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FLOTATION ENRICHMENT OF RESISTANT GOLD ORES

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Abstract. Ores of the Vasilkovsky deposit include arsenopyrite, pyrite, pyrrhotite, marcasite, gold, chalcopyrite, sphalerite, galena, faded ore (tennantite), bismuthine, native bismuth, lellingite, molybdenite, cubanite, bornite, antimonite, relict minerals, magnetite, apatite and apatite chromite, sericite, chlorite, potassium feldspar, tourmaline), quartz, carbonates (siderite, ankerite, calcite), fluorite, barite. Arsenopyrite is the main ore mineral. It contains the bulk of gold, as well as impurities - copper, cobalt, nickel, bismuth, zirconium, titanium, lead, zinc, antimony, silver, molybdenum. Bismuth and its minerals are widespread, they are constantly associated with arsenopyrite, forming intergrowths with native gold, less often with chalcopyrite and faded ore. Native gold is distributed very unevenly, forms the finest precipitates ranging in size from tenths of a micron to 0.063 mm, grows together with quartz, arsenopyrite, pyrite and bismuth minerals. Rich ores were formed by combining bismuth-containing associations with arsenopyrite. The role of gold in arsenopyrite increases with depth. Ores are of the gold-quartz-sulfide type. Quartz in ore up to 90 %, sulfides - from 3 to 5 %. The content of harmful impurities (arsenic) reaches 2 % or more. Ores are refractory, require special technology for the beneficiation and extraction of gold.

Introduction. Gold in ores is present in more than 20 mineral forms, but native gold is mainly of industrial importance, represented by metal particles of various sizes, composition, shape and structure with many minerals, most often with quartz, pyrite, arsenopyrite, and barite. Tellurides, sulfides, organometallic, sorbed, water-soluble and other gold compounds are much less commonly present. The chemical composition of native gold is not very constant. Of the geochemical properties for gold, the most characteristic are: siderophilic (connection with elements of the iron family); chalcophilic (connection with six chemical elements, analogues of sulfur and arsenic); lithophilic (its hydroxide forms, usually in a colloidal state); biophilic (its concentration in connection with organic matter); neutral (all its native forms of finding), etc. Typical impurities in native gold are silver, copper, iron, arsenic, bismuth, tellurium, selenium, manganese, lead, palladium, platinum and other elements that form isomorphic mixtures or surface films ("shirts"). The native gold content is 75–90 % [1, 2].

At present, the main difficulties of the gold mining industry in Russia are associated with the extraction and processing of refractory hard and poor gold-bearing ores and technogenic raw materials, characterized by a high content of finely divided gold up to micro and nanoscale. Gold flotation is used for refractory gold-bearing ores and products containing 1-3 g/t of gold. During flotation processing of polymetallic ores, gold is simultaneously recovered in appropriate concentrates (copper, zinc, etc.). The extraction of gold into copper and zinc concentrates is from 30 to 35 %, the remaining gold goes into pyrite concentrate and 10-15 % into dump tailings.

We have established the optimal regime of the flotation enrichment scheme. Research on the development of technology for recovery of gold from refractory ores was made on three samples of Vasilkovskoye stockwork deposits. In this case, various combinations of the special flotation and hydrometallurgy processes are used, in particular in combination with sulfidation processes with the aim of converting minerals from the oxidized form (sulfates, carbonates) to easily floated sulfide. Combined processes for the processing of oxidized and mixed ores, for example, use a combination of flotation processes.

The aim of the research is the selection and justification of the combined gravity-flotation method of enrichment of refractory gold-bearing raw materials and the hydro and pyrometallurgical method of processing enrichment products based on the study of the technological properties of the feedstock and enrichment products.

Methods. The properties of impurity gold differ from the properties of pure gold: impurities reduce the density of gold particles, change the structure, gold becomes less noble in chemical terms. Impurities of iron give gold magnetic properties. Differences in gold composition are noticeably manifested in flotation. Impurities reduce the flotation ability of gold, and the more, the easier they are oxidized. Often, gold particles have surface coatings consisting of oxides of iron and manganese, acanthite, covellite, galena, kaolinite and some other minerals. Coatings, besides natural origin, also appear as a result of mechanical grinding of the gold surface with solid particles during grinding. As a rule, gold with coatings floats worse than gold with a clean surface [2].

The forms of gold release are the most diverse: disseminated, vein-interspersed, vein, spongy, dendritic, scaly, lamellar-nodosum, in oxidized films, porous, magnetic, in intergrowths and others. Flaky and scaly particles float better.

