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MODELING OF METAL LEACHING PROCESSES IN THE DISINTEGRATOR

One of the key problems of mining production is the involvement in the production of substandard metal-containing raw materials of technogenic origin. The problem of using substandard raw materials for traditional methods of enrichment is associated with the problem of strengthening the mineral resource base of metallurgy. Among the directions of extraction of metals from ores, the priority of the problem of waste-free production or the inclusion of waste products from the tailings of primary processing into use without restrictions on sanitary conditions is noted. The article substantiates the feasibility of implementing a new direction for the mining industry: involvement in the production of substandard metal-containing raw materials of technogenic origin by leaching in a high-speed disintegrator mill. The results of the state of the mineral resource base of non–ferrous metals are given. New data on the extraction and loss of metals in the process of ore dressing are presented. A decrease in the gap between the content in processing waste and in ore reserves was noted. It is shown that the total value of metals in waste is comparable to the value of potential mineral resources in the subsurface. The expediency of assessing the possibilities of technologies for the utilization of man-made reserves by modeling the processing indicators is substantiated. It is concluded that the problems of using mining waste should be solved in a single package by creating a technological cycle of extraction and processing of man-made waste, the use of which can make the development of technogenic deposits economically profitable. The purpose of research on the prospects of solving the problem concerned is to prove the possibility of extracting metals from man-made raw materials to the desired level which is achieved by using the method of mathematical modeling of metal leaching processes.

Keywords: *metal, technogenic raw materials, mining production, extraction, disintegrator, algorithm, regression*
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Introduction

The problem of using substandard raw materials for traditional methods of enrichment is formed by the need to strengthen the mineral resource base of metallurgy, which became complicated with the transition of industry to a new management system at the end of the last century [1–4].

In the copper sub-sector of the Urals, 220 million tons of enrichment tailings have been accumulated, in which the copper content (0.34–0.37%) is close to the condition (0.35–0.50%). In the tailings of the enrichment of Ural ores, sulfur accounts for 30–50% of the tailings value, precious metals 25–45%, copper 10–20% and zinc 10–15%.

The tailings of the enrichment of copper-nickel ores of the Norilsk ore node contain industrial concentrations of platinoids, gold and silver already available to modern processing technologies.

When enriching tungsten-molybdenum ores, up to 60% of copper, up to 81% of bismuth, up to 62% of tantalum, gold, silver and other elements are not extracted. In the dumps of the Tyrnyauz integrated works, the metal content exceeds 0.04% when the condition during production is > 0.1% WO_3. For new processing technologies, dumps of substandard ore are a technogenic deposit suitable for mining at a lower cost than when extracting metals from ledge ores.

In the tungsten-molybdenum subindustry, the tailings of flotation and flotation-gravity concentration contain about 400 thousand tons of molybdenum and more than 100 thousand tons of tungsten.

The total value of metals in waste, according to an approximate estimate, is comparable to the value of the extracted metal.

The problems of using mining waste should be solved together with environmental problems. The negative impact of tailings storages on the environment is manifested on the territory 10 times or more larger than the area occupied by the waste itself [5–7].

The insufficiency of the environmental measures taken is obvious from the fact that large areas of land are occupied by waste products of the 4th and 5th hazard classes. Environmental impacts from waste are regional and global in nature. Soil horizons are enriched with ore components of dumps in which they are not isolated from water systems and have an impact on the surrounding area.

The possibilities of reducing the negative impact on the environment are associated with the creation of a single technological cycle "ore processing– waste storage — disposal".

The main contradictions in the processes of production activity and waste generation of industrial enterprises can be resolved through the utilization of technological and substandard mineral raw materials in the cycle of complex development of non-ferrous metals.

Information about new processes for obtaining metals, including from substandard metal-bearing raw material, is given in the works [8–12]. Aspects of the interface of the new technology with neighboring areas of science are touched upon in the works [13–16]. The issues of expediency of mastering the promising direction of technology are outlined in the works [17–19]. The economic and organizational aspects of the problem are covered in a number of works [20–23]. The issues of practical implementation of technologies with leaching of metals from ores are considered in the works [24–28].

The analysis of publications indicates that the possibilities of metal ore dressing technologies are limited to the use of one type of energy. This does not allow metals to be extracted from ores to a sanitary safe level and increases the storage volumes of mining and enrichment tailings.

