BENEFICATION AND PROCESSING OF MINERALS

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Study of gold ore processing by flotation methods

Pavel K. Fedotov[a], Alexander E. Burdonov[b], Yuriy V. Novikov[c], Nikita V. Terentiev[d], Ilya O. Bogdanyuk[e]
[a–e]*Irkutsk National Research Technical University, Irkutsk, Russia*
Corresponding author: Yuriy V. Novikov, 89500505553r@gmail.com

Abstract. The article deals with the studies of gold-bearing ore benefication by flotation methods. The object of the study is a low-sulfide gold-quartz type of ores with the following petrographic composition: quartz – 90 %, quartz-chlorite schists – 10 %. The ore from this deposit consists of the weathering crust rocks including iron-mica rocks with veins and spots of granoblastic quartz. The purpose of the research is to develop an optimal flotation regime for obtaining sulfide gold-bearing concentrate. The influence of ore size, reagent mode, flotation redistribution structure, and flotation time on operations was recorded during the experiment. The paper presents the results of studying the chemical composition of the ore by the method of silicate and optical emission analysis. The flotation process used butyl potassium xanthate as a collector and a combination of pine essential oils as a foaming agent. The Hancock concentration efficiency criterion was determined based on a series of experiments. The following technological indicators of ore processing were identified: gravity concentrate with the gold grade of 1165 g/t with the yield of 0.3 % and the recovery of 73.74 %; flotation concentrate (after purification II) with the gold grade of 68.9 g/t with the yield of 1.52 % and a recovery of 22.05 %. Its silver content was 15.9 g/t. The total gold recovery was 95.79 %, with the yield of 1.82 % and the gold grade of 249.9 g/t. The gold grade in the flotation tailings was 0.19 g/t.

Keywords: gold, ore, flotation, concentrate, tailings, recovery, material composition, technological research

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ОБОГАЩЕНИЕ И ПЕРЕРАБОТКА ПОЛЕЗНЫХ ИСКОПАЕМЫХ

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Исследование переработки руд золоторудного месторождения флотационными методами

Павел Константинович Федотов[a], Александр Евгеньевич Бурдонов[b], Юрий Витальевич Новиков[c], Никита Витальевич Терентьев[d], Илья Олегович Богданюк[e]
[a–e]*Иркутский национальный исследовательский технический университет, г. Иркутск, Россия*
Автор, ответственный за переписку: Новиков Юрий Витальевич, 89500505553r@gmail.com

Резюме. В представленной статье описано исследование обогащения золотосодержащих руд флотационными методами. Объектом изучения являлся малосульфидный золото-кварцевый тип руд, который имеет следующий петрографический состав: кварц – 90 %, кварц-хлоритовые сланцы – 10 %. Руда этого месторождения состоит из пород коры выветривания – железисто-слюдяных пород с прожилками и пятнами гранобластового кварца. Целью исследования стала разработка оптимального режима флотации для получения сульфидного золотосодержащего концентрата. В ходе эксперимента фиксировалось влияние крупности руды, реагентного режима, структуры перераспределения флотации, времени флотации на операции. В работе представлены результаты исследования химического состава руды методом силикатного и оптико-эмиссионного анализа. В процессе флотации в качестве собирателя использовали такие реагенты, как бутиловый ксантогенат калия, а в качестве пенообразователя –

комбинацию эфирных масел сосны. На основе серии экспериментов был установлен критерий эффективности обогащения Хэнкока. Выявлены следующие технологические показатели переработки руды: гравиоконцентрат с содержанием золота 1165 г/т с выходом 0,3 % и извлечением 73,74 %; флотоконцентрат (после второй очистки) с содержанием золота 68,9 г/т с выходом 1,52 % и извлечением 22,05 %. Содержание серебра в нем составило 15,9 г/т. Общее извлечение золота составило 95,79 % при выходе 1,82 % и содержании золота 249,9 г/т. Содержание золота в хвостах флотации составило 0,19 г/т.

