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DEVELOPMENT OF THE METHOD TO OPERATIVELY CONTROL QUALITY OF IRON ORE RAW MATERIALS AT OPEN AND UNDERGROUND EXTRACTION

A. Azaryan
Doctor of Technical Sciences, Professor*
E-mail: azaryan325@gmail.com
A. Gritsenko
Researcher
Research section**
E-mail: andryuha_person@mail.ru
A. Trachuk
PhD, Associate Professor*
E-mail: art2015@i.ua
D. Shvets
Assistant*
E-mail: i.am.dmitriy.shvets@gmail.com
*Department of modeling and software**
**Kryvyi Rih National University
Vitaliya Matusevicha str., 11,
Kryvyi Rih, Ukraine, 50027

Основним завданням гірничодобувної промисловості є підвищення ефективності видобутку і переробки залізорудної сировини. Одним з основних факторів, які сприяють вирішенню завдання, є визначення вмісту заліза в рудному тілі на початковому етапі технологічного ланцюжка. Широко застосовувані в даний час для досягнення мети традиційні методи хімічного аналізу не є достатньо оперативними і потребують близько двох годин для отримання результатів. Як правило, це не дозволяє належним чином коригувати параметри технологічного процесу переробки руди, а лише дає можливість констатувати стан виробничого процесу на момент відбору проби.

Існуючі методи вирішення цього завдання, що є достатньо оперативними, базуються на використанні прямих методів. Це ядернофізичний (взаємодія гамма-випромінювання з гірничою масою), магнітометричний (зміна відносної магнітної проникності при взаємодії з магнітним залізом), ультразвуковий (зміна поширення ультразвукових хвиль у досліджуваному матеріалі) методи.

З метою підвищення точності визначення процентного вмісту корисного компонента в досліджуваній гірській масі, в роботі вдосконалено ядернофізичний метод визначення вмісту заліза загального в кусковий руді. Удосконалення методу дозволяє підвищити точність контролю вмісту корисного компонента в досліджуваному матеріалі на 1,5 % за рахунок реєстрації не тільки відбитих від поверхні гамма-квантів, а й поглинених часток. Експериментально встановлено рівень чутливості (К=1,32–1,38), що характеризує зміну інтенсивності зареєстрованого випромінювання від зміни вмісту заліза в матеріалі, що опромінюється. Також встановлено рівень статистичної похибки (<0,65 %) для забезпечення допустимої точності вимірювань.

На основі даного методу запропонована інформаційно-вимірювальна система для здійснення моніторингу, аналізу та прогнозування якісних характеристик руди в умовах рудозбагачувальної фабрики. Використання даної системи дозволяє технологічному персоналу оперативно втручатися у виробничий процес і коригувати якісно-кількісні параметри руди

Ключові слова: якість мінеральної сировини, каротаж свердловин, гамма-випромінювання, залізо загальне, магнітне залізо

1. Introduction

The most important direction in the development of mining industry is to improve the efficiency of extraction and processing of mineral resources [1].

There are different techniques to improve the efficiency of extraction and processing of minerals: changing the enrichment technology, applying modern automated control systems, improving the accuracy of control over technological parameters. One of the techniques to improve performance efficiency is operational control over the content of a mineral component in the mountain rock.

Lack of operational quality control leads to losses of ores and clogging of the blasted rock mass at the stage of iron ore extraction, as well as to fluctuations in the parameters of technological process at the stage of ore processing, and, as a consequence, to fluctuations in the quality of the concentrate.

Operational control over the iron content in the mountain mass makes it possible to improve the efficiency of the production process through the implementation of a possibility to timely adjust the parameters of technological process of extraction and processing of iron ore.

Thus, improving the accuracy of determining the content of a mineral component in iron ore under conditions of quarries and ore-enrichment plants is a relevant scientific challenge.

2. Literature review and problem statement

Existing methods of operative control over the content of a mineral component in iron ore can be divided into three types: nuclear-physical, based on the interaction between gamma radiation and the irradiated mountain mass; magnetometric, using a change in the relative magnetic permeability when interacting with magnetic iron; and ultrasonic, based on changing the ultrasonic wave propagation in the examined material.

