ISSN 0026-2617, Microbiology, 2014, Vol. 83, No. 5, pp. 568–576. © Pleiades Publishing, Ltd., 2014.

EXPERIMENTAL ARTICLES

Leaching of Pyrite–Arsenopyrite Concentrate in Bioreactors during Continuous Cultivation of a Thermoacidophilic Microbial Community

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Received December 10, 2013

Abstract—A community of thermoacidophilic chemolithotrophic microorganisms was shown to exhibit enhanced efficiency of leaching and biooxidation of the gold-bearing pyrite–arsenopyrite flotation concentrate in continuous mode of cultivation. Under the optimal values of growth parameters, the degree of oxidation of sulfide arsenic, iron, sulfur, and antimony in the line of three laboratory reactors ($D = 0.004\ h^{-1}$) was 99.55, 98.87, 99.65, and 97.08%, respectively, while gold recovery from the solid biooxidation residue was 97.4%.

Keywords: flotation concentrate of gold-bearing pyrite–arsenopyrite ore, thermoacidophilic chemolithotrophic microbial community, bioreactors, three-stage continuous process, oxidation parameters, gold recovery

DOI: 10.1134/S0026261714050269

Two approaches to improved technologies for continuous leaching of sulfide minerals presently exist. The first one implies the monitoring of the stable growth of microbial communities with high levels of Fe and S oxidation in the course of biooxidation (BO) of gold-bearing sulfide ores and concentrates under optimal conditions, as well as development of molecular techniques for assessment of community composition and determination of resistance to heavy metal ions (PCR, RFLP, RT-TCR, FISH, T-RFLP, etc.). The second one is optimization of conditions for the functioning of such communities: development of reactors and technological lines, determination of the optimal operating conditions in each reactor including the parameters of temperature (stable or varying), and utilization of combined technologies, which include both the chemical and microbiological stages [1–10]. Communities developing at moderate temperatures (45–50°C) always contain bacteria *Acidithiobacillus* (*Ab.*) *caldus*, various *Sulfobacillus* and *Leptospirillum* species, and archaea of the family *Ferroplasmaceae*. Stability of the composition of the community is important for its functioning during the oxidation of pyrite and arsenopyrite gold-bearing concentrates, especially at low pH values close to 1. This pH is not favorable for active development of most of the components of the community and promotes selection of the acid-tolerant microorganisms, which results in the instability of the system [11]. Increased pH (to 1.8–2.0) may, however, result in accumulation of iron hydroxide precipitates.

In the course of investigation of BO of pyrite–arsenopyrite gold-bearing flotation concentrate, an active thermophilic community of acidophilic chemolithotrophic microorganisms (ACM) was obtained [12], which contained both aboriginal microorganisms and those from an experimental community as the dominant members. Optimal conditions for BO of sulfide flotation concentrate, such as pH, temperature, mineral composition (N, P, K, Mg), and the concentration of metabolized organic carbon, were determined by batch cultivation of the community (in flasks under shaking) [13].

The goal of the present work was to develop an efficient multistage continuous process for biooxidation of flotation concentrate using the biohydrometallurgical technology for gold recovery from refractory sulfide ore by a thermophilic community of chemolithotrophic microorganisms.

MATERIALS AND METHODS

Subjects. The subjects of research were gold-containing silica-alumina flotation concentrate of a refractory pyrite–arsenopyrite ore and communities of thermophilic acidophilic chemolithotrophic microorganisms (ACM).

Concentrate composition. The concentrate consisted of silica-alumina mass with inclusions of sulfide minerals. The size of flotation concentrate particles

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was –0.074 mm (pulverescent). Pyrite (35%) and arsenopyrite (8%) were the major sulfide minerals; small amounts of stibnite (0.56%) were present. Silicate and carbonate minerals constituted 49 and 5.5%, respectively. According to chemical analysis, flotation concentrate contained 20.9% total iron, 19.2% sulfide iron, 3.63% arsenic (total and sulfide one), 20.44% total sulfur, 19.87% sulfide sulfur, 0.08% elemental sulfur, 0.56% total antimony, 0.28% sulfide antimony, 1.42% calcium, and 1.58% magnesium.

Microbial community. The thermophilic community of acidophilic chemolithotrophic microorganisms obtained in our previous work [12] contained the aboriginal strains isolated from the sulfide concentrate—bacteria *Ab. caldus* and *Alicyclobacillus tolerans* and an archaeon related to *"Acidiplasma cupricumulans"* (family *Ferroplasmaceae*)—as well as strains from the experimental community (collection of the Laboratory of Chemolithotrophic Microorganisms, Winogradsky Institute of Microbiology) adapted to oxidation of the same ore concentrate—a bacterium *Sulfobacillus thermotolerans* and an archaeon *Ferroplasma acidiphilum*.

