UDC 622:502

S. V. CHMYKHALOVA[1], *Associate Professor, Candidate of Engineering Sciences, tchmy@mail.ru*

[1] *National University of Science and Technology – NUST MISIS, Moscow, Russia*

EFFECTIVENESS EVALUATION OF MINING AS A NATURAL AND TECHNICAL SYSTEM WITH A DECREASE IN THE CONTENT OF A USEFUL COMPONENT OF THE ORE-RAW MATERIAL BASE

Mining is characterized by increasingly intensive use of natural resources, increasing waste and environmental degradation. These problems are compounded by the fact that almost all mining enterprises are experiencing intensive depletion of mineral reserves.

The impact of a decrease in the content of a useful component in a mineral, as well as losses and dilution during its extraction on the prospects for the development of mining can be estimated by calculating the quantity of finished products and the amount of waste obtained from the extracted mineral, as well as the intensity of production of finished products and waste per unit of time. With a decrease in the content of the useful component, the quantity of finished products per conventional unit of rock mass decreases, and the amount of waste increases. Losses and dilution reduce the content of the useful component in the mineral.

We will analyze these processes and their consequences by the method of material balances. By the material balances of mining, we take the equity between the amounts of substance at the "inputs" and "outputs" of the object before and after the transformations are carried out in it, i.e. from the processes of extraction the rock mass from the bowels to obtaining the finished product.

Material balances of production facilities are often also called "eco-balances", thereby emphasizing the special role of this method in assessing environmental pollution by a production facility. From the rock mass – mineral deposits, in the process of its extraction, the following components are formed: overburden rocks and minerals. The overburden rocks are stored in dumps, and the minerals are supplied for further processing and treatment. In the treatment process, we get the finished product and the enrichment tails, which are a waste of mining.

Based on the material balance method, a methodology has been developed for the economic evaluation of the efficiency of mining by traditional methods (open-cut or underground), which makes it possible to predict the efficiency of mining development and assess the reasonability of using traditional mining technologies. With a certain value of the content of the useful component, mining by traditional methods becomes unprofitable.

Keywords: *natural and technical system, material balance, content of useful component in ore, losses, dilution, concentrate yield, tailings yield, total cost of products of mining*

DOI: *10.17580/em.2021.02.08*

Introduction

Mining production is characterized by intensive depletion of mineral reserves (MR) and, accordingly, increasingly intensive use of natural resources. The support of processing industries with ore-mineral raw materials of the required quantity in the conditions of natural deterioration in the quality of the mineral resource base is currently taking place due to the modernization of mining and processing enterprises (mine technical (technological) subsystem), intensification of the processes of extraction, processing and enrichment of MR in accordance with new natural (mining and geological) conditions.

In the presented study, these processes and their consequences are analyzed by the method of material balances, by which we take the equity between the amounts of substance at the "inputs" and "outputs" of the object before and after the transformations are carried in it, i.e. from the processes of extraction of the rock mass from the bowels to obtaining the finished product.

A decrease in the content of the useful component in the mineral leads to a more intensive extraction of it from the mineral deposit, i.e. to an increase in the extraction of MR, intensification of mining, processing and treatment of minerals, increased environmental pollution by industrial waste due to an increase in their quantity. These processes are in contradiction with the requirements of the public to the state of environment.

Analysis of the state of mineral resources indicates that in the future a more tense situation with the extraction of minerals of the required quality is expected.

The purpose of this work is to develop a methodology for assessing resource and environmental indicators of mining.

To achieve this goal:

- the content of the useful component in minerals at some mining enterprises is analyzed;
- a model is proposed for assessing the impact of reducing the content of the useful component in MR on the output of finished products and waste production by the material balance method;
- an assessment of the impact of losses and dilution during mining (according to the available data of AO APATIT)
- a model of the economic evaluation of the production of MR based on the material balance method has been developed.

The study allows to identify some patterns, predict the main indicators of the development of mining and assess the feasibility of using traditional mining technologies (open-cut or underground).

Quality analysis of minerals at some mining enterprises

The resource intensity of the production of competitive products is characteristic of a mining enterprise. Competitive products are those whose complex of consumer and cost properties ensures commercial success in the mining on the market. The group of factors affecting the level of competitiveness includes economic indicators and the quality of marketable products that form the cost and price of products, market demand, the ability to meet the public's request for the state of the environment and the reduction of man-made risks of mining, which has formed recently [1]. Technological risks of mining are the subject of independent research and are not included in this study.