Ключевые слова: золото, руда, флотация, концентрат, хвосты, извлечение, вещественный состав, технологические исследования

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Introduction

The main source of gold is primary gold deposits, and for all types of ores of such deposits, complex technological processing processes have been formed. From the analysis of works [1–4], it can be concluded that the most common technology for processing oxidized and gold-bearing sulfide ores are the gravity-flotation schemes with subsequent metallurgical redistribution.

Each of the above-mentioned technological processes has its advantages and disadvantages. A special place among them is occupied by flotation due to the large number of factors affecting the efficiency of the process. One of the main parameters is the recovery size before flotation [5, 6]. The reagent mode also influences the efficiency of the process, the degree of pulp aeration, flotation time, pH of the medium, conditioning, pulp density [7, 8], and many others [9–13].

The purpose of the research was to work out the optimal flotation mode for obtaining sulfide gold-bearing concentrate, namely, to study the size of ore grinding, reagent mode, and the structure of the flotation redistribution, and the flotation time for operations. It should be noted that the work is a continuation of the theme of developing a technology for processing gold-bearing ores. Studies of washability by gravity methods are presented in [14]

Materials and methods

The object of research is a low-sulfide gold-quartz type of ore with the following petrographic composition: quartz – 90 %, quartz-chlorite shale – 10 %.

The starting material and enrichment products were investigated using assay-atomic absorption, atomic-emission, X-ray phase analysis methods, and electron microscopy.

The ore of this deposit consists of the rock of the weathering crust – ferruginous-mica rocks with veins and spots of granoblastic quartz. To determine the chemical composition, silicate and optical emission analyzes of the deposit ore were performed (Table 1). The content of noble metals was determined by assay analysis [15].

More than 60 % of the ore consists of aluminum and silicon oxides. By the content of sulfide sulfur (0.35 %), the ore can be attributed to poor sulfide. ICP-OES analysis showed a low content of harmful impurities in the ore. The As content is 0.47 %, and the antimony content is less than 5 g/t. The average gold grade in the ore is 4.56 g/t, and the silver grade is 2 g/t. It has been

Table 1. Analysis results of ore silicates
Таблица 1. Результаты анализа силикатов руды

Elements and connections	Content, %	Elements and connections	Content, %
SiO_2	52.4	TiO_2	1.73
Al_2O_3	9.9	CaO	1.71
Fe	11.6	S general	0.37
MgO	1.83	S sulfide	0.35
As	0.46	Na_2O	1.16
Cu	0.04	P_2O_5	0.22
K_2O	1.21	Zn	0.04
MnO	0.15	Cr_2O_3	0.01

established that ore with a size of -15 mm is characterized by a low yield of small-sized grades (the content of steps less than 0.2 mm is 9.91 %). The gold content in different size classes is different. For ore with size -15 mm, the metal content is in the range from 1.44 to 6.9 g/t; for ore -2 mm – from 2.8 to 4.3 g/t. Gold in ore is mainly found in significant grades, so in the +0.5 mm grade for ore with a size of -15 mm, there is 85.94 % of the metal, for ore -2 mm – 49.12 %. The share of free gold in ore with a size of -2 mm and 95 % -0.074 mm is respectively – 7.57 and 74.17 %, available for cyanidation – 74.67 and 96.93 %. The minerals and quartz insoluble in aqua regia contain 2.87 and 1.02 % of the metal, respectively [15].

Results and their discussion

To determine the optimal degree of grinding of gravity tailings for flotation concentration, a series of tests was carried out on material with a particle size of 70, 80, 85, 90 and 95 % -0.071 mm. The operations of the main and control flotation were carried out. Experimental conditions: Main flotation: Potassium butyl xanthate (PBX) = 300 g/t, Pine oil (PO) = 20 g/t, flotation time 5 min. Control flotation: PBX = 150 g/t, PO = 20 g/t, time – 5 minutes.