Given the behavior in technological operations, gold particles size is divided into large (larger than 70 microns), small (smaller than 70, but larger than 1 mm) and finely dispersed (smaller than 1 mm). It is advisable to isolate very large (larger than 0.5-0.6 mm), and in finely dispersed - colloidal or submicroscopic (finer than 0.1 mm) [2].

The work was carried out using a complex of experimental and analytical research methods, including mathematical modeling methods using computers, mathematical statistics, physical modeling, experimental studies on various scale models and technological studies under production conditions. Physical, physicochemical methods were used in experimental studies Chemical and flotation methods: flotation 'laboratory and industrial tests on ores of various substance.

Experimental research. Development of flotation scheme of enrichment .The selection of the flotation enrichment mode for ore samples 1 and 3 was carried out by the method of the planned experiment (steep ascent) with variables: grinding size, consumption of butyl xanthogenate and foamer T-66 and T-80, consumption of copper sulfate and soda. A fractional replica of the four-and five-factor experiment was implemented. According to the results of the experiments, it was found that it is not possible to obtain flotation tails of the initial ore of sample 1 with a gold content less than 1.0 g/t at a grinding size of ore up to 80-85 % and less than 0.074 mm. The yield of flotation concentrate depends on the flow rate of the foamer and was 8-12 %. In the enlarged experiment (Fig. 1) the following results were obtained when returning the industrial product of primary flotation concentrate and 11th flotation concentrate: At the expense of the 1st flotation: T-80 – 50 g/t; Xanthogenate – 175 g/t.

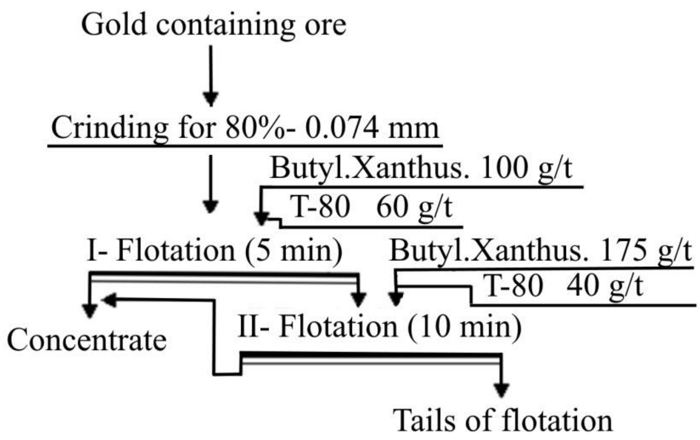

Figure 1 – Scheme of balance experiments in single-stage grinding

During the 11th flotation T-80 – 50 g/t, xanthogenate – 175 g/t and 80 % grinding fineness class less than 0.074 mm flotation concentrate yield was 11.75 with a gold content of 77.8 g/t and the extraction of gold concentrate 90.7 %. The gold content in the flotation tails was 1.0 g/t. Analysis of gold losses in flotation tailings by size classes showed that more than 60 % of all gold losses occur in classes larger than 40 microns. At the output of these classes 43.81 g/t, the content of gold in them was 1.45 g/t, and the loss of gold with them is 61.55 %. The distribution of gold by size classes of sedimentation analysis of flotation tailings of sample 1 is presented in Table 1.

Table 1 – Distribution of gold by classes of sedimentation analysis of flotation tails

Classes, mm	Output, 100 %	Gold content, g/t	Division, 100 %
+60	24.63	1.8	41.7
-60+40	19.18	1.1	19.85
-40+20	18.60	0.65	11.37
-20+0	37.59	0.5	27.08
Total	100	4.05	100

For sample 2 ore, flotation enrichment studies were conducted on gravity tailings with a gold content of 2.4 g/t according to the method of the planned experiment (steep ascent), a fractional replica of the four-factor experiment with variables was implemented:

1) Size of grinding in the class is smaller than 0.074 mm (X 1);
2) Consumption of the foamer T-80 (H2);
3) consumption of butyl xanthogenate (H3);
4) Consumption of copper sulfate (X 4).

The matrix of experiment planning is given in Table 2, the scheme of experiments is presented in Figure 1, the conditions of the experiments are given in Table 2, and the results are given in Table 4. according to this Table, the results of the splanned experiments were processed [1-8].

