VALERY V. MOROZOV (*National University of Science and Technology MISiS*)
VALERY M. SHEK (*National University of Science and Technology MISiS)*
YURY P. MOROZOV *(Ural State Mining University)*
LODOY DELGERBAT (*Joint Mongolian-Russian Enterprise "Erdenet Mining Corporation"*)

IMPROVING INTELLIGENT CONTROL OF ENRICHMENT PROCESSES BASED ON ORE SIZING VISIOMETRIC ANALYSIS

For the flotation process, the use of open control loops used as ore quality input parameters is effective. The operational analysis shall be performed to determine the ore quality including its material and mineral composition and structure. The main operational analysis is measurements of X-ray and visible spectrum areas.

New techniques and devices have been developed to improve accuracy of ore composition measurements. Specific lighting systems that alternate micro-focused and flat light flows were used to analyze the conveyed ore. These systems ensure high measurement accuracy of the conveyed ore. A special flat-bed plant for fine ore visiometric analysis have been developed a part of the existing sampling and analysis system. The flat-bed plant ensures higher accuracy of ore mineralogical composition measurements.

Modern ore visiometric analysis systems help create an effective automated control approach for enrichment processes based on advanced monitoring of ore sizing. The systems implemented at the Erdenet enrichment plant (Mongolia) contributed to higher levels of copper and molybdenum extraction.

Keywords: ore enrichment, reduction in size, flotation, automated control, algorithm, optimization, ore size determination, visiometric and X-ray fluorescent analysis

INTRODUCTION

The analysis of ore and/or enrichment products in the X-ray and visible sub-spectrum [1, 2] is a new approach based on ore size radiometric data, which can improve the control efficiency of enrichment processes. A key advantage of such techniques is the ability to take operational measurements of ore composition parameters and enrichment products, including mass fraction of specific minerals.

Previously, Russian and foreign experts determined the size of processed ore based on measurements of source ore material composition and its enrichment flotation products with X-ray fluorescent analyzers [3, 4]. However, an adequate determination of ore size is only possible with the operational measurement of mineral composition parameters such as the ore oxidation level and ratio of basic mineral forms [5, 6].

Ore size operation analysis can be implemented based on the continuous measurement of mineral composition directly in the process flow or based on the analysis of samples specifically taken from this ore sample flow.

ORE SIZE VISIOMETRIC ANALYSIS METHOD

Reliable separate determination of ore minerals is possible with modern color pattern identification formats. The RGB format, which presents any color as a combination of red, green and blue, is an ideal format for primary processing of the color image. Other parameters, the most important of which are hue, saturation and value (HSV), are determined based on these three main parameters [7].

First, video images of all field minerals are entered in the system's database. Main ore copper minerals as well as primary (granodiorite and granosyenite) and accessory (quartz and sericite) rock forming minerals are presented in Figure 1.

Software processing methods are used to create computer-aided images (reference standards) of the main minerals. The mineral spectrum characteristics in the wave radiation visible range are the source of data (database) during visiometric analysis of ore mineral composition (Figure 2).

Fig. 1. Photographs of ore and rock forming minerals of copper-molybdenum ores.

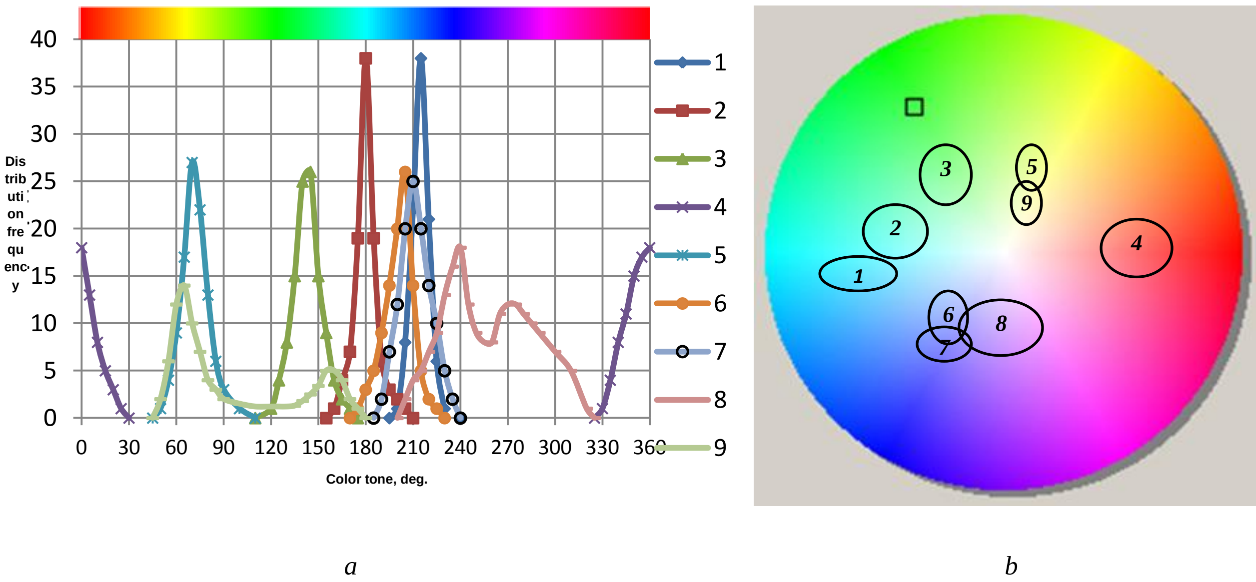

Fig. 2. HSV color characteristics of minerals: *1* – azurite; *2* – turquoise; *3* – malachite; *4* – cuprite; *5* – chalcopyrite; *6* – chalcocite; *7* – bornite; *8* – covellite; *9* – pyrite.

