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THE JOURNAL WAS FOUNDED IN 1940

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The scientific journal News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences has been indexed in the international abstract and citation database Scopus since 2016 and demonstrates stable bibliometric performance.

The journal is also included in the Emerging Sources Citation Index (ESCI) of the Web of Science platform (Clarivate Analytics, since 2018).

Indexing in ESCI confirms the journal's compliance with international standards of scientific peer review and editorial ethics and is considered by Clarivate Analytics as part of the evaluation process for potential inclusion in the Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (AHCI).

Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылымды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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CHANGES IN THE TEMPERATURE OF A PILE OF SELF-IGNITING BLASTED ORE UNDER OPERATIONAL CONDITIONS

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Abstract. *Introduction.* In open-pit mining operations involving the extraction of sulfide ores prone to spontaneous combustion, the wetting of stockpiles has a significant impact on their chemical activity and temperature regime. Traditional dust suppression methods can intensify oxidation processes, leading to increased temperatures and emissions of sulfur compounds, thereby creating environmental and operational risks. *Methods.* This study employs a mathematical modeling method for the low-temperature oxidation of a blasted ore pile, involving the solution of a boundary-value problem for the heat conduction equation (Stockwell et al., 2006). To determine the kinetic parameters, an analysis of steady-state oxygen diffusion in sorbent particles was conducted, and an analytical relationship between the oxygen sorption rate constant and particle size was obtained. The experimental part included laboratory and field studies using complex-action solutions. *Results.* It was established that the key factor in the temperature regime of the stockpile is the density of heat sources, determined by the sum of the oxygen sorption rate constants of various ore fractions. A dependence of the sorption rate on particle size and diffusion parameters was obtained. It was experimentally confirmed that the use of solutions based on wetting agents reduces the oxidation rate and temperature rise: under production conditions, the temperature increase was 4.8 K when using the solution, compared to 9.2 K when moistened with water. *Discussion.* A comparison of theoretical and experimental data revealed a qualitative agreement between them, confirming the adequacy of the proposed model. It was found that the antioxidant effect of the solutions is due to the blocking of small pores and a reduction in oxygen access to the reaction-active zones. The use of complex-action solutions allows for the simultaneous reduction of dust formation, oxidation intensity, and sulfur dioxide emissions, which improves the environmental and technological safety of mining operations.

Keywords: hydrodust suppression, mechanism of solution distribution during the wetting of ore piles, low-temperature oxidation of blasted ore piles, spontaneous combustion, oxygen sorption rate constant, density of heat sources, diffusion in the molecular pores of the sorbent

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ӨНДІРІС ЖАҒДАЙЫНДАҒЫ ӨЗДІГІНЕН ТҰТАНАТЫН ЖАРЫЛҒАН КЕН ҮЙІНДІНІҢ ТЕМПЕРАТУРАСЫН ӨЗГЕРУІ

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Аннотация. ***Өзектілігі.*** Ашық тау-кен жұмыстары жағдайында өздігінен жануға бейім сульфидті кендерді игеру кезінде үйінділерді ылғалдандыру олардың химиялық белсенділігі мен температуралық режиміне айтарлықтай әсер етеді. Шаңды басудың дәстүрлі әдістері тотығу процестерін күшейтуі мүмкін, бұл температураның жоғарылауына және күкірт қосылыстарының шығарылуына әкеліп соғады, экологиялық және өндірістік тәуекелдерді тудырады. Әдістері. Жұмыста жылу өткізгіштік теңдеуінің шеткі мәселесін шеше отырып, жарылған кен үйіндісінің төмен температуралы тотығуын математикалық модельдеу әдісі қолданылды (Stockwell et al., 2006). Кинетикалық параметрлерді анықтау үшін Сорбент дәніндегі оттегінің стационарлық диффузиясына талдау жасалды және оттегінің сорбция жылдамдығы константасының бөлшектердің мөлшеріне аналитикалық тәуелділігі алынды. Эксперименттік бөлім кешенді ерітінділерді қолдана отырып, зертханалық және табиғи зерттеулерді қамтыды. ***Нәтижелері және қорытындылар.*** Үйіндінің температуралық режимінің негізгі факторы кендердің әртүрлі фракцияларымен оттегінің сорбция жылдамдығының тұрақтыларының жиынтығымен анықталатын жылу көздерінің тығыздығы болып табылады. Сорбция жылдамдығының бөлшектердің мөлшеріне және диффузия параметрлеріне тәуелділігі алынды. Ылғалдандырғыш негізіндегі ерітінділерді қолдану тотығу жылдамдығын және температураның өсуін төмендететіні эксперименталды түрде расталды: өндіріс жағдайында температураның жоғарылауы сумен ылғалдандырылған кезде 9.2 К-ге қарсы ерітіндіні қолданған кезде 4.8 К құрады. ***Талқылаулар.*** Теориялық және эксперименттік деректерді салыстыру олардың ұсынылған модельдің сәйкестігін растайтын сапалы сәйкестігін көрсетті. Ерітінділердің тотығуға қарсы әсері ұсақ тесіктердің бітелуіне және реактивті аймақтарға оттегінің қол жетімділігінің төмендеуіне байланысты екендігі анықталды. Кешенді әсер ететін ерітінділерді қолдану шаң түзілуін, тотығу қарқындылығын және күкіртті газ шығарындыларын бір мезгілде азайтуға мүмкіндік береді, бұл тау-кен жұмыстарының экологиялық және технологиялық қауіпсіздігін арттырады.

