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RADIOMETRIC SORTING OF ORE IN IN-SITU URANIUM LEACHING

The article analyzes present-day technological innovations in in-situ borehole leaching of uranium, and discusses their influence on eco-friendliness, safety and efficiency of the process. The authors describe the key aspects of modern approaches to radiometric sorting of uranium ore, including automation, machine learning and other novel techniques, and discuss economic efficiency of radiometric separation of uranium ore. For the control of operating conditions in in-situ leaching, a system of automatic control with the dynamic pulse–frequency modulation is proposed. The system features high interference immunity and simplicity of hardware and software implementation. In addition, the scope of the discussion embraces prospects of technological advance in this area of research and potential contribution of new technologies to the environmental impact mitigation, mineral mining efficiency and sustainable development of the mining industry.

Keywords: *automation, control, process flows, sorting, leaching uranium*
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Introduction

Radioactivity of uranium as against other minerals and enclosing rocks governs specifics of uranium deposits and preconditions new methods of uranium production and leaching. Radioactivity measurements and electronic instrumentation can enable a higher level of performance of uranium mining and processing plants.

Uranium mines use in-situ manual sorting of ore for many years. Portable radiation meters offer new capabilities in this regard. At the present time, radiometric sorting during mining of complex uranium ore lodes helps reduce losses and also serves as a primary method of ore leaching. Employment of in-situ analytical radiometers of the type of RKS in quick assaying of ore and rocks in different transport containers (boxes, carriages, skips and motor cars) allowed radiometric sorting of uranium ore in such containers everywhere on the ground and under the ground [1–3].

The present-day mines use totally automated radiometric sorting of uranium ore. High accuracy of assaying and possibility of prompt adjustment of cut-off grades for sorting products allows considering radiometric sorting of ore in transport containers as a pre-leaching method. The method of automated radiometric sorting and the design of radiometric sorting machines–separators elevated the value of radiometric sorting as the pre-leaching method. It is now possible to carry out high-output and economic separation of high-grade and low-grade ores, remove barren rock from marketable feedstock of hydrometallurgy, or to produce a few concentrates of the same quality as the high-grade gravity concentrates have. The introduction of the multi-stage radiometric uranium sorting allowed revision of mining systems and their components, and rejection of underproductive systems with scrupulous selection of standard-quality ore, and shifting to high-efficient systems of bulk or half-bulk mining. Development of automated uranium sorting using radiometers revealed the need for auxiliary operations to improve the radiometric separation performance. Such operations are grinding of coarse fractions, classification of original ore within a narrow range of size, removal of unsizable fines, provision of uniform stream/portion/lumpy ore feed to radiometric separators, jigging etc. The package of the listed mechanical operations and radiometric sorting was named as the method of radio-mechanical (or radiometric) uranium ore processing, and the radiometric sorting is a major component of the method. Radiometric sorting is workable in containers, in face areas and in all other cases when radioactivity measurement is the main operation and needs no auxiliary and labor-intensive mechanical operations to be involved in the sorting process. For evaluating results and efficiency of the radiometric sorting process, it is possible to use some indicators from theory and practice of mineral beneficiation, with some deviations from agreed notations in order to simplify mathematical descriptions and to extend these indicators to geological exploration and mine operation [1, 4–6].

At the stage of uranium exploration, radiometric survey of rock mass allows estimating and adjusting an ore assaying procedure, and optimizing cut-off grades of uranium for distinguishing between high-grade and low-grade ores, or for mapping areas of different ore grades. Radioactivity measurements may be decisive in evaluation of commercial prospects of mining low-grade and extremely radioactive uranium ores. We define radioactive ore as uranium ore with nonuniform distribution of the useful component; it is expedient to separate such ore into rich and depleted grades. The depleted grades should be classified as tailings of radiometric sorting (substandard quality ore), or as ore grades to be subjected to subsequent processing using a simple and cheaper technology. Non-radioactive ore is defined as material inexpedient for the radiometric sorting because of sufficient uniformity of the useful component distribution. Radioactivity of one and the same ore type depends, among other things, on the unit volume, therefore, this unit volume value should be mentioned among the characteristics of ore sorting (lump radioactivity, portion radioactivity in portions of certain weight, bogie radioactivity, etc.) [1, 2, 7, 8].