Among the issues of extracting metals from ores, the priority is given to the task of waste-free production or ensuring the possibility of including secondary processing products in use without restrictions.

There is a correlation between the production volumes, the technological level of mining enterprises, the storage methods of mineral raw materials that are substandard for traditional technologies and the state of environmental ecosystems, therefore, the problem of using mining

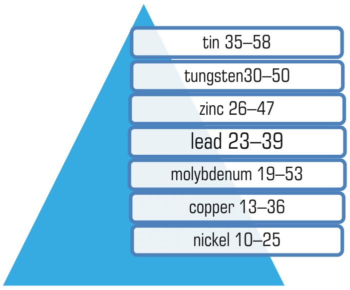

Fig. 1. Proportion of unextracted metals from their quantity in crude ore, %

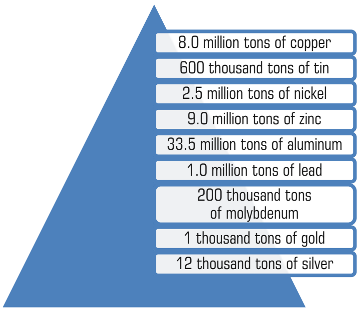

Fig. 2. Stocks of non-ferrous metals in processing waste

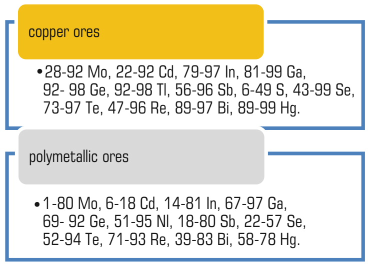

Fig. 3. Losses of non-ferrous metals during enrichment

waste should be solved in a single package "ore processing- waste storage — disposal".

The necessity and possibility of extracting metals from technogenic mineral raw materials to a sanitary safe level is justified by methods of mathematical modeling of recycling processes, including mechanochemical activation of metal leaching processes in the disintegrator.

The purpose of the article is an experimental proof of the possibility of extracting metals from technogenic mineral raw materials to a safe level by optimizing technological leaching processes using the method of mathematical modeling.

Theory of the question

A promising technology for leaching metals from ores simultaneously with the mechanical activation of the process in a high-speed disintegrator mill is based on a combination of the phenomenon of loosening bonds in a mineral particle under intense action (J. Hint) and accelerating the penetration of leaching reagents to the grains of metals to change their phase state.

The foundations of the technology of processing tailings of enrichment were laid by the works of V. Ya. Mostovich, I. N. Dukhanin, Ostroushko, M. N. Tedeev, V. K. Bubnov, etc. N. P. Laverov, B. N. Laskorin, V. A. Chanturia, V. Zh. Arens, V. K. Bubnov and others contributed to the theory and practice of leaching. The greatest success has been achieved in the leaching of copper, uranium, gold and zinc, to which the works of A. I. Kalabin, V. P. Novik-Kachan, I. K. Lutsenko and others were devoted.

Research methodology

The availability of the basic sectors of the Russian economy with reserves of the main types of minerals is estimated during the analysis of statistical data on the state of the mineral resource base of non–ferrous metals.

The determination of the function between the function and the independent factors is carried out by the method of multiple regression, implemented in the program Statistica 6.0.

On the basis of regression calculations performed in the Maple 9.5 environment, a mathematical model of the process of extracting metal from the concentration tailings in the complex of mining and ore processing is constructed. The basis for research is information about non-ferrous metals lost in the concentration tailings (**Fig. 1**).

The reserves of non-ferrous metals in Russia's processing waste are equivalent to the reserves of several new deposits (**Fig. 2**).

The recovery rate of the main minerals is 65–78%, and associated elements in the extraction of non–ferrous metals — 10–30%. In, Ga, Tl, Bi, and Hg are almost completely lost in the flotation tails. Losses of other metals are characterized by **Fig. 3**.

Materials and methods of analysis

The unified leaching model takes into account the main factors of metal leaching from the concentration tailings.

Methods of transferring metal into solution are taken into account using a variable «n»:

n1 — leaching of metals in agitators (basic);

n — leaching in the agitator after mechanical activation in the disintegrator;

n — leaching in the disintegrator.

The quality of processed tailings is taken into account using a variable «m»:

m1 — extraction of metals from concentration tailings with a higher content;

m2 — extraction of metals from concentration tailings with a lower content.

