E3S Web of Conferences **417**, 05013 (2023) https://doi.org/10.1051/e3sconf/202341705013
GEOTECH-2023

Prerequisites for applying the risk-based approach to assessing the explosive and fire hazardous properties of underground mining materials

Vladimir Rodionov[1], *Igor* Skripnik[2], *Tatyana* Kaverzneva[3], *Sergey* Zhikharev[4], *Sergey* Kriklivyy[5], and *Sergey* Panov[6]

[1]Saint-Petersburg Mining University, 199106, Saint Petersburg, Russia

[2]Saint-Petersburg University of the State Fire Service of the Ministry of Emergency Situations of Russia, 196105, Saint Petersburg, Russia

[3]Higher School of Technosphere Safety of Peter the Great St. Petersburg Polytechnic University, 195251, Saint Petersburg, Russia

[4]Mining Institute of the Ural Branch of the Russian Academy of Science, 614007, Perm, Russia

[5]Saint-Petersburg State Institute of Technology, 190013, St. Petersburg, Russia

[6]Saint-Petersburg State University of Industrial Technologies and Design, 191186, Saint Petersburg, Russia

Abstract. The relevance of the work is due to the introduction of new high-intensity mining technologies underground, the conduct of mining operations at ever greater depths of coal and ore, changes in the explosive properties of the extracted raw materials, as well as incidents and accidents of varying severity occurring at mining facilities. There is an opinion that one of the causes of accidents and emergencies in mines is the inability to take into account both the features of the manifestation of the properties of the rock mass and the change in the explosive properties of minerals. The problem of applying a risk-oriented approach, namely a comprehensive assessment of the risk of accidents, in this case fires and/or explosions, has not been resolved. The applied risk calculation methods are diverse, as a rule, the accuracy of the results is low, and none of them allows taking into account all the identifiable hazards that lead to the occurrence of endogenous and exogenous fires, as well as explosions of hybrid mixtures in the space of mine workings. This article attempts to study in detail the prerequisites for applying a risk-based approach to solving this problem. Theoretical approaches and risk assessment in mines and mines are considered and methods are given that allow in express mode to obtain up-to-date information on the explosive and fire hazardous properties of the extracted raw materials.

1 Introduction

Currently various authors continue to search for new opportunities for applying the risk-based approach in various sectors of the national economy [1, 2, 3]. We agree with the opinion of these authors and believe that there are many prerequisites for the application of risk-based approach to underground mining operations associated with the extraction of minerals. First of all, due to the fact that objects of this kind, in accordance with Russian legislation, are usually classified as hazardous production facilities of the first and second hazard categories. Secondly and thirdly, we believe that the application of the risk-based approach makes it necessary to pay more attention to the engineering and technical management of mines and mines, to high-risk areas. This makes it possible to take both preventive measures in time and to identify and eliminate weaknesses in the technological process of mining. In our opinion, this will make it possible to avoid the negative consequences of the implementation of various scenarios of the risk of an accident of one kind or another [4, 5].

In addition, the effectiveness of the use of risk-based approach has been proven at numerous high-risk facilities both abroad and in our country. Therefore, we believe that the prerequisites for the use of risk-based approach at the objects of the mineral resource complex in the field of assessing explosive and fire hazardous properties and, therefore, their impact on the stability of the object under conditions of increased risk exist and are not in doubt.

The only problem is to determine which part of the risk calculation to take into account these properties and how to determine them.

2 Purpose and tasks of the research

The purpose of the work was to identify the prerequisites, i.e. to assess the possibility of applying a risk-based approach to assessing the explosive properties of minerals mined underground. At the same time, the authors of the work believe that the main task of the risk-based approach, regardless of the area of its application, is to achieve the goals set by reducing risks.

3 Problem statement

In accordance with the goal set, the authors of the work formulated several areas of research that are aimed at solving the set tasks.

Based on this, at the initial stage of our study, which will be continued in this direction, the main tasks are the tasks of determining the influencing factors.