As shown in Figure 2, *b*, the resolution of mineral spectrum characteristics is higher when using a two-parameter recognition system: color – HSV saturation. Fully using the HSV format features increases the reliability of mineral determination up to 0.95 even for such complicated systems as chalcopyrite – pyrite or chalcocite – covellite, bornite.

The program uses simple interval limits of RGB energy for a single image area (pixel). 3D areas of RGB energy intervals for surveyed color minerals, and general image element energy are formed on the basis of two-dimension probability areas (areal) that describe the presence of mineral products in the HSL system. Recognition takes place on 3-dimension probability areas of HSL system mineral products single pixel color pairs; the neuron networks technique and system learning approach is used.

Figure 3 presents a source image of the aggregate of chalcopyrite and bornite and covellite (*a*), and recognition data (*b*).

The recognition efficiency is high even for close spectrum minerals such as covellite and bornite. It should be noted that the aggregate size shown in the Figure is 2 mm.

The mass fraction of oxidized minerals, primary and secondary copper, pyrites, quartz, sericite, mica as well as other minerals whose ratio describing ore size is determined with spectrum mineralogical analysis.

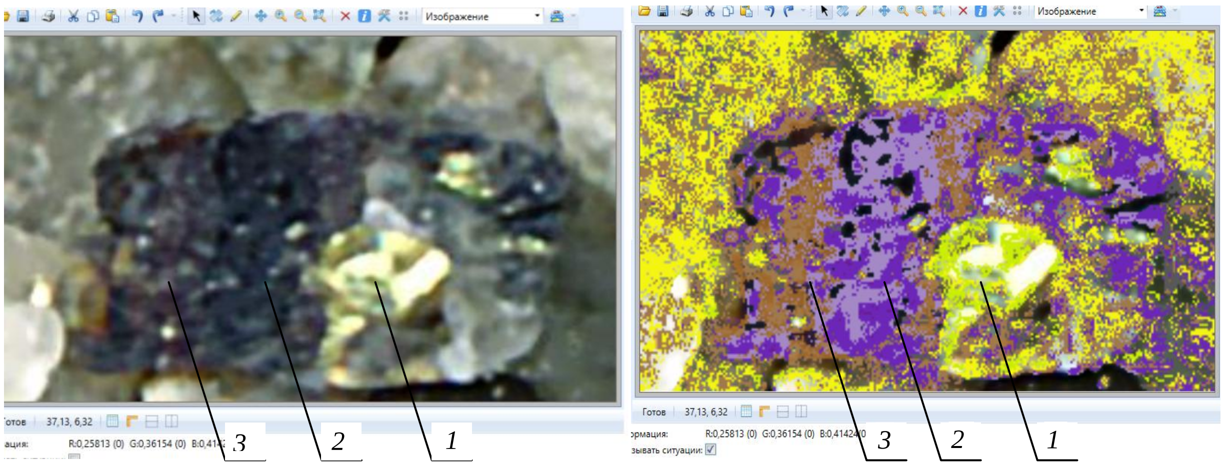

Fig.3, *a*. Image of the aggregate of sulphide copper minerals in copper-molybdenum ore and recognition data: *1* – chalcopyrite; *2* – bornite; *3* – covellite.