It was found that the efficiency of concentration increases to the size of ore grinding 90 % -0.071 mm. With finer grinding, the efficiency begins to decrease slightly. This indicates that a slight increase in gold recovery is achieved due to a significantly more significant increase in the concentrate yield, namely: an increase in output by 0.8 % gives an increase in gold recovery by 0.36 %. Therefore, the size of the crushing of gravity tailings equal to 90 % -0.071 mm was taken as optimal for flotation.

It is known from the practice of flotation of sulfide minerals that the creation of an acidic environment often has an activating effect on flotation and, at the same time, leads to a decrease in the yield of concentrate [16–20].

In this connection, a series of tests were delivered to clarify the optimal pH value of the pulp for flotation when using sulfuric acid as a regulating reagent. The natural pH in the cell was 8.35 and was subsequently reduced to 5.61 and 4.57 by the addition of sulfuric acid. The reagent mode was by the flow of the medium regulator. The size of ore grinding was chosen at 85 % -0.071 mm. It was found that a decrease in the pH of the pulp from 7.85 to 4.57 leads to a reduction in the yield of the flotation concentrate from 6.4 to 2.4 % while reducing the recovery of gold into the focus of the leading flotation from 80.66 % to 61.76. At the same time, the Hancock enrichment efficiency criterion also decreased from 74.26 to 59.36. Therefore, lowering the pH of the slurry hurts the flotation results.

It was found that the pH value of water should not be higher than 8.5 to prevent the depression of iron-containing sulfides (pyrite and arsenopyrite), which are gold carriers. This is already known: at high pH, pyrite and arsenopyrite begin to depress. An increase in pH above this value will contribute to a decrease in the recovery of arsenopyrite, the content of fine gold which reaches 20 g/t, and then pyrite, which may also contain fine gold. Together, this will lead to a decrease in gold recovery into concentrate. Obtained data well known to researchers.

To clarify the consumption of xanthate, a series of tests were performed on gravity tailings with a particle size of 90 % -0.071 mm, in which the consumption of PBX varied from 100 to 400 g/t. Flotation was carried out in a natural environment at pH = 7.85. The main and control flotation time was taken, equal to 5 minutes.

It was found that the maximum value of the concentration efficiency and the highest gold recovery in concentrate correspond to the consumption of the PBX equal to (400+200) g/t. Taking into account that the enrichment indicators in the last test (400+200 g/t) only slightly differ from the indicators of the previous test (300+150), a further increase in the collector consumption was considered inappropriate. Therefore, the consumption of the PBX, equal to (400+200) g/t, was considered optimal for further research. Experimental conditions: grinding size 90 % -0.071 mm. Main flotation: PBX, CM = 60, flotation time 5 min. Control flotation: PBX, PO = 20 g/t, time – 5 minutes.

To determine the optimal flotation time for operations at the selected collector flow rate, tests were performed to study the kinetics of the main, control and cleaning operations of flotation. In all tests, a fractional survey of concentrates was performed and the gold content was deter-

mined in each fraction. The tests were carried out on the optimal reagent mode with the ore grinding size 90 % -0.071 mm. The results of the experiments are shown in Tables 2 and 3.

Analysis of the results obtained made it possible to determine the optimal flotation time for the operations:

– Primary flotation 10–12 minutes; exceeding this time does not give a tangible increase in the extraction of gold into a concentrate and leads to dilution of the concentrate;

– Control flotation 9–11 minutes; after this time, the extraction of gold into the middling product of the control flotation practically stops;

– First clean-up flotation is 3–5 minutes; exceeding this time leads to a sharp decrease in the quality of the concentrate;

– The high gold content in the first fraction of the cleaning operation, which is almost twice the average content in the concentrate, indicates the advisability of including the second cleaning operation in the flotation scheme.