Materials and methods

Distribution of a useful component in ore, as any random phenomenon, obeys the laws of mass phenomena, and its investigation involves mathematical statistics. The radiometric ore sorting analysis may include determination of distribution pattern of a variable value which in the test mass phenomenon is a content of a useful component in a certain unit volume of ore, Δy. This random variable may have any values over the range of a minimum (β_{min}) to a maximum (β_{max}) content of the useful component. Since the variable β in case of infinite number of tests may assume any values in the specified range, this variable is continuous and a set of its values is a random function [7, 9–12].

At a sufficiently high number of tests aimed to determine the useful component content β per unit volumes Δy of the whole mass of test ore, it is possible to find the law this random value obeys. Generally, this law can be expressed as a functional dependence below:

$$\beta = f(y). \tag{1}$$

By distributing the obtained values of β from β_{max} to β_{min} over the test interval, we obtain a steadily decreasing function of this random variable.

Accordingly, the general law of the useful component distribution in ore mass, i.e. radioactivity, can be expressed as a continuous function β which gradually decreases from β_{max} to β_{min} over the interval of the ore yield $y = 0$ to $y = 1$. Functional dependence (1) is denoted by us as a characteristic of ore radioactivity.

Thus, radioactivity of ore is the ore property characterized by distribution of a radioactive matter in ore mass in accordance with the law of the steadily decreasing function $\beta = f(y)$ which points at the radiometric sorting potential of the ore. Radioactivity of uranium ore is governed by the nonuniformity of mineralization and by the value of unit volumes.

Because of a vast variety of practical characteristics of radiation contrast, it is impossible to analyze theoretically the functional dependence $\beta = f(y)$ using a definite family of curves. Therefore, to find general relationships between radiation contrast of ore and the optimal sorting data of this ore, it was necessary to examine some mathematical laws of distribution of a random value. With this end in view, the present authors studied the radiation contrast characteristics which agreed with the useful component distributions by the logarithmic law, exponential law, converging binomial series, steadily decreasing exponential function, normal law curve and by the laws of high-power cubic polynomial. Theoretical characteristics of radiation contrast, built in conformity with these laws of distribution, to a certain degree cover the whole range of practical curves. The radiation contrast in the form of the curve of uranium content per unit volume, β, and the ore yield y allows analyzing this dependence using mathematical methods. Amount of the original ore in the radiation contrast curve is given by the constant value $y = 1$. Amount of the enriched ore in this curve is given as a variable y per different values of uranium content in unit volumes, β, i.e. per different cut-off grades for separation of enriched ore and sorting tailings. The area under the radiation contrast curve represents the amount of uranium in the original ore, F_c, defined by an integral [7, 9–12]:

$$F_c = \int_0^1 f(y)dy. \quad (2)$$

The mathematical analysis of the integral expression can determine the radiation contrast and its behavior per each content of the useful component, and can help select the main production data and rational separation level for the uranium content of the enriched product and sorting tailings. The separation level between the enriched product and tailings, coincident with the maximum value of the radiation contrast, is further defined as the optimum mode of radiometric sorting, and the production data of this sorting mode are denoted as the optimized production data.

Radiometric sorting of uranium ore can be carried out in various modifications. Some its components can be included in mining process flows such as dressing or chemical processing. The actual set of mining operations includes: selective extraction of different ore grades based on the useful component content in accordance with in-situ radiometric assaying; broken ore sorting in face area using radiometers; quick-test assaying and ore sorting in transport containers (carts, boxes, bogies, skips, shovel buckets, dump trucks, etc.) both in mine and on ground surface; radiometric sorting using mechanical conveying equipment (stage loaders, conveying belts of surface infrastructure at both surface and underground mines). Radiometric sorting of original ore or middlings (for instance, coarse jigging tailings) at gravity separation plants and radiometric processing of ore before its hydrometallurgical treatment at radiometric concentration factories are the initial or intermediate chains of the ore processing flowsheet.