Cultivation. To obtain the inoculum for the first reactor, the thermophilic ACM community was grown for 5–6 days in batch mode in round-bottomed 250-mL flasks with 100 mL of iron-free 9K medium [5] containing sulfide concentrate on a Unimax 1010 shaker with Incubator 1000 (Heidolph, Germany) at 47°C and 200 rpm. The 9K medium [14] contained the following (g/L): $(NH_4)_2SO_4$, 3.0; KCl, 0.1; $K_2HPO_4 \cdot 3H_2O$, 0.5; $MgSO_4 \cdot 7H_2O$, 0.5; $Ca(NO_3)_2 \cdot 4H_2O$, 0.01, and yeast extract (YE), 0.02%; pH 2.0. The inoculum (10% vol/vol) was introduced into the first 2-L reactor containing 0.6 L of the medium with the optimal composition determined in our previous study [13] (g/L): $K_2HPO_4 \cdot 3H_2O$, 0.53; $(NH_4)_2SO_4$, 1.6; $MgSO_4 \cdot 7H_2O$, 2.5; and YE, 0.3.

The experiments were carried out in a continuous mode with periodic pulp addition/removal in a line of three identical reactors. The total pulp volume was 1.8 L. The reactors were equipped with baffles. Temperature was maintained at the optimal level (46.5–48°C) by a TW 3 ultrathermostat (ELMI, Germany). Pulp density was 20% (wt/vol), aeration rate was 3 min^{-1}, and agitation rate was 450–480 rpm. In order to decrease evaporation, each reactor was connected to a backflow condenser. In accordance with the results of preliminary optimization of growth conditions, pH in reactors I, II, and III was maintained at 1.8 (2.0), 1.6, and 1.4, respectively. Since the inoculum was grown at pH 2.0, pH value in reactor I exceeded the optimum by 0.2 U (pH 2.0) at the initial stage of development of the population. Concentrated H_2SO_4 and 10% $NaHCO_3$ were used to adjust pH of the medium. Biooxidation of sulfide ore flotation concentrate was carried out for 15 days. The times for complete replacement of the volume (1800 mL) at flow rates of 0.004 and 0.01 h^{-1} were 240 and 96 h, respectively.

The dominant groups of microorganisms at different stages of continuous cultivation of the community were revealed by subcultivation in flasks with the optimal medium with 0.03% YE at 47°C. Elemental sulfur or Fe^{2+} was used as an energy source (10 g/L) at initial pH 1.8, 1.6, or 1.4. The cells from the liquid phase of the pulp grown at stabilized pH in reactors I, II, and III were used as inocula.

Analytical techniques. Enumeration of microbial cells was carried out by direct count and by the terminal dilution method. The physiological state of the cultures was observed under phase contrast using a Mikmed microscope (Russia) or an Olympus CX41 microscope equipped with a camera.

Analysis of the chemical composition of the gold-bearing pyrite–arsenopyrite flotation concentrate and of the solid biooxidation residue was carried out on a Hariba Jobin Yvon Activa-S atomic emission spectrometer (France) using the inductively coupled plasma method.

In the liquid phase of the pulp, pH and Eh (relative to the normal hydrogen electrode) were measured using a pH-150M millivoltmeter (Belarus). The concentrations of iron (ferric and ferrous) and total arsenic were determined as described in [2, 13]. The content of iron, arsenic, and sulfur in the solid phase was determined by the fire assay. Mineral composition was determined using X-ray diffraction on a Philips X-pert Pro diffractometer (The Netherlands). Gold content in the concentrate and in the residue were determined by the assay method. Sorption cyanidation was carried out after biooxidation under the following conditions: pulp density, 30% (wt/vol); pH 10.2–10.5 (adjusted with NaOH); aeration, 25 L/h; sorbent content (carbon Norit 3515), 8%; temperature, 20°C; duration, 48 h; gold adsorption on the sorbent, 99–100%.

Statistical treatment of the results was carried out using the Student's criterion at 5% confidence level [15].

RESULTS AND DISCUSSION

Confirmation of optimization efficiency of the cultivation conditions achieved in batch mode BO under continuous cultivation. The first series of experiments was aimed at determination of dependence of bacterial oxidation of the concentrate under continuous conditions on pH of 20% pulp in the range of optimal pH 1.8–1.4 determined at the previous stage of research, which was carried out in batch mode [13]. It was assumed that confirmation was required for the optimal pH values determined under a different BO mode. In each reactor of the technological line, pH therefore varied by 0.2 U. Thus, pH values from 2.0 to 1.6, from 1.8 to 1.6, and from 1.6 to 1.4 were adjusted for reactors I, II, and III, respectively. BO of the concentrate was carried out for at least ten days at each pH value. $NaHCO_3$ solution (10%) used for pH stabiliza-

tion acted also as an additional carbon source (CO_2) for the microorganisms. Thus, CO_2 (1–5%) increased 1.5–3 times the rate of pyrite oxidation by moderately thermophilic sulfobacilli [16, 17].