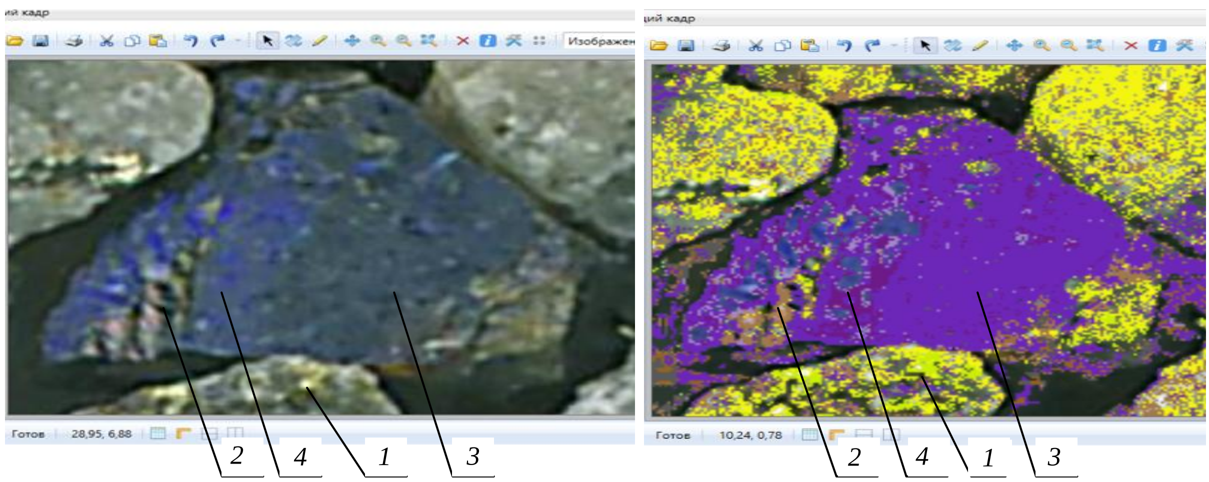

Fig. 3, *b*. Image of the aggregate of copper minerals in copper-molybdenum ore and recognition data: *1* – chalcopyrite; *2* – bornite; *3* – covellite; *4* – azurite.

This approach is most effective when we assess the ore oxidation level which can be calculated as a ratio of the integral intensity of spectrum characteristics of oxidized minerals to the general intensity of spectrum characteristics of all copper minerals. The ore oxidation level can be determined as a ratio of the mass fraction of copper in oxidized minerals to the general mass fraction of copper. Spectrum mineralogical analysis can also be used to determine the ratio between primary (chalcopyrite) and accessory (bornite, chalcocite, covellite) sulphide copper minerals. We can also determine the presence and measure the mass fraction of talc, mica, sericite and other minerals that have an impact on the flotation process.

The processable ore size is determined through its similarity to main process ore types [8]. The approach that we use is aimed at determining final ore size and composition – the fractions of main process ore types. X-ray fluorescent analyzer data (material composition, video-image analysis sensors data) are used as input data for analysis system.

Ore size is calculated using the multi-criteria accessory calculation method. The required solution is presented by standard ore types. The ore is presented as a combination of five ore types, while in-ore fraction of each ore type is determined. The system's mathematical pattern is responsible for calculating available ore size across six or more essential ore parameters (for example, copper, molybdenum and iron content in ore, mass fraction of oxidized copper minerals, accessory sulphide ore minerals in ore, primary copper minerals and sericite). Other parameters can also be used: for example, grain size composition, ore crushing, and grindability capacity [9].

The multi-criteria task solution is reduced to determining how much the reference point belongs to a specific set of points on a plane (2-dimension space) or on any other "plane". Such a calculation approach is used to determine the "similarity" of processed ore to any of five known ore types and establish the fractions of any of the five ore type in the ore available for processing [8]. Therefore, first of all we shall determine the distance from the point whose coordinates correspond to the ore available for processing, to any of the points whose coordinates correspond to the ore types established by process engineers as reference ore types (Figure 4).

Then, following valuation and assessment of the parameter significance, we shall use calculation equations to determine target mass fractions of standard ore types in the processable ore.

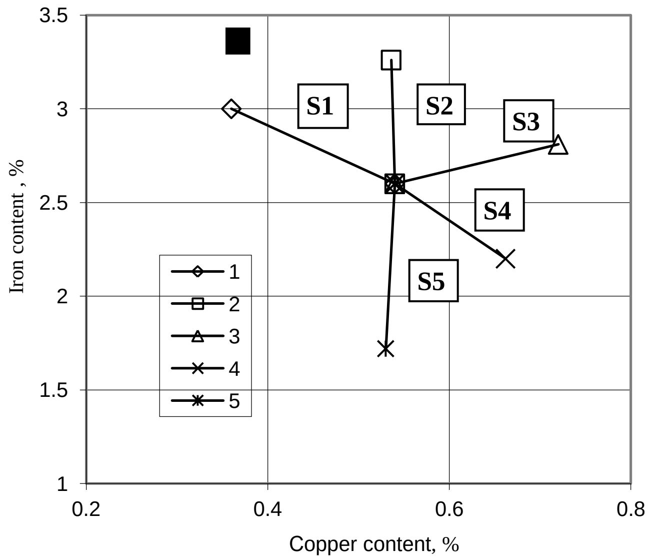

Fig. 4. Example of determining ore composition in 2-dimension space 1, 2, 3, 4, 5 – ore types; 6 (■) – current ore type; S1, S2, S3, S4, S5 – deviation of current ore parameters from types 1, 2, 3, 4, 5 ore.

The standardized deviation value (S_i) of the ore mix parameter (Z_n) from reference ore parameters (Z_{ni}) shall be calculated using the following formula:

$$S_i = \left(\left|Z_n - Z_{ni}\right|\right) / Z_{ni}, \text{ where } i = 1 - 5. \quad (1)$$

The standardized value for similarity of ore mix parameters to reference ore parameters shall be calculated using the following formula:

$$D_i = 1 / S_i, \text{ where } i = 1 - 5, \quad (2),$$

where S_i is the standardized deviation of ore mix parameters from reference ore parameters.