At the optimal modes established at the prospecting stage of research, an experiment was set up for flotation of gravity separation tailings in an open cycle to clarify the concentration indicators. The flotation scheme included the principal, control, and two cleaning operations (Table 4).

Experimental conditions: particle size 90 % -0.071 mm. Main flotation: PBX = 400 g/t, PO = 60 g/t, flotation time 10 min. Control flotation with kinetics: PBX = 200 g/t, PO = 20 g/t, flotation time 10 min. Cleaner flotation I: time 5 minutes. Cleaner flotation II: time 2 minutes.

Table 2. Study results of kinetics of the main and control ore flotations
Таблица 2. Результаты изучения кинетики основной и контрольной флотаций руды

Products	Time, m	Yield	Gold content, g/t	Gold extraction, %	Progressive total			Hancock criterion
					Yield, %	Gold content, g/t	Gold extraction, %	
Flotation concentrate	1	1.3	52.5	61.73	1.3	52.5	61.73	60.43
	2	2.6	8.4	19.75	3.9	23.1	81.48	77.58
	3	2.6	1.32	3.1	6.5	14.39	84.58	78.08
	4	1.5	1.22	1.66	8	11.92	86.24	78.24
Total flotation concentrate		8	11.92	86.24	–	–	–	–
Control flotation concentrate	1	0.8	0.93	0.67	0.8	0.93	0.67	–
	2	1.4	0.59	0.75	2.2	0.71	1.42	–
	3	2.3	0.47	0.98	4.5	0.59	2.4	–
	4	1.5	0.35	0.47	6	0.53	2.87	–
Total control flotation concentrate		6	0.53	2.87	–	–	–	–
Total primary and control flotation concentrate		14	7.04	89.11	–	–	–	–
Flotation tails		86	0.14	10.89	–	–	–	–
Total gravity tailings		100	1.11	100	–	–	–	–

Table 3. Study results of ore flotation kinetics
Таблица 3. Результаты изучения кинетики флотации руды

Product	Yield, %	Gold content, g/t	Gold extraction, %
Scrap concentrate 1 min	1.1	64.2	64.81
Scrap concentrate 2 min	1.1	13.1	13.22
Scrap concentrate 3 min	0.5	4.2	1.93
Total re-flotation concentrate	2.7	32.27	79.96
Re-flotation industrial product	5.2	1.24	5.92
Industrial product control flotation	5	0.64	2.94
Total concentrate	12.9	7.5	88.81
Flotation tailings	87.1	0.14	11.19
Total gravity tailings	100	1.09	100

Table 4. Results of an open experiment on flotation of gravity benefication tailings
Таблица 4. Результаты открытого эксперимента по флотации хвостов гравитационного обогащения

Product	Yield, %	Gold content, g/t	Gold extraction, %
Recycling flotation concentrate II	1.4	58.1	72.2
Industrial product recycle flotation II	1.8	5.4	8.63
Industrial product recycle flotation I	4.3	1.54	5.88
Flotation control industrial product	5.1	0.71	3.21
Total flotation concentrate	12.6	8.04	89.92
Flotation tailings	87.4	0.13	10.08
Total gravity tailings	100	1.13	100

It was found that after the second cleaning, a concentrate with a gold content of 58.1 g/t with a yield of 1.4 % can be obtained from the tailings of gravity concentration. The total recovery of gold in flotation products was 89.92 %, with an output of 12.6 %. The gold content in the tailings of the control flotation was 0.13 g/t. These results can be considered satisfactory. In the selected mode, conducting an experiment in a closed cycle is advisable to establish the ore concentration indices according to the gravity-flotation scheme.

Experience in the gravity-flotation concentration of the original ore. To establish the indicators of the initial ore beneficiation according to the gravity-flotation scheme, a test was performed in which flotation was performed with the return of middlings (5 closed cycles) according to the mode worked out at the preliminary stage of research. The flotation was fed with the tailings of gravity separation, performed on a Knelson centrifugal concentrato. The scheme of the experiment is shown in Figure.