The sustainable development of mining depends on many factors that are the subject of research [1, 2]. The mineral industry makes a significant contribution to the “Sustainable Development Agenda for the period up to 2030”, provided that the principles of sustainable development are understood and implemented in production [3].

Table 1. Content of the useful component in the Run-of-Mine ore, % [6–8, 10–15]

Industry, enterprise	1960	1965	1970	2009	2011	2013	2014
Iron and steel industry Kmaruda plant (F_{total})	55.5	57.6	49.5			33.07	
Kovdorskiy GOK (F_{total})		29.9	23.0	21.7			
Phosphoric AO APATIT (P_2O_5)	19.51	17.07	17.08	13.16			12.54
Kovdorskiy GOK (P_2O_5)		6.94			6.43		

Mining, as a complex natural and technological system, serves as a converter of the rock mass created by nature into a finished product that meets the requirements of consumers. At the same time, the rock mass is part of the environment, and the impact on this rock mass, i.e. its extraction is carried out using various technologies and technical means [4, 5].

The impact of a decrease in the content of a useful component in MR on the prospects for the development of mining can be estimated by calculating the quantity of finished products and the amount of waste obtained from the extracted mineral, as well as the intensity of production of finished products and waste per unit of time. With a decrease in the content of the useful component in the MR, the quantity of finished products per conventional unit of rock mass decreases, and the amount of waste increases. Losses and dilution of the mineral reduce the content of the useful component in it, and, consequently, the quantity of finished products [6–7].

We will analyze these processes and their consequences by the method of material balances. By the material balances of mining, we take the equity between the amounts of substance at the “inputs” and “outputs” of the object before and after the transformations are carried out in it, i.e. from the processes of extraction the rock mass from the bowels to obtaining the finished product [4–5].

Currently, the material balances of production facilities are often referred to as “eco-balances”, thereby emphasizing the special role of this method in assessing environmental pollution by a production facility. From the rock mass – mineral deposits, in the process of its extraction, the following components are formed: overburden rocks and minerals. The overburden rocks are stored in dumps, and the minerals are supplied for further processing (fragmenting and grinding) and enrichment. In the treatment process, we get the finished product (concentrate or others) and the enrichment tails, which are also waste of mining [4–5]. A decrease in the content of a useful component in a mineral leads to an increase in the extraction volume of mineral, and consequently, to an increase in production waste. In this study, overburden rocks are not taken into account, because their quantity is not directly affected by the content of the useful component in the mineral.

Over a sufficiently long period of time, the content of useful components may slightly vary around some average values. Let’s call this period the “period of relatively stable operation” of mining. However, due to the constant development of mineral reserves, the average parameters characterizing the quality of the extracted rock mass (first of all, the content of the useful component in the developed rock mass) begin to affect the quantity and quality of the finished product [4–9]. **Table 1** contains data on the content of the useful component in run-of-Mine Ore, which is published in open sources.

[13] shows changes in the content of the useful component at AO APATIT for the period from 1960 to the present. Processing of open-source data showed that for the period from 1960 to 2017 (for 57 years) the content of the useful component decreased from 19.51% to 12.17%, which is 0.19% per year. And the yield of enrichment tailings increased from 50% to 70% over the same period. With a decrease in the content of the useful component, the amount of processed ore increases to obtain the required amount of concentrate and, as a result, more waste is generated as a result of processing.

Analysis of the state of mineral resources indicates that in the future a more tense situation is expected with the providing consumers with technological raw materials of the required quality. Mineral losses in the subsurface and dilution also reduce the content of the useful component in the extracted mineral, compared with its balance content.

Assessment of the impact of losses and dilution during mining

During mining operations, the content of the useful component in the extracted rock mass decreases in comparison with the balance content [8]. This decrease is due to the loss of ore and its dilution.

Mining is a natural and technical system, the basis of which is the mining and geological conditions of the occurrence of minerals. Technical or technological (mine technical) system, provides the maximum possible extraction of minerals, taking into account the technical (technological) capabilities of equipment, technologies and economic feasibility.

The influence of the natural system on the technical one in general terms can be determined by the following indicators of the quality of the natural environment [4, 5, 14]:

α_{prov} – useful component content of proven and mineable reserves; σ_{prov} – variability of useful component content of proven and mineable reserves; λ – an indicator of the complexity of natural conditions or the lack of complete and reliable information about the mineral deposits.