Calculation of the mass fraction of individual ore type (γ_i) in ore mix:

$$\gamma_i = kD_i / \sum\left(kD_i\right), \text{where } i = 1 - 5 \quad (3),$$

where k are significance coefficients of individual measured ore parameters.

The significance coefficients of individual measurement ore parameters are adaptive-adjustable parameters; the initial source for the adjustment of these parameters is actual ore size obtained from the samples taken and processed using classical techniques.

The size measurement operation is repeated at set time intervals. The final results of ore size and processed medium analysis are presented as time curves in Figure 5. These curves describe changes in processed ore composition.

Upgrading the optical analysis system for conveyed ore

Joint research by scientists from NUST MISiS and Erdenet Mining Corporation resulted in the development and testing of a new ore advanced diagnostic method based on optical analysis of ore composition.

The video-image analysis system (Figure 6) provides digital ore images. This was built with modern telemetric and software and hardware facilities. The system allows real-time data to be obtained on ore mineralogical composition and ore type. The system can also provide data on ore grain size distribution in the breakage operation and mineral impregnation.

The analyzer operates in two alternating modes. In operating mode 1: deflector *5* generates diffused light for uniform illumination of the sample. In mode 2: plane-parallel light flow is generated by deflector *6*. This promotes maximum image "contrast", which is necessary to measure ore sizing.

Conveyed ore undergoes continuous scanning. All data received from the system will be processed and averaged. Then, ore size and grading will be recognized subject to the algorithm described above. The obtained data are used for automated control of ore processing and floating processes.

Ore sample optical analyzer

The disadvantage of the conveyed ore analysis is low measurement reliability due to low definition of captured images. This is due to the insufficient homogeneity of the sample plane section and the impossibility of focusing on the entire ore surface.

Joint research by scientists from NUST MISiS and Erdenet Mining Corporation resulted in testing a new ore diagnostic method based on flat-bed analysis of mineral composition. The high accuracy of visiometric analysis is ensured by special devices embedded into the sampling system, and further ore sample analysis by the Quality Assurance Department. A sample analysis plant has been developed to support sample analysis using this method.

The plant includes a sample table made from transparent glass, a light flow source, optical system, and optical converter.

The measurement technique includes ore sample pre-processing, forming a measurement area in the form of a plane sample section, illumination and recording images of the sample plane section in the visible sub-spectrum. Sample images are illuminated and recorded from bottom to top, in 2D scanning mode.

By "placing" grains, significant reduction in sample roughness is possible. An almost plane-parallel, evenly illuminated surface without

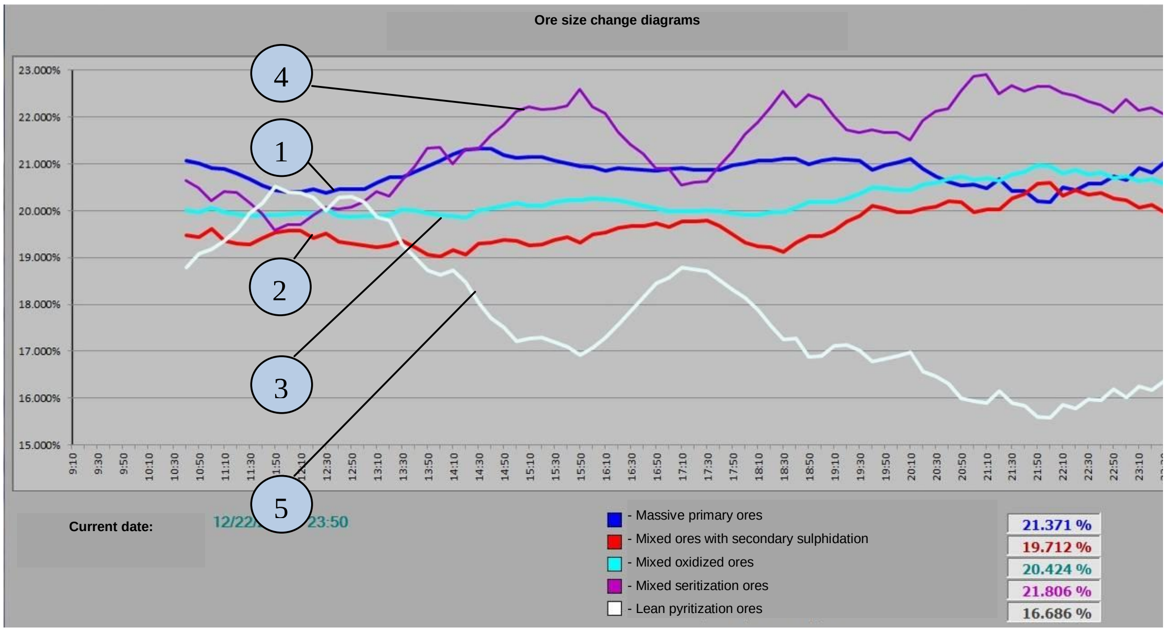

Fig. 5. Change in current ore composition: *1* – massive primary ores; *2* – mixed ores with secondary sulphidation; *3* – mixed oxidized ores; *4* – mixed seritization ores; *5* – lean pyritization ores.