Biooxidation of flotation concentrate was carried out in feed-batch mode at flow rate of 0.004 h^{-1}. The optimal composition of the pulp liquid phase was used (see Materials and Methods). In bioreactor I, variation of pH at 2.0, 1.8, and 1.6 revealed almost the same efficiency of the process within pH range 1.8–2.0. In reactor II, all parameters of growth and biooxidation indicated a more stable process at pH 1.6 than at pH 1.8. Variation of pH within the 1.4–1.6 range in reactor III revealed higher rates of the process at pH 1.4 (detailed data are not shown). Thus, analysis of the results of three-stage continuous process of leaching/oxidation of the sulfide concentrate by the ACM community revealed that the pH range 1.4–1.8 was optimal for biooxidation, similar to the earlier results obtained in batch mode.

Continuous cultivation of the ACM community. Based on the results obtained, subsequent experiments were carried out at the optimal pH values of the pulp for each reactor, with the same flow rate (0.004 h^{-1}), for a longer period (15–20 days) without significant fluctuations of pH and growth parameters. Throughout the day, the pulp pH was adjusted to the required value (1.8, 1.6, and 1.4) with $NaHCO_3$ or H_2SO_4, and pH variations were recorded and summed up. Characteristics of the process of sulfide concentrate biooxidation are presented on Figs. 1 (a, b)–3 (a, b).

In the course of continuous growth in reactor I (Fig. 1a), the microbial community remained stable, ~(20–30) × 10^8 cells/mL, and included acidithiobacilli, sulfobacilli of various size, archaea, and small rod-shaped cells. No endospores were detected.

After 4.5 volumes were exchanged in reactor I, iron concentration in the pulp liquid phase reached the average value of 17.2 g/L, with 95–97% of it as ferric iron (Fig. 1b). The average concentration of total arsenic was 4.2 g/L; the overall decrease in the maintained pH (1.8) was 0.47 U. These results indicated active leaching/oxidation of iron and oxidation of the sulfur component of the sulfide minerals. Thus, in reactor I at pH maintained at ~1.8, considerable oxidation of the sulfides of flotation concentrate by the ACM community adapted to this concentrate occurred.

In bioreactor II (Fig. 2a), the average cell number of the ACM community at pH 1.6 was 24.5 × 10^8 cells/mL, which was close to the values in reactor I. The community contained the same microorganisms. Sporulating and refractory cells were seldomly observed. The population consisted mostly of vegetative cells.

Iron concentration measured in the liquid phase of the pulp was 18.68 g/L, and Eh was 849 mV. Since partial iron precipitation from the liquid phase as iron oxides could not be ruled out, the overall iron concentration was probably higher. Importantly, together with ferric iron (on average 96% of the total value), ferrous iron was also present (Fig. 2b). This was an indication of iron bioleaching occurring at the second stage of continuous cultivation at pH 1.6. Arsenic leaching also took place, with arsenic concentration in the liquid phase increasing to 6.05 g/L. The pH value decreased to 1.35, which was an indication of active oxidation of the sulfur component of sulfide minerals of the concentrate.

Thus, gradual continuous leaching and oxidation of sulfide minerals of the concentrate occurred in reactors I and II, which was evident from the values of the biological and physicochemical parameters.

The results presented on Fig. 3a show good preservation of the microbial community in reactor III at pH 1.4 (on average 21 × 10^8 cells/mL). Most of the cells were found to decrease in size. Some cells contained poly-β-hydroxybutyrate granules. Some spore-forming organisms were in the phase of sporulation; mature spores (oval and spherical) were also found. Serial terminal dilutions in selective media revealed that apart from bacteria *Ab. caldus* ans *S. thermotolerans*, as well as rod-shaped heterotrophic bacteria *Al. tolerans*, the community contained archaea of the family *Ferroplasmaceae*. While they were present in the other two reactors, in reactor III their abundance increased and comprised ~30% of the total cell number (Fig. 4).

In reactor III, the average iron concentration in the pulp liquid phase was 17.75 g/L (Figs. 3a, 3b), with 99–100% of it as ferric iron (Fig. 3b). The Eh value was 845 mV, arsenic concentration was 5.2 g/L. The maintained pH value (1.4) decreased to 1.3, which was an indication of continued S^{2-}/S^0 oxidation to sulfate. A certain decrease in iron and arsenic concentrations in the pulp liquid phase suggested their precipitation from the pulp, since some of the precipitates obtained after BO of the concentrate, its separation from the liquid phase, and mild acid treatment were dissolved.

Three-stage continuous cultivation in the optimal medium under optimal temperature and pH (1.8, 1.6, and 1.4 in reactors I, II, and III, respectively) resulted in BO stabilization at each stage, which provided for good results in terms of the parameters of leaching and sulfide oxidation; iron and arsenic concentrations in the liquid phase and oxidation of reduced sulfur compounds (RSC). This scheme of the continuous process made it possible to maintain the ACM community in an active state and to preserve the microbial groups involved in sulfide oxidation.