These indicators determine the quality of the mineral. And the quality of the extracted ore, i.e. the quality of the technical (technological) system during mining operations is defined as [6, 7, 9, 13, 14]:

$$q = f(\alpha_{prov}, \sigma_{prov}, K_{ld}, \lambda),$$

where K_{ld} – the quality of mining operations, which is characterized by the loss of the mineral during its extraction and

Table 2. Decrease in the content of the useful component in the balance and extracted ore mass of AO Apatit from 2002 to 2014

Year	2002	2005	2008	2011	2014
α_{prov} (average content of P_2O_5)	13,77	13,08	12,91	13,16	12,54
α_{prod}	11,84	11,25	11,10	11,32	10,78

Table 3. Output of enrichment tailings of balance and extracted ore in the conditions of AO APATIT

Year	2002	2005	2008	2011	2014
γ_{prov}, %	67,28	69,12	69,6	68,9	70,56
γ_{prod}, %	72,4	74,0	74,4	73,8	75,3

dilution; q – the quality of the extracted mineral, including the content of the useful component, as one of the main indicators of the mineral. As shown in [16], the quality of a mineral is a complex concept that depends on the number of properties of a mineral.

The content of the useful component in the extracted ore α_{prod} taking into account losses and dilution is determined from the expression [6, 7, 9, 14]:

$\alpha_{prod} = \alpha_{prov} \times (1-R)/(1-P)$, %,

where α_{prov} – is the content of the useful component in the subsurface reserves; R – the dilution coefficient; P – the loss coefficient.

The content of the useful component in the balance and extracted ore mass may differ downwards due to losses and dilution, data for AO Apatit are given in Table 2 [10, 13]. The data of AO Apatit are given in **Table 2** [13, 14]. The data for a later period are the property of the company and fully correspond to the trends shown in Table 2.

Thus, ore mass with a lower content of the useful component than in balance ores due to ore losses and dilution enters on enrichment. Dilution and loss of ore during mining lead to a decrease in the content of the useful component in the extracted ore compared to the balance ore (by about 1.5%), and, consequently, to a decrease in the yield of concentrate, an increase in the amount of waste and an increase in ore production to maintain market demand.

The main technological indicators of the treatment process are: the extraction of valuable (useful) components into concentrates or their content in concentrate β, the yield and quality of enrichment products γ, and the presence of valuable components Θ in the tailings of enrichment [13, 14].

We denote the output of the enrichment tailings – γ_{prod} for produced ore and γ_{prov} for proven ore reserves.

The calculation will be carried out according to the method [13, 14]. We will take that the content of useful components in the finished product is $\beta = 39\%$ [16], and the content of useful components in the tailings of enrichment is $\Theta = 1{,}5\%$. The output of the enrichment tailings for the balance and extracted ore are presented in **Table 3**.

Thus, dilution leads to an increase in the formation of enrichment tailings of the extracted ore compared to the balance ore by about 4.7–5.2%.

Methodology for performance assessment of mining enterprises based on finished products and waste

Performance indicators of mining enterprises are important for determination of the performance of equipment for the production of finished products, the production of waste from minerals per unit of time, which enables to control these processes for the stable operation of mining.

The external indicators of the functioning of the plant, characterizing the intensity of its production activity, are classified into "input" and "output" [4–5].

We attribute to the input indicators (see **figure**) $W_{r.m}$ – the productivity of the plant based on the raw materials of the developed rock mass as the main natural resource and $\Sigma W_{p.i}$ – the total productivity based on additional resources consumed during the production process.

The output indicators are assumed as: W_{output} is the productivity of the plant, W_{strip} is the productivity of stripping, $W_{h.r}$ is the output of host rocks and $\Sigma W_{o.j}$ – the total output of additional waste in the course of production.

The equation of the material balance of the plant with continuous manufacturing or quasi-continuous manufacturing has the form:

$$W_{r.m} + \Sigma W_{p.i} = W_{out} + W_{strip} + W_{h.r} + \Sigma W_{o.j}. \quad (1)$$

Dividing the left and right sides of equation (1) by W_{out} we get a new expression for the material balance:

$$w_{r.m} + \Sigma w_{p.i} = 1 + w_{strip} + w_{h.r} + \Sigma w_{o.j}. \quad (2)$$

where $w_{r.m} = W_{r.m}/W_{out}$; $\Sigma w_{p.i} = \Sigma W_{p.i}/W_{out}$; $w_{strip} = W_{strip}/W_{out}$; $w_{h.r} = W_{h.r}/W_{out}$; $\Sigma w_{o.j} = \Sigma W_{o.j}/W_{out}$ – specific productivity of the plant.