Paper [2] considers a mathematical model for determining the content of iron in ore using the intensity of the scattered gamma quanta. However, the paper contains no information on the accuracy of the method used. Papers [3, 4] modeled the processes of collimation of the gamma radiation receiver for a portable NaJ(Tl) detector system. These papers report the results of research into dependence of the number of reflected gamma quanta on thickness of the layer of the irradiated material. In [3], authors consider only the Compton scattering of particles, while paper [4] proposes the use of high-energy gamma radiation sources whose application is difficult in order to control the content of iron in the ore material. Article [5] considered the operational quality control of mineral raw materials in pulp products but failed to consider controlling the content of iron in solid media. Paper [6] describes parameters of the scintillation sensors for registration of scattered gamma quanta, however, there is no information on the accuracy of particle registration. Studies [7, 8] describe methods to control the quality of raw materials at a conveyor belt, which makes their application impossible during open cast mining. In general, the papers consider the application of the Compton gamma scattering only, excluding a photoelectric effect.

Magnetometric methods are described in [9] based on the analysis of factors influencing the accuracy of determining magnetite in the ore material; the authors describe possible ways to eliminate errors of measurements; paper [10] analyzed work of the sensor, taking into consideration the perturbing factors influencing the measurement accuracy; the authors derived dependences of the sensor readings on the results of chemical analysis of iron content in ore. However, these methods do not make it possible to determine the content of general iron in the ore material. In article [11], authors proposed a technique to control the content of magnetic iron in the crushed ore based on the pondermotive measuring method, which implies the implementation of a given method in liquid media only (pulp products). Paper [12] examined control over the content of magnetite in the lumpy ore at a conveyor belt; however, there are no data on the experimental verification of the described principles. Publication [13] reports results of studying the autogenerating method of control over the content of magnetic iron in dressing products. The paper lacks information on errors in the proposed method. In addition, the use of several magnetic characteristics (magnetic permeability, coercive force, and others) is considered in [14, 15]; however, the authors did not describe their application in order to analyze a mineral component in iron ore. Paper [16] describes a method for determining the content of a ferromagnetic component in the flow of iron ore slurry. However, it is not readily applicable for determining the iron content in a solid medium.

Ultrasonic test methods that are based on measuring the processes of ultrasonic volumetric and surface waves propagation, as well as high-energy ultrasound in liquid and solid media, have been widely used in mining. Papers [17, 18] propose the use of dynamic effects of high-energy ultrasound for detecting mineralogical varieties of iron ore during its processing. That does not make it possible to achieve the required accuracy in determining the mineral component in iron ores. Articles [19, 20] describe the principles of ultrasonic control of the ore materials' characteristics; however, the authors give no information on the practical application of these principles under industrial conditions. Papers [21, 22] considered the ultrasonic control methods, based on the measurements of processes of ultrasonic volumetric and surface waves propagation, as well as high-energy ultrasound in liquid and solid media. These methods are rather critical in terms of the granulometric composition of the investigated medium, which is why it is impossible to use them in order to control quality of lumpy ore. Studies [23, 24] considered models of ultrasound propagation in a cavitating fluid, which is unacceptable for solid media.

Paper [25] describes the application of the Mössbauer spectrometry method for examining the composition of ferromanganese ores. Applied research into this method is considered in [26]. However, the Mössbauer spectrometry method does not demonstrate the required level of efficiency and requires the use of expensive equipment.

There is a known technique [27] that implies carrying out an ore analysis using the energy dispersed X-ray spectroscopy method. The method implies that under the influence of X-rays atoms of the examined sample are excited thereby emitting an x-ray emission characteristic for each chemical element. The energy spectrum of this radiation characterizes the qualitative and quantitative composition of the sample and makes it possible to determine the content of iron and impurities in the starting ore.

This system is an analyzer that consists of several mechanical, pneumatic, and electronic devices, integrated into a single system, placed in the container. The device performs the pneumatic sampling, pneumatic transmission, it grinds the sample and analyzes it using the energy dispersed X-ray spectroscopy, and makes it possible to remotely monitor the fluctuations in quality of starting ore and to change the frequency of sampling. However, this technique is a complex, cumbersome and costly system, which hinders its implementation in open and underground mining.

At present, particular attention is paid to those control methods that improve the efficiency of the production process [28] and its reliability [29]. Paper [18] considered a technique to determine the iron-rich ore pieces using fuzzy clustering; article [30] proposed, based on a given method, a device to control the size of ore at a conveyor belt of an ore-enrichment plants, as well as rapid recognition of its mineral-technological varieties. A given method is not possible to use when conducting the logging of blast holes. Logging is described in paper [31]; however, there is no information about the errors of determining the iron content in wells. Studies [32 33] considered the process of determining the content of a mineral component in raw materials at a conveyor belt, but there are no data on the application of these methods in the analysis of iron ore.