The type of extracted metals is taken into account using the variable «p», for example:

p1 — zinc;

p2 — lead;

pn — other metal.

In the Maple 9.5 environment, regression models are calculated, on the basis of which a unified mathematical model of the process of transferring metals from the concentration tailings into the production solution is built.

Deterministic algorithms of three-dimensional interpolation were used to improve the quality of modeling. Graphical representation of regression models is implemented using B-spline in software "gnuplot" [Golik V. I., Klyuev R. V 2023; Golik, V. I., Dmitrak 2020].

Received results

For variables n, m, p, the regression model under study has the same linear structure with respect to the coefficients α_k and is a polynomial of the second degree with respect to variables X_1, X_2, X_3, X_4, so the general model will have the form:

$$\varepsilon = \varepsilon(n;m;p) = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2 + a_3 \cdot X_3 + a_4 \cdot X_4 + \\ + a_5 \cdot X_1^2 + a_6 \cdot X_2^2 + a_7 \cdot X_3^2 + a_8 \cdot X_4^2 + a_9 \cdot X_1X_2 + \\ + a_{10} \cdot X_1X_3 + a_{11} \cdot X_1X_4 + a_{12} \cdot X_2X_3 + a_{13} \cdot X_2X_4 + a_{14} \cdot X_3X_4, \quad (1)$$

where $a_k = a_k(n;m;p); k = 0.1,...14; n = 1,2,3; m = 1.2; p = 1.2$

The equation $\varepsilon = \varepsilon(n;m;p)$ for $\varepsilon(1;m;p), \varepsilon(2;m;p), \varepsilon(3;m;p)$ is defined by Lagrange interpolation polynomial:

$$\varepsilon(n;m;p) = \frac{(n-2)(n-3)}{2}\varepsilon(1;m;p) + \\ + (n-1)(n-3)\varepsilon(2;m;p) - \frac{(n-1)(n-2)}{2}\varepsilon(3;m;p). \quad (2)$$

Similarly, $\varepsilon = \varepsilon(n;m;p)$ is expressed in terms of the function:

$$\varepsilon(n;m;p) = -(m-2)\varepsilon(n;1;p) + (m-1)\varepsilon(n;2;p). \quad (3)$$

Respectively, $\varepsilon = \varepsilon(n;m;p)$ is expressed in terms of functions $\varepsilon(n;m;1), \varepsilon(n;m;2)$:

$$\varepsilon(n;m;p) = -(p-2)\varepsilon(n;m;1) + (p-1)\varepsilon(n;m;2). \quad (4)$$

Combining formulas (3) and (4), we obtain dependence $\varepsilon = \varepsilon(n;m;p)$ on the functions $\varepsilon(n;1;1), \varepsilon(n;1;2), \varepsilon(n;2;1), \varepsilon(n;2;2)$:

$$\varepsilon(n;m;p) = (m-2)(p-2)\varepsilon(n;1;1) - (m-2)(p-1)\varepsilon(n;1;2) - -(m-1)(p-2)\varepsilon(n;2;1) + (m-1)(p-1)\varepsilon(n;2;2). \quad (5)$$

Substituting equations for $\varepsilon(1;m;p), \varepsilon(2;m;p), \varepsilon(3;m;p)$ we get:

$$\varepsilon(n;m;p) = \frac{(n-2)(n-3)}{2}\big[(m-2)(p-2)\varepsilon(1;1;1) - -(m-2)(p-1)\varepsilon(1;1;2) - (m-1)(p-2)\varepsilon(1;2;1) + +(m-1)(p-1)\varepsilon(1;2;2)\big] - (n-1)(n-3)\times \times\big[(m-2)(p-2)\varepsilon(2;1;1) - (m-2)(p-1)\varepsilon(2;1;2) - -(m-1)(p-2)\varepsilon(2;2;1) + (m-1)(p-1)\varepsilon(2;2;2)\big] + +\frac{(n-1)(n-2)}{2}\big[(m-2)(p-2)\varepsilon(3;1;1) - (m-2)\times \times(p-1)\varepsilon(3;1;2) - (m-1)(p-2)\varepsilon(3;2;1) + (m-1)\times \times(p-1)\varepsilon(3;2;2)\big]. \quad (6)$$