The original ore was crushed to a 60 % -0.071 mm particle size and enriched by centrifugal separation to extract free gold and rich intergrowths. The tails of centrifugal separation were recrushed to a particle size of 85 % -0.071 mm and fed to flotation, in which the main, control, and two cleaning operations were provided. The flotation was carried out in a closed cycle with a turnover of middlings. The results of ore dressing according to this scheme are shown in Table 5.

As a result of enrichment, the following products were obtained:

1. Gravity concentrate with a gold grade of 186 g/t with a yield of 1.84 % and a recovery of 72.82 %.

2. Flotation concentrate (after the II cleaning) with a gold content of 70.3 g/t yields 1.46 % and recovery of 21.84 %.

The total recovery of gold into the gravity concentrate and flotation concentrate of the II cleaning up was 94.66 %, with a yield of 3.3 % and an Au content of 134.81 g/t. The gold content in the flotation tailings was 0.2 g/t.

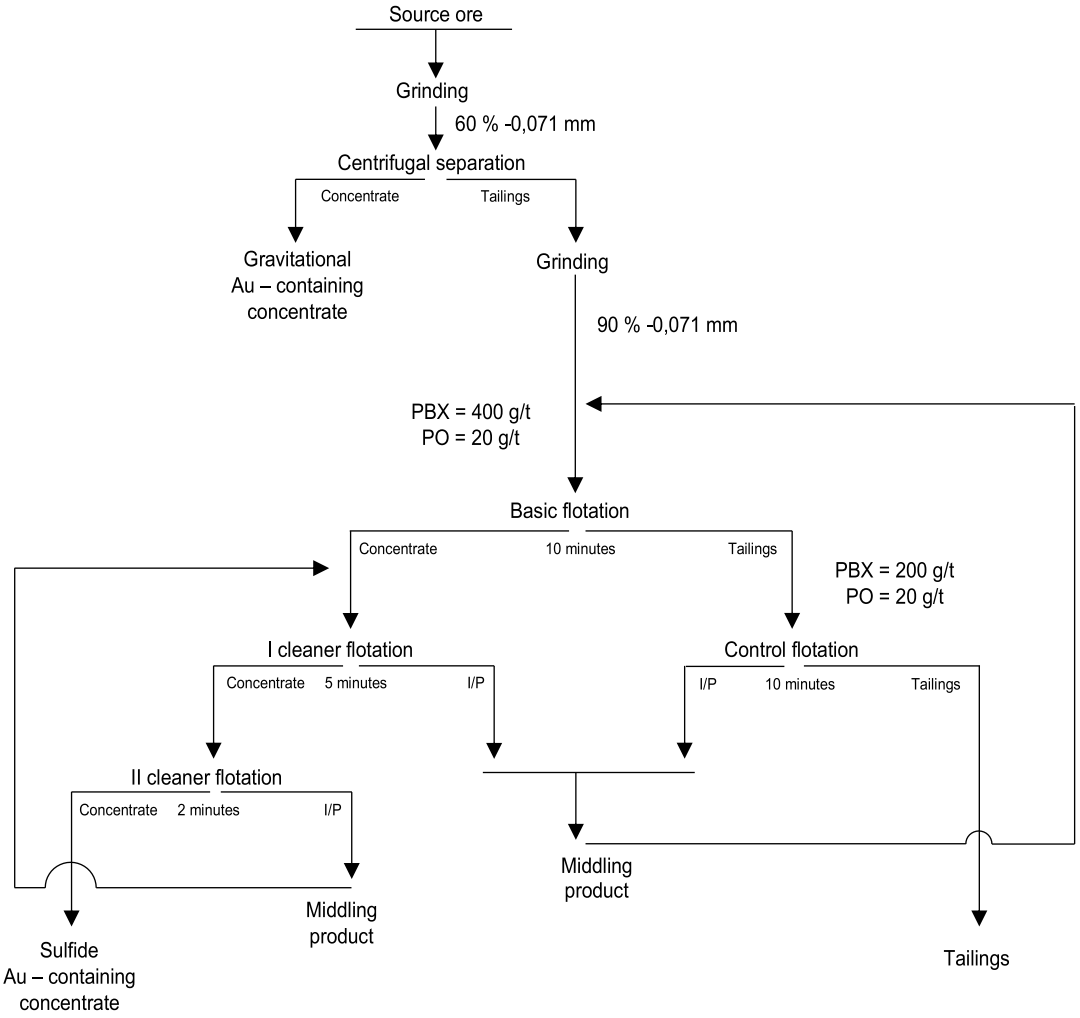
Due to the turnover of middlings, it became possible to reduce the consumption of the foaming agent in the main operation from 60 to 20 g/t while maintaining foaming. This consumption was adopted when performing a closed experiment on an enlarged ore sample.