In our opinion, such factors can be both shortcomings in the system for monitoring the technological process and production processes (hereinafter referred to as TP&PP), including training workers in safety measures when working at a hazardous production facility, and the lack of up-to-date data on physical and chemical properties, primarily indicators of the explosion and fire hazard of mined minerals. Currently, a number of works provide information that this kind of initial data can be obtained using various research express methods, some of which can be applied directly at the site of mining in a mine or mine.

We believe that risk assessment is an integral and most important part of the risk-based approach. With the introduction of hazardous production facility management systems based on risk management, senior management should have a good understanding of the objectives pursued by risk assessment. In this case, there must be an understanding by the top management, at least the chief engineer and technical director of the risk vulnerability of the hazardous industrial facility entrusted to them as a whole.

4 Methodology: materials and methods

The methodology developed by the authors for applying the risk-oriented approach, which takes into account the results of assessing the explosive properties of underground minerals, is based on practical experimental methods, primarily methods of synchronous thermal and

X-ray fluorescence analysis (X-RAY), practice-oriented methods of personnel training and theoretical risk assessment methods.

In their work on the application of risk-based approach to the tasks set, the authors of the work relied on the work of other researchers in this field and a number of legal documents, including federal norms and rules in the field of industrial safety regulating the issues of ensuring industrial safety at objects of reference mining [2, 6]. One of these documents is GOST R 58652-2019 "Mining equipment. Multifunctional security systems for coal mines. Principles of ensuring industrial safety" [7].

In this legal document the application of risk-based approach is considered from the standpoint of the basic principles of ensuring industrial safety. So, for example, taking into account the tasks facing us, in the general case for hazardous industrial facilities for underground mining of ore and non-metallic minerals, it is possible to represent a hazardous production facility in the form of a controlled facility, visualized in the form of a diagram in Fig. 1 [2, 7].

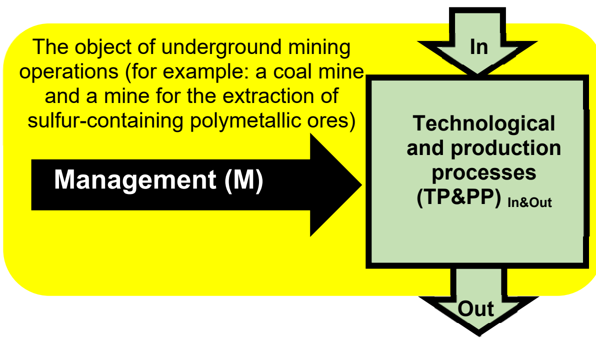

Fig. 1. Scheme of representation of hazardous production facility, mine as a managed object.

Due to the fact that the mine is considered as a managed facility, it is necessary to clarify that each hazardous production facility of this kind has its own environment, connections and elements that are closely interconnected with each other and affect the safe operation of the mine [7, 8].

The environment of a mine, depending on its location, is a set of interacting spheres: geosphere, biosphere, anthroposphere and technosphere, etc. [3, 8].

Elements should be understood as ore and host rocks, engineering structures that ensure the normal operation of the mine, mining and mining equipment, control and signaling systems, as well as miners and engineering and technical personnel working at the mine [9, 10, 11].

At the same time, the environment and elements of a hazardous industrial facility of a particular hazard category are certainly interconnected by material, energy and information links. They are characterized both by hazards (H) and threats (T), as well as by vulnerabilities in relation to various threats (elements) and possible control actions on these elements.

Therefore, in Figure 1, the hazardous production facility mine (hereinafter, the term mine will be used) is presented as a controlled facility, where the input flow In is converted into the output flow Out (minerals and waste rock, interstratal water entering the space of mine workings and various gas mixtures formed there, production waste, miners, information, etc.).

The input flow should be understood as all flows that come from outside into the mine space, primarily electricity, water, air, equipment and instruments necessary for mining operations, as well as miners, including information coming through monitoring systems and directly through mining dispatcher [12, 13, 14].