As a first approximation, we can assume:

$\Sigma W_{p.i} = \Sigma W_{o.j}$ and $\Sigma w_{p.i} = \Sigma w_{o.j}$.

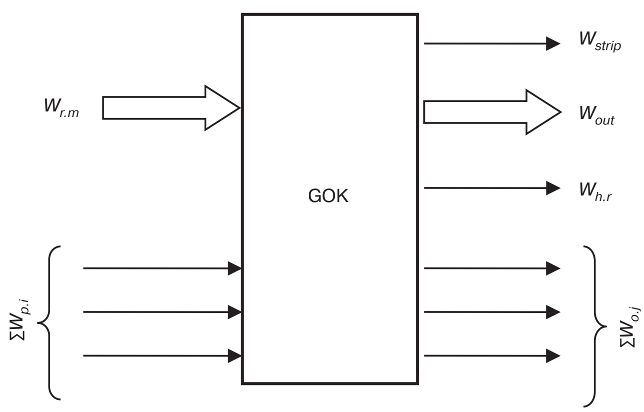
With this assumption, the material balance equations take a simpler form:

$$W_{r.m} = W_{out} + W_{strip} + W_{h.r}, \quad (3)$$

$$w_{r.m} = 1 + w_{strip} + w_{h.r}. \quad (4)$$

Specific (dimensional) indicators are supplemented with relative (dimensionless) indicators. Consider some of them. At the same time, we will limit ourselves to those that are directly related to the production activities of mine sites.

Mine sites are converters of extracted materials into physical products. It is obvious that the relative indicators of their production activities should be appropriate – physical. As such indicators, we propose to use the "material" efficiency of mining – material efficiency, and, by analogy with material efficiency, the coefficient of industrial waste – CIW.



External indicators of the functioning of the plant characterizing the intensity of its productive activity

The formula for calculating the material efficiency is:

$\eta_m = W_{out}/W_{r.m} = 1/w_{r.m}$. (5)

The material efficiency can be calculated by the formula:

$\psi_m = 1 - \eta_m$. (6)

The material efficiency of the production process characterizes the completeness of the conversion of the raw material – rock mass into the finished product – metal concentrates, produced by the plant. The material CIW gives a perspective of the amount of production waste generated during the production process. This waste is completely released into the environment.

Taking into account the drop in the content of the useful component in the ore mass, it can be concluded that the material efficiency of the production process decreases and the CIW – coefficient of waste production increases.

The indicators $w_{r.m}$ and $\Sigma w_{p.i}$ characterize the efficiency of the site, and the indicator $\Sigma w_{o.j}$, w_{strip}, $w_{h.r}$ – its environmental friendliness. By the efficiency of a production site, we understand its ability (property) to perform specified functions with the minimum possible consumption of primary and additional resources. We call the environmental friendliness of an industrial facility its ability (property) to perform a given job with the minimum possible pollution of the environment by hazardous production waste.

A decline in the quality of ore leads to an increase in the production of waste per unit of finished products. These data for AO Apatit are given in [13]. In 1960 γ_{conc} = 0,49, and γ_{tail} = 0,51, then in 2008 these indicators changed for the worse γ_{conc} = 0,31, γ_{tail} = 0,69, and in 2018 γ_{conc} = 0,29, γ_{tail} = 0,71 – there was less concentrate, and the number of tailings of enrichment – production waste – increased. The quality of the concentrate is determined by a number of indicators, including the content of the useful component, which is recorded in the relevant documents, for example, GOST [16]. The quality indicators of finished products at AO Apatit are successfully achieved at processing plants.

Economic indicators of the feasibility of mining by traditional methods

The assessment of the full self-cost of production ensures commercial success in the mining on the market. It consists of the self-cost of ore extraction (open-cut and underground), ore transportation to processing plants, ore crushing and grinding processes, and other expenses.