Түйін сөздер: гидроокшаулау, кен үйіндісін ылғалдандыру кезіндегі ерітіндінің таралу механизмі; жарылған кен үйіндісінің төмен температуралы тотығуы; өздігінен жану, оттегінің сорбция жылдамдығының тұрақтысы, жылу көздерінің тығыздығы, сорбенттің молекулалық кеуектеріндегі диффузия

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ИЗМЕНЕНИЯ ТЕМПЕРАТУРЫ НАВАЛА САМОВОСПЛАМЕНЯЮЩЕЙСЯ ВЗОРВАННОЙ РУДЫ В ПРОИЗВОДСТВЕННЫХ УСЛОВИЯХ

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Аннотация. *Актуальность.* В условиях открытых горных работ при разработке сульфидных руд, склонных к самовозгоранию, увлажнение навалов оказывает существенное влияние на их химическую активность и температурный режим. Традиционные методы пылеподавления могут интенсифицировать процессы окисления, что приводит к росту температуры и выбросам сернистых соединений, создавая экологические и производственные риски. ***Цель***. Оценить изменение температурного режима навала самовоспламеняющейся взорванной руды в производственных условиях и обосновать эффективность применения растворов комплексного действия для снижения интенсивности окислительных процессов. ***Методы***. В работе использован метод математического моделирования низкотемпературного окисления взорванного навала руды с решением краевой задачи уравнения теплопроводности. Для определения кинетических параметров проведен анализ стационарной диффузии кислорода в зерне сорбента и получена аналитическая зависимость константы скорости сорбции кислорода от размера частиц. Экспериментальная часть включала лабораторные и натурные исследования с применением растворов комплексного действия. ***Результаты и выводы***. Установлено, что ключевым фактором температурного режима навала является плотность тепловых источников, определяемая совокупностью констант скорости сорбции кислорода различными фракциями руды. Получена зависимость скорости сорбции от размера частиц и параметров диффузии. Экспериментально подтверждено, что применение растворов на основе смачивателей снижает скорость окисления и рост температуры: в производственных условиях повышение температуры составило 4,8 K при использовании раствора против 9,2 K при увлажнении водой. Сравнение теоретических и экспериментальных данных показало их качественное совпадение, что подтверждает адекватность предложенной модели. Выявлено, что антиокислительный эффект растворов обусловлен блокированием мелких пор и снижением доступа кислорода к реакционно-активным зонам. Применение растворов комплексного действия позволяет одновременно снижать пылеобразование, интенсивность окисления и выбросы сернистого газа, что повышает экологическую и технологическую безопасность горных работ.

Ключевые слова: гидрообеспыливание, механизм распространения раствора при увлажнении навала руды; низкотемпературное окисление взорванного навала руд; самовозгорание, константа скорости сорбции кислорода, плотность тепловых источников, диффузия в молекулярных порах сорбента

Introduction. The moisture content of sulphide ores affects their chemical activity, which largely determines the temperature regime of a blasted pile. To investigate the temperature regime of the pile, a mathematical model has been proposed for the low-temperature oxidation of a blasted pile of ores prone to spontaneous combustion under open-pit mining conditions (Stockwell et al., 2006). The solution to the boundary value problem of the heat conduction equation has been analyzed, and it has been established that the density of heat sources plays a significant role in the temperature regime of the blasted ore pile. Its value is determined, primarily, by the sum of the oxygen sorption rate constants (Ūн) of the individual ore fractions comprising the blasted pile. To determine the oxygen sorption rate constant for various ore fractions (Ūн), a problem concerning the steady-state diffusion of oxygen within a sorbent particle was formulated and solved, and an analytical relationship between the oxygen sorption rate and particle size was derived.

The temperature distribution along the depth of the pile as a function of time was investigated theoretically. To verify the theoretical conclusions, as well as the results of experiments conducted under laboratory conditions, a study was carried out to determine the effect of complex-action solutions on ore stockpiling under industrial conditions. Analysis of the data obtained showed that the pattern of temperature changes in the stockpile under field conditions qualitatively corresponds to the theoretical one. This gives reason to believe that the use of a complex-action solution reduces the rate of oxidation and the rise in temperature in heaps of sulphide ores prone to spontaneous combustion, as well as the associated release of sulphur dioxide into the atmosphere. In open-cast mining operations involving high-performance mining equipment, one of the main processes responsible for the intensive release of dust into the atmosphere is the excavation of rock mass. To reduce dust levels, the blasted ore pile is moistened with water or solutions of various chemical reagents (Henglein, 1969). However, when mining ores prone to spontaneous combustion, this method cannot be applied in the same way as in quarries operated under normal geological conditions. This is because water intensifies the oxidation process, which can lead to the ore spontaneously combusting and releasing sulphurous gas into the environment. This results in the loss of valuable ore components, a deterioration in beneficiation rates, and environmental and economic damage. Sulphurous gases, interacting with atmospheric moisture and under the influence of catalysis and photochemical reactions, oxidise to form a solution of sulphurous acid (H_2SO_4). This increases the danger posed by this compound – sulphurous compounds, moving with the air mass, spread over considerable distances and are converted into sulphates. Sulphur compounds have a harmful effect on the respiratory systems of humans and animals, and destroy chlorophyll in plants, thereby impairing photosynthesis, slowing their growth, reducing the quality of agricultural crops and diminishing their productivity (Ukem et al., 2025).

In view of the above, it is necessary under such conditions to use solutions with a combined action, i.e. those possessing both antioxidant properties and a dust-suppressing effect. It is also important to ensure that the solutions have low surface tension, are non-toxic and inexpensive, are simple to prepare, and do not adversely affect ore beneficiation parameters.

For excavation work in open-cast mining, it is necessary to wet the driest layer of the ore mass, which contains a large proportion of fine particles and releases the highest percentage of dust into the atmosphere. Therefore, under such conditions, it is necessary to use liquids that can penetrate not only the large but, above all, the small pores of the fine ore particles without accelerating the oxidation process. Such liquids may include aqueous solutions of wetting agents. For example, adding 0.2% of the wetting agent DB (oxyethylated dibutylphenol) to water reduces the surface tension of the water from 0.073 N/m to 0.028 N/m (Cybulski et al, 2015).