Thus, we can conclude that the nuclear-physical method of control over the content of iron in an ore material, based on the registration of scattered gamma quanta, is one of the most promising, although it has insufficient accuracy. In this regard, the development of the method and improving its accuracy is an important and relevant scientific challenge.

3. The aim and objectives of the study

The aim of this study is to improve the nuclear-physical method of control over the content of a mineral component in ore mass in order to enhance its accuracy.

To accomplish the aim, the following tasks have been set:

– to determine the dependence of intensity of the scattered, absorbed and integral gamma radiation on the content of a mineral component in iron ore;

– to establish the level of sensitivity that characterizes a change in the intensity of the registered radiation on a change in the content of iron in the irradiated ore;

– to determine a value for the statistical error in order to provide for the permissible measurement accuracy;

– to construct a method of the nuclear-physical control that would reduce an error in determining the content of a mineral component in iron ore;

– to design, based on the proposed method, an automated information-measuring system, which would enable the collection and representation of information from all sections of mining production at a central server, for continuous monitoring, analysis and prediction of qualitative characteristics of ore.

4. Research methods and materials

Our research has established that the methods that control the useful component using the scattered gamma radiation (Compton scattering) do not possess the required level of accuracy.

Generalization of known approaches reveals that the existing method is based on processing the data on the reflected signal (Fig. 1).

When applying such an approach, the gamma quanta with initial energy E_0 are emitted by gamma radiation source 5 and penetrate mountain mass 1. Part of gamma quanta is reflected from the surface of the rock mass and is dispersed at a certain angle, depending on the source of gamma radiation used. When a gamma-quantum interacts with matter, part of its energy is absorbed and this quantum leaves the absorber with the energy that is less by the magnitude of the absorbed energy (E_{abs}). The scattered gamma-quanta are registered by monocrystal NaJ 3, turning into light energy. The brightness and duration of the flash depends on the energy of a gamma-quantum. Using detector 4, flashes turn into electrical pulses whose quantity is determined by a counting device. Applying the preliminary established dependences based on the number of registered pulses, one determines the content of iron in the mountain mass.

However, because the size of the sesnor's monocrystal is much less than the irradiated area of a material, then the number of scattered gamma quanta, registered by the sensor, is approximately 10–15 % of the flow of the scattered gamma radiation (Fig. 2). This predetermines a significant number of unregistered scattered particles that leads to errors in determining the content of a mineral component in the irradiated material. Increasing the area of a monocrystal is economically inexpedient, and it makes the installation cumbersome and complicates its operation.

Therefore, in order to improve accuracy of the method described, we accept a hypothesis about the appropriateness of taking into account not the Compton scattering of gamma-quanta (E_{scatt}) only, but also the particles, absorbed by matter (photo-effect, E_{abs}), and the gamma quanta that passed through a layer of matter (E_{passed}).

According to the law of energy preservation, energy of the scattered gamma quanta can be derived from

$$E_{\text{scatt}}=E_0-(E_{\text{abs}}+E_{\text{passed}}). \qquad (1)$$

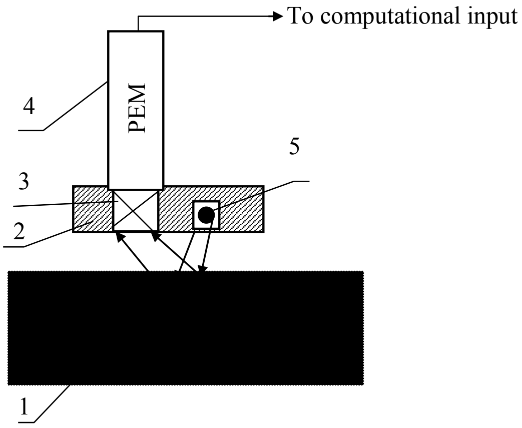

Fig. 1. Geometry of interaction between gamma-radiation and mountain rocks: 1 – mountain rock; 2 – lead protection from a radiation source; 3 – monocrystal NaJ; 4 – detector (photo-electron multiplier); 5 – radiation source (Am–241)

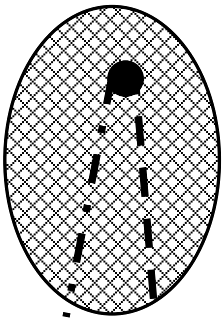

Fig. 2. Vector field of the scattered gamma radiation at the surface of the absorber

Energy value of primary gamma quanta E_0, emitted by the source, is determined experimentally: a particle source is set opposite the detector to register the power of radiation per unit of time.