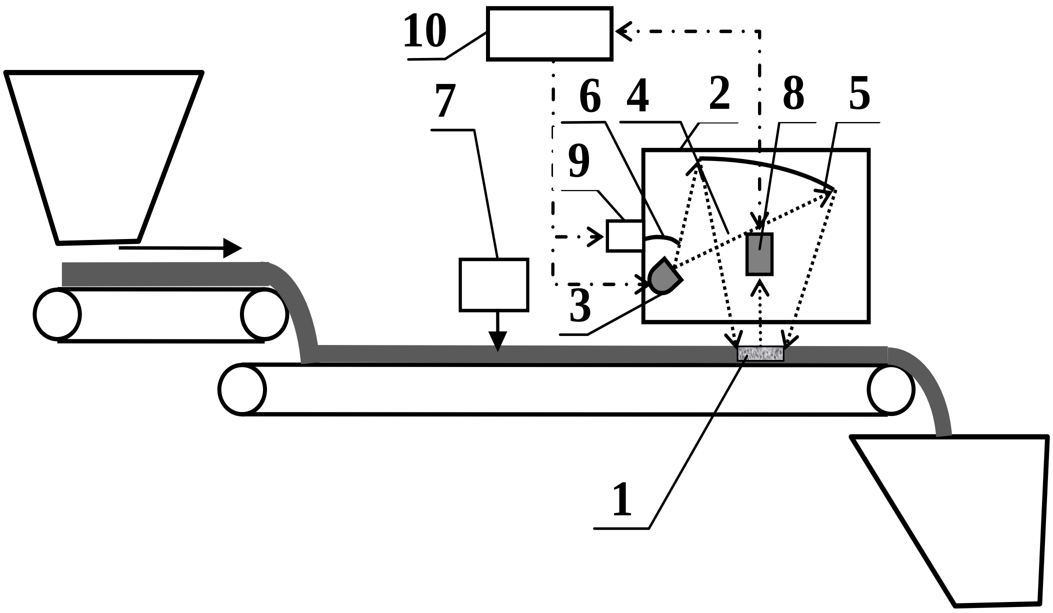

Fig. 6. Telemetric analyzer of ore size and quality. *1* – measurement area; *2* – body, *3* – light source, *4* – light flow; *5*, *6* – main and accessory deflectors; *7* – sprayers; *8* – video camera; *9* – deflector drive; *10* – microprocessor.

shaded sections will be formed. This ensures high image definition and reliability of mineral determination.

Control of enrichment processes based on ore sizing data

Initially, ore quality is inspected at ore development and transportation phases. This control process includes control for in-flow ore averaging, as well as separation of primary flow by mostly sulphide and mostly mixed ore flows. The proposed enrichment approach and automated enrichment control equipment are presented in Figure 8.

Phase 1 consists of sample taking and ore mineralogical analysis at the mining phase. "Ore oxidation" and "ore antecedence" are two criteria used to assess ore quality. Numerically, the "ore oxidation" criterion corresponds to that part of the ore which is in an oxidized mineral state (azurite, cuprite, malachite, chrysocolla, etc.). The "ore antecedence" will be calculated as an ore part in the form of chalcopyrite mineral (primary sulphide copper mineral). Depending on these parameters, the formed oxidized ore flows are sent for desalinization of primary and mixed ore available for enrichment.

To calculate optimum degradation and flotation parameters for various ore sizes, most typical ore samples were surveyed, and degradation and flotation process schedules were developed. Since it was impossible to obtain an ore sample of specific sizing, experts performed statistical processing of available data and developed "standard" ore enrichment models for massive primary ores (MPO), mixed secondary sulphide ores (MSSO), lean pyritization ores (LPO), mixed cetirizine ores (MSO), and mixed oxidized ores (MOO).

The model results presented as optimum degradation and flotation parameters for various ore size (Table 1) were recommended to be implemented in Erdenet enrichment plant's automated control systems.

Optimum degradation and flotation parameters were used in calculating setting functions SF for local automated systems of automated feedback regulation systems [10]. The process was subject to regulation after all input parameters, selected in accordance with ore sizing, were set.

The setting function value SF of any process parameter was calculated as a weighted optimum mean value of these parameters for every standard ore size (SF_i), taking into account the ore size contribution to ore mix subject to formula (4)

$$SF = \sum \gamma_i SF_i, \qquad (4),$$

where γ_i – is a relative mass fraction of ore type i available for ore mix processing.

The calculation data set includes the flow of reagents, ore processing, degradation sizing, etc.

While calculating reagent consumption, we may also take into account possible effects that can occur when processing various ore types. The ore cross-effect can be presented with correction coefficients L_i. Then, equation (4) will take the following form;

$$SF = \sum L_i \gamma_i SF_i. \qquad (5)$$

Pre-set functions were used as a basic level of local degradation and flotation automated control systems. Using the ore sizing determination procedure improves automated control reliability. Control stability improved by 5 % to 7 % after implementing the ore sizing determination algorithm. Maintaining optimum degradation and reagent consumption rate under current ore flotation provides a higher level of copper and molybdenum extraction to copper or molybdenum concentrate by 0.3 and 1.1 % respectively, as well as reagent consumption by 2–3 %.