The rate of ore oxidation is determined by the temperature conditions of the blasted pile. It follows that the effect of the wetting liquid – selected as a complex-action solution – on the rate of ore oxidation can be assessed by measuring the temperature change in the wetted blasted ore pile.

*Literary review***.** In theory, spontaneous combustion is determined by three physical factors: the chemical reactivity of the oxidizable materials, the flow of air to them, and the rise in temperature within the mass due to the accumulation of heat generated by oxidation (Minghe et al., 2017).

A comprehensive and ideal assessment of spontaneous combustion would involve determining the quantitative values of all three physical parameters. However, in most cases, this is not feasible. Therefore, to evaluate the spontaneous combustion process, it was decided to determine the quantitative value of at least one of these parameters.

Moistening of sulfide ores affects their chemical activity, which largely determines the temperature regime of the blasted pile. Therefore, when selecting solutions, the chemical activity index of the moistened ore was chosen as the criterion for evaluating their antioxidant properties. Various methods have been proposed to determine this index, but the closer the conditions under which the test is conducted are to those under which spontaneous combustion occurs in natural conditions, the more accurately the selected method will characterize the tendency toward spontaneous combustion. Based on these considerations, the method developed at the A.A. Skochinsky Institute of Geology and Mineral Resources (Dyadkin et al., 1993) was selected for choosing a complex-action solution under laboratory conditions. The selected method allows for determining the rate of oxygen absorption from the air and comparing the experimental results obtained when studying the influence of various solutions on the chemical activity of sulfide ores.

The essence of the method is as follows: a sample of ore, ground to a specific particle size that constitutes a significant portion of the blasted ore pile, is placed in a vessel. The bottom of the vessel is covered with gauze to prevent the loss of fine ore particles during liquid drainage. Glass rods are then placed to separate the damp gauze from the ore sample, which is treated with the solution under study. After the specified time, air samples are taken from the vessels and analyzed to determine the rate of oxygen absorption. Since the rate of oxygen absorption depends on its concentration, which does not remain constant over time, the kinetic constant of the sorption rate serves as an indicator of chemical activity.

The kinetic constant for the sorption rate is calculated using the following equation (Rusdiarso et al., 2016):

$$U = -\frac{V\,(B-23{,}8)}{Pt\,760}\ln\frac{(1-Co)Ca}{Co\,(1-Ca)},\ \mathrm{ml/(g\cdot hr)}, \qquad (1)$$

where V – volume of air in the vessel, ml;

P – ore sample weight, g;

t – time from the start of sorption to the collection of the air sample from the vessel;

B – barometric pressure at the start of sorption, mm Hg;

23.8 – vapor pressure of water at T = 250 °C, mm Hg;

C_a – oxygen concentration in the collected air sample, fractions of a unit;

C_o – initial oxygen concentration in the air, fractions of a unit.

The analysis data obtained allow us to determine the chemical activity indices of ore samples moistened with various solutions and water. The lower the value of this index for an ore sample, the greater the antioxidant property of the solution used for moistening. Subsequently, the solutions selected based on their antioxidant properties will be studied for their dust suppression effectiveness (Peixia Hu et al., 2024). A study of the patterns of changes in air dustiness and dust suppression efficiency when moistening blasted ore with a solution at different specific flow rates is conducted on an experimental setup that simulates the process of hydraulic dust suppression during excavation work. For this purpose, a specially designed setup is used, ensuring the following conditions: similarity of turbulent air flows; similarity of the motion of solid dust particles relative to air flows; and similarity of the motion and impact of bulk material against an obstacle (Zhandildinova et al., 2023).

Solutions possessing both antioxidant and dust-suppressing properties will be tested under industrial conditions. Following this, the most effective solution will be selected for practical application.

The rate of oxidation of ores prone to spontaneous combustion under industrial conditions is characterized by the temperature profile of the pile. Based on this, the nature of the effect of solutions used for air dedusting on the ore oxidation process can be assessed by the temperature dynamics of the moistened stockpile (Bamidele et al., 2019).

The change in the temperature of the stockpile of blasted ore in quarries can be described by a mathematical model of the form (Hongjiang Wang et al., 2013):

$$T_t = aT_{yy} + \theta. \quad (2)$$

At the initial moment of time (immediately after blasting), the temperature throughout the entire volume of the ore pile is assumed to be uniformly distributed and equal to the initial temperature formed as a result of mixing during the explosion.

At the upper surface of the ore pile, the temperature at any given time is equal to the ambient or externally specified temperature, which may vary with time depending on environmental conditions.

At the base of the ore pile, the temperature at any given time is maintained at a specified value, reflecting the thermal conditions of the underlying ground or contact layer, which may also be constant or time-dependent.

Materials and methods. Material: self-igniting blasted ore. All samples were of analytical grade and were used without prior treatment.

Method: mathematical modelling of the low-temperature oxidation process of a blasted pile of self-igniting ores in open-pit mining conditions.

To solve the equation (2) let us express the function $T_{(y,t)}$ as a sum:

$$T_{yt} = \omega(y,t) + v(y,t). \quad (3)$$

The auxiliary temperature function is defined as the solution of a non-homogeneous heat conduction equation in which the rate of temperature change with time is determined by the combined effect of thermal diffusion within the ore pile and internal heat generation due to oxidation processes.

The internal heat generation term is represented as a function that characterizes the density of heat sources within the ore pile, taking into account the contribution of oxidation reactions and their spatial distribution.

At the upper boundary of the pile, the auxiliary function satisfies a prescribed temperature condition that corresponds to the external thermal regime acting on the pile surface.

At the lower boundary of the pile, the auxiliary function is constrained by a specified temperature condition reflecting the thermal interaction between the ore pile and the underlying base.