In turn, the power of the registered scattered gamma radiation depends on absorption coefficient μ, which varies depending on the content of a mineral component in ore (Fe), as well as on the monocrystal's coverage of particle scattering angle ξ:

$$E_{scatt}=f(E_{abs}*\mu*\xi), \qquad (2)$$

where

$$\mu=f(Fe). \qquad (3)$$

The intensity of the gamma quanta, registered by the detector, obeys the law of Lambert-Bouguer-Beer and is described equation (2).

$$N=N_0*e^{-\mu_M*\rho*x} \qquad (4)$$

where N_0 is the primary number of γ-quanta, falling on the sample, μ_m is the mass attenuation coefficient. Magnitude $1/\mu_m$ characterizes the penetration depth of γ-quantum, ρ is the surface density, g/cm^3, x is the thickness of the absorber cm.

Thus, the essence of the proposed method is as follows:

1. Mountain mass is irradiated with the source of gamma quanta.

2. One registers the particles that are scattered by rock and which passed through a layer of the material, and one determines the number of gamma quanta that were absorbed by matter.

3. The content of a useful component is calculated based on the power of gamma quanta, registered as a result of the Compton scattering and a photo-effect as a function of the ratio of the scattered gamma quanta to those absorbed.

The experimental setup is shown in Fig. 4. It consists of gamma-ray source 2 based on the isotope Am-241 with a radiation energy of 60 KeV, which ensures the required sensitivity to a change in the mass fraction of a mineral component in the mountain mass; detectors of the scattered 4 and passed 5 gamma-radiation; computing block 6 that calculates the number of absorbed gamma quanta. The content of iron in ore is calculated depending on the ratio of intensity of the scattered and absorbed gamma radiation. Measurement results are shown on a digital display of the device.

The research results have shown that when using a low-energy radiation source Am-241 the magnitude N_{passed} could be neglected, because at the absorber's thickness exceeding 40 mm and for the ore with a density of ≥ 2 g/cm^3 a gamma quantum is completely absorbed in the ore. Therefore, equation (1) can be written in the following form

$$E_{\text{scatt}}=E_0-E_{\text{abs}}. \qquad (5)$$

The experimentally derived dependences of intensity of the scattered, absorbed, and integral gamma radiation, on the content of a mineral component are shown in Fig. 3.

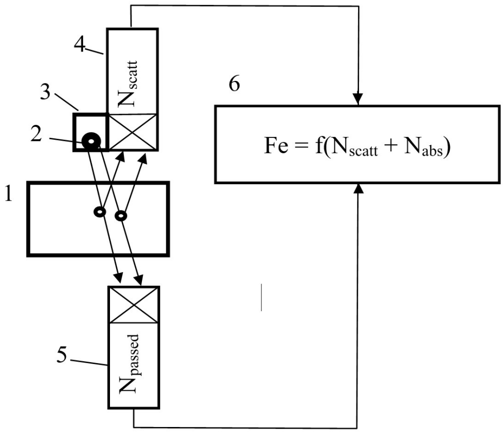

Fig. 3. General functional diagram of interaction between gamma radiation and matter: 1 – mountain rock; 2 – source of gamma-radiation; 3 – protective container; 4 – registration sensor of scattered gamma radiation; 5 – registration sensor of passed gamma-radiation; 6 – computational unit of iron content in ore

The derived patterns describe the Lambert-Bouguer-Beer law and demonstrate that an increase in the iron content in ore leads to an increase in the contribution of the absorbed radiation intensity (Fig. 4), which results in the improved accuracy of quality control.

The analytical expression for the integral flux of gamma radiation has been derived:

$$N=2\cdot10^{-3}\,Fe^3+0.0152Fe^2-1.836Fe+48.1 \qquad (6)$$

with the approximation reliability $R^2=0.98$.