The equations for $\varepsilon(n;m;p)$ with specific values n, m, p are determined from regression dependencies, describing the leaching processes. Regression equation of zinc extraction during agitation leaching of tails (n1, m1, p1):

$$\varepsilon(1;1;1) = 39.02 + 5.51X_1 - 11.09X_2 + 5.6X_3 + 1.43X_4 + +3.58X_1^2 + 6.48X_2^2 - 9.39X_3^2 - 9.38X_4^2 - 2.61X_1X_2 - -0.62X_1X_3 - 1.86X_1X_4 - 3.0X_2X_3 - 1.48X_2X_4 + 1.41X_3X_4. \quad (7)$$

where X_1 —sulfuric acid content, g/l; X_2 —sodium chloride content, g/l; X_3 —ratio of a liquid substance to a solid by mass; X_4 —duration of the process; X_5 —number of revolutions of the disintegrator rotor.

$$X_1 = \frac{C_{H_2SO_4} - 6}{4};\ X_2 = \frac{C_{NaCl} - 90}{70};\ X_3 = \frac{(W:H) - 7}{3};$$

$$X_4 = \frac{t - 0.625}{0.375};\ X_5 = \frac{f - 125}{75}. \quad (8)$$

The regression equation of zinc extraction during agitation leaching (n1; m2; p1):

$$\varepsilon(1;2;1) = 39.35 + 6.76X_1 - 18.88X_2 - 0.62X_4 - 11.6X_1^2 + +7.19X_2^2 + 2.03X_4^2 - 2.84X_1X_2 - 1.39X_1X_3 - 0.89X_1X_4 - -2.04X_2X_3 + X_2X_4 - 2.45X_3X_4. \quad (9)$$

The regression equation of lead extraction during agitation leaching (n1; m2; p2):

$$\varepsilon(1;2;1) = 42.43 + 16.8X_2 + 2.68X_3 + 0.93X_4 - -3.89X_1^2 - 19.31X_2^2 + 2.36X_4^2 + 2.12X_1X_2 - -0.9X_1X_4 + 1.73X_2X_3 + 1.04X_3X_4. \quad (10)$$

The regression equation of zinc extraction when leaching activated tailings outside the disintegrator (n2; m2; p1):

$$\varepsilon(2;2;1) = 36.37 + 9.96X_1 - 11.56X_2 + 1.07X_3 - 6.53X_1^2 + +5.63X_2^2 - 1.00X_3^2 - 3.95X_5^2 - 1.21X_1X_2 - 5.79X_1X_3 - -4.16X_2X_3 - 0.74X_2X_5 - 1.15X_3X_5. \quad (11)$$

The regression equation of lead extraction when leaching activated tailings outside the disintegrator (n2; m2; p2):

$$\varepsilon(2;2;2) = 29.91 + 1.1X_1 + 10.63X_2 + 6.15X_3 + 2.09X_5 - -2.41X_1^2 - 26.29X_2^2 + 3.84X_3^2 + 9.25X_5^2 + 1.21X_1X_2 - -0.72X_1X_3 + 3.21X_1X_5 + 4.81X_2X_3 + 1.08X_2X_5 - 1.00X_3X_5. \quad (12)$$

The regression equations of zinc extraction when leaching activated tailings in the disintegrator (n 3; m 2; p1):

$$\varepsilon(3;2;1) = 32.15 + 11.4X_1 - 14.04X_2 + 0.68X_3 + +1.85X_5 - 2.90X_1^2 + 9.25X_2^2 - 2.53X_4^2 - 0.39X_1X_2 - -1.95X_1X_3 + 1.32X_1X_5 + 1.47X_2X_3 + 4.84X_2X_5 + 3.61X_3X_5. \quad (13)$$

The regression equations of lead extraction when leaching activated tailings in the disintegrator (n 3;m 2; p 2):

$$\varepsilon(3;2;2) = 39.44 - 1.17X_1 + 16.76X_2 + 1.28X_3 - -0.55X_4 - 5.64X_1^2 - 14.81X_2^2 - 0.86X_3^2 - 4.09X_1X_3 - -1.42X_1X_4 - 0.42X_2X_3 - 1.00X_2X_4 - 0.82X_3X_4. \quad (14)$$

A single model is a regression dependence for each specific process and metal. It is implemented in the environment of Maple 9.5, Matlab, Matcad, etc. For the base points of modeling, the most and least intensive impact of factors is selected — two series, in one of which the values of factors are assumed to be maximum (max), and in the second — minimum (min).