At the initial moment of time, the auxiliary function satisfies a condition consistent with the initial temperature distribution in the ore pile, ensuring continuity with the physical state immediately after blasting.

Let us choose an auxiliary function $\omega(y,t)$ т such that $\overline{\mu}(t) = 0$ and $\overline{T_1}$=0, for this, it suffices to set

$$\omega(y,t) = T_H + \frac{y}{H}[T_1 - \mu(t)] \qquad (4)$$

In that case, equation (3) reduces to an equation with zero boundary conditions. The solution to this problem can be expressed as a Fourier series in eigenfunctions $\left\{sin\frac{\pi n}{H}y\right\}$

$$v\,(y,t) = \sum_{n=1}^{\infty} v_n(t) sin\frac{\pi n}{H}y \qquad (5)$$

To find the function $v\,(y,t)$ we need to determine the functions $v_n(t)$. To do this, let's express the function $\theta\,(y,t)$ as a series:

$$\overline{\theta}\,(y,t) = \sum_{n=1}^{\infty} \overline{\theta}_n(t) sin\frac{\pi n}{H}y, \qquad (6)$$

where $\overline{\theta}_n(t) = \frac{2}{h}\int_o^H \overline{\theta}(\varepsilon,t)\, sin\frac{\pi n}{H}\varepsilon d\varepsilon$ (7)

Substituting the proposed solution formula into equation (7), we obtain

$$\sum_{n=1}^{\infty} sin\frac{\pi n}{H}y \left\{(\frac{\pi n}{H})^2\right\} av_n(t) + v_n^1(t)\overline{\theta}_n(t) = 0 \qquad (8)$$

This equation is satisfied if all the expansion coefficients are zero, i.e.

$$v_n^1(t) + \left(\frac{\pi n}{H}\right)^2 av_n(t) = \overline{\theta}_n(t) \qquad (9)$$

The solution to equation (9) will take the form:

$$v_n(t) = e^{-\left(\frac{\pi n}{H}\right)^2 at}\left[\int_0^t \overline{\theta}_\tau\, e^{\left(\frac{\pi n}{H}\right)^2 a\tau} d\tau + C_n\right], \qquad (10)$$

$C_n -$ constant of integration.

The general solution of the heat conduction problem is represented as a superposition of several components, including:

(i) a transient term describing the redistribution of temperature within the pile over time;

(ii) a term accounting for the influence of boundary conditions; and

(iii) a term reflecting internal heat generation associated with oxidation processes in the ore mass.

The fourth term on the right-hand side of expression (9) accounts for temperature variations at the top of the pile, while the last term accounts for heating not associated with ore oxidation. These factors have the same effect on both the ore pile treated with solutions and the untreated ore pile. Furthermore, they do not significantly affect the temperature regime of the pile. Therefore, they can be neglected.

After neglecting secondary effects—such as external temperature fluctuations at the surface and non-oxidative heat contributions—the temperature distribution within the ore pile is primarily governed by internal heat generation and thermal diffusion processes. Under these assumptions, the solution simplifies to a form where the temperature field is controlled mainly by the density of internal heat sources.

The density of heat sources is defined as a function of the specific heat released during oxygen sorption, the average oxygen sorption rate constant of the ore mass, the current oxygen concentration, and the heat capacity of the ore. This parameter quantitatively characterizes the intensity of internal heat generation due to oxidation reactions.

An investigation of how oxygen concentration varies with pile depth (y) revealed a relationship of the form (Puyuan Liu et al., 2022):

$$C = C_o e^{\left(-\frac{\overline{u}_H \gamma}{\Pi v_f} y\right)}, \tag{11}$$

where C_o – oxygen concentration in the air, expressed as a fraction of unity;
γ – bulk density of the ore, kg/m^3;
Π – ore porosity coefficient, expressed as a fraction of unity;
v_{f} – air filtration velocity in the pile, m/s.

Taking into account the variation of oxygen concentration with depth in the pile, the density of heat sources is expressed as a function of the initial oxygen concentration in air, ore porosity, bulk density, air filtration velocity, and thermophysical properties of the material. This relationship reflects the coupling between gas transport and heat generation within the porous medium.

Analysis of equation (11) has shown that the value of *(θ)* is determined primarily by the value of $(\overline{u}_H)$, i.e., by the set of oxygen sorption rate constants for the individual ore fractions comprising the bulk sample.

Determining the quantitative values of the constants for all ore fractions, especially the larger ones, poses certain difficulties. This necessitates the theoretical establishment of the dependence of the ore's oxygen sorption rate constant on the size of the grain particles and, based on this, the determination of the average value of the oxygen sorption rate constant for the ore pile. To this end, the process of oxygen sorption by a piece of ore was investigated. The sorption rate is governed by the slowest of the elementary processes constituting sorption—diffusion in the molecular pores of the sorbent (Huiming Qi et al., 2026). In general, it can be assumed that within a grain of a porous sorbent, in particular sulfide ore, there is an equilibrium between the rate of change of oxygen concentration with time and a quantity defined as the difference between the inflow of oxygen into the pores via diffusion and its absorption from these pores. This equilibrium, taking into account the diffusion equation with outflow, is described as (Tulegulov et al., 2022):

$$\frac{dC_o}{dt} = D\nabla^2 C_c - \frac{u_k \gamma}{\Pi_c} C_c, \qquad (12)$$

where C_c – oxygen concentration at point (x, y, z) of the sorbent particle at time (t);

D – oxygen diffusion coefficient, m²/s;

u_k – oxygen sorption rate constant in the kinetic region at oxygen concentration, m³/(kg·s);

γ_c – bulk density of the sorbent, kg/m³;

∇^2 – Laplace operator;

Π_c – sorbent porosity coefficient, fractions of unity.