Thus, it turns out that the main goal of the normal operation of the mine is to obtain the maximum economic efficiency resulting from the transformation of the input stream (In) into the output (Out) using the control (M) of the technological process (TP) and production processes (PP). Since these two concepts TP and PP are inextricably linked, the abbreviation (TP&PP) will be used further in the text of the article. Since the transformation (TP & PP) In & Out is characterized by risks R, then the management of this kind of object should be carried out taking into account the costs, both for preventing and minimizing and compensating for damage from incidents (A) and accidents Y [7, 15].

TP&PP elements can be divided into basic and supporting elements: the main elements that ensure the extraction of minerals and which are necessary for any type and level of danger; providing - are used to fulfill industrial safety requirements and the list of which is determined by the types and levels of hazards.

Thus, the occurrence and development of accidents at the managed object occurs as a result of the transformation of the input stream (TP&PPIn) into the output stream (TP&PPOut).

The process of converting the input stream to the output, shown in the diagram of Figure 2, is accompanied by the process of sequentially converting hazards (Hazards – "H") into threats (Threats – "T"): H → CH-T, threats in an accident (Accidents – "A"): T→CT-A and accidents to damages (Damages –"D") A→CA-D, this process is visualized in the diagram of Figure 2 [7, 16, 17].

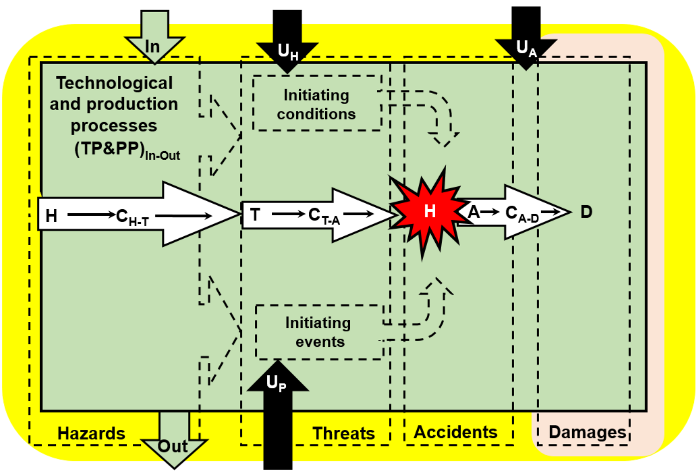

Fig. 2. Scheme of sequential transformation under the influence of influencing factors, dangerous modes into emergency (fire/explosion) with the occurrence of damage.

Taking into account the problem raised in the article, it must be taken into account that in our case, the explosive and fire hazardous properties of circulating substances and materials, depending on the type of controlled object and the technologies used, will be different even for raw materials of the same type, for example: brown coal, coal and anthracite.

Therefore, when considering the application of risk-based approach, it is a well-known fact that coal mines will have the largest explosive and fire hazardous component (for example, a mine can be classified as super-category in terms of gas factor - methane), while gas and combustible dust load may be absent in mines. In this case, the constant presence of hazards (H) of one kind or another (explosive hybrid mixtures, endogenous foci, etc.) is implied [6, 12, 17].

In addition, during the operation of the TP & PP mine, when the elements interact with each other, as well as with the environment of the HIF controlled object, the hazards (H) present on it are converted into threats (T) of uncontrolled processes of energy and substance release. In the presence of such transformations, which are realized in the form of accidents (A), each of which is characterized by probabilities (P). At underground mining facilities, threats should be understood primarily as the threat of toxic (CO, CO_2, SO_2, H_2S and other "fire" and pyrolysis gases), thermal and high-explosive damaging factor formed during the explosion of methane-air, dust-air or hybrid mixtures, damage workers and destruction of equipment and structures (damaging factors of fire/explosion), etc.