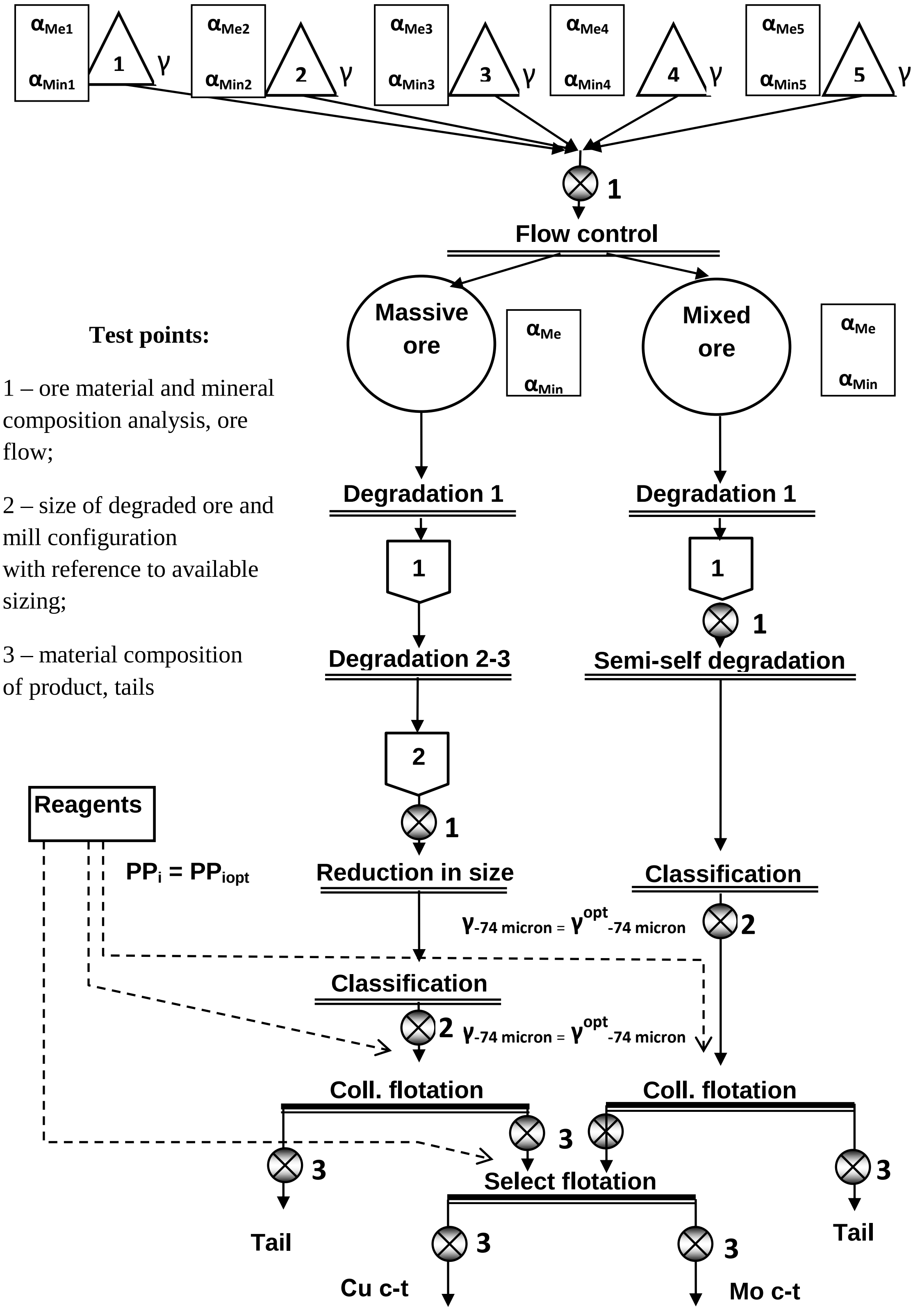

Fig. 8. Block Diagram - Formation of current ore flow as a mixture of specific process ore types and location of sampling points, IM – impregnation of valued components

Table 1

Optimum degradation process parameters and classification – target functions in control systems

Process parameters	MPO	MSSO	LPO	MOO	MSO
Degradation size, %, Class – 74 micron	67.50	64.50	67.00	66.00	66.00
Ore conveyed to mill, t/m^{3}h	1.65	1.74	1.71	1.75	1.75
Pulp density, %	43.50	41.00	41.50	40.00	40.00
Consumption of AeroMX-5140 collecting agent	10.00	12.00	13.00	17.50	10.00
Consumption of MIBK foaming agent	13.00	16.00	16.00	19.00	13.00
Lime consumption	1100.00	1300.00	1300	1300.00	1100.00

Note. Massive primary ores (MPO); mixed secondary sulphide ores (MSSO); lean pyritization ores (LPO); mixed cetirizine ores (MSO) and mixed oxidized ores (MOO).