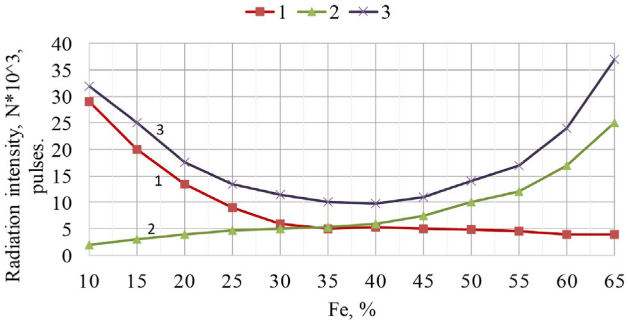

Fig. 4. Dependence of intensity of the scattered, absorbed, and integral gamma radiation, on the content of a mineral component: 1 – scattered, 2 – absorbed, 3 – integral gamma radiation

In the course of our study, we assessed an error of the proposed method. In determining the magnitude of an error, we focused on the sensitivity values K, which is derived from

$$K_1=\frac{\Delta N}{\Delta q}\ \text{pulses/\%}, \qquad (7)$$

and also

$$K_2=\frac{K_1*100}{\overline{N}}, \qquad (8)$$

where Δq is the range of change in the iron content, %; ΔN is the range of change in intensity when the content changes by Δq, pulses/s; $\overline{N}$ is the mean value of intensity in the range ΔN, pulses/s.

The study that we conducted has shown that sensitivity K_2=1.32–1.38. In other words, a change in the content of iron by 1 % leads to a change in the intensity of radiation by approximately 1.3 %.

Therefore, in order to achieve a 0.5 % accuracy of operational control over ore quality, it is necessary to ensure the conditions for intensity measurement with an error ≤±0.65 %, or the standard deviation must not exceed ±0.2 % (≈1/3 of the permissible error).

Thus, the proposed improvement to a nuclear-physical method implies determining the content of a mineral component in the ore material with respect to the Compton scattering and a photo-effect. Compared with the method based on registration of the scattered gamma particles only, the proposed technique makes it possible to improve the accuracy of determining the content of iron by 1.5 %.

5. Discussion of results of designing and applying the hardware tools for operative quality control of ore

Based on the improved method to control the content of iron in ore, we propose a comprehensive information-measuring system for operative control over the quality and weight of sinter ore at the conveyor with the following parameters:

– the range of content Fe_{common} – 0–70 %, Fe_{magn} – 0–45 %;

– the minimum, maximum thickness of a rock mass layer at a conveyor belt – 30–300 mm;

– the grain size class of sinter ore is 0–2 mm;

– the speed of a conveyor belt is 1 m/s;

– ore moisture content is not higher than 7 %.

The functional diagram of a multi-channel information-measuring system is shown in Fig. 4 where the central server is a dedicated computer with the installed server software, connected to a Modbus network and the enterprise network TCP/IP. In addition, the central server hosts a database; a Modbus network is the network that is used to transfer information between physical devices within the system and the central server; the physical device is a device connected to the Modbus network, it provides for a certain functionality. The system employs the following types of devices:

– a magnetic susceptibility sensor, intended for measurement of magnetic iron at a conveyor belt;

– sensors for registration of gamma-quanta, designed for determining the content of total iron in a flow of ore at a conveyor belt;

– conveyor scales of various modifications, intended to measure the current weight of rock mass at a conveyor belt;

– information display, designed to indicate measurement results;

– point of control – a set of physical devices to measure and display information about the content of magnetic iron in a flow of ore at a conveyor belt.

The control point includes a scattered gamma radiation sensor, a sensor of magnetic susceptibility, conveyor scales, information display.

The server software is a program that runs on the central server, it is designed to collect information from devices within a ModBus network, to calculate the content of total iron and magnetic iron and store measurement results in a database. The client software is a program installed on a computer that is connected over a TCP/IP network to the central server, intended for downloading information of the server software module, for generating, display and printing of tabular and graphical reports on the results of measurements.

The ultimate result of the system's operation is to determine the content of iron in the rock mass flow at a conveyor belt.

The use of a given system is described in the composition of APCS over the process of ore preparation for enrichment [34].