Evaluation of radiometric sorting efficiency, with regard to technical-and-economic indicators of ore mining and processing, as well as optimization of radiometric sorting uses complex and labor-intensive calculations and grapho-analytical approximation [4]. Both methods require sufficiently exact values of technical-and-economic indicators of mining and processing performance, as well as the useful component distribution in ore at different intermediate stages of ore mining and sorting. Such values are only obtainable at well-studied deposits. However, these methods are inapplicable in evaluation of an optimal cut-off grades of high-grade or low-grade ore at the stage of uranium exploration, or in calculation of optimal cut-off grade and tailings yield in radiometric sorting of various intermediate grades of ore. There are known attempts of quantifying radiation contrast of ore with a certain regard to the useful component distribution but without any relation to technical-and-economic indicators of mining and processing efficiency. The quantity indicator of the radiation contrast of ore is often determined by the theoretical or actual yield of tailings of radiometric sorting below a certain cut-off grade value. Evidently, in this case, it is impossible to perform the quantitative comparison of the radiation contrast of ores which are similar by the useful component distribution pattern but different by the value of average useful component content. Sufficiently rich ore with extremely nonuniform distribution of the useful component but free from numerous nests with the useful component content below a conditional cut-off grade can be erroneously placed in the category of nonradioactive ore in this case. Moreover, the value of the cut-off grade is largely provisional in this case as it is unrelated with the pattern of the useful component distribution in a specific ore type. There is a known method of calculating the radiation contrast factor as a ratio of the average radiation activity in the richest ore lumps or portions to the average radiation activity of the total ore mass. This factor, as the coefficient of variation in the useful component content per samples of certain weight, is inapplicable for the evaluation of radiometric sorting efficiency as it only shows the scattering amplitude of the useful component contents in ore. This factor is unable to determine the sorting production data not to mention their optimization. There is also a proposed method of using an expression from mineral processing theory for total separation efficiency of processing products as an indicator of the ore radiation contrast. Although this indicator sufficiently well describes the useful component distribution in the original ore, it is of no appreciable practical interest as it has no connection with the specific technical-and-economic indicators. Indeed, the optimal separation level from the formula of the total process efficiency for the ore grades or for the sorting products, which is always equal to the average content of the useful component of ore, irrespective of the ore radiation contrast or the ore mining and processing conditions, offers no answers to the main practical questions of optimizing cut-off grade for distinguishing between high-grade and low-grade ore in reserves appraisal, selecting rational grading of ore in mining ore deposits with highly variable ore content and, finally, calculating an economically optimal value of cut-off grade for separation of rich product and tailings of radiometric sorting before hydrometallurgical processing of ore [7, 9–12].

Assessment of radiometric sorting capacities, calculation of production data and optimization of cut-off grades for separation of enriched and depleted ore fractions needs finding an expression of relative technical-and-economic efficiency of radiometric sorting. The relative economic efficiency of radiometric sorting can be expressed as a ratio of the amount of expenses per unit metal in the end product of hydrometallurgical processing of non-sorted ore to the amount of expenses per unit metal in the end product of hydrometallurgical processing of sorted ore. The value of the economic efficiency indicator determines the reduction in cost of unit uranium production in the product of hydrometallurgical processing of ore as a result of the preliminary radiometric ore sorting. Obviously, the economic effect of radiometric sorting means that the efficiency indicator is higher than 1. If the efficiency indicator is 1, radiometric sorting is economically inexpedient.

Results

The economic efficiency of radiometric sorting is an extremum function and depends on variables of sorting, hydrometallurgical processing and economic efficiency of ore mining, sorting and processing. For the operating mines and processing plants, when these values are known, such formula can be used to determine the optimum conditions of radiometric sorting and the produced economic effect. However, in the analysis of general laws of radiometric sorting efficiency with regard to the main technical-and-economic indicators and typical patterns of the useful component distribution in ore, the use of formula (2) is troublesome because of many-valuedness of solutions governed by the variables included in the formula.

Radioactive ores can be divided into sub-groups of weak, moderate, high and extreme radiation. These subgroups have different economic effects of sorting. The ratio of expenses connected with ore mining and processing in the context of sustainable development of the uranium industry keeps a certain dynamic equilibrium. Alongside with the improvement and cheapening of hydrometallurgical processing technology, the cost of mining also continually decreases, in particular, owing to introduction of less costly and more advanced mass mining systems which permit higher dilution of ore to be later on subjected to compensatory radiometric sorting [9, 12–14].