CONCLUSION

Joint research by scientists from NUST MISiS and Erdenet Mining Corporation resulted in further development of the flotation regulation approach based on advanced assessment of processed ore sizing. New techniques and devices for automated measurement of composition of conveyed and sampled ore have been tested. The control algorithm uses ore size data and available information on optimal degradation and flotation process parameters. Implementation of the proposed system will help to reduce losses of valued components and reagent consumption by 3–5 %.

Reference

1. Daniel Sbárbaro, René del Villar Advanced Control and Supervision of Mineral Processing Plants. – Springer-Verlag London Limited, 2010. – 332 p.
2. Hyotyniemi H., Ylinen R. Modelling of visual flotation froth data // Automation in mining, mineral and metal processing 1998. In: Preprints of a 9th IFAC Symposium, Cologn, Germany, 1-3 Sept. 1998. – Pergamon, 1998. – p. 309-314.
3. Mojlanen Ja., Timperi Ju., Kemppinen H. Principy komp'juternogo upravlenija flotacionnym processom na baze novoj produkcii Outotec – videosistemy Frothmaster [*Computer control principles flotation process on the basis of new products Outotec - video Frothmaster*] // Math. universities. Mining Journal. – 2010. – No. 2. – pp. 89-92.
4. Hyotyniemi H., Koskinen K., Saloheimo K. Calibration of an X-ray fluorescence analyzer using clustered components // Future Trends in automation in mineral and metal processing. – Preprints of IFAC Workshop, Finland, 22-24 August 2000. – IFAC, Copy-set Oy, Helsinki, 2000. – p. 219-224.
5. Olli Haavisto, Jani Kaartinen, and Heikki Hyötyniemi. 2006. Optical spectrum based estimation of grades in mineral flotation. In: Proceedings of the 2006 IEEE International Conference on Industrial Technology (ICIT 2006). Mumbai, India. – 2006, pp. 2529-2534.
6. Morozov V., Davaasambuu D., Ganbaatar Z., Delgerbat L., Topchaev V., Sokolov I., Stolyarov V. Modern systems of automatic control of processes of grinding and flotation of copper-molybdenum ore. In: 16th IFAC Symposium on Control, Optimization and Automation in Mining, Minerals and Metal Processing, Volume 15, Part1, IFAC (ed.), 2013. – pp. 166-171.
7. Agoston, Max K. Computer Graphics and Geometric Modeling: Implementation and

Algorithms. London: Springer. – 2005. pp. 300-306. ISBN 1-85233-818-0.
8. Morozov V.V., Ganbaatar Z., Lodojravsal Ch. at al. Obogashhenie medno-molibdenovyh rud s primeneniem kompleksnogo radiometricheskogo analiza sortnosti rudy [*Enrichment of copper-molybdenum ores using an integrated radiometric analysis of ore grade*] // Mining information-analytical bulletin. – 2011. – No. 12. – pp. 176-182.
9. Ulitenko K.Ja., Morozov V.V., Bokani L. Razrabotka i obosnovanie metodov povyshenija jeffektivnosti processov rudopodgotovki na osnove primenenija mnogourovnevyh adaptivnyh sistem regulirovanija [*Development and justification of methods to increase the efficiency of ore dressing processes based on the use of multi-level adaptive control systems*] // Plaksinskie chtenija [Plaksin read] / Materialy mezhdunarodnoj nauch-prakt. konf. [Proc. of the int. scientific-practical conference.] – Kazan, 2010 – pp. 19-22.
Ganbaatar Z., Djelgjerbat L., Duda A.M., Morozov V.V. Upravlenie obogashheniem medno-molibdenovyh rud na osnove kompleksnogo radiometricheskogo analiza rudy [*Management enrichment copper-molybdenum ores based on a comprehensive analysis of radiometric ore*] // Plaksinskie chtenija [Plaksin read] / Materialy mezhdunarodnoj nauch-prakt. konf. [Proceedings of the int. scientific-practical conference.] – Ekaterinburg, 2011. – pp. 118-121.

