different dosages of sulfhydryl collector (from 126 to 500 g/t) was analyzed.

In was determined that with different dosages of agents in these experiments the metal recovery in the concentrate slightly increased from 26.4 to 29.0%, at the same time the loss of gold with tailings was insignificantly reduced (by 4%), the metal content in the tailings remained roughly the same (0.2 g/t).

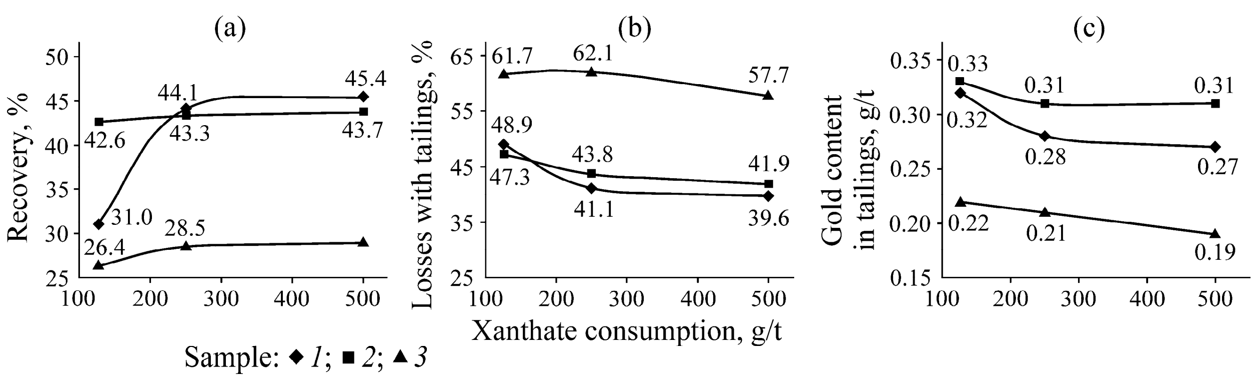

Fig. 4. The dependence of gold recovery in (a) froth flotation product and (b) tailings on the consumption of collector under constant conditions of surface mechanical attrition treatment, application of dispersing agent SHMP (500 g/t); (c) effect of collector dosage on the metal content in flotation tailings.

The process parameters obtained for tailings samples 1, 2 and 3 are given in Fig. 4. Flotation processing made it possible to achieve gold content in the tailings of 0.31, 0.27 and 0.19 g/t for Samples 1, 2 and 3, respectively, gold recovery in the froth product was 30.0−45.4%, which means that 1/2 of gold in the tailings could be extracted without implementation of complicated technologies in the processing plant.

CONCLUSIONS

The studies on the material composition of the samples represented by tailings of sulfide, mixed and oxidized ores processing were undertaken. It was determined that the composition of old tailings is represented by the same minerals as the primary ores processed at the plant in different years. The main nonmetallic mineral is quartz, ore minerals include pyrite, arsenopyrite, the sample of oxidized tailings is characterized by the presence of hydrous iron oxides.

According to the results of chemical analysis, the sample with relatively high grade of gold was a sample with mixed composition, where gold content was 0.61 g/t, the content of gold in the sample of sulfide tailings was 0.57 g/t. Technological refractoriness is to a greater extent typical of the oxidized tailings' sample, where gold content does not exceed 0.3 g/t. All samples are characterized by high concentrations of slime fraction: size yield –0.044 mm—50–60%; size yield –0.020 mm—14–27% (depending on the sample). At the same time there is a deficiency of fine slime with grain size of less than 10 (15) μm. This may be indirectly indicative of slime agglomeration during storage or after extraction of material from test boreholes.

Flotation studies of the samples of tailings material have revealed the possibility of additional gold extraction and obtaining of residue content of metal in tailings only in case of surface mechanical attrition treatment and subsequent soaking of material in the presence of dispersing agent SHMP (500 g/t). The highest recovery in the froth flotation products and residue content of metal in tailings are provided by reagent mode considering the feeding of copper (II) sulfate, kerosene, butyl xanthate, Flotanol; in the process of scavenger flotation the collector consumption is 108 g/t, the frother consumption—7.2 g/t. gold contents in the tailings were 0.31, 0.27 and 0.19 g/t for the samples of material with mixed, sulfide, and oxidized composition, respectively.