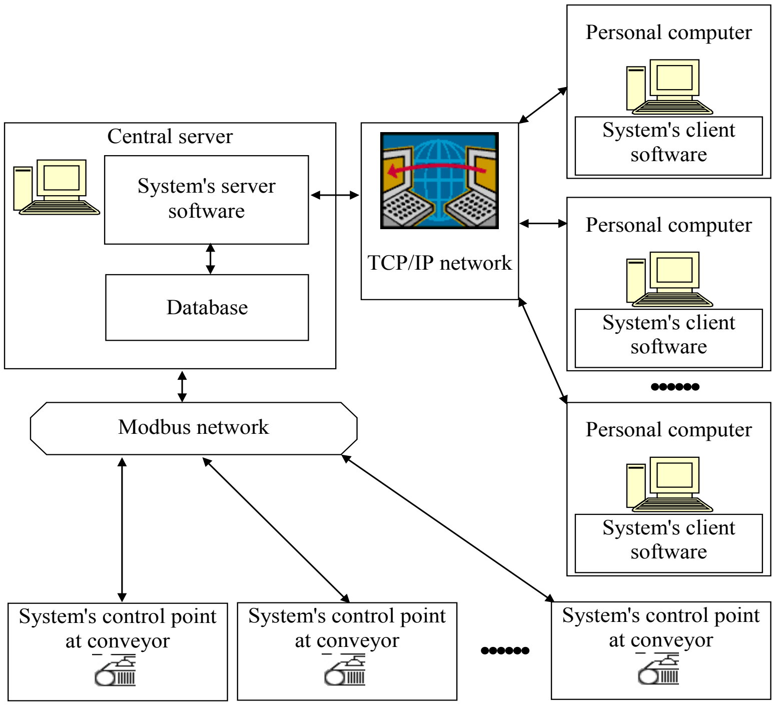

Fig. 5. Functional diagram of a multi-channel information-measuring system

The benefits of this study are as follows:

– the improved nuclear-physical method to control the content of a mineral component in ore makes it possible to improve the accuracy of measurements by 1.5 %, which provides an opportunity to reduce fluctuations in the iron content in the resulting product at an enrichment plant – the concentrate;

– we have developed an information-measuring system that enables the collection, analysis, and visualization of qualitative-quantitative characteristics of ore mass in real time, which makes it possible to operatively manage the enrichment technology, to improve the informational value of the production process, and stabilize the quality of iron ore concentrate. This is possible due to the fact that the system provides control over the content of both magnetic and total iron using the improved nuclear-physical method that makes it possible to enhance the accuracy of determining a mineral component.

When a large-scale application of the proposed system is executed, the following restrictions might be imposed:

1. Insufficient quantity of operational tools to control quality of minerals.

2. The lack of the feedback system "control point – transmission of obtained results – rapid decision making".

3. Lack of trained personnel.

4. The absence of tools and the concept of quality control over mineral resources at an enterprise.

5. The lack of a local and a global network in the system of operational control over quality and management of mineral resources.

7. Conclusions

1. We have derived dependences for determining the content of a mass fraction of total iron (Fig. 4). It was established that increasing the content of a mineral component in iron ore decreases the number of scattered gamma quanta, starting at Fe>30 %, while the number of the absorbed particles increases.

2. We have experimentally established the sensitivity level (K=1.32–1.38), which characterizes a change in the intensity of registered radiation due to a change in the content of iron in the irradiated material;

3. We have determined the level of a statistical error (<0.65 %) in order to ensure the permissible measurement accuracy when using the nuclear-physical method taking into consideration the absorbed gamma quanta;

4. The nuclear-physical method has been developed for determining the content of total iron in iron ore, taking into account the Compton scattering of gamma-particles and a photo-effect, based on the Lambert-Bouguer-Beer formula. The developed method makes it possible to reduce a statistical error in determining the content of a mineral component in iron ore by 1.5 per cent;

5. Based on the improved nuclear-physical method, we have proposed an information-measuring system that collects and displays information from all sections of mining production at a central server. The proposed system provides for determining both the magnetic and total iron

using the proposed method to control total iron, which makes it possible to improve the accuracy of determining a mineral component and to reduce fluctuations in quality of the concentrate. The existence of a continuous monitoring, analysis, and forecasting of the qualitative characteristics of ore makes it possible for technological personnel to operatively intervene in the production process and to adjust the qualitative-quantitative parameters of ore.