Determination of the dominant groups of microorganisms in the thermophilic ACM community in the course of continuous cultivation. As was mentioned above, variations in the preadjusted pH value resulting from substrate oxidation were recorded. For the composition of the concentrate used in the present work, the major reactions were as follows:

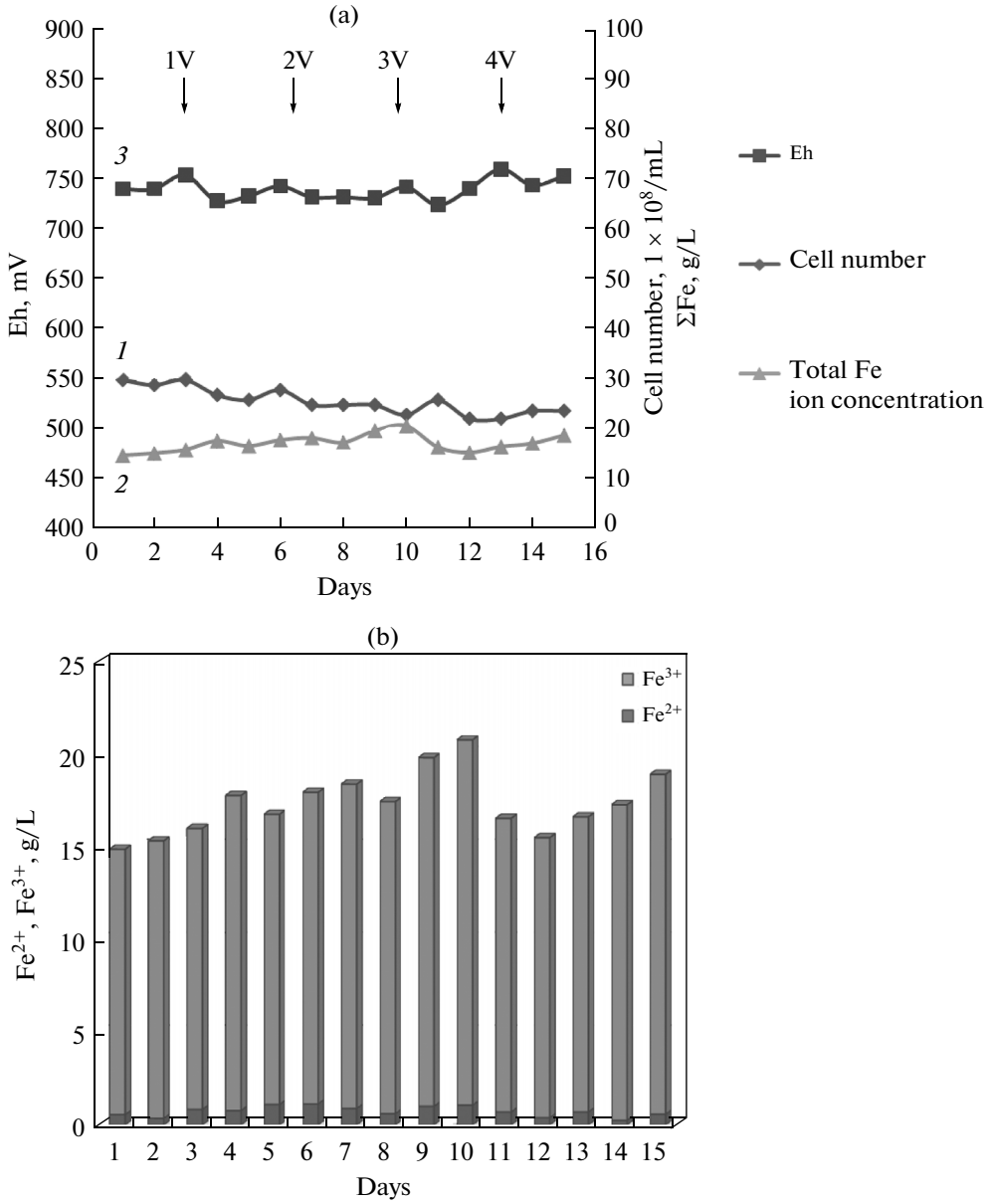

Fig. 1. Characteristics and dynamics of continuous biooxidation of 20% pulp of pyrite–arsenopyrite flotation concentrate in reactor I at pH 1.8–2.0. Characteristics of continuous BO (a): cell numbers/mL (*1*), total concentration of iron ions, g/L (*2*), and Eh, mV (*3*). Volume exchanges (1V, 2V, 3V, 4V) are indicated by arrows. Dynamics of iron leaching and oxidation (b): Fe^{3+} (□) and Fe^{2+} (■).