Thus, risks (R) are associated with vulnerabilities (V) of coal mine elements. This will affect the probabilities (P) of dangerous events and the amount of damage from them [10, 11]. Further, they, in turn, will characterize the loss of stability of the object of underground mining operations for the extraction of minerals to the impact of hazard factors. In this case, a certain accident (A) will be caused by the coincidence in time and space of a number of factors. These factors belong to the group of initiating conditions (IC) and initiating events (IE) (hereinafter IC&IE), which in turn ultimately leads to the release of matter or energy (q). At the same time, the impact on these factors is possible through the control (TP & PP) in normal (UH) and pre-emergency (UP) modes. Triggering conditions and events (IC&IE) correspond to the output of parameter values (TP&PP) beyond the boundaries of safe (normal) operating and required, in accordance with federal norms and rules by industry regulatory legal acts, ranges [7, 9, 10]. In this case, their transition to the region of unacceptable values will occur, as a result of which the requirements of the existing regulatory legal acts will be violated [7].

The authors of the article understand that accidents at such hazardous production facilities can develop according to different (J-th) scenarios, according to the "event tree" developed at each facility. In this case, various types of damage D will be observed. We believe that it is possible to influence the scenario for the development of such accidents (A) and the final damage (D), both with the help of automatic control and process control systems (APCS). At the same time, an important role is played by the mining dispatcher who monitors and provides information support for TP&PP, as well as security, protection and rescue (SPR) systems, primarily for the personnel of the facility located at that moment in the mine workings. The systems of the current monitoring, primarily the multifunctional safety systems (MFSS), without fail include the functions of managing the TP & PP of the facility in the event of various emergency modes (UA). if such opportunities exist. The authors of the work also understand that incidents and accidents leading to an emergency situation and the resulting dangers (H) and threats (T) of various origins, as well as accidents (A) damage from them (D) and risks in general, can apply not only to individual elements or their groups, but also to the entire mine (mine) as a whole.

Thus, as mentioned above, the RPO base is the risk calculation, i.e. conducting a comprehensive risk assessment.

According to the current legal documents, for a mine as a hazardous industrial facility, it is necessary to calculate the integrated risk [3, 12, 14]. However, it is necessary to clearly realize and understand that integrated risk management is primarily understood as a risk calculation method, as a result of which a generalized view of the risk management system is formed. While the results of investigations of numerous accidents at HIFs clearly show that not a generalized approach is required, but close attention to the cause-and-effect problem of emergency situations at hazardous industrial facilities. In this case, it is necessary to develop certain factor indicators, which are additionally taken into account when calculating the integrated risk for objects where self-heating, spontaneous combustion processes are possible, leading to endogenous fires, exogenous fires and explosions of gas-air (methane-air), gas-dust-air or dust-air explosive mixtures formed in the space of mining workings [15, 16].

However, at the moment it is generally accepted that the integrated risk in the form in which it is set out in a number of regulatory legal acts [7] is a general characteristic of the normal functioning of underground mining facilities for the extraction of minerals:

$$R_{\Sigma} = \Sigma_V \Sigma_H \Sigma_O \Sigma_L R_{VHOL}(x) Y_{VHOL}(x) \quad (1)$$

Thus, the integrated risk for all elements (O) of the mine, as well as their vulnerabilities (V), various hazards (H) and damage levels (L) takes into account the potential risk (RVHOL(x)) of hitting the "object", the damage from this damage (YVHOL(x)), depending on the distance between the "object" and the epicenter of the accident (x).

The potential risk included in equation (1), according to which the calculation of the integrated risk (RΣ) should be carried out, depends on the probability of an accident PFTA(qj). In other words, (RVHOL(x)), depends on the release of energy or matter (qj), as well as the probability of development (PETA(qj) of one or another in accordance with one or another accident scenario (A) and the conditional probability of hitting the “object” (PFTA(x/qj)), located at a distance (x) from the epicenter of the accident (A) - the place of release of energy or matter:

$$R_{VHOL} = P_{FTA}(q_j) P_{ETA}(q_j) P_{FTA}\left(\frac{x}{q_j}\right) \quad (2)$$

According to the conditions described above, the control action on the probability of occurrence of an accident PFTA(qj) is possible through the control of the technological process and the production process in normal and pre-accident modes (see Figure 2, these are UH and UP).