The parameters of agitation leaching of mechanically activated concentration tails in the disintegrator are compared with the parameters of leaching of reagent solutions in the disintegrator (**Table**).

Leaching results

Factor value	Leaching options	
	Mechanically activated tails in the agitator	Solutions of reagents in the disintegrator
Minimum	0.03	0.02
Maximum	4	10

Based on the obtained data of experiment 1, graphs illustrating the solution of regression equations of tailings leaching are constructed (**Fig. 4**).

The graphical solution of the regression equation of leaching of the tailings previously mechanically activated in the disintegrator is shown in **Fig. 5**.

The joint consideration of the graphs indicates the advantage of the tailings leaching option in the disintegrator.

This option is recommended for disposal of tailings of ore dressing of rock deposits with a minimum content of carbonates and clay products and with a maximum content of iron.

Discussion of the results

The experimental data obtained in all cases of solving the regression equation with the corresponding coefficients of determination based on the Fisher criterion at a significance level of 95% are accepted as plausible. This allows us to state with 95% probability that the leaching method with mechanochemical activation is more effective in comparison with the traditional agitation method.

The involvement of technogenic deposits in the economic turnover allows to solve the problems of the mineral resource complex and ecology at the same time. It reduces the costs of prospecting and exploration of new deposits, frees up land occupied by waste and eliminates sources of environmental pollution.

In some cases, with a favorable combination of circumstances, the profit received from the disposal of concentration tailings and metallurgy,

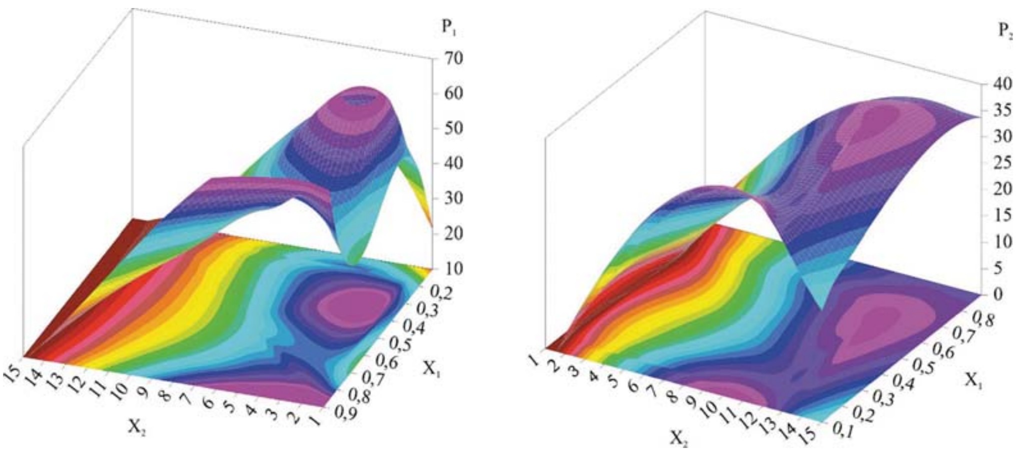

Fig. 4. Equation solution models (basic option) with parameters (n_1; m_1; p_1) and (n_1; m_1; p_2); P_1 — zinc extraction, %; P_2 — lead extraction, %