The full self-cost of mining C_{total} can be expressed by the following formula:

$C_{total} = C_{under} + C_{surf} + C_{haul} + C_{crush} + C_{grind} + C_{proc} + C_{other} + P_{sales}$, (7)

where C_{under} is the cost of underground mining; C_{surf} is the cost of surface mining; C_{haul} is the cost of ore haulage; C_{crush} is he cost of crushing; C_{grind} is the cost of grindng; C_{proc} is the cost of further ore processing; C_{other} is the other expenses; P_{sales} is the sales cost (storage and shipment).

With an increase in ore production output due to a drop in its quality, almost all indicators increase, which leads to an increase in the full self-cost of production, despite the improvement of mining technologies, the use of highly efficient equipment for transporting ore from the mining site to the processing plant, digitalization and dispatching of mining.

For analysis of the full self-cost of production, it is reasonable to use specific cost indicators per 1 ton of rock mass. The full self-cost is given by:

$C_{total} = c_{under}M_{under} + c_{surf}M_{surf} + c_{haul}(M_{under} + M_{surf}) + c_{crush}(M_{under} + M_{surf}) + c_{grind}(M_{under} + M_{surfe}) + c_{proc}(M_{under} + M_{surf}) + C_{other} + c_{waste}M_{waste} + p_{sales}M_{fp}$, (8)

where c_{under} is the underground mining cost per 1 t of ore; c_{surf} is the surface mining cost per 1 t of ore; M_{under}, M_{surf}, M_{waste}, M_{fp} are the ore mass produced by underground method, ore mass produced by surface method, mass of waste and mass of finished product, respectively; c_{haul} is the haulage cost per 1 t of ore; c_{crush} is the crushing cost per 1 t of ore; c_{grind} is the grinding cost per 1 t of ore; c_{proc} is the cost of other processing methods per 1 t of ore; C_{other} is the other production costs; c_{waste} is the cost of waste per t of ore; p_{sale} is the sales cost per 1 t of ore.

For the successful sale of finished products of mining

$C_{total} \le \text{Price } M_{fp}$, (9)

where Price – the market price of 1 ton of the product of this type of finished products of mining.

The evaluation methodology given by the study shows that with a decrease in the quality of ore, there may come a time when the extraction of minerals by traditional methods becomes unprofitable.

In this case, the transition to mining by other means should be considered, for example, physicochemical methods or modernization or liquidation of the enterprise [17, 18].

Conclusions

The main task of mining in conditions of depletion of mineral reserves is the modernization of production, by which we mean:

- reduction of losses and dilution;
- improvement of the mining management system and implementation of a modern quality system at all stages of ore extraction and processing: ore extraction, averaging of its parameters, ore processing, quality management of the finished product;
- implementation of additional operations into the technological process for deeper processing of minerals in order to reduce significant emissions into the environment;
- dispatching and digitalization throughout the chain of ore extraction and processing;
- based on the evaluation methodology given in this study, it is possible to predict at what content of the useful component it is unprofitable to extract minerals using traditional methods, and it is necessary to switch to other, more economically and environmentally appropriate methods of extraction, for example, physicochemical geotechnologies, as well as modernization or liquidation of the enterprise.

References

1. Mine 2019 : Resourcing the future. Available at: https://www.pwc.com/gx/en/energy-utilities-mining/publications/pdf/pwc-mine-report-2019.pdf (accessed: 28.10.2021)
2. Sustainability Reporting in the Mining Sector Current Status and Future Trends. United Nations Environment Programme. 2020. Available at: https://www.unep.org/resources/report/sustainability-reporting-mining-sector (accessed: 28.10.2021)
3. Damigos D., Valakas G., Gaki A., Adam K. The factors impacting the incorporation of the sustainable development goals into raw materials engineering curricula. *Journal of sustainable mining*. 2021. Vol. 20, Iss. 3. pp. 178–192.