In addition, such an impact on the scenario of the development of an accident PETA(qj) is possible with the help of APCS and SPR and on the conditional probability of damage PFTA(x/qj) in emergency modes (see Figure 2 - UA) [7, 17].

We believe that at this stage of development of scientific and technological progress it is still impossible (possible - but it will be economically inexpedient, not profitable, economically unprofitable, etc.) to design, build and operate an absolutely safe hazardous industrial facility for underground mining. We believe that the main task of managerial management is to develop such a business model in which there will be maximum economic efficiency (EE) of converting input flows into output EE $(TP\&PP)_{In\text{-}Out}$ (U)) → max, taking into account risk management, where U = { UH, UP, UA}. In this case, probably, the main goal of risk management will not be to reduce the risk to zero, but to reduce it to an acceptable level (ACCEPTABLE RISK LEVEL), i.e. R(U) < RA.

We believe that the above installations and assumptions will be valid only if comprehensive comprehensive work is carried out at the hazardous industrial facilities, both among the personnel, and work is carried out to assess the explosive properties of the extracted raw materials and identify the conditions under which, under a certain set of circumstances, the occurrence of and the development of an accident of various scales.

5 Discussion and results

At this stage, we propose to additionally determine the probability of an accident PFTA(qj), namely an endogenous or exogenous fire, as well as the occurrence of conditions for the explosion of gas-vapor-dust-air mixtures, taking into account the management decisions implemented at the enterprise. These decisions should be aimed at explanatory and preventive work among the staff, as well as a comprehensive monitoring of their knowledge, skills and abilities through various kinds of testing, including before starting a shift. At many

 https://doi.org/10.1051/e3sconf/202341705013

enterprises, this proposal has been implemented, but due to the anthropogenic factor, many incidents that later develop into an emergency continue to occur. Rostekhnadzor also notes this in its annual reports, namely, that the reason for many incidents is the low level of knowledge and exactingness of the management personnel themselves [6, 8, 12]. In addition, for a better understanding of the issues raised in this article, it is a well-known fact that everyone knows the common truths regarding the omens (predictions, harbingers) of the emergence of endogenous foci. Moreover, many of these parameters can be determined both organoleptically and visually. For example, when a self-heating center occurs, a specific smell of coal pyrolysis products, or hydrogen sulfide appears (during spontaneous combustion of “sulfur-containing rocks”), visibility changes due to an increase in humidity (during the thermal destruction of organic mass, a large amount of water vapor is released), etc. Unfortunately, despite the obvious all these listed and other easily identifiable (without the help of equipment) signs of the initiation of a combustion center, few people pay attention, hoping for someone else. The main question here is who they can be. As a result, you can enter in a fresh stream, but the exit will probably already be organized in the process of carrying out evacuation measures.

In addition, we believe that the parameter PFTA(qj) proposed by us should also include factors that take into account the physicochemical and explosive properties of the extracted raw material. This means that such an assessment of properties is carried out at the enterprise or based on publicly available data more than 40 years ago. So, for example, the explosive and fire hazardous component of bituminous coal grows with increasing depth and this is a well-known fact, but it is difficult to find research papers that describe new data on this issue.

Therefore, in this article, taking into account the fact that work in this direction continues, we will only mention especially informative methods for assessing the explosive and fire properties of mineral raw materials.