Experience in the gravity-flotation concentration of the original ore on the enlarged sample. To clarify the technological parameters of the gravity-flotation ore concentration and the production of concentrates for hydrometallurgical research, a closed experiment was set up on an enlarged sample (90 kg). The scheme and the reagent mode were adopted similar to a fast experiment on five weighed samples of ore, but flotation was carried out on machines of larger volume with chambers of 12 l, 3 l, and 1.5 l.

The experiment was carried out on a circulating water supply, organized according to a "short" scheme. In this case, water for the needs of flotation was taken from the settled tail products. Fresh water was used only for the first closed-loop test. As a result of enrichment of the enlarged sample of ore, the following effects were obtained:

1. Gravity concentrate with a gold content of 1165 g/t with a yield of 0.3 % and an extraction of 73.74 %.

2. Flotation concentrate (after the II cleaning) with a gold content of 68.9 g/t with an output of 1.52 % and an extraction of 22.05 %. Its silver content was 15.9 g/t.



Flow diagram of a closed experiment on gravity-flotation ore benefication
Схема проведения закрытого эксперимента по гравитационно-флотационному обогащению руд

Table 5. Ore beneficiation results according to the gravity-flotation scheme (closed experiment)
Таблица 5. Результаты обогащения руды по гравитационно-флотационной схеме (закрытый эксперимент)

Product	Yield	Gold content, g/t	Gold extraction, %	Ferrum content, %	Ferrum extraction, %	Sulfur content, %	Sulfur extraction, %
Grinding ore to a particle size of 60 % -0.071 mm. Enrichment by centrifugal separation at KS MD3							
Gravity concentrate	1.84	186	72.82	17.55	8	6.58	31.32
Grinding to a particle size of 90 % -0.071 mm. Main flotation: butyl xanthate = 400 g/t, pine oil = 20 g/t, flotation time 10 min. Control flotation: butyl xanthate = 200 g/t, pine oil = 20 g/t, flotation time 10 min. I cleaning: flotation time 5 minutes II cleaning: flotation time 2 minutes							
Concentrate II cleaning	1.46	70.3	21.84	27	9,76	13.21	49.9
Industrial product recycle flotation II	0.32	10.6	0.72	21.36	1.69	5.14	4.26
Industrial product recycle flotation I	1.02	1.54	0.33	10.05	2.54	1.12	2.96
Flotation control industrial product	0.98	1.27	0.26	8.32	2.02	0.71	1.8
Total flotation concentrate	3.78	28.8	23.16	17.11	16.02	6.02	58.91
Gravity and flotation concentrate II cleaning	3.3	134.81	94.66	21.73	17.76	9.51	81.22
Tailings	94.38	0.2	4.02	3.25	75.98	0.04	9.77
Initial ore	100	4.7	100	4.04	100	0.39	100

The total recovery of gold in the gravity concentrate and flotation concentrate of the II cleaning was 95.79 %, with a yield of 1.82 % and an Au content of 249.9 g/t. The gold content in the flotation tailings was 0.19 g/t.