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4 \text{ (microorganisms)};$$

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O \text{ (microorganisms)};$$

$$FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S^0;$$

$$2FeAsS + 7O_2 + H_2SO_4 + 2H_2O \rightarrow 2H_3AsO_4 + Fe_2(SO_4)_3.$$

Acid is formed in the course of pyrite oxidation and is consumed by arsenopyrite oxidation and dissolution of the carbonate minerals. Secondary reactions associated with precipitation of arsenic and jarosites are also important:

$$2H_3AsO_4 + Fe_2(SO_4)_3 \rightarrow 2FeAsO_4;$$

$$3Fe_2(SO_4)_3 + 12H_2O + M_2SO_4 \rightarrow 2MFe_3(SO_4)_2(OH)_6 + 6H_2SO_4,$$

where $M^+ = K^+$, Na^+, or H_3O^+.

The cell population of the ACM community adapts to varying pH of the medium by regulation of the oxidation of the substrates (iron or sulfur) by the relevant enzymes. In order to reveal the dominant groups of iron- and sulfur-oxidizing microorganisms at different

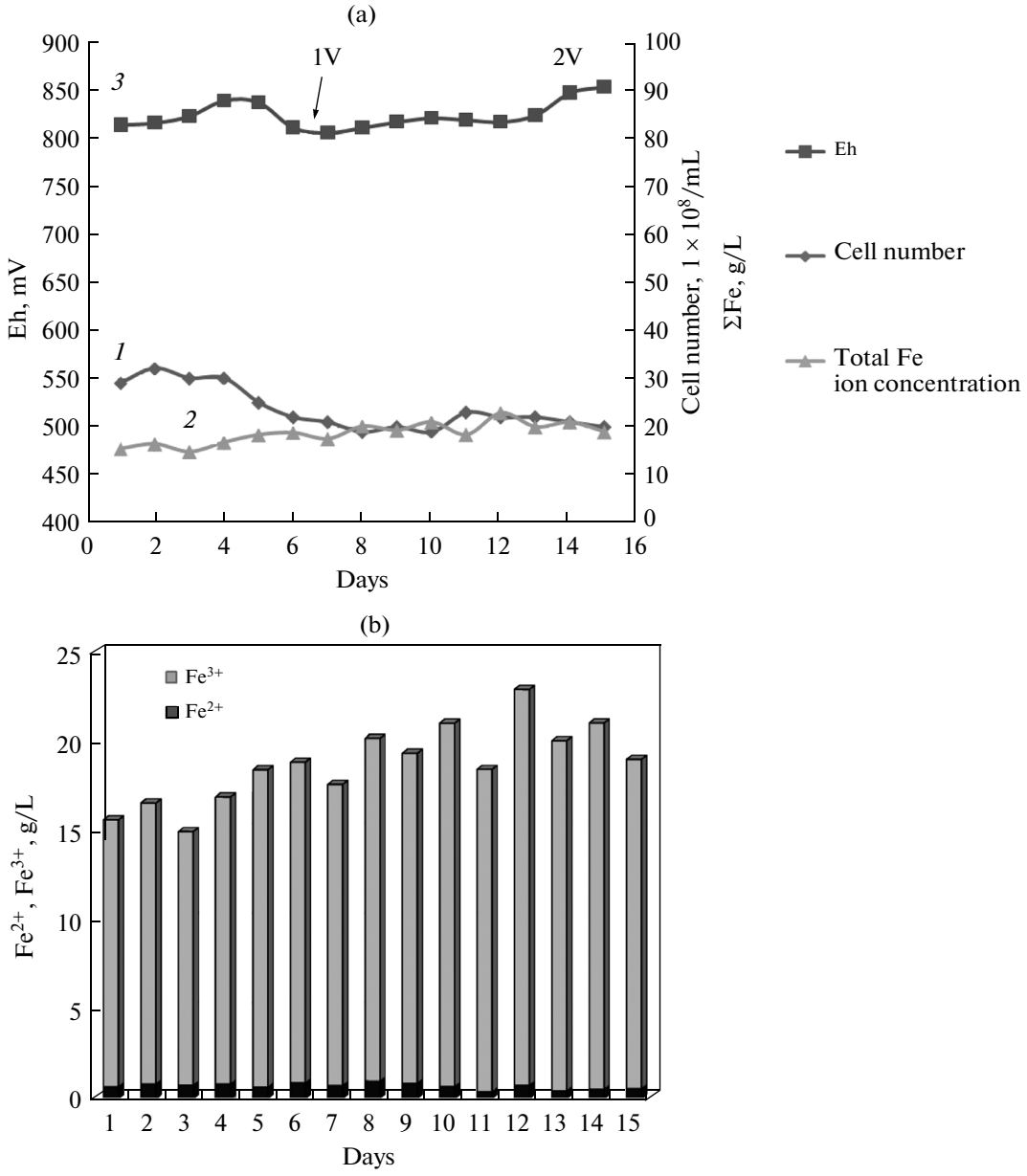

Fig. 2. Characteristics and dynamics of continuous biooxidation of sulfide ore flotation concentrate in reactor II at pH 1.6. Characteristics of continuous BO (a): cell numbers/mL (*1*), total concentration of iron ions, g/L (*2*), and Eh, mV (*3*). Dynamics of iron leaching and oxidation (b).

stages of development of the ACM community, the liquid phase of the pulp from each reactor was subcultured in the flasks containing a single oxidation substrate (S^0 or Fe^{2+}) instead of the complex substrate of the cultivation medium (sulfide ore concentrate).