4. Chmykhalova S. V. Resource and ecological assessment of the rock mass blastability. *Izvestiya vuzov. Gornyy zhurnal*. 2006. No. 6. pp. 51–59.
5. Chmykhalova S. V. The mine – as natural-technical systems. *GIAB*. 2018. No. S1. pp. 343–349.
6. Kozhiev Kh. Kh., Lomonosov G. G. Mining system of quality management of mineral raw materials. 2 ed. Moscow : MGGU, 2008. 292 p.
7. Lomonosov G. G. Improving the quality of products of the mining production as a factor in increasing the effectiveness of the Russian mining and processing complex. *Ratsionalnoe osvoenie nedr*. 2015. No. 2. pp. 51–61.
8. Lomonosov G. G. Ore quality management in open pit mining. Moscow : Nedra, 1975. 224 p.
9. Lomonosov G. G. Mining qualimetry: Educational aid. 2nd ed. Moscow: Gornaya kniga, 2007. 201 p.
10. Belousov V. V. Optimal extraction values of reserves of apatite-nepheline ores are a basis of rational subsurface managment at JSC “Apatit”. *Gornyi Zhurnal*. 2009. No. 9. pp. 58–61.
11. Petrik A. I., Byhovec A. I., Soharev V. A., Perein V. N., Serdukov A. L. Modernization of the mineral resource base in the strategy of long-term development of the Kovdorsky GOK. *Gornyi Zhurnal*. 2012. No. 10. pp. 12–17.
12. Beloborodov V. I., Zakharova I. B., Andronov G. P., Filimonova N. M. Flotation technology for low-ferruginous apatite-bearing ores, the kovdor deposit. *Vestnik of MSTU*. 2009. Vol. 12, No. 4. pp. 690–693.
13. Chmykhalova S. V. Procedure of predictive estimate of ore quality in the minral mining industry. *Gornyi Zhurnal*. 2019. No. 8. pp. 18–23.
14. Chmykhalova S. Quality of mineral wealth as a factor affecting the formation of refuse of ore mining and processing enterprises. *Problems of Complex Development of Georesources : Proceedings of the VII International Scientific Conference. 2018.* E3S Web of Conference. 2018. Vol. 56. 04018.
15. Savelyev V. M., Lazebnaya M. B. Modernization of crushing and concentrating complex at «Kombinat KMAruda» JSC. *Gornyi Zhurnal*. 2013. No. 4. pp. 55–56.
16. GOST 22275-90. Concentrate of apatite. Specifications. Moscow : Izdatelstvo standartov, 1991. 19 p.
17. Arens V. Zh., Gridin O. M., Kreynin E. V., Nebera V. P., Fazlullin M. I. et al. Physical and chemical geotechnology. Moscow : Gornaya kniga, 2010. 575 p.
18. Arens V. Zh. Geotechnology. Moscow : Izdatelstvo NITU MISiS, 2018. 100 p. EM

UDC 662.73

T. N. GZOGYAN[1], *Head of Laboratory, mehanobr1@yandex.ru*
S. R. GZOGYAN[1], *Senior Researcher*
E. V. GRISHKINA[1], *Researcher*

[1] *Belgorod State University, Belgorod, Russia*

COMPARATIVE TECHNOLOGICAL EVALUATION OF SCHEMES FOR THE ENRICHMENT OF OXIDIZED FERRUGINOUS QUARTZITES

A set of studies on the comparative evaluation of the technological properties of oxidized quartzites of the Starooskolsky ore district of the KMA was carried out. The relative pulverizability of oxidized quartzites during the first stage of grinding to a fineness of 50% of the minus 0.045 mm class relative to non-oxidized ones of current production was established, which was 1.06–1.08 d. units. The comparative assessment of the enrichability was carried out according to three technological schemes: flotation → magneto-flotation → magnetic. The efficiency of enrichment of oxidized quartzites according to Hancock-Luiken, taking into account the fact that the initial ore contains several valuable components (martite, hematite, magnetite), is determined by the magnetic scheme as effective (n = 63.12%), by the magnetic flotation scheme as effective (n = 1.27%), by the flotation scheme as almost effective (n = 46.63%). According to the magnetic scheme of enrichment in a low - and high-intensity magnetic field, a concentrate with a maximum mass fraction of iron of 60.79% was obtained.

Keywords: *oxidized ferruginous quartzites, martite, hematite, magnetite, technological properties (enrichability, pulverizability), low-intensity magnetic separation, high-intensity magnetic separation, flotation, concentrate, tailings*
DOI: *10.17580/em.2021.02.09*

Introduction

Oxidized ferruginous quartzites (OFQ) are not industrially processed in Russia, but are mined along with unoxidized and stockpiled with the formation of technogenic deposits, which creates a difficult environmental situation, so the issue of their involvement in processing is of particular relevance. The problem of using their huge reserves, including those in special dumps, is still unresolved. The obstacle for effective use of OFQ is not only organizational and economic issues, but also, first of all, the level of scientific preparation of the technology of their enrichment and practical readiness of the machine-building industry to provide the technology with modern enrichment equipment [1–6].