Table 2 – Matrix planning of experiments on the flotation [8-14]

Indicators	Variable factor			
	Size of grinding %, smaller than 0.074 CL.	Extraction, g/t	Butyl xanthogenate, g/t	Copper sulphate, g/t
Basic level	75	60	125	75
The range of variation in	10	20	25	75
Top level	85	80	150	150
Lower level	65	40	100	0
№ samples experiments				
159	-	-	-	-
160	+	-	-	-
161 167	-	+	-	-
162	+	+	+	-
163 168	-	-	+	+
164 169	+	-	+	+
165	-	+	-	+
166 170	+	+	+	+

Table 3 – Conditions for conducting experiments [8-14]

№ samples experiments	Size of grinding %, smaller than 0.074 CL.	Reagent consumption, g/t		
		T-80	Butyl xanthogenate	Copper sulphate
159	65	40	100	0
160	85	40	100	0
161	65	80	100	0
162	85	80	150	0
163	65	40	150	150
164	85	40	150	150
165	65	80	100	150
166	85	80	150	150
167	65	80	100	0
168	85	40	150	150
169	65	40	150	150
170	85	80	150	150

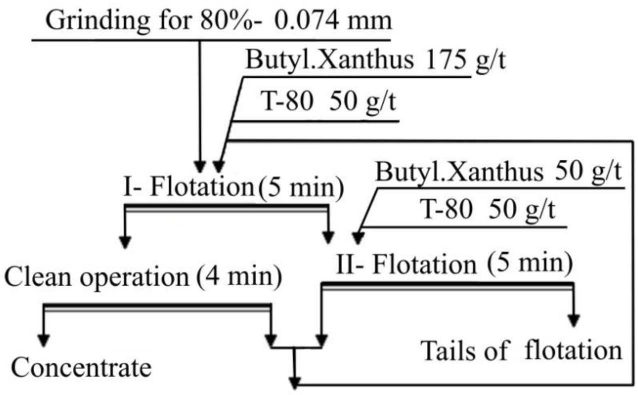

Figure 2 – Scheme of the experiments on the flotation

Table 4 – Results of experiments performed on the experiment planning matrix [9-15]

№ experiment numbers	Products	Output, %	Gold content, g/t	Weight of gold, g/t	Division, %
1	Concentrate	5.81	25.1	1.458	60.72
	Tails	94.19	1.0	0.942	39.24
	Source	100	2.4	2.4	100
2	Concentrate	5.88	24.8	1.459	60.78
	Tails	94.12	1.0	0.941	39.22
	Source	100	2.4	2.4	100
3	Concentrate	6.81	22.91	1.56	65.0
	Tails	93.19	0.9	0.84	35.0.
	Source	100	2.4	2.4	100
4	Concentrate	8.5	16.4	1.3935	58.06
	Tails	91.5	1.1	1.0065	41.94
	Source	100	2.4	2.4	100
5	Concentrate	9.63	13.7	1.316	54.83
	Tails	90.37	1.2	1.084	45.17
	Source	100	2.4	2.4	100
6	Concentrate	8.79	20.0	1.762	73.42
	Tails	91.21	0.7	0.638	26.58
	Source	100	2.4	2.4	100
7	Concentrate	9.94	16.0	1.59	66.25
	Tails	90.06	0.9	0.81	33.75
	Source	100	2.4	2.4	100
8	Concentrate	9.27	17	1.58	65.8
	Tails	90.73	0.9	0.82	34.2
	Source	100	2.4	2.4	100
9	Concentrate	6.55	19.5	1.279	53.29
	Tails	93.45	1.2	1.121	46.71
	Source	100	2.4	2.4	100
	Tails	90.41	0.9	0.81	33.9
	Source	100	2.4	2.4	100
10	Concentrate	8.4	11.1	0.934	38.92
	Tails	91.6	1.6	1.466	61.08
	Source	100	2.4	2.4	100
11	Concentrate	8.76	17.0	1.488	61.98
	Tails	91.24	1.0	0.912	38.02
	Source	100	2.4	2.4	100
12	Concentrate	9.59	11.8	1.59	66.1

Results and discussion. The reproducibility of experiments is estimated by variance

$$\sigma_x^2 = \frac{\sum_{i=1}^{n}\left(X_i - \mathrm{X}^{\leftarrow}\right)}{\mathrm{N-1}}, \qquad (1)$$

where $X^{\leftarrow}$ is the average value of the optimization parameter; X_i is the value of the optimization parameter of an individual repetition; N is the number of experiments.

Table 5 – Variance of experiments (has been compiled to calculate the variance)

№ samples	E_1*	E_2**	$E_1+E_2/2$	σ_x^2
159	60.76	-	60.76	-
160	60.78	-	60.78	-
161 167	65.0	53.29	59.15	68.44
162	58.06	-	58.056	-
163 168	54.83	38.92	46.88	126.405
164 169	73.42	61.98	67.7	65.37
165	66.25	-	66.25	-
166 170	65.8	66.1	65.95	0.045
			$\sum=481.53$	$\sum=260.26$

*E_1 is distribution as a percentage of concentrate in the first group of experiments, **E_2 is distribution as a percentage of concentrate in the second group.