S^0 oxidation. Inoculation of the ACM community from reactor I into the medium with S^0 resulted in active sulfur oxidation (Table 1). In this variant, the greatest decrease of initial pH by 0.08, 0.22, and 0.35 U was observed during 1–3 days of cultivation. The highest specific growth rate was 0.1 h^{-1}. The highest yield was observed on the third day of cultivation. Terminal dilutions revealed the dominance of *Ab. caldus* (40–60% of the total cell number). Sulfobacilli were the second most numerous group. On the third day of growth their number was the same as the number of small and large spherical cells of archaea.

In the medium with sulfur, ACM communities from reactors II and III oxidized it rapidly. By the third day, pH decrease was 0.25 and 0.15 U, respectively (Table 1), indicating considerable activities of sulfite oxidase and APS reductase, which catalyze the terminal stages of RSC oxidation to sulfate [17, 18]. At pH 1.6 and 1.8, cell yields, community composition,

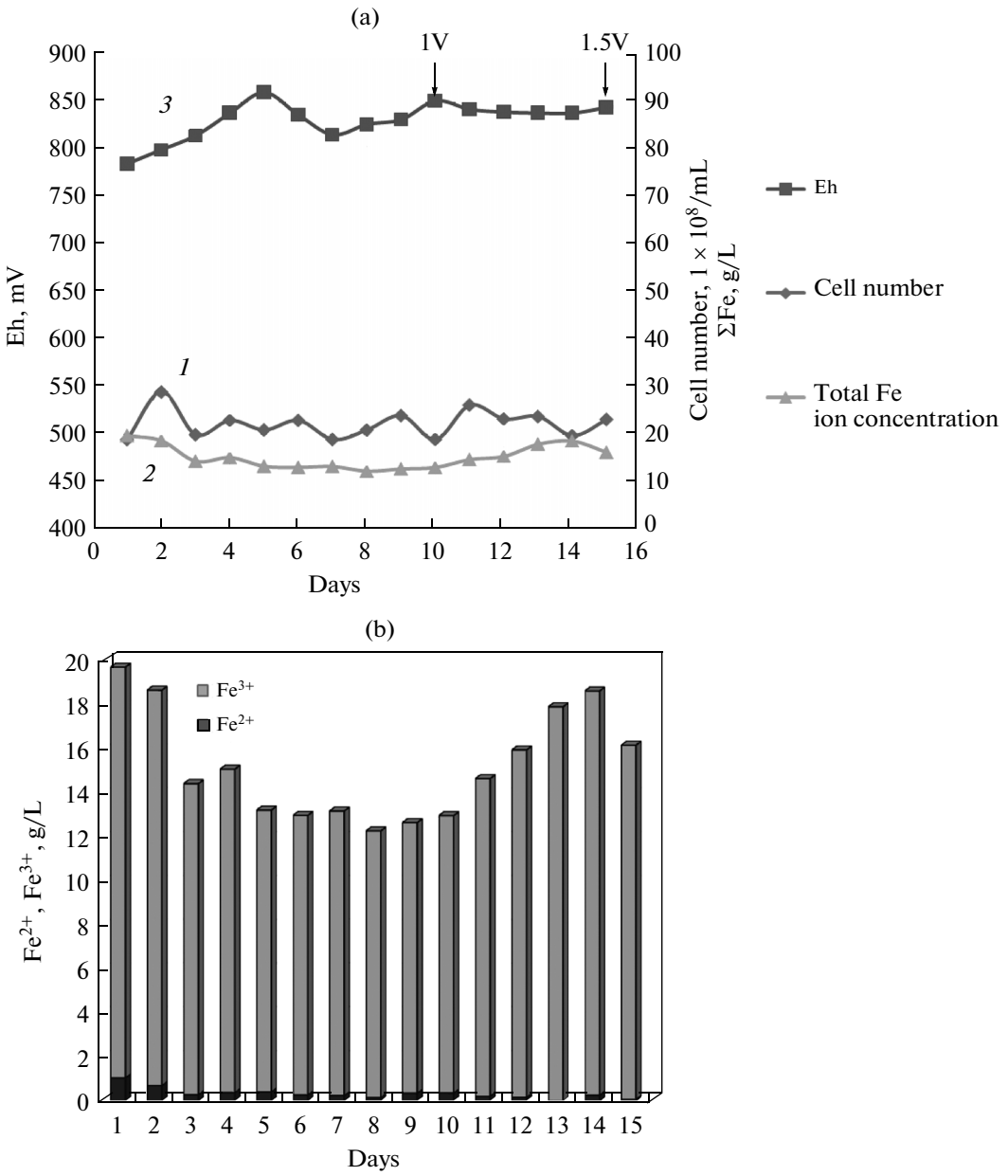

Fig. 3. Characteristics and dynamics of continuous biooxidation of sulfide ore flotation concentrate in reactor III at pH 1.4. Characteristics of continuous BO (a): cell numbers/mL (*1*), total concentration of iron ions, g/L (*2*), and Eh, mV (*3*). Dynamics of iron leaching and oxidation (b).

and specific growth rates ($\mu = 0.09$ h^{-1} at pH 1.6) for batch [13] and continuous cultures were similar. Specific growth rate of the population from reactor III (0.07 h^{-1}) and the yield at pH 1.4 (Table 1) were ~1.8 times lower than in batch cultures.

Inoculations showed that stability of RSC oxidation at pH 1.6 and 1.8 was characteristic of *Ab. caldus*, and to a lesser degree of sulfobacilli (which commence sporulation on the third day of growth) and archaea. The latter were relatively numerous (up to 25% of the total cell number), with numerous dividing cells.

Fe oxidation. A similar series of experiments was carried out with ACM community grown in the medium with Fe^{2+} as the energy source (Table 2).

