Substantiation of informational system for coal seam outburst danger continuous prediction with high level of the result veracity

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Received 5 April 2022; accepted 19 April 2022; published 15 July 2022.

The application field, the construction principle, the content of data system for coal seam outburst danger continuous prediction and its integration with the subsystems of a coal mine multifunctional safety system are substantiated. Widely known models for initiating gas-dynamic phenomena in underground mines are analyzed. It is shown that to describe the process of sudden coal and gas outburst preparation the most suitable model is the one that consists of two stages: the creation of a coal block structure by means of developing the crack system (the first stage) and squeezing the blocks out of the mouth of the future outburst cavity (the second stage). Basic factors important for reliable prediction of outburst danger are substantiated on their basis. The influence of failing to take into account the basic factors of the outburst danger for some instrumental and geophysical methods of prediction is analyzed. It is demonstrated that the most reliable geophysical method, at present, is the spectral-acoustic one. The description of the procedure for experimental determination of the outburst danger limit value indicator for this method and for certain coal workings is introduces. *KEYWORDS:* Sudden coal and gas outburst; instrumental and geophysical methods of prediction; outburst danger factors; the procedure of experimental determination of outburst danger criteria; multifunctional safety system of a coal mine.

Citation: Shadrin, A. V., Yu. A. Diyuk, and A. S. Teleguz (2022), Substantiation of informational system for coal seam outburst danger continuous prediction with high level of the result veracity, *Russ. J. Earth. Sci., 22,* ES4001, doi:10.2205/2022ES000799.

Introduction

Sudden coal and gas outbursts are dangerous due to their disastrous consequences. Starting from a certain depth they take place practically in all coal basins of the world: in Russia, Ukraine, China, Kazakhstan, the USA, Australia, Poland and many other countries.

Based on multi-year researches made by different scientific research groups it is determined that coal seam outburst danger depends on a number of parameters which include ground pressure, in-situ gas pressure, filtration-reservoir strength properties of a coal seam, its structure, presence of disjunctive or plicative faults, coal humidity and the technology applied for coal excavation etc. [*Black,* 2017; *Chernov and Puzyrev,* 1979; *Fan et al.,* 2017; *International...,* 1995; *Geng et al.,* 2017; *Khodot,* 1961; *Vardar et al.,* 2018; *Yu,* 1992; *Zhang and Li,* 2005].

For continuous outburst danger prediction some methods for controlling basic influencing factors were developed. These methods can be roughly divided into two groups: instrumental and geophysical. The prediction made by instrumental methods is based on measuring the parameters which characterize stress state of gas-saturated coal massif.

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http://rjes.wdcb.ru/doi/2022ES000799-res.html

The measuring can be fulfilled directly in a massif or in coal and gas samples collected during drilling the