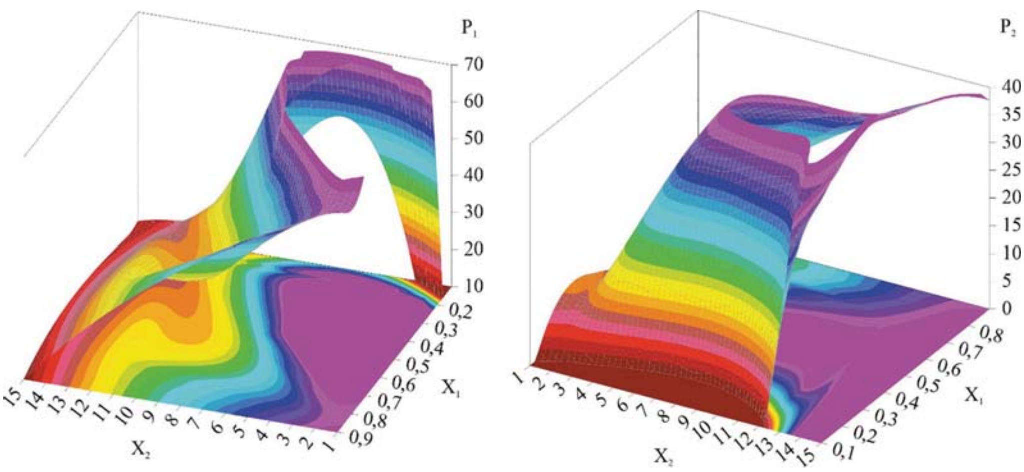

Fig. 5. Equation solution models for the option of agitation leaching of activated tailings with parameters (n_1; m_1; p_1) and (n_1; m_1; p_2)

taking into account environmental damage, can be determined by the solution of the model:

$$P_x = \frac{\sum_1^{n_0}(C_{TO} - Z_{OO} - Z_{OM})Q_0}{t_0} + C_p^0 + \frac{\sum_1^{n_m}(C_{TM} - Z_{OM} - Z_{MM})Q_M}{t_M} + C_p^M,$$

where P_x — annual profit from tailings processing, RUB./t; C_{TO} — the cost of selling products of processing of concentration tailings, RUB./t; Z_{00} — enrichment costs of concentration tailings, RUB./t; Z_{OM} — costs of metallurgical conversion of concentration tailings, RUB./t; n_0 — the amount of extracted components from concentration tailings; Q_0 — concentration tailings mass, t; t_0 — processing time of concentration tailings, year; $C_p{}^0$ — penalties for concentration tailings storage, RUB./t; C_{TM} — the cost of selling products of processing of metallurgy tailings, RUB./t; Z_{OM} — enrichment costs of metallurgy tailings, RUB./t; Z_{MM} — costs of metallurgy of metallurgy tailings, RUB./t; n_m — the amount of extracted components from metallurgy tailings; Q_M — metallurgy tailings mass, t; t_M — processing time of metallurgy tailings, year; $C_p{}^M$ — penalties for metallurgy tailings storage, RUB./year.

An example of the application of the leaching method of concentration tailings in a disintegrator. From the concentration tailings of the Mizur factory of the Sadonsky integrated works with the content, %: zinc — 0.95, lead — 0.84, iron — 4.4%, the extraction of metals into solution was 10–70%.

Russian non-ferrous metallurgy enterprises are characterized by a tendency to increase the volume of processing of reserves of technogenic deposits by leaching:

—copper and nickel in the Sverdlovsk and Murmansk regions and the Krasnoyarsk Territory;

—molybdenum with uranium in the Chita region;

—zinc and tin in the Sverdlovsk region.

Mining enterprises in Russia have technogenic reserves of ore processing tailings, in most cases technologically opened. Therefore, the data obtained are valuable as pioneering developments of a new direction.

The outcomes obtained as a result of this study are consistent with the conclusions of specialists in the field of mining in Russia and abroad [29–34].

Conclusions

Comparison of the results of basic agitation leaching of metals with the method of preliminary mechanical activation in the disintegrator and subsequent leaching in the disintegrator, for example, for the conditions of Sadon ores at the level of significance $\alpha = 0.05$ shows that the proportion of lead extraction increased by 1.4 times, and zinc — by 1.1 times.

The method of metal leaching in the working organ of the disintegrator, in comparison with the method of activation in the disintegrator and leaching outside it, provided approximately equal extraction, however, the duration of the process was reduced from 15–60 minutes to several seconds, in other words, by 2 orders of magnitude.

According to our research, when leaching in a disintegrator, the extraction of metals into solution increases by 10–25% in comparison with the method of agitation leaching, and with an increase in processing cycles, it can reach a level satisfying sanitary standards.

The expediency of leaching metals from technogenic mineral raw materials is justified by methods of mathematical modeling of recycling processes. The relationships between the function and independent factors are determined by the multiple regression method implemented in the Statistica 6.0 program. A single model is implemented in the Maple 9.5 environment, Matlab, Mathcad, etc**.**

The technology of mechanochemical activation of the leaching of the concentration tailings of the Mizursky factory of the Sadonsky integrated works provided the extraction of metals into solution in the range of 10–70%.

The proposed technology in the world practice is the only one that provides waste-free utilization of technogenic mineral raw materials. It is recommended for use in new and existing metal deposits with a combination of certain geological and technological conditions.

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