The variants with pH 1.6 and 1.8 exhibited the most active Fe^{2+} oxidation, with ferric iron concentrations by the end of cultivation 8.25 and 8.0 g/L, respectively. Inoculation of the ACM community from reactor III, in which continuous cultivation was carried out at pH 1.4, Fe^{3+} concentration in the culture liquid was lower (6.6 g/L), which was in agreement with the lower cell number in this variant. The variant with pH stabilization at 1.8 resulted in the highest cell numbers

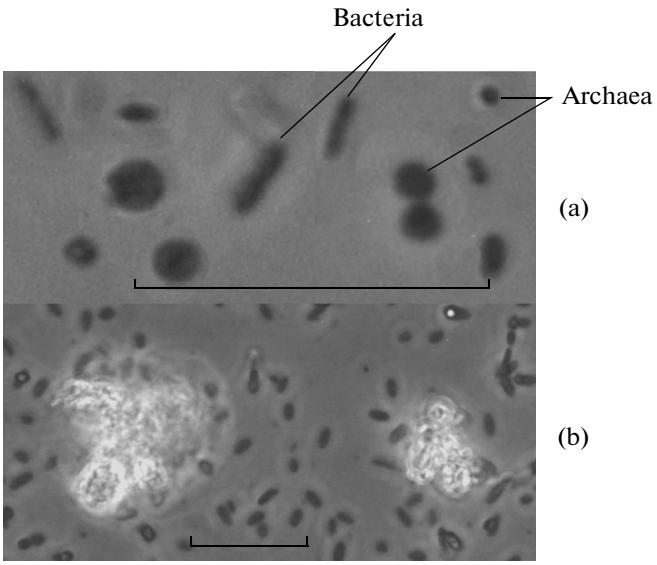

Fig. 4. The cells of the ACM community in reactor III during continuous biooxidation of 20% pulp of sulfide flotation concentrate: archaea and bacteria (a) and cell adhesion to concentrate particles (b). Scale bar is 10 μm.

(on average 24.7×10^7 cells/mL); the maximal specific growth rate μ_{max} was 0.102 h^{-1}. At pH 1.6, μ_{max} and cell yield were somewhat lower: 0.095 h^{-1} and 21.8×10^7 cells/mL. At pH 1.4, the community from reactor III grew in the medium with iron at $\mu_{max} = 0.084\ h^{-1}$ to the cell yield of 16.2×10^7/mL, which was lower than in other experimental variants, but higher than in the medium with sulfur. The iron-oxidative activity of the cells was probably practically the same at different pH values and depended only on the number of cells.

Within the pH range for which good iron oxidation was observed, the earlier obtained result was confirmed: the optimal zone for iron oxidation by a thermophilic ACM community lied at pH 1.6–1.8.

At pH 1.8 and 1.6, sulfobacilli predominated in the community (55–80%). Archaea of the family *Ferroplasmaceae* and very small cells were minor components, although their number increased to 30% at pH 1.6 and especially at pH 1.4. While acidithiobacilli were present in the inoculum taken from the reactors, in the medium with iron their cells lysed or were converted to very small persistent forms.

This part of the study made it possible to conclude that the most active iron- and sulfur-oxidizing microorganisms, which are about equally abundant in the developing community, may be involved in competition when sulfide concentrate is present in the medium. This is probably the reason for the fluctuating iron concentrations in the pulp liquid phase (Fig. 3b).

