Methods of ore processing by microwave radiation

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The article analyzes Russian developments — methods for processing ores, rocks using microwave radiation. The methods were developed at the Institute of Geotechnical Mechanics of the Academy of Sciences of the Ukrainian SSR, IPKON RAS, IRE RAS, SUSU, Binotek LLC, IG KarRC RAS, JSC "Uralelektromed", St. Petersburg State University, St. Petersburg Mining University, NPK "Mekhanobr-tekhnika", UrFU and etc. As the authors of the developments note, microwave processing of rocks and ores in most ways is used to form gaps in it, a fractured structure, remove oxide films from the surface of mineral phases, due to differences in the electromagnetic properties of the ore and non-ore phases. This effect can occur in the microwave frequency range at powers from 0.5 to 50 kW, radiation duration from 0.5 to 600 s, with a heating temperature of ore phases from 150 to 500 °C. As the analysis showed, microwave processing is used for grinding rocks, ores, as well as to increase the efficiency of such processes as grinding, heating, leaching, flotation. As a result of the study, a technological scheme for preparing ore for the process of bacterial-chemical oxidation using microwave was developed.

Key words: bacterial-chemical oxidation, microwave radiation, ore, rock, super-high-frequency radiation.

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Introduction

Today, in mining and mineral processing technologies, super-high-frequency radiation is increasingly being utilized. However, due to the high energy costs of SHF treatment and the necessity of controlling the level of SHF treatment to prevent negative changes in the ore phase of the mineral, these technologies have not found universal application. Still, super-high-frequency processing has a number of advantages over traditional convective heating, crushing, grinding, due to rapid and selective heating of ore phases absorbing microwave radiation.

The application of microwave energy in extractive metallurgy, in particular biohydrometallurgy, is still in the early stages of development, but today significant advances have been made in research related to the use of microwave systems in the extraction processes of metals such as Au, Ag, Ni, Co, Cu, Cu, Fe, U.

The aim of the work is to analyze the methods of ore processing using microwave radiation and to develop a technological scheme of ore preparation for the process of bacterial-chemical oxidation using microwave radiation.

1. Review of Russian developments of ore processing methods using microwave radiation

One of the first developments in the field of mineral processing/refining is the technology of grinding using microwave radiation developed by the Institute of Geotechnical Mechanics of the Academy of Sciences of the Ukrainian SSR in 1987 [1]. In this method the rock (thin-bedded ferruginous quartzite) was crushed and pulverized as a result of irradiation by electromagnetic waves with frequency 2375 MHz, wavelength 12.63 mm, power up to 3 kW, duration of 5 min, final temperature 450–500 °C. The effect was achieved due to obvious differences in the electromagnetic properties (values of dielectric loss angle tangents, dialectric and magnetic permeabilities) of the metal and non-metallic phases. The metal phase, intensively absorbing microwave energy, was heated (standing waves provide equally intensive heating sources), in contrast to the non-metallic phase, the temperature of which practically did not change. As the temperature increased, the grains of the metal phase thermally expanded in the relatively cold shell of the non-metallic phase, resulting in weakening or reduction to zero of the phase adhesion forces. Thermal expansion led to an increase in stresses and strains at the phase boundary, and when contact strength was reached, fractures and cracks appeared in the ore structure. The obtained microcracked structure allowed to significantly accelerate the process of further ore grinding using mills at grades – 0.074 + 0.05 mm, 0.05 + 0.02 mm [1].

In 1999, IPCON RAS and IRE RAS developed a method of processing of refractory ores or their enrichment products to obtain Au and Ag [2]. In this method before leaching the refractory ore was affected by electromagnetic pulse of microwave range with amplitude of electric field component intensity (150 kV, 1-50 MV/m) greater than the electrical strength of ores and duration of the impulse front (10 ns), less than the time of formation of spark discharge in air gap. The effect of using electromagnetic pulses of microwave range, taking into account the inhomogeneity of ores and electrically conductive inclusions in it, ensured the development of breakdown due to the increase of electric field intensity. Therefore, the channels formed in the process bound Au, Ag particles to the surface, which intensified further leaching of metals. South Ural State University continued research [2] on the impact on ores by electromagnetic pulses and in 2016 the invention [3] was published. The ores were exposed to nanosecond electromagnetic pulses with a duration of less than 1 ns, an edge duration of less than 0.1 ns, a repetition rate of more than 1 kHz and an amplitude of more than 15 kV, with a pulsed field strength amplitude of 100 kV/cm.