"Gornye nauki i tehnologii"/ "Mining science and technology", 2016, No. 2, pp. 29-38	
Title:	**Improving the intelligent methods of management of processes of enrichment on the basis of visiometrics analysis of the grade of the ore**
Author 1	Full name: **Valery V. Morozov** Company: **The National University of Science and Technology MISiS** Work Position: **Professor** Scientific Degree: **Doctor of Engineering Science** Contacts: **dchmggu@mail.ru**
Author 2	Full name: **Valery M. Shek** Company: **The National University of Science and Technology MISiS** Work Position: **Professor** Scientific Degree: **Doctor of Engineering Science** Contacts: **shek@geotwo.ru**
Author 3	Full name: **Yury P. Morozov** Company: **Ural State Mining University** Work Position: **Professor** Scientific Degree: **Doctor of Engineering Science** Contacts: **tails2002@inbox.ru**
Author 4	Full name: **Delgerbat Lodoy** Company: **Erdenet Mining Corporation, Mongolia** Work Position: **Chief Specialist at ACS** Scientific Degree: **Doctor of Engineering Science** Contacts: **delgerbat@erdenetmc.mn**
DOI:	**http://dx.doi.org/10.17073/2500-0632-2016-2-31-42**
Abstract:	For the flotation process using of open control loops, which are used as input parameter of the ore quality, is effective. To determine the quality of ore, on-line analysis of its elemental and mineral composition and structure is carried out. The basis of the operational analysis is the measurement of X-ray and visible light. To improve the accuracy of determining ore mineralogical composition, new techniques and facilities have been developed. At the conveyor ore analysis special lighting systems were tested, using alternating focused and flat light fluxes. Such systems provide highly accurate in-stream measurements of ore properties. A special flatbed facility for optical spectrum-based estimation of fine-crushed ore has been developed, being incorporated into the existing system of ore sampling and analysis. Application of the flatbed facility renders possible a high accuracy of determining ore mineralogical composition. Modern systems for optical spectrum-based estimation of ore grade provide a basis for effective automated control of ore beneficiation processes, based on the principle of advanced ore grade control. The systems implemented at the Erdenet processing plant

(Mongolia) contributed to increasing copper and molybdenum recovery.

Keywords: mineral processing, milling, flotation, automatic control, algorithm, optimization, estimation of ore grade, visible and RFA analysis

References:

1. Daniel Sbárbaro, René del Villar Advanced Control and Supervision of Mineral Processing Plants. – Springer-Verlag London Limited, 2010. – 332 p.
2. Hyotyniemi H., Ylinen R. Modelling of visual flotation froth data // Automation in mining, mineral and metal processing 1998. In: Preprints of a 9th IFAC Symposium, Cologn, Germany, 1-3 Sept. 1998. – Pergamon, 1998. – p. 309-314.
3. Mojlanen Ja., Timperi Ju., Kemppinen H. Principy komp'juternogo upravlenija flotacionnym processom na baze novoj produkcii Outotec – videosistemy Frothmaster [*Computer control principles flotation process on the basis of new products Outotec - video Frothmaster*] // Math. universities. Mining Journal. – 2010. – No. 2. – pp. 89-92.
4. Hyotyniemi H., Koskinen K., Saloheimo K. Calibration of an X-ray fluorescence analyzer using clustered components // Future Trends in automation in mineral and metal processing. – Preprints of IFAC Workshop, Finland, 22-24 August 2000. – IFAC, Copy-set Oy, Helsinki, 2000. – p. 219-224.
5. Olli Haavisto, Jani Kaartinen, and Heikki Hyötyniemi. 2006. Optical spectrum based estimation of grades in mineral flotation. In: Proceedings of the 2006 IEEE International Conference on Industrial Technology (ICIT 2006). Mumbai, India. – 2006, pp. 2529-2534.
6. Morozov V., Davaasambuu D., Ganbaatar Z., Delgerbat L., Topchaev V., Sokolov I., Stolyarov V. Modern systems of automatic control of processes of grinding and flotation of copper-molybdenum ore. In: 16th IFAC Symposium on Control, Optimization and Automation in Mining, Minerals and Metal Processing, Volume 15, Part1, IFAC (ed.), 2013. – pp. 166-171.
7. Agoston, Max K. Computer Graphics and Geometric Modeling: Implementation and Algorithms. London: Springer. – 2005. pp. 300-306. ISBN 1-85233-818-0.
8. Morozov V.V., Ganbaatar Z., Lodojravsal Ch. at al. Obogashhenie medno-molibdenovyh rud s primeneniem kompleksnogo radiometricheskogo analiza sortnosti rudy [*Enrichment of copper-molybdenum ores using an integrated radiometric analysis of ore grade*] // Mining information-analytical bulletin. – 2011. – No. 12. – pp. 176-182.
9. Ulitenko K.Ja., Morozov V.V., Bokani L. Razrabotka i obosnovanie metodov povyshenija jeffektivnosti processov rudopodgotovki na osnove primenenija mnogourovnevyh adaptivnyh sistem regulirovanija [*Development and justification of methods to increase the efficiency of ore dressing processes based on the use of multi-level adaptive control systems*] // Plaksinskie chtenija [*Plaksin read*] / Materialy mezhdunarodnoj nauch-prakt. konf. [*Proc. of the int. scientific-practical conference.*] – Kazan, 2010 – pp. 19-22.
10. Ganbaatar Z., Djelgjerbat L., Duda A.M., Morozov V.V. Upravlenie obogashheniem medno-molibdenovyh rud na osnove kompleksnogo radiometricheskogo analiza rudy [*Management enrichment copper-molybdenum ores based on a comprehensive analysis of radiometric ore*] // Plaksinskie chtenija [*Plaksin read*] / Materialy mezhdunarodnoj nauch-prakt. konf. [*Proceedings of the int. scientific-practical conference.*] – Ekaterinburg, 2011. – pp. 118-121.