The reproducibility of experiments is estimated by the Cochran criterion. The calculated Cochran's criterion is:

$$\frac{\sigma_{\max}^2}{\Sigma\sigma_x^2}=\frac{126.405}{260.26}=0.49,$$

where $\sigma_{\max}^2$ - maximum dispersion, $\Sigma\sigma_x^2$ - sum of all variances.

Table criterion for confidence interval 95 % = 0.96. Since the results are reproducible. The coefficient of the regression equation are found by the formula

$$b_i=\frac{\sum_{i=1}^{N}\varepsilon_i}{N}, \qquad (2)$$

where N is the number of experiments; $\sum_{i=1}^{N}\varepsilon_i$ is the sum of the values of the optimization parameters (gold extraction).

$$b_0=\frac{60.76+60.78+59.15+58.06+46.88+67.7+66.25+65.95}{8}=59.69$$

$$b_1=\frac{-60.76+60.78-59.15+58.06-46.88+67.7-66.25+65.95}{8}=2.43$$

$$b_2=\frac{-60.76-60.78+59.15+58.06-46.88-67.7+66.25+65.95}{8}=1.66$$

$$b_3 = \frac{-60.76 - 60.78 - 59.15 + 58.06 + 46.88 + 67.7 - 66.25 + 65.95}{8} = -1.04$$

$$b_4 = \frac{-60.76 - 60.78 - 59.15 - 58.06 + 46.88 + 67.7 + 66.25 + 65.95}{8} = 1.0$$

Regression equation:

$$\varepsilon = 59.69 + 2.43X_1 + 1.66X_2 - 1.04X_3 + 1.0X_4,$$

where n is the number of repeated experiments.

Confidence coefficients equation

$$\sigma_{b_i}^2 = \frac{\sigma_\varepsilon^2}{N} = \frac{65.06}{8} = 8.13,$$

$$\sigma_{(b)_i} = \sqrt{8.13} = 2.85 \quad \text{so then} \quad \sigma_{(b)_i} = \frac{\sqrt{2.85}}{\sqrt{4}} = 1.43.$$

It shows that all calculated coefficients at variables X_1; X_2; X_3; X_4 are insignificant, i.e. experiments on flotation were put in an optimum (stationary) mode. Therefore, in order to increase gold recovery by flotation, it is necessary to study other options, for example, with finer ore grinding or stadium flotation. In this direction, the following experiments were made: flotation of the initial ore and stadium flotation [8-12].

Flotation of the initial ore is finer grinding than it was accepted in the formulation of the planned experiments 85 % of the class 0.074 mm (Table 4). The results of the experiments are presented in Table 5, the consumption of the T-80 foamer was increased to 110 g/t, xanthegenate to 175 g/t, the duration of flotation up to 25 minutes [12-17].

Table 6 – Effect of ore grinding size on gold recovery by flotation

№ samples	Products	Output, %	Gold content, g/t	Division, %	The content of the class less than 0.074 mm, %
13	Concentrate	8.15	36.5	78.24	90.15
	Tails	91.85	0.9	21.76	
	Source	100	3.8	100	
14	Concentrate	9.25	32.8	79.51	93.5
	Tails	90.75	0.9	21.49	
	Source	100	3.8	100	
15	Concentrate	9.56	32.2	80.97	
	Tails	90.44	0.8	19.03	
	Source	100	3.8	100	
16	Concentrate	10.95	29.0	84.59	
	Tails	89.05	0.7	26.41	
	Source	100	3.8	100	

Conclusion.

1. The obtained results show that with an increase in the Tonina of ore grinding, the gold content in the flotation tails decreases to 0.7 g/t. However, it is not possible to

obtain flotation tails that are dump-like in terms of gold content. The maximum recovery of gold into concentrate was 84.59 %.

2. High-level experience in multi-stage flotation were delivered high-level experience in multi-stage flotation. The results of the consolidated experience are presented in Table 6.

3. The consolidated (balance) experiment according to the scheme in Figure 1 was performed under the following conditions:

– the size of the grinding of gravity tails in the 1st flotation-65 % CL. smaller than 0.074 mm;

– fineness of the tailings of the 2nd flotation 77.9% CL. finer than 0.050 mm;

– the mode of the 1st flotation:

- duration of flotation – 5 min;
- consumption of T-80 – 60 g/t;
- consumption of xanthogenate – 75 g/t;

– the mode of the 2nd flotation:

- duration of flotation – 10 min;
- consumption T-80 – 20 g/t;
- consumption of xanthogenate – 25 g/t;

– 3rd flotation mode:

- duration of flotation – 15 min;
- consumption T-80 – 20 g/t;
- consumption of xanthogenate – 50 g/t.

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