When solving equation (12), it is assumed that the oxygen concentration (C_c) is independent of time, i.e., $\frac{dC_c}{dt} = 0$, and that the sorbent particle has the shape of a porous, spherically symmetric sphere of radius R (Dyussebayev et al., 2022). Equation (12) then takes the form:

$$\frac{d}{d_\tau}\left(\tau^2 \frac{dC_c}{d_\tau}\right) = \beta^2 \tau^2 C_c \, . \qquad (13)$$

For the spherical ore particle, the oxygen concentration satisfies the following conditions:

- at the outer surface of the particle, the oxygen concentration is equal to that of the surrounding medium;
- at the center of the particle, the concentration gradient is zero, reflecting symmetry and the absence of directional flux.

A characteristic parameter is introduced that combines the effects of diffusion, sorption kinetics, porosity, and particle size. This parameter determines the relative influence of diffusion resistance and reaction rate within the particle.

The spatial distribution of oxygen concentration within the particle is described by an analytical function obtained from solving the steady-state diffusion equation with a reaction term. This solution includes an integration constant determined from the imposed boundary conditions.

The average oxygen concentration in the sorbent (ore) is defined as (Yue Zhang et al., 2025):

$$\overline{C} = \frac{1}{V_o} \int \frac{\text{B}}{r} sh\beta r dV, \tag{14}$$

where V_o – the volume of the sphere of radius *R;*
Ω – the region over which the integration is performed.

The average oxygen concentration within the particle is determined by integrating the local concentration over the entire particle volume and normalizing it by the particle volume. This value represents the effective concentration governing the overall reaction rate.

For practical applications, the analytical expression for the average oxygen concentration can be simplified using a series expansion. In this approximation, a dimensionless parameter is introduced that characterizes the degree of oxygen deficiency within the particle: the larger its value, the lower the average oxygen concentration.

When the value of the dimensionless parameter characterizing oxygen transport resistance within the particle is sufficiently small, the average oxygen concentration inside the ore grain can be approximated by a simplified relationship. In this approximation, the average concentration is directly related to the external oxygen concentration and is reduced by a factor that accounts for diffusion limitations and sorption intensity within the particle.

This simplified form reflects the fact that, under weak diffusion resistance, the oxygen concentration inside the particle remains close to the ambient value, with only a minor decrease due to consumption in the reaction process.The rate constant for oxygen sorption by a sorbent is proportional to its kinetic constant and the average oxygen concentration (Weidong Liu et al., 2025). Therefore, taking into account certain mathematical transformations, the dependence of the oxygen sorption rate constant on particle size can be expressed as:

$$u(R) = u_k \frac{3(\beta R cth \beta R - 1)}{(\beta R)^2}; (C_k = 1), \tag{15}$$

where $\beta = \sqrt{\frac{U_{\text{к}} * \square\text{c}}{\text{Пс} * D}}$, m^{-1},

u_k – the rate constant for oxygen sorption in the kinetic region at an oxygen concentration, $\text{C}_{\text{к}}$, $\text{m}^3/(\text{kg} \cdot \text{s})$;

c – the bulk density of the sorbent, kg/m³;

Π_c – sorbent porosity coefficient, fractions of a unit;

D – oxygen diffusion coefficient, m²/s.

In expression (15), the dimensionless product βR x characterizes the oxygen deficit in the ore grain; the larger it is, the lower the average oxygen concentration. Therefore, the value βR is referred to as the outflow parameter. The diffusion and porosity coefficients are interrelated quantities. They determine the interaction of oxygen with the ore-liquid complex. Therefore, the product $\Pi_c D$ is commonly referred to as the "interaction coefficient." As u_k decreases and ß increases, the sorption rate $u(R)$ ecreases. This phenomenon occurs when there is limited oxygen access to the sorbent grains, which can be achieved by blocking the pores with liquid. It follows that these values are the primary parameters of the antioxidant action of solutions used to moisten ores prone to spontaneous combustion.

The average value of the oxygen sorption rate constant for a bulk of blasted ore $(\overline{u_H})$ is the sum of the sorption rate constants for all fractions comprising the bulk, i.e. (Ioni et al., 2024):

$$\overline{u_H} = \sum_{i=1}^{N_{\phi}} n_i u(R_i), \text{ m}^3/(\text{kg·s}), \tag{16}$$

where n_i – the content of the i-th fraction interval, in fraction units;

$u(R_i)$ – the oxygen sorption rate constant for the i-th fraction with radius R_i, m³/(kg·s);

– the number of fractions.

Results and discussions. The values of the oxygen sorption rate constants for small ore pieces are determined experimentally. The constants for large pieces are determined using equation (15). For this purpose, the values of U_k and β, obtained from the experimental data $U(R_i)$ and R_i for small ore fractions (Tables 1 and 2) are used.

Table 1. Dependence of the oxygen sorption rate constant of metacolloidal ore on particle size and oxidation time (T = 298 K, ore from the top layer of the stockpile).

Average particle size, R·10⁻² m	Oxygen sorption rate constant, , m³/(kg·s)								
	Raw ore			DB-0.25% (oxyethylated dibutylphenol)			Water		
	1-7 days	8-14 days	> 14 days	1-7 days	8-14 days	> 14 days	1-7 days	8-14 days	> 14 days
0.038	9.50	2.63	6.10	6.83	5.03	5.44	20.31	23.11	27.1
0.100	7.44	2.33	4.90	5.22	3.78	4.50	15.86	10.39	13.1
0.200	4.64	1.81	3.20	4.36	3.14	3.75	7.00	5.72	6.4
0.375	2.94	1.75	2.30	2.28	2.50	2.39	3.86	3.42	3.6
1.000	1.50	1.42	1.50	1.42	1.97	1.69	1.64	2.36	2.0

To calculate and a system of Gauss normal equations was formulated, which reduces to a single transcendental equation for and is solved using the method of proportional parts. The calculated values are given in Table 3.

Table 2. Dependence of the oxygen sorption rate constant on the fractional composition and type of ore (T = 298 K, freshly mined ore with significant natural moisture content).