References

1. Lutsenko I. Definition of efficiency indicator and study of its main function as an optimization criterion // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 6, Issue 2 (84). P. 24–32. doi: https://doi.org/10.15587/1729-4061.2016.85453
2. Azaryan A., Azaryan V. Use of Bourger-Lambert-Bera law for the operative control and quality management of mineral raw materials // Metallurgical and Mining Industry. 2015. Issue 1. P. 4–8.
3. Experimental and simulated study of detector collimation for a portable 3″ × 3″ NaI(Tl) detector system for in-situ measurements / Kiran K. U., Ravindraswami K., Eshwarappa K. M., Somashekarappa H. M. // Journal of Radiation Research and Applied Sciences. 2015. Vol. 8, Issue 4. P. 597–605. doi: https://doi.org/10.1016/j.jrras.2015.07.006
4. Sabharwal A. D., Sandhu B. S., Singh B. Investigations of effect of target thickness and detector collimation on 662 keV multiply backscattered gamma photons // Radiation Measurements. 2009. Vol. 44, Issue 4. P. 411–414. doi: https://doi.org/10.1016/j.radmeas.2009.06.010
5. Azaryan A. A., Azaryan V. A., Trachuk A. A. Quick response quality control of mineral raw materials in the pipeline // European Science and Technology. Materials of the V International scientific and practice conference. Munich, 2013. P. 325–331.
6. Azaryan A. Research of influence single crystal thickness NaJ (TL) on the intensity of the integrated flux of scattered gamma radiation // Metallurgical and Mining Industry. 2015. Issue 2. P. 43–46.
7. Kurth H., Edwards M. Use of on-belt analysers for improved process control of conveyed materials // Proceedings Metallurgical Plant Design and Operating Strategies (MetPlant 2008). Melbourne, 2008. P. 493–507.
8. Minnett R. C. A. The state of sampling practice in the South African minerals industry // Proceedings Sampling Conference. Melbourne, 2010. P. 31–50.
9. Azaryan A. A., Azaryan V. A., Driga V. V. Sistema operativnogo kontrolya kachestva zhelezistyh kvarcitov na konveyere // Kachestvo mineral'nogo syr'ya. 2011. P. 184–191.
10. Analiz rezul'tatov ekspluatacii datchika zheleza magnitnogo v usloviyah GOKa «ArselorMittal Krivoy Rog» / Azaryan A. A., Driga V. V., Shvydkiy A. V. et. al. // Metallurgicheskaya i gornorudnaya promyshlennost'. 2008. Issue 2. P. 111–113.
11. Azaryan A. A., Kucher V. G., Shvec D. V. Perspektivy postroeniya sistem avtomaticheskogo regulirovaniya processa magnitnoy separacii na baze pogruzhnyh analizatorov soderzhaniya magnitnogo zheleza // Kachestvo mineral'nogo syr'ya. 2017.
12. Shvec D. V. Avtomaticheskoe upravlenie processom izmel'cheniya magnetitovyh rud na osnove opredeleniya ih prochnosti // Kachestvo mineral'nogo syr'ya. 2018. Vol. 2.
13. Azaryan A. A., Dryga V. V., Cybulevskiy Yu. E. Issledovanie avtogeneratornogo metoda kontrolya soderzhaniya zheleza magnitnogo v produktah obogashcheniya // Kachestvo mineral'nogo syr'ya. 2005. P. 117–123.
14. Sandomirskij S. G. Perspectives of development of magnetic control of the large-size cast iron castings structure // Litiyo i Metallurgiya. 2011. Issue 3 (62). P. 157–162.
15. Sandomirskij S. G. Magnetic control of the steel and cast iron articles structure. Modern state (review) // Litiyo i Metallurgiya. 2008. Issue 2 (46). P. 33–42.
16. Porkuyan O. V., Sotnikova T. G. Kombinirovannyy metod opredeleniya otnositel'nogo soderzhaniya magnetita v tverdoy faze zhelezorudnoy pul'py // Vestnik Nac. tekhn. un-ta «KhPI». 2010. Issue 12. P. 29–36.
17. Morkun V., Tron V., Goncharov S. Automation of the ore varieties recognition process in the technological process streams based on the dynamic effects of high-energy ultrasound // Metallurgical and Mining Industry. 2015. Issue 2. P. 31–34. URL: http://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_2/006Tron.pdf
18. Morkun V., Tcvirkun S. Investigation of methods of fuzzy clustering for determining ore types // Metallurgical and Mining Industry. 2014. Issue 5. P. 11–14. URL: http://www.metaljournal.com.ua/assets/Journal/3-MorkunTs.pdf
19. Morkun V., Morkun N. Estimation of the Crushed Ore Particles Density in the Pulp Flow Based on the Dynamic Effects of High-Energy Ultrasound // Archives of Acoustics. 2018. Vol. 43, Issue 1. P. 61–67. doi: https://doi.org/10.24425/118080
20. Goncharov S. A. Povyshenie effektivnosti obogatitel'nyh tekhnologiy putem vozdeystviya vysokoenergeticheskogo ul'trazvuka na pererabatyvaemoe syr'e // Visnyk Kryvorizkoho natsionalnoho universytetu. 2009. Issue 23. P. 236–239.
21. Study of the ultrasonic propagation law in the gas-liquid two-phase flow of deepwater riser through numerical simulation / Xu Y., Guan Z., Jin Y., Tian Y., Liu Y., Xu C., Shi Y. // Journal of Petroleum Science and Engineering. 2017. Vol. 159. P. 419–432. doi: https://doi.org/10.1016/j.petrol.2017.09.051