Conclusions

Flotation beneficiation of the initial ore sample proceeds ineffectively due to a large amount of sizeable free gold in the ore, which is poorly extracted into a foam product. The overall level of gold recovery into flotation concentrate in all experiments remained relatively low, in the range of 49.13 – 76.36 %.

In a closed experiment on the enrichment of an enlarged sample of ore, the following ore enrichment indicators were obtained:

– Gravity concentrate with a gold content of 1165 g/t with an output of 0.3 % and an extraction of 73.74%; its silver content was 274 g/t;

– Flotation concentrate (after the II cleaning) with a gold content of 68.9 g/t with an output of 1.52 % and an extraction of 22.05 %; its silver content was 15.9 g/t;

– The total recovery of gold in the gravity-flotation concentrate was 95.79 %, with a yield of 1.82 % and an Au content of 249.9 g/t;

– Gold content in flotation tailings is 0.19 g/t.

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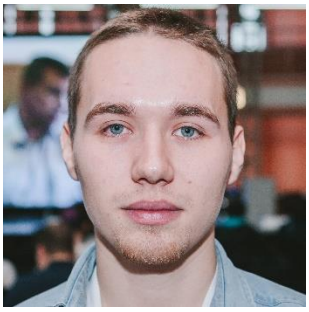
Information about the authors / Информация об авторах

Pavel K. Fedotov,
Dr. Sci. (Eng.), Professor,
Professor of the Department of Mineral Processing
and Environmental Protection named after S. B. Leonov,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russia,
fedotov@istu.edu.
Федотов Павел Константинович,
доктор технических наук, профессор,
профессор кафедры обогащения полезных ископаемых
и охраны окружающей среды им. С. Б. Леонова,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
fedotov@istu.edu.

Alexander E. Burdonov,
Cand. Sci. (Eng.), Associate Professor,
Associate Professor of the Department of Mineral Processing
and Environmental Protection named after S. B. Leonov,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russia,
slimbul@inbox.ru,
https://orcid.org/0000-0001-5298-445X.
Бурдонов Александр Евгеньевич,
кандидат технических наук, доцент,
доцент кафедры обогащения полезных ископаемых
и охраны окружающей среды им. С. Б. Леонова,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
slimbul@inbox.ru,
https://orcid.org/0000-0001-5298-445X.



Yuriy V. Novikov,
Postgraduate Student,
Institute of Subsoil Use,
Irkutsk National Research Technical University,
Irkutsk, Russia,
89500505553r@gmail.com.
Новиков Юрий Витальевич,
аспирант,
Институт недропользования,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
89500505553r@gmail.com.

Nikita V. Terentiev,
Student,
Irkutsk National Research Technical University,
Irkutsk, Russia,
mc_krofly@mail.ru.
Терентьев Никита Витальевич,
студент,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
mc_krofly@mail.ru.

Ilya O. Bogdanyuk,
Student,
Irkutsk National Research Technical University,
Irkutsk, Russia,
super_mario99@mail.ru.
Богданюк Илья Олегович,
студент,
Иркутский национальный исследовательский технический университет,
г. Иркутск, Россия,
super_mario99@mail.ru.

Contribution of the authors / Вклад авторов

Fedotov P. K. defined the problem, developed the concept of the article and performed the critical analysis of literature. Burdonov A. E. described the results and formulated the conclusions of the study. Novikov Yu. V. collected statistical data, presented results in tables and graphs. Terentiev N. V., Bogdanyuk I. O. conducted the experiments.

Федотов П. К. – постановка проблемы, разработка концепции статьи, критический анализ литературы. Бурдонов А.Е. – описание результатов и формирование выводов исследования. Новиков Ю.В. – сбор статистических данных, табличное и графическое представление результатов. Терентьев Н.В., Богданюк И.О. – проведение экспериментов.

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