Ore type	Average particle size, $R \cdot 10^{-2}$ m	Oxygen sorption rate constant, , $m^3/(kg \cdot s)$			
		Raw ore	Solvents		Water
			DB-0.25%	DB-0.5%	
Metacolloidal	0.150	9.31	6.78	7.58	13.33
	0.375	5.92	4.42	3.47	7.72
	0.750	3.56	2.19	1.89	4.03
	1.500	1.94	1.14	1.67	2.14
Crystalline	0.150	1.06	1.00	1.00	1.83
	0.375	0.94	0.89	0.86	1.67
	0.750	0.94	0.61	0.69	0.92
	1.500	0.94	0.53	0.56	0.92

Table 3. Key parameters of the ore oxidation process in a blasted pile.

Exper-iment No	Type and moisture content of the raw ore	Condition of the ore	Days	, I/m	$m^3/(kg \cdot s)$	m^2/s	$m^3/(kg \cdot s)$
1	Metacolloidal 1%	Raw ore	1-7	0.20	9.08	9.177	2.33
			8-14	0.04	2.28	5.56	1.08
		DB-0.25%	1-7	0.12	5.69	15.83	1.89
			8-14	0.06	4.06	45.00	1.75
		Water	1-7	0.40	24.22	6.11	3.86
			8-14	0.40	23.36	5.83	3.72
2	Metacolloidal 4.5%	Raw ore	1-7	0.09	177.75	47.22	3.53
		DB-0.25%	- -	0.15	9.11	16.677	2.75
		DB-0.50%	- -	0.10	6.78	30.56	2.75
		Water	- -	0.16	26.00	27.78	7.58
3	Crystalline 4.5%	Raw ore	1-7	0.01	1.06	411.11	0.74
		DB-0.25%	- -	0.03	0.86	38.89	0.49
		DB-0.50%	- -	0.03	0.97	44.44	0.54
		Water	- -	0.03	1.69	75.00	0.96

To verify the validity of the theoretical description of the oxygen sorption mechanism in an ore sample, a graph showing the dependence of the oxygen sorption rate on the flow rate was plotted using experimental data (Tables 1 and 2) and calculated data (Table 3, Figure 1). It clearly illustrates a satisfactory agreement between the theoretical curve and the experimental data points. This indicates the validity of the theoretical description of the mechanism of the oxygen sorption process in a piece of ore.

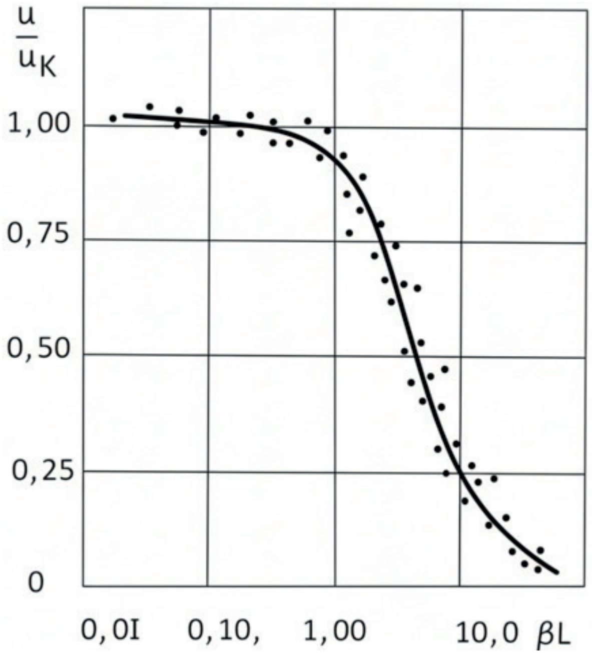

Figure 1. Dependence of the relative value of the oxygen sorption rate constant on the flow rate parameter.

The graph (Fig. 1) shows that the rate of oxygen sorption decreases as the flow parameter (*βR*) increases. The sharpest decrease is observed when the *βR* parameter changes from 1 to 10.

Considering that the determining factor in βR is the particle size (R), an increase in the minimum size of ore particles under industrial conditions may have a positive effect on reducing the oxidation process of sulfide ore aggregates.

A comparison of the values of U_k and for metacolloidal ore, as shown in Table 3, indicates that in the first stage (days 1–7), the kinetic constant of the sorption rate U_k and the “oxygen reduction coefficient” β for the initial ore are higher than in the second stage (days 8–14). This indicates that in the first stage, the ore has sufficient moisture for intensive electrochemical oxidation, and at the same time, the moisture, being present in large pores, creates a significant oxygen deficit; in the second stage, however, due to reduced moisture, the intensity of oxidation is low and the oxygen deficit is small. These effects are observed, but to a much lesser extent, in the sample treated with DB solution and are almost absent in the sample treated with water.

The relatively low value of U_k for various ore grades with different moisture contents (Experiments 1, 2, 3), treated with a DB wetting agent solution does not indicate that this solution is a chemical inhibitor, since in solid oxidizable materials, particularly in sulfide ore, radical-mediated reactions play a very minor role and do not govern the electrochemical reaction. Therefore, the most likely explanation for the relatively low value of the sorption rate kinetic constant U_k for the sample treated with the DB solution is that this solution reduces the sorption capacity in those areas of the ore that have the highest oxygen flux. These areas are small pycnometric pores, which the DB solution fills (blocks) due to its low surface tension. This circumstance has a positive aspect in terms of extending the duration of the antipyrogenic action of the DB wetting solution, since the evaporation of moisture from small pycnometric pores is highly impeded.

Thus, it can be concluded that the presence of moisture, including in the form of solutions, influences oxidative processes in the grain, and the nature (pyrogenic or activating) of this influence depends to a significant extent on the distribution of this moisture within the sorbent grain: if moisture is distributed in small pycnometric pores, an antipyrogenic effect occurs; if moisture is distributed predominantly in large pores, its presence activates the oxidation process due to the formation of air (oxygen) gaps in the small pycnometric pores.