22. Love wave propagation in heterogeneous micropolar media / Kundu S., Kumari A., Pandit D. K., Gupta S. // Mechanics Research Communications. 2017. Vol. 83. P. 6–11. doi: https://doi.org/10.1016/j.mechrescom.2017.02.003
23. Louisnard O. A simple model of ultrasound propagation in a cavitating liquid. Part I: Theory, nonlinear attenuation and traveling wave generation // Ultrasonics Sonochemistry. 2012. Vol. 19, Issue 1. P. 56–65. doi: https://doi.org/10.1016/j.ultsonch.2011.06.007
24. Louisnard O. A simple model of ultrasound propagation in a cavitating liquid. Part II: Primary Bjerknes force and bubble structures // Ultrasonics Sonochemistry. 2012. Vol. 19, Issue 1. P. 66–76. doi: https://doi.org/10.1016/j.ultsonch.2011.06.008
25. Studying phase structure of burned ferrous manganese ores by method of nuclear gamma – resonance spectroscopy / Shayakhmetov B., Issagulov A., Baisanov A., Karakeyeva G., Issagulova D. // Metallugiyja. 2014. Vol. 53, Issue 2. P. 231–234.
26. Mossbauer forward scattering spectra of ferromagnets in radio-frequency magnetic field / Dzyublik A. Ya., Sadykov E. K., Petrov G. I., Arinin V. V., Vagizov F. H., Spivak V. Yu. // Yaderna fizyka ta enerhetyka. 2013. Vol. 13, Issue 1. P. 73–82.
27. Iron Ore Composition Monitoring Using an Automated On-Line X-Ray Spectrometer Analyzer / Viana S. A. A., Souza A. S., Araujo W. C., Ribeiro R. V. // URL: http://www.apc-analytics.com/sites/default/files/pdf_documents/isa_show_2008_-_solas_brauer_0.pdf
28. Development of the method for modeling operational processes for tasks related to decision making / Lutsenko I., Oksanych I., Shevchenko I., Karabut N. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 2, Issue 4 (92). P. 26–32. doi: https://doi.org/10.15587/1729-4061.2018.126446
29. Development of the method of quasi-optimal robust control for periodic operational processes / Lutsenko I., Fomovskaya E., Koval S., Serdiuk O. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 4, Issue 2 (88). P. 52–60. doi: https://doi.org/10.15587/1729-4061.2017.107542
30. Cvirkun S. L. Avtomaticheskaya sistema soprovozhdeniya krupnokuskovoy rudy na konveyernoy lente // Visnyk Kryvorizkoho natsionalnoho universytetu. 2014. Issue 36. P. 229–234.
31. Azaryan A. A., Gritsenko A. N. Mobile station for logging of blast holes // Novi technologiyi. 2011. Issue 4. P. 52–55.
32. Arena T., McTiernan J. On-belt analysis at Sepon Copper operation // Proceedings Metallurgical Plant Design and Operating Strategies (MetPlant 2011). Melbourne, 2011. P. 527–535.
33. Use of an online elemental analyser to optimize the sinter process at ThyssenKrupp Steel Europe, Duisburg, Germany / Delwig C., Fettweis H., Schnitzler T., Wienströer S., Ferguson S., Noble G. // Proceedings Iron Ore Conference. Melbourne, 2011. P. 381–388.
34. Azaryan A., Pikilnyak A., Shvets D. Complex automation system of iron ore preparation for beneficiation // Metallurgical and mining industry. 2015. Issue 8. P. 64–66. URL: https://www.metaljournal.com.ua/assets/Journal/english-edition/MMI_2015_8/011Azaryan.pdf