The heterogeneity of ores, different dialectric and magnetic permeabilities of its constituent components were used for its further grinding in the work [4]. The ore was exposed to microwave radiation with a volumetric intensity of 10^9–10^{16} W/m^3, duration of 0.5 s (using pulsed microwave radiation with duration of 1 μs – 0.001 s), with heating the metal component of the ore by 150–200 °C.

Known methods of treatment of sulfide copper-nickel ores using microwave radiation to accelerate its further processing by heap leaching [5, 6]. Prior to leaching, ore particles with size 15 cm or less were subjected to microwave irradiation with frequency 0.3–300 GHz, pulse duration from 0.001 to 1 s, between-pulse period – 0.02–2 s, power 1–50 kW. According to the authors [5, 6] irradiation caused high local point heating of ore components susceptible to microwave radiation, such as chalcopyrite, chalcocite, in which valuable metals are concentrated. The difference in the values of thermal expansion of sulfide ore components led to the formation of thermal stresses and as a consequence of thermal deformations - microcracks in the particles. The formed microcracked structure allowed to accelerate the process of heap leaching of sulfide ore, to increase the qualitative, quantitative characteristics of the process.

Binotec LLC proposed a technology for enrichment and extraction of Au, Pt, Pd from refractory, low-grade ores [7]. Before microwave treatment of flotation tailings of Gaisky MPP (up to 25% pyrite, more than 50% quartz), providing heating of ore up to 180–280 °C, ore was subjected to fractionation in upward flow with variable hydrodynamic regime. Then leaching of Au, Pt, Pd into aqueous solution was carried out. Microwave treatment in this temperature range, as in [5, 6, 8], provided local heating of metal microinclusions and ensured the formation of cracks in the crystalline phase, which facilitated the access of leaching solution to the previously blocked surfaces of microinclusions.

In 2011–2013, the IG KarNC RAS developed a method of enrichment of quartz raw materials [9]. To intensify the purification of natural quartz, two-stage exposure to super-high-frequency radiation in certain power ranges was used. The power of exposure at the first stage was 240–360 W (duration 1–2 min), at the second stage – 540–900 W (duration 3–5 min). As studies [9] have shown, the specified power ranges provided maximum, almost complete stripping of mineral impurities, oxide films and gas-liquid inclusions, including those of nanoscale dimensions. Electromagnetic energy instantly penetrated into quartz grains and concentrating in their center increased the temperature in the thermal center of grains, while the external temperature of grains had a low value.

There is a known method of stripping ores by subjecting it to an electromagnetic field with a frequency ≥300 GHz [10]. The essence of the claimed method is similar to the work [1] and consists in the different degree of wave energy absorption, in the difference of heating of metal and non-metallic components of raw materials, in the difference of temperature expansions, due to which there will be thermal deformations in the ore material, and then ruptures and cracks. The authors of the invention note that the formed fractured structure accelerates further processes of separation of valuable components from the ore material [10].