Theoretical calculations of the temperature distribution along the depth of the pile as a function of time were performed by substituting the values of the variables involved. In this process, temperature values corresponding to the initial and boundary conditions were used, as well as parameters determining the density of the heat sources. Analysis of the results showed that wetting with the DB solution leads to an increase in the specific heat capacity of the ore and a decrease in the rate of oxygen sorption. Both factors contribute to a decrease in temperature within the pile of blasted ore. It was also established that the depth of the spontaneous combustion focus is determined by the sorption capacity of the ore in the pile and its height.

To verify the theoretical conclusions, as well as the results of experiments conducted under laboratory conditions, studies to determine the effect of complex-action solutions on the ore pile should be continued under production conditions (Jianqiu Qin et al., 2026). For this purpose, a block of industrial ore was selected for drilling, blasting, and excavation. The block consisted of metacolloidal and crystalline ores. Vertical boreholes with a diameter of 243 mm were drilled to a depth of 6 m. The distance between the boreholes was 2 m. Boreholes No. 1–13 were drilled through the metacolloidal ore body, and boreholes No. 14–32 through the crystalline ore body (Figure 2). Prior to the block's detonation, temperatures were measured at various depths within the drilled boreholes. The temperature difference between the upper and lower parts of the borehole is approximately 6 K. The block was blasted 8 days after the completion of drilling operations and the exposure of the side surface. The height of the resulting pile was about 7 m, and the volume of the blasted metacolloidal ore was about 900 m³. The bulk density of the ore was 3500–4000 kg/m³. The loosening coefficient was 1.25–1.30.

The pile of metacolloidal ore was divided into three sections, after which it was wetted. One section was treated with a DB solution, another with water, and a control section that was not wetted was left between them. The layout of the measurement points is shown in Figure 2.

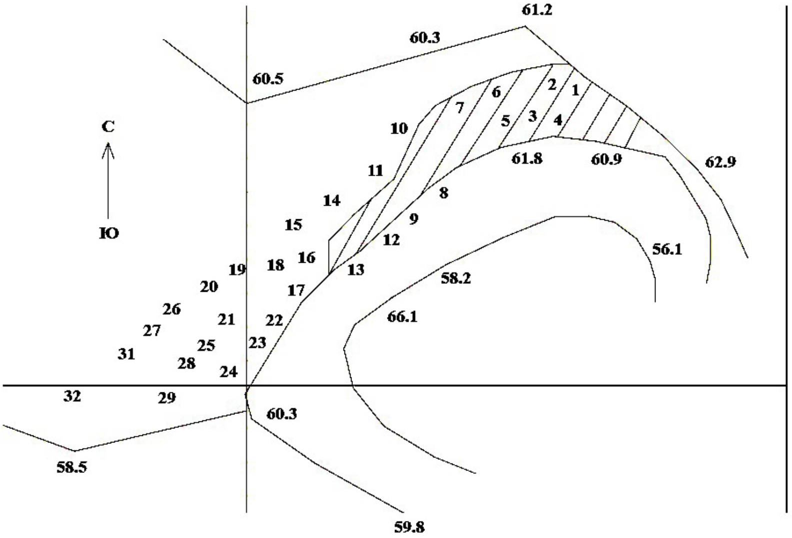

Figure 2. Layout of blast holes and measurement points in Block.
No. 1–13: holes for metacolloidal ore; No. 14–32: holes for crystalline ore;
area of boreholes 1, 2, 3, 4 – water-treated pile section; area of boreholes 3, 4, 5, 6 – untreated section; area of boreholes 5, 6, 7, 8 – section treated with DB solution; (+ measurement sections).

The intensification of the oxidation process was assessed based on changes in temperature within the blasted pile. To monitor the gas temperature conditions in the pile, 12 perforated pipes were driven into it, with electric thermocouple sensors lowered to a depth of approximately 2 meters, where the hot spot with the highest temperature is located.

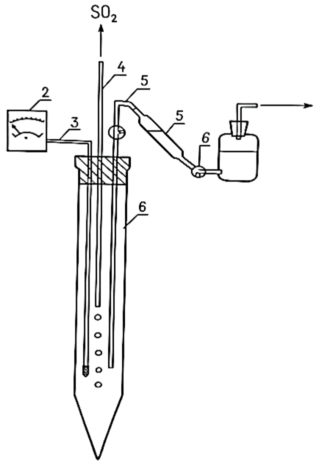

Figure 3. Layout of equipment and instruments for determining the gas temperature conditions in a bulk cargo.
1 – perforated pipe; 2 – temperature measuring device; 3 – temperature sensor; 4 – probe; 5 – connecting hose; 6 – Zeeger pipette; 7 – three-way valve.

All pipes were sealed with rubber caps fitted with ports for tubes, through which air samples were collected daily at the same time using a vacuum pump and Zeiger pipettes. The air samples were analyzed using a gas analyzer. The temperature in the pile was measured using an electric thermometer. The sulfur dioxide content was determined using an aspirator and indicator tubes according to a well-known method. The layout of the equipment and instruments used to determine the temperature and gas conditions in the blasted ore pile is shown in Figure 3 (Manfeng Li et al., 2024). At the same time, microclimatic data for the area where the block was located were determined and recorded. The average air temperature during the experiments was 303.8 K, and the relative humidity was 44%. These microclimate conditions contributed to the intensification of the oxidation process in the pile of blasted ore.

Depending on the nature of wetting, the temperature in the pile of blasted ore changed as follows. The temperature at a depth of 1.5 m in the section wetted with water increased by 9.2 K (from 295.1 to 304.3 K). At the same time, in the section wetted with the DB solution, the temperature rose by only 4.8 K (from 292.7 to 297.0 K). Moreover, the temperature of this section was lower than that of the control section (299.9 K). Thus, the antipyrogenic property of the DB solution was demonstrated here.