Both competitive and sequential utilization of two substrates (polythionates and iron) have been described in the literature [19]. Inhibition of the sulfur oxidation pathway by ferrous iron ions (at concentrations 2×10^{-2} M and higher) and the presence of nitrates, which inhibit iron oxidation and thus favor polythionate oxidation, have been discussed as the hypothetical reasons for the competition [20].

In our experiments, competition for the substrate between acidithiobacilli, sulfobacilli, and sulfur-oxidizing archaea was possible in the case of RSC oxidation; in the case of iron oxidation, competition between sulfobacilli and iron-oxidizing archaea could occur. Understanding of the optimal technological parameters of BO and dependence of predominance of the known forms of active microorganisms upon these parameters will make it possible to regulate the degree of sulfur and iron oxidation by adjusting the required ratio of the microorganisms involved.

Analysis of the products of BO of sulfide ore flotation concentrate by ACM community during continuous cultivation. The elemental composition of the original gold-bearing pyrite–arsenopyrite flotation concentrate and of the products of its oxidation in reactor III at the end of continuous cultivation at 0.004 h^{-1} flow rate is shown in Table 3. The degree of oxidation of the sulfide forms of the elements listed in Table 4 confirmed that the ACM community oxidized the original concentrate almost completely. The degrees of oxidation for sulfide forms of arsenic, iron, sulfur, and antimony were 99.55, 98.87, 99.65, and 97.08%, respectively.

Thus, continuous biooxidation of flotation concentrate of refractory sulfide ores by the ACM community in feed-batch mode in a line of three reactors was characterized by intensive oxidation of sulfide minerals, as could be seen from the growth parameters and from the results of analysis of the biooxidation residue. Efficiency of the process was in agreement with high gold recovery by sorption cyanidation of the resi-

Table 1. Growth dynamics of the thermophilic ACM community from bioreactors in the medium with S^0

Reactor no.	pH	Medium acidification to pH			Cell number, 1×10^7/mL		
		1 day	2 day	3 day	1 day	2 day	3 day
I	1.8	1.72	1.58	1.45	0.6	5.18	23.8
II	1.6	1.54	1.49	1.35	1.0	5.94	22.5
III	1.4	1.38	1.30	1.25	0.74	4.30	12.6

Table 2. Growth dynamics of the thermophilic ACM community from bioreactors in the medium with Fe^{2+}

Reactor no.	pH	Fe^{3+} concentration, g/L			Cell number, 1×10^7/mL		
		1 day	2 day	4 day	1 day	2 day	4 day
I	1.8	2.4	5.0	8.0	0.8	6.9	24.7
II	1.6	2.9	4.8	8.25	0.7	6.7	21.8
III	1.4	1.3	3.7	6.6	0.8	5.8	16.2

Table 3. Elemental composition of the original flotation concentrate and biooxidation residue

Substrate	Content, %								
	As_{total}	As_S	Fe_{total}	Fe_S	Sb_{total}	Sb_S	S_{total}	S_S	S^0
Original concentrate	3.63	3.63	20.9	19.2	0.56	0.28	20.44	19.87	0.08
Residue III	1.14	0.04	10.3	0.53	0.56	0.02	4.64	0.17	0.02

Table 4. Oxidation degree of sulfide forms of the elements in reactors during feed-batch cultivation of the ACM community at $D = 0.004\ h^{-1}$

Reactor no.	Oxidation degree, %			
	As_s	Fe_s	S_s	Sb_s
III	99.55	98.87	99.65	97.08

due (Table 5). Gold recovery from the original flotation concentrate (prior to BO) was low (15.1%). Gold recovery from biooxidation residues was 97.4%. Cyanide consumption for gold recovery was 11.1 g/kg.

The results of oxidation of pyrite–arsenopyrite gold-bearing flotation concentrate by a selected thermophilic ACM community in continuous mode at $0.004\ h^{-1}$ flow rate in three sequential bioreactors confirmed that maintenance of the optimal technological parameters (pH, temperature, medium composition, and pulp density) resulted in a high degree of oxidation of sulfide minerals and high gold recovery. The major technological patterns were preserved as the flow rate increased 2.5-fold (to $0.01\ h^{-1}$). Under these conditions, gold recovery was 87.5%, which is a good result for a laboratory setup.

ACKNOWLEDGMENTS

The work was supported by the Russian Foundation for Basic Research, project no. 13-08-00046.

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Table 5. Results of sorption cyanidation of the original flotation concentrate and of biooxidation residue after continuous cultivation of the ACM community under optimal technological conditions

Substrate	Total biooxidation time, days	Gold recovery, %	Consumption, g/kg	
			NaCN	CaO
Original flotation concentrate	–	15.1	12.0	4.51
Biooxidation residue from reactor III	15	97.4	11.1	51.07

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Translated by P. Sigalevich