REFERENCES

1. Chanturia, V.A., Innovation Methods in Mineral Processing Technologies of Ores with Complex Composition, *GIAB*, 2009, vol. 15, no. 12, pp. 9–25.
2. Bantshi, A.M. and Makuvise, P., Extraction of Gold from Sands and Slimes Tailings Dump from Mazowe Mine, Zimbabwe, *Minerals, Metals and Materials Series*, 2017, pp. 507–517.
3. Dudeney, A.W.L., Chan, B.K.C., Bouzalakos, S., and Huisman, J.L., Management of Waste and Wastewater from Mineral Industry Processes, Especially Leaching of Sulphide Resources: State of the Art, *Int. J. of Mining, Reclamation and Environment*, 2013, vol. 27, no. 1, pp. 2–37.
4. Maboeta, M.S., Oladipo, O.G., and Botha, S.M., Ecotoxicity of Mine Tailings: Unrehabilitated Versus Rehabilitated, *Bulletin of Environmental Contamination and Toxicology*, 2018, vol. 100, no. 5, pp. 702–707.
5. Sudibyo, Aji B.B., Sumardi, S., Mufakir, F.R., Junaidi, A., Nurjaman, F., Karna, and Aziza, A. Taguchi Optimization: Case Study of Gold Recovery from Amalgamation Tailing by Using Froth Flotation Method, *AIP Conference Proceedings,* 2017, vol. 1805, no. 1, id 050003.
6. Evdokimov, S.I. and Evdokimov, V.S, Placer Mining Waste Processing Technology, *Ekol. Promysh. Rossii*, 2017, vol. 21, no. 9, pp. 10–15.
7. Evdokimov, S.I. and Evdokimov, V.S., Technology of Combined Development of Ores and Legacy Gold Placers, *Tsvet. Met.*, 2017, no. 9, pp. 20–28.

8. Bekturganov, N.S., Arystanova, G.A., Koizhanova, A.K., and Erdenova, M.B., Comparative Study of the Methods for Gold Recovery from Man-Made Flotation Tailing, *Tsvet. Met.*, 2016, no. 10, pp. 69–72.
9. Zinchenko, Z.A. and Tyumin, I.A., Rresearches of Gold Extraction from Flotation Tailings of Djijicrut Deposit Narrow Level by Thiourea, *Dokl. Akad. Nauk Resp. Tajikistan*, 2013, vol. 56, no. 10, pp. 796–800.
10. Bogdanovich, A.V., Vasil'ev, A.M., Shneerson, Ya.M., and Pleshkov, M.A., Recovery of Gold from Old Tailings of Copper-Zink-Pyrite Ores, *Obogashch. Rud*, 2013, no. 5, pp. 34–44.
11. Zelenov, V.I., *Metodika issledovaniya zoloto- i serebrosoderzhashchikh rud* (Gold- and Silver-Bearing Ore Research Techniques), Moscow: Nedra, 1989.
12. Algebraistova, N.K., Alekseeva, E.A., and Kolyago, E.K., Mineralogy and Processing Technology of Old Tailings from Artem'evskaya Gold Recovery Plant, *GIAB*, 2000, no. 6, pp. 191–197.
13. Lygach, V.N., Ladygina, G.V., Samorukova, V.D., and Shubuderov, A.V., Additional Recovery of Gold from Tailings of Poor Gold-Bearing Ores of the Southern Urals. http://www.giab-online.ru//files/Data /2007/8/25_Ligach24.pdf.
14. Meimanova, Zh.S. and Nogaeva, K.A., Investigation of Flotation Processing of Old Tailings from PF Solton-Sary, *Nauka Nov. Tekhnol.*, 2014, no. 2, pp. 15–16.
15. Lodeishchikov, B.B., *Tekhnologiya izvlecheniya zolota i serebra iz upornykh rud* (Technology of Gold and Silver Recovery from Refractory Ores), Irkutsk: Irgiredmet, 1999.
16. Bragina, V.I. and Konnova, N.I., Recovery of Valuable Minerals from Tailings, *GIAB*, 2011, no. 12, pp. 165–169.
17. Alekseev, V.S. and Banshchikova, T.S., Rebellious Gold Extraction from Gravity Concentrates and Placer Tailings by Chemical Reagents, *J. Min. Sci.*, 2017, vol. 53, no. 4, pp. 756–761.
18. Chanturia, V.A., Kozlov, A.P, Matveeva, T.N., and Lavrinenko, A.A., Innovative Technologies and Extraction of Commercial Components from Unconventional and Difficult-to-Process Minerals and Mining-and-Processing waste, *J. Min. Sci.*, 2012, vol. 48, no. 5, pp. 904–913.
19. Glembotsky, V.A., *Flotatsionnye metody obogashcheniya* (Flotation Methods of Processing), Moscow: Nedra, 1981.