The measurement results showed that active oxygen absorption occurs in the untreated section and the section moistened with water. The average oxygen concentration in these sections was 17.2% and 16.9%, respectively. In the section treated with the DB solution, the oxygen concentration was 19.2%. This demonstrates once again that in the section treated with the DB solution, the oxidation process proceeds more slowly than in the control and water-treated sections. Under the conditions under consideration, with the height of the blasted pile at approximately 7 m, the depth of the fire zone is within the range of 1.5–2.0 m, and the smallest temperature increase in the vicinity of the fire zone is observed in the pile moistened with DB solution (Figure 4).

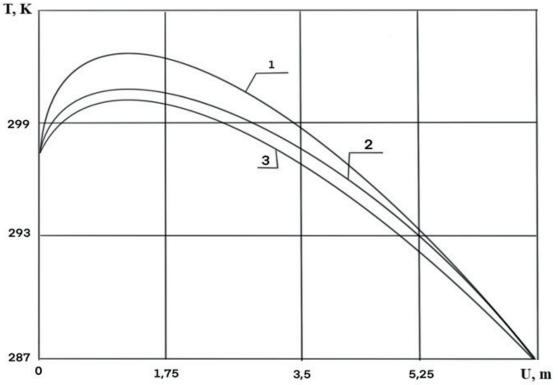

Figure 4. Temperature distribution with depth in the pile (13 days).
1 – section treated with water; 2 – control section; 3 – section treated with DB solution.

Figure 5 shows graphs of temperature changes in the ore pile over a 13-day period at depths of 1.5 and 2.0 m, plotted using calculated and experimental data. As the analysis shows, the pattern of temperature changes in the stockpile under field conditions qualitatively corresponds to the theoretical model. This suggests that the use of a complex-action solution can reduce the rate of oxidation and temperature rise in stockpiles of sulfide ores prone to spontaneous combustion, as well as the associated release of sulfur dioxide into the atmosphere.

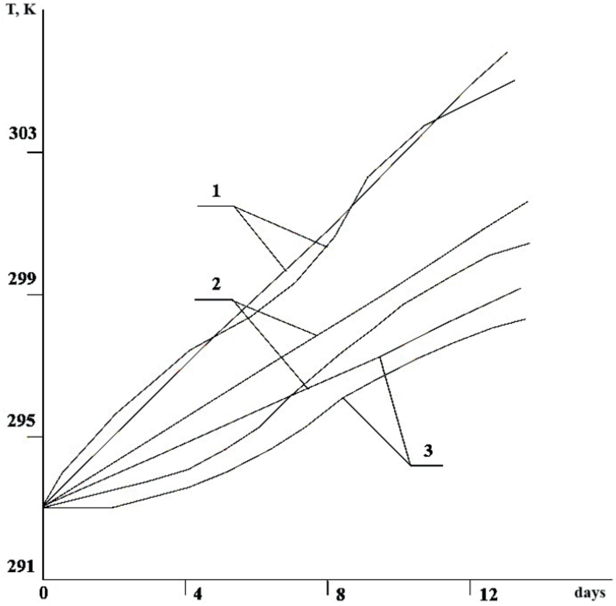

Figure 5. Temperature change as a function of the duration of the pile.
1 – with water moistening; 2 – without moistening; 3 – with moistening using a DB solution.

The results obtained make it possible to determine the specific consumption rate of a multi-action solution for wetting a pile of blasted ore prior to the onset of self-heating. This will reduce dust emissions to within the permissible exposure limit, prevent the intensification of the oxidation process in ores prone to spontaneous combustion, and reduce sulfur dioxide emissions into the environment.

Conclusion.

1. A mathematical model of the low-temperature oxidation process of a blasted pile of self-igniting ores in open-pit mining conditions has been developed and solved.
2. An analytical solution of the heat balance equation under the corresponding boundary conditions showed that the density of heat sources (θ) plays a significant role in the temperature regime of a pile of blasted ore prone to spontaneous combustion under open-pit mining conditions. An expression for calculating its value has been derived. It has been established that this value (θ) is primarily

determined by the sum of the oxygen sorption rate constants of the various ore pieces comprising the pile.

3. To determine the oxygen sorption rate constant for various ore fractions, a problem concerning the steady-state diffusion of oxygen in a sorbent particle was formulated and solved, and an analytical relationship between the oxygen sorption rate and particle size was derived.

4. The process of oxygen sorption by a piece of ore was investigated, and the dependence of the oxygen sorption rate constant of the ore on particle size was obtained. The main parameters of the antioxidant action of solutions used to moisten ores prone to spontaneous combustion were determined.

It was established that as decreases and ß increases, the oxygen sorption rate decreases. This phenomenon occurs when there is limited oxygen access to the sorbent grains, which can be achieved by blocking the pores with liquid. It follows that these values are the main parameters of the antioxidant action of solutions used to moisten ores prone to spontaneous combustion.

To calculate and a system of Gauss normal equations was formulated, which was reduced to a single transcendental equation for β and solved using the method of proportional parts.

5. The temperature distribution with depth in a pile of blasted ore as a function of time was investigated theoretically.

6. To verify the theoretical conclusions, as well as the results of experiments conducted under laboratory conditions, studies to determine the effect of complex-action solutions on the ore pile were continued under production conditions.

Analysis of the obtained data showed that the pattern of temperature changes in the pile under field conditions qualitatively corresponds to the theoretical one. This gives reason to believe that the use of a complex-action solution allows for a reduction in the rate of oxidation and temperature rise in piles of sulfide ores prone to spontaneous combustion, as well as the associated release of sulfur dioxide into the atmosphere.

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