The absolute value of radioactivity in this case varies within wider ranges. The quantity indicator of radiation activity is mainly required for the sufficiently accurate optimization of the sorting mode (especially, at the stages of exploration, appraisal of ore reserves and valuation of commercial viability of mining) rather than for the accurate estimate of the economic effect of radiometric sorting. Therefore, the comparative quantitative assessment of radiation activity of ore can use a simpler expression of radiation contrast indicator.

In a perfect process flow of radiometric sorting, when all unit volumes with the useful component content higher than the preset cut-off grade belong to the concentrated products and all unit volumes with the useful component content lower than the preset cut-off grade belong to the depleted product, formula (2) determines the process capacities of radiometric sorting depending on natural distribution of the useful component with regard to the main technical-and-economic indicators and, thus, quantify the radiation contrast of ore.

So, radiometric sorting is not an independent process. It should be assumed as a stage in a unified work package—ore mining, processing and hydrometallurgical treatment interrelated by common technical-and-economic indicators.

Modeling of in-situ borehole leaching facilitates efficient introductuion of automation systems in the process [9, 13, 14]. Modeling of in-situ leaching dynamics can help optimize the process monitoring and control, enhance efficiency and reduce potential accident risks. The listed studies emphasize the importance of the analysis of in-situ uranium leach models as they reveal dynamics of the process. The modern scientific community shows a growing interest in modeling in-situ leach processes with a view to enhancing efficiency of the method.

An important trend of improving in-situ leaching efficiency is designing and use of automated systems for the leaching process monitoring and control. Such systems allow precise control and effectivization of the process.

Discussion

This research suggests to control operating conditions of in-situ leaching using automatic control systems with the dynamic pulse–frequency modulation (DPFM).

Control systems with DPFM enjoy wide application. Such systems boast high interference immunity, and simple hardware and software implementation. Systems with DPFM can control pumping speed in in-situ uranium leaching.

Figure depicts an automatic control system (ACS) with DPFM and a reduced continuous part (RCP). The control regime involves a series coupling of a filter (F) and a pulsing device (PD) with parametric feedback [9, 10]. Single pulses are sent to the inlet of RCP including a control object and a generating filter. The input signal $f(t)$ represents a random stationary process with the known statistical characteristics [9, 12, 15, 16].

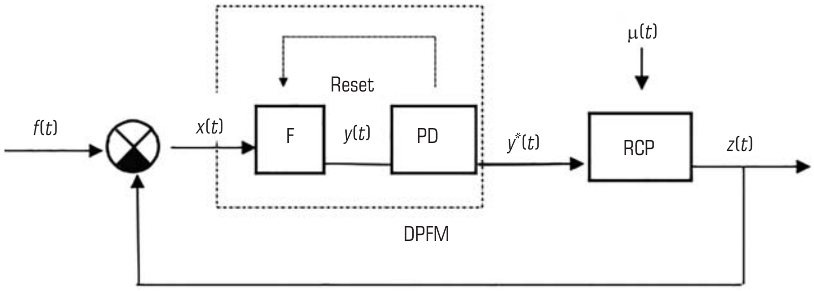

Figure. Structure chart of ACS with DPFM

Equations of motion of ACS with DPFM with regard to equations of its components and closure conditions take the form of [1]:

$$x(t) = f(t) - H\ [z(\tau),\ \int_0^{\tau} q_f(\tau-\theta)\ y^*(\theta)d\theta,\ \tau_0,\ \lambda / t_0 \le \tau \le t]; \quad (3)$$