One of these simple methods, simple because even a simple miner can master it, is the X-ray fluorescence analysis method (X-Ray). We had two spectrometers at our disposal: a handheld (portable) Thermo Scientific NITON XL2 spectrometer and a stationary X-SPEC-50H [6]. For work in the mine, we tested the Thermo Scientific NITON XL2, which has an explosion-proof design, as well as an embedded computer that runs the Nucleus RTOS industrial operating system. In addition, it has a specialized base for studying the composition of mining materials. The device, principle of operation and method of data visualization are not difficult for a modern mining engineer or a qualified miner. We believe that as a result of its application it is possible to determine the percentage of pyrite sulfur in the rock mass, adjust the further process of mining useful ore and develop additional preventive measures aimed at both preventing spontaneous combustion of broken rock mass and preventing the explosion of sulfide-containing rock dust [3 , 6, 17]. Thus, it is possible to add the fact of an increase in its influence (weight) depending on the sulfur content in the rock mass to the PFTA(qj) parameter we propose.

When performing this study and identifying both the prerequisites and the determination of informative methods related to the provision of the possibility of assessing the explosive and fire hazardous properties of minerals, we turned our attention to the possibilities of synchronous thermal analysis. Unfortunately, this method belongs to highly scientific analytical methods for studying thermochemical transformations in a substance during its destruction in an oxidizing or inert environment. However, we are aware of the presence of such equipment in a number of mining companies, and therefore, as an example in Figure 3, we have given the results of a study of one of the rock samples. The samples were studied on a STA 449 F3 Jupiter running the NETZSCH Proteus Termal Analysis software package [6, 9, 12].

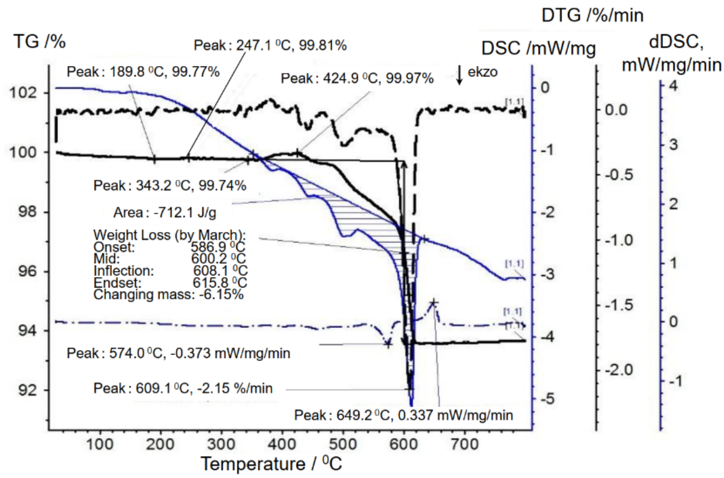

Fig. 3. The result of STA of the ore body-quartz metasomatite with arsenopyrite and tourmaline. The results are got by V. A. Rodionov.

The STA method allows you to evaluate such explosive and fire hazardous indicators as smoldering temperature, autoignition temperature, as well as assess the tendency of substances to spontaneous combustion, and much more.

Some alternative to this method can be other methods that can be applied in the factory laboratory by simple personnel without special education. One such method is the method for assessing the combustibility of a material, described in the OSSS "Fire and explosion hazard of substances and materials. Nomenclature of indices and methods of their determination". It is a method for experimental determination of a group of non-combustible solids and materials. The essence of the experimental method for determining combustibility is to create temperature conditions conducive to combustion and to evaluate the behavior of the studied substances and materials under these conditions. However, this method requires a special laboratory setup. Therefore, we believe that at one stage or another the installation can be replaced by a simple muffle furnace (thermostat), the main thing is that it can provide the temperature regime specified in the procedure. The authors tested various variants of these methods.

6 Conclusion

As a conclusion, I would like to note that the authors of the work faced a number of difficulties, primarily with obtaining initial statistical data on incidents and accidents at underground mining facilities, as well as a large amount of theoretical information and methods for studying mining materials. Based on the results obtained, it was established that at present there are indeed prerequisites for the use of a risk-based approach to address issues related to ensuring industrial safety at the objects considered in this article. To solve the tasks set, it was decided to divide the work into several research areas. The division into areas of research will be carried out according to the explosive and fire hazardous components of the extracted raw materials. At this stage, mines and mines were considered together, but in the future, coal mines will be considered separately from mines that produce polymetallic sulfur-containing ores. The authors believe that the division of the research direction is expedient from the point of view of more accurate identification and determination of influencing factors and determination of the numerical values of the weight components when calculating the risk, taking into account the dynamics of mining operations and changes in the physicochemical and fire-explosive properties of mining materials. The capabilities of the team of authors and the material and technical support allow us to continue work in this direction.