In 2017 Uralelectromed JSC proposed to treat breakage and slag by microwave radiation for 1–10 minutes with a power of 500 W [11]. After irradiation, the breakage and slag were pulverized, coarse metal particles were extracted by gravity methods, and the gravity tailings were subjected to flotation. The impact of super-high-frequency radiation on sludge and slag breakage took place simultaneously throughout the entire volume, but inhomogeneously, since the material contained components with different electromagnetic susceptibility. The authors explain the positive effect of using microwave exposure by the heterogeneity of breakage and slags. On the one hand, they consisted of ceramic refractory and silicate-oxide slag, absolutely immune to super-high-frequency radiation. Even with prolonged processing, the heating of these substances is extremely insignificant. On the other hand, breakage and slag included grains of metallic and sulfide structures (Au, Ag). In the field of microwave energy these valuable components were heated very quickly. As a result of different heating of susceptible and non-susceptible components, thermal deformations occurred inside the breakages and slags, which allowed their subsequent separation along the deformed boundaries and efficient uncovering of valuable components. Also in the process of research [11] it was found that at exposure power of more than 500 W and duration of more than 1–10 min valuable components of breakage and slag can melt down.

St. Petersburg Mining University in 2016–2017 investigated the effect of microwave radiation duration on Au coalescence in the process of its extraction from refractory carbonaceous ores. The duration of the process was 15–25 minutes, at a radiation power of 1.0–1.5 kW. It was found that due to super-high-frequency and high-temperature impact, de-precipitation of minerals and gas-liquid inclusions and release of crystallochemical water, leading to the appearance of additional defects, occurs. As a result, self-purification of sulfide minerals from atoms of dispersed Au occurs by driving it away to the peripheral parts of grains and intergranular space, where ultradisperse individuals are formed. Based on the studies, the developed method [12] allows to increase the extraction efficiency due to the enlargement of Au ultraparticles, provides an opportunity for further extraction of ultradisperse individuals by flotation or gravitational methods.

Continuing research St. Petersburg Mining University in 2019 patented a method of processing slobomagnetic carbon-containing raw materials using electromagnetic radiation in the microwave range [13]. Microwave exposure was applied to ash and slag waste of <2 mm size with frequency 2000–3000 MHz, radiation power 400–800 W, with exposure duration from 2 to 3 min. Then the obtained material was separated in a low-intensity magnetic field. As in [8, 10], microwave treatment led to intensive heating of the weakly magnetic components susceptible to microwave. In the process of heating, weakly magnetic components were reduced with the carbon present in the material to strongly magnetic forms, which made it possible to further separate them in the magnetic field [13]. A similar method of using super-high-frequency exposure for microwave irradiation of H_2SO_4 production waste in the roasting of pyrite was reported by the researchers earlier. The exposure frequency was 2.45 GHz, magnetron power – 5 kW [14].

In order to reduce energy costs by 70% compared to [15, 16], while increasing the degree of recovery of KCl in the concentrate (≈97%) due to the point thermal microwave impact on the components of potash ore (250–300 °C), providing structural changes in minerals,

Table
Main technical characteristics of the methods of ore processing by microwave radiation