$$y(t) = \Phi[y(\tau),\ x(\tau)|t_n + 0 \le \tau \le t_{n+1} - 0]; \quad (4)$$

$$y\left(t_{n+1} - 0\right) = \lambda_{n+1}\ \Delta; \quad (5)$$

$$y\left(t_{n+1} + 0\right) = 0; \quad (6)$$

$$\lambda_{n+1} = \ \operatorname{sign} y\left(t_{n+1} - 0\right); \quad (7)$$

$$y^*(t) = \sum_n \lambda_{n+1}\ \delta\left(t - t_{n+1}\right), \quad (8)$$

where $x(t)$ is the error signal; λ^* is the characteristic of randomness of the functional H; τ^* is the lag of the control object; θ is the threshold of the pulsing device; $y(t)$ is the output signal of the filter F; $z(t)$ is the signal at the output of the open-loop system; $y^*(t)$ is the outlet signal of DPFM; τ_0 is a parameter to take into account the lag of the object; δ is the unit function; Δ is the harmonic vibration; t is the time of the output signal of DPFM; t_n is the signal value at the outlet of the open-loop system; q_f is the series coupling of the filter F; $z(\tau)$ is the signal of the time lag of the control object; $y(\tau)$ is the output signal of the control object; $x(\tau)$ is the error signal of the control object; $\mu(t)$ is the magnetic field.

The motion equations of ACS with DPFM (1)–(6) are nonuniform from the viewpoint of types of the involved equations. In connection with this, it is necessary to transform them to reduce to uniformity in the form of homogenous structural schemes, i.e. models composed of uniform types of equations (structural model). On this basis, it is possible to build mathematical models of ACS with DPFM for the analysis and synthesis of such control systems [9, 12, 15, 16].

Conclusions

Automation and machine learning are the efficient tools of optimization of in-situ leaching at the reduced environmental impact. The machine learning algorithms are also usable for continuous monitoring and early detection of anomalies and prevention of accidents. Furthermore, automated systems promote efficient control of water resources and radiation safety at uranium deposits. All these measures aim to improve eco-friendliness, efficiency and safety of in-situ leaching, which is critical for the sustainable development in the mining industry. For the control of operating conditions of in-situ leaching, a system of automatic control with the dynamic pulse–frequency modulation of control signals is proposed. The system features high interference immunity and simplicity of hardware and software implementation.

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COMPARISON OF APPROACHES TO ASSESSING ENERGY EFFICIENCY OF TECHNOLOGICAL PROCESSES

This paper examines the issues of assessing the energy efficiency of technological processes to ensure sustainable development and rational management of mining enterprises in accordance with international standard ISO 50001. The main idea of the work is a comparative analysis of the traditional approach based on the calculation of specific energy consumption (SEC) values, used by many domestic and foreign enterprises as a key indicator of efficiency, and an approach based on the stochastic frontier analysis (SFA) methods. The rationale for the need to assess energy efficiency is given, taking into account the nonlinearity and stochasticity of technological processes of mining enterprises, as well as the features of the technical and operational characteristics of individual energy-consuming objects and environmental conditions. During the work, the computational experiments were carried out as a case-study of production activities of EKG-10 excavators for 2021–2023. Based on the results of the work, the nonlinear relationship between the key parameters of energy efficiency monitoring and the adequacy of the proposed method for solving the problem is proved. The comparative estimates of potential energy losses with different approaches to analyzing the activities of enterprises are presented, showing potential hidden energy losses when using SEC of more than 30% of the total volume.

Keywords: *specific energy consumption, SEC, stochastic frontier analysis, SFA, Cobb–Douglas production function, opencast mining enterprises, energy efficiency, ISO 50001:2018, excavator, sustainable development*

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Introduction

Energy efficiency of technological processes remains one of the critical objectives of smart production management for over half a century [1–4]. An essential advance in the sphere of energy efficiency became possible with the advent of the energy management concept in the 1980s. The concept of energy management included a system approach to resource management in industry owing to the development of procedures for the energy consumption measurement and analyses at different stages of production. An important element of this approach was the introduction of energy audits which estimated current energy costs and revealed bottle necks in enhancement of energy efficiency [5, 6]. At the turn of the 1990s and 2000s, the international standards of energy management began developing to ensure a systematized approach to energy consumption control in industry. One of the highlights in this sphere was international standard ISO 50001 accepted in 2011. The standard defined the general principles and requirements for the energy management systems to help industries control and reduce consumption using measurable indicators. ISO 50001 uses the plan–do–check–act cycle (PDCA), which assumes persistent improvement of energy control. The standard became a framework for the long-term energy saving strategies at many Russian and foreign mining companies [4, 5, 7–10]. The results of the standard introduction are not only the reduction of expenditures connected with energy but the increased resistance to fluctuations of the market of energy sources.