References

1. C. Bao, J. Wan, D. Wu, J. Li, Journal of Risk Research **2019** 1-17 (2019) http://dx.doi.org/10.1080/13669877.2019.1588912
2. S.V. Balovtsev, O.V. Skopintseva MIAB. Mining Inf. Anal. Bull. **10,** 153-165 (2022) https://doi.org/10.25018/0236_1493_2022_10_0_153
3. V.A. Rodionov, V.D. Tsygankov, S.Ya. Zhikharev, D.S. Kormshchikov, Mining Inf. Anal. Bull. (MIAB) **10**, 69-79 (2021)
4. N.R. Rahayu, S. Santoso, European Journal of Business and Management Research **6(4)**, 1-6 (2021) https://doi.org/10.24018/ejbmr.2021.6.4.913
5. V.N. Mikhaylova, S.V. Balovtsev, N.R. Khristoforov Mining Inf. Anal. Bull. **5**, 228-234 (2018) https://doi.org/10.25018/0236-1493-2018-5-0-228-234
6. V.A. Rodionov, G.N. Karpov, A.V. Leisle Mining Inf. Anal. Bull. **6-1,** 198-213 (2022) https://doi.org/10.25018/0236_1493_2022_61_0_198
7. National standard of the Russian Federation. GOST R 58652-2019 Mining equipment. Multipurpose safety systems for coal mines. Principles of industrial safety providing https://docs.cntd.ru/document/1200169347
8. M.L. Rudakov, E.N. Rabota, K.A. Kolvakh Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu **(4)**, 88–93 (2020)
9. V. Rodionov, I. Skripnik, Yu. Ksenofontov, T. Kaverzneva, J. Idrisova, I. Alibekova, AIP Conference Proceedings **2467**, 080004 (2022) https://doi.org/10.1063/5.0093906
10. K.A. Kolvakh Mining Inf. Anal. Bull. (MIAB). **3,** 124-132 (2023) https://doi.org/10.25018/0236_1493_2023_3_0_124
11. S.V. Balovtsev, Mining Inf. Anal. Bull. **11**, 218-226 (2018) https://doi.org/10.25018/0236-1493-2018-11-0-218-226
12. V. Rodionov, M. Tumanov, I. Skripnik, T. Kaverzneva, C. Pshenichnaya, IOP Conference Series: Earth and Environmental Science **981(3)**, 032024 (2022) https://doi.org/10.1088/1755-1315/981/3/032024
13. Y. Liang, J. Zhang, L. Wang, H. Luo, T. Ren, Journal of Loss Prevention in the Process Industries **57**, 208–222 (2019) https://doi.org/10.1016/j.jlp.2018.12.003
14. I.V. Klimova, Yu.G. Smirnov, V.A. Rodionov, Occupational Safety in Industry **1**, 46–50 (2022) https://doi.org/10.24000/0409-2961-2022-1-46-50
15. A.V. Kornev, A.A. Meshkov, Mining informational and analytical bulletin (MIAB) **6(23)**, 3-19 (2020) https://doi.org/10.25018/0236-1493-2020-6-23-3-19
16. S.V. Balovtsev, Mining Science and Technology **7(4)**, 310–319 (2022) https://doi.org/10.17073/2500-0632-2022-08-18
17. S.V. Balovtsev, O.V. Skopintseva Mining Inf. Anal. Bull. **(2–1),** 40-53 (2021) https://doi.org/10.25018/0236-1493-2021-21-0-40-53