Source, year	Radiation frequency, MHz	Power, kW	Duration, sec	SHF Radiation intensity /metal component heating temperature, W/m^3 / °C	Effect of microwave radiation on ore
[1], 1987	2375	Up to 3	300	– /450–500	Formation of microcracked rock structure due to differences in electromagnetic properties of metal and non-metallic phases
[2], 1999	300–300000	Electric field intensity – 1-50 MV/m	Impulse front time – 10×10^{-9}	– / –	Formation of channels in refractory ores due to breakdown, which intensifies further leaching of Au and Ag
[3], 2016	Pulse recurrence – 1 kHz	Electric field intensity – 100 kV/cm	Impulse front time – less than 0.1×10^{-9}	– / –	Formation of microcracked structure in the ore, which intensifies further leaching of Au and Ag
[4], 2008	300– 300000	–	0.5 (impulse front time – less than 1×10^{-6}– 1×10^{-3})	10^9–10^{16}/ 150–200	Formation of microcracked ore structure (thin-bedded ferruginous quartzites) due to differences in electromagnetic properties of metal and non-metallic phases
[5, 6], 2008	0.3-300	1–50	(Impulse front time –1×10^{-3}–1; one-pulse time – 2×10^{-2}–2)	– / –	Formation of microcracked structure in copper-nickel ore (particle size 15 cm and less), which intensifies further heap leaching
[7], 2012	300–300000	0.7	1200	– / 180–280	Formation of a microcracked structure in the ore, which intensifies further leaching
[9], 2013	300–300000	0.24–0.36	60–120	– / –	Formation of microcracked structure in natural quartz, removal of oxide films and gas-liquid inclusions
		0.54–0.9	180–300		
[10], 2015	300000	–	–	– / –	Formation of microcracked ore structure, acceleration of further extraction of valuable components
[11], 2017	300–300000	0.5	60–600	– / –	Formation of microcracked structure of slags and breakages due to differences in electromagnetic properties of their components
[12], 2018	300–300000	1–1.5	900–1500	– / –	Decrepitation of minerals and gas-liquid inclusions of refractory carbonaceous ores to improve Au recovery
[13], 2019	2000–3000	0.4–0.8	120–180	– / –	Reduction of weakly magnetic components of ash and slag waste to strongly magnetic forms in the process of microwave heating
[14], 2007	2450	5	7200	– / –	Exposure to super-high- frequency radiation with subsequent separation of material into magnetic fraction and non-magnetic residue
[17], 2019	2450	1	600–1200	– / 250–300	Microwave exposure for point heating of individual ore components
[18], 2021	2450	1.5	1200–1800	– / 200–250	Sulfatization of refractory nickel-containing phases of nickel-cobalt ore

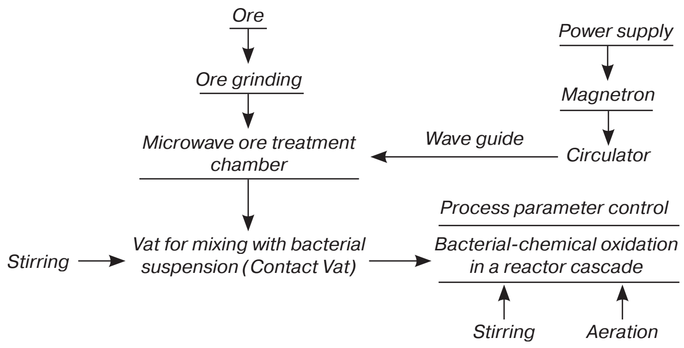

Figure. Developed technological scheme of ore preparation for the process of bacterial-chemical oxidation using microwave technology

with minimal thermal impact on the salt minerals NPK "Mekhanobr-Technika" has developed a method of enrichment of potash sylvinite ores. [17]. The method was carried out at the frequency of super-high-frequency radiation 2.45 GHz, power of 1 kW and duration of 10–20 min. This method has a significant difference from the developments [5, 6] with the use of "shock" exposure to microwave radiation with short pulses.

Ural Federal University investigated the method of processing oxidized nickel-cobalt ore (Ni content – 0.9% and Co – 0.06%), which allows to reduce the duration of sulfatization in 10–15 times, operating costs in 5–10 times, with Ni recovery in solution – 90–95% [18]. It has been found that microwave exposure significantly increases the sulfatization of refractory nickel-containing phases, in contrast to the known methods [19–21]. The experiments were carried out in a laboratory microwave oven. Penetrating wave influence sharply intensifies mass transfer of the process. Decomposition of refractory mineral phases with formation of soluble Ni compounds took place at temperatures of 200–250 °C, within 20–30 minutes. At lower values of temperature and duration the sulfatization efficiency decreased, while the increase of these parameters did not increase the sulfatization efficiency. Also, the experiments showed the growth of sulfatization at the application of super-high-frequency energy in an atmosphere of water vapor.

The main technical characteristics of ore processing methods [1–7, 9–14, 17, 18] are presented in **Table**.

2. Technological scheme development of ore preparation for bacterial-chemical oxidation process using microwave technology

The development of efficient metal recovery processes after the bacterial-chemical leaching/oxidation stage is key to accelerating the entire biohydrometallurgical process.

For almost ten years NIGTC FEB RAS has been conducting research on the effect of microwave radiation on sulfide cobalt-copper-nickel ore of the Shanuch deposit with the content of sulfide minerals – pyrrhotite 65–75%, pentlandite 20–25%, violarite 10%, chalcopyrite 2–5%. The experiments were conducted with an intensity of ≈0.7 W/cm^2, power of 900 W and duration from 20 to 100 s. The study established that irradiation of ore by microwave radiation intensifies the process of bacterial-chemical leaching. Treatment of ore with 100 s duration raised the Ni concentration increase rate in solution by 57%, Co by 52%, and Cu by 24% [22–27].

To intensify the bacterial-chemical leaching/oxidation process, a process flow diagram was developed as shown in the **Figure**.

The ground ore (particle size 100 μm) is fed into the microwave treatment chamber. The microwave system has the ability to adjust the power from 0.5 to 5 kW, duration – 100–500 s and radiation frequency – 300–2450 MHz, intensity ≥0.7 W/cm^2. After the super-high-frequency treatment chamber, the treated ore enters the contact vat, where it is mixed with bacterial suspension (rotation speed 100–400 rpm). From the vat, the slurry is pumped to a cascade of reactors for bacterial-chemical oxidation.

For further design and installation of the super-high-frequency reactor for polymer slurries, it is necessary to purchase the appropriate microwave system components. Components of necessary, adjustable frequency range (300–2450 MHz), as well as necessary, adjustable output power (500–5000 W) are developed and produced in Russia by enterprises such as – JSC SPE "MAGRATEP", LLC "Microwave Components and Systems", JSC "Microwave Systems", PJSC "Kovylkinskiy Electromechanical Plant" [28–31].

Conclusion

The analysis of Russian developments in the field of ore processing using microwave radiation has shown that super-high-frequency treatment of rocks, ores (refractory, sulfide copper-nickel, iron ores, refractory carbonaceous ores, etc.) in most of the methods/technologies is used for formation of microcracked structure, fractures, formation of microchannels, removal of oxide films, decompression of minerals and gas-liquid inclusions) in the majority of methods/technologies is used for formation of microcracked structure, fractures, formation of microchannels, removal of oxide films, de-precipitation of minerals and gas-liquid inclusions, due to differences in electromagnetic properties of metal and non-metallic phases. This effect can occur in the microwave frequency range at powers from 0.5 to 50 kW, radiation duration from 0.5 to 1200 s, with metal phase heating temperature from 150 to 500 °C. As the review has shown, microwave treatment is used for grinding rocks, ores, to increase the efficiency of such processes as grinding, leaching, flotation. As a result of the study the technological scheme of ore preparation for the process of bacterial-chemical oxidation using microwave was developed.

References

1. Pat. SU No. 1326334 A1. Int. Cl. B02 C19/18. Method of Processing Materials. Korobskoj V. K., Chelyshkina V. V. Appl. 1985.05.05, Publ. 30.07.1987, Bull. No. 28.

2. Pat. RU No. 2139142 C1. Int. Cl.[6] B03B 7/00, B02C 19/18. Method of Processing of Materials Containing Noble Metals.

Chanturija V. A., Lunin V. D., Bunin I. Zh., Guljaev Ju. V., Cherepenin V. A., Vdovin V. A., Korzhenevskij A. V., Sedel'nikova G. V., Krylova G. S. Appl. 12.04.1999, Publ. 10.10.1999.

3. Pat. RU No. 2605012 C1. Int. Cl. C22B 11/00, B03B 7/00, C22B 3/02, C22B 3/04. Method and Device for Processing Ores Containing Precious Metals. Krymskij V. V., Litvinova E. V., Mingazheva J. G. Appl. 23.07.2015, Publ. 20.12.2016 Bull. No. 35.

4. Pat. RU No. 2318028 C2. Int. Cl. C22B 1/00, B02C 19/18. Method Used for Formation of the Electromagnetic Radiation with the High Intensity of the Field and Treatment of the Materials with Its Help, for Example, Softening of the Multiphase Materials. Kingman S. U. Appl. 01.04.2003, Publ. 27.02.2008, Bull. No. 6.

5. Pat. RU No. 2329310 C2. Int. Cl. C22B 1/00. Microwave Treatment of Ores. Batterkhehm R. D., Ehzdehjl L., Sho R. U., Kross K. R. Appl. 30.05.2003, Publ. 20.07.2008, Bull. No. 20.

6. Pat. RU No. 2389806 C2. Int. Cl. C22B 1/00. Processing Mineral Material with Microwaves. Appl. 30.09.2005, Publ. 20.05.2010, Bull. No. 14.

7. Pat. RU No. 2441079 C1. Int. Cl. C22B 11/00, C22B 1/00, C22B 3/04. Method of Producing Noble Metals from Refractory and Lean Ores. Nizov V. A. Appl. 22.11.2010, Publ. 27.01.2012, Bull. No. 3.

8. Pat. RU No. 2375475 C1. Int. Cl. C22B 11/00, C22B 03/06. Method Of Enrichment Of Persistent Base Ores And Extraction From It Of Precious Metals. Sychev A. I., Obysov A. V., Dul'nev A. V., Tsarev V. V., Tertyshnyj I. G. Appl. 20.05.2008, Publ. 10.12.2009, Bull. No. 34.

9. Pat. RU No. 2483024 C2. Int. Cl. C0 B 33/12. Method for Beneficiation of Natural Quartz Material. Appl. 22.06.2011, Publ. 27.05.2013. Bull. No. 15.

10. Pat. RU No. 2540101 C1. Int. Cl. C22B 1/00, B02C 19/18. Method And Device for Opening Ore. Regenfuss P., Shtreek A. Appl. 09.12.2012, Publ. 10.02.2015, Bull. No. 4.

11. Pat. RU No. 2617192 C1. Int. Cl. C22B 7/00, C22B 11/00, B03D 1/018, C22B 3/04. Method for Enrichment of Metalliferous Scum and Slag. Korolev A. A., Krestyaninov A. T., Mastyugin S. A., Krayukhin S. A., Lobanov V. G., Gibadullin T. Z., Voinkov R. S., Khafizov A. T. Appl. 31.12.2015, Publ. 21.04.2017, Bull. No. 12.

12. Pat. RU No. 2648400 C1. Int. Cl. B03D 1/02. Extracting Ultrafine Gold Particles from Steering Carbon Ore Method. Afanasova A. V., Aleksandrova T. N. Appl. 22.03.2017, Publ. 26.03.2018, Bull. No. 9.

13. Pat. RU No. 2677391 C1. Int. Cl. C22B 1/00. Method for Processing Low-Magnetic Carbon Containing Raw Materials. Aleksandrova T. N., Kuskov V. B., Nikolaeva N. V. Appl. 2018.02.19, Publ. 16.01.2019, Bull. 2.

14. Pat. RU No. 2305711 C1. Int. Cl. C22B 11/00, C22B 3/06. Method of Extraction of the Noble Metals From the Ash-Waste of The Sulfuric Acid Production. Chernyshev V. I., Tertyshnyj I. G., Ofitserov S. V., Parshin V. S., Obysov A. V. Appl. 2005.12.07, Publ. 10.09.2007. Bul. 25.

15. Pat. RU No. 2684380 C1. Int. Cl. C01D 3/08, B01J 19/12, B03D 1/001, C05D 1/04, B03D 101/02, B03D 103/10. Method Of Enrichment Of Potassium Silvinite Ores. Arsentev V. A., Gerasimov A. M., Lazareva V. V., Ustinov I. D. Appl. 08.05.2018, Publ. 08.04.2019, Bull. No. 10.

16. Pat. SU No. 453389 A1. Int. Cl. C05D 1/01, B03D 1/00. Method of Obtaining Potash Fertilizers. Komarov V. S., Mozhejko F. F., Aleksandrovich Kh. M., Varlamov V. I. Appl. 10.03.1972, Publ. 15.12.1975, Bull. No. 49.

17. Pat. US No. 2772775. Int. Cl. 209-11. Treatment of Sylvinite Ore. Atwood G. E. Appl. 02.03.1953, Publ. 04.12.1956.

18. Pat. RU No. 2756326 C2. Int. Cl. C22B 23/00, C22B 1/06, H05B 6/64. Method for Processing Oxidized Nickel-Cobalt Ore. Lobanov V. G., Polygalov S. E., Kolmachikhina O. B., Makovskaya O. Yu., Savenya M. V., Shadrina E. A. Appl. 03.03.2020, Publ. 29.09.2021, Bull. No. 28.

19. Pat. RU No. 2078841 C1. Int. Cl. C22B 23/00. Method Of Oxidized Nickel Ores Processing To Produce Nickel And Cobalt. Smirnov Ju. M., Pashkovskij A. A., Redinin I. Ju., Smirnov A. Ju. Appl. 11.01.1993, Publ. 10.05.1997.

20. Pat. RU No. 2287597 C2. Int. Cl. C22B 23/00. Method of Reprocessing of the Oxygenated Nickel-Cobalt Ores. Sinegribov V. A., Kol'tsov V. J., Logvinenko I. A., Mel'nik D. V., Batshev V. I. Appl. 27.08.2004, Publ. 20.11.2006, Bull. No. 32.

21. Pat. RU No. 2596510 C1. Int. Cl. C22B 23/00, C22B 1/06, C22B 3/04. Method of Processing Oxidized Nickel Ores. Rybkin S. G., Aksenov A. V., Senchenko A. E., Grinkevich A. V. Appl. 22.05.2015, Publ. 10.09.2016, Bull. No. 25.

22. Kioresku A. V. Applications of Microwave Energy in Extractive Metallurgy. *Mining Informational and Analytical Bulletin*. 2018. No. 12/S57. pp. 307–316.

23. Kioresku A. V. Features of Microwave Heating of Different Types of Ore And Minerals. *Mining Informational and Analytical Bulletin*. 2018. No. 12/S57. pp. 317–324.

24. Kioresku A. V. Bioleaching Of Nickel, Copper And Cobalt From Ore Irradiated With Microwave Radiation. *Advances in Current Natural Sciences*. 2019. Iss.12. pp. 51–56.

25. Trukhin Yu. P., Iodis V. A., Khainasova T. S. Microwave and Ultrasound Activation of Kinetics of Bacterial-Chemical Processes of Leaching of Cobalt-Copper-Nickel Ores of the Shanuch Deposit. *Mining Informational and Analytical Bulletin*. 2021. No. 11/S19. pp. 113–123.

26. Iodis V. A., Trukhin Yu. P. Development Of A Large Flow Cascade Bacterial-Chemical Reactor With Microwave Activation For Bacterial-Chemical Processing Of Cobalt-Copper-Nickel Ore. *Mining Informational and Analytical Bulletin*. 2021. No. 11/S19. pp. 124–135.

27. Trukhin Yu. P., Iodis V. A. Development of a Enlarged Flow-Through Cascade Bacterial-Chemical Reactor with Use and Microwave Activation for Bacterial-Chemical Processing of Cobalt-Copper-Nickel Ore. *Mining Informational and Analytical Bulletin*. 2021. No. 11/S19. pp. 147–158.

28. JSC Scientific and Production Enterprise "Magratep". Products. URL: https://magratep.ru/production/ (Accessed Date: 21.07.2023).

29. Microwave Components and Systems. Products. URL: https://mwaves.ru/ (Accessed Date: 21.07.2023).

30. Microwave Systems JSC. Products. URL: https://www.mwsystems.ru/goods/index.html (Accessed Date: 21.07.2023).

31. Public Joint Stock Company "Kovylkinsky Electromechanical Plant". Industry. URL: http://www.deskemz.ru/pages/industry.html (Accessed Date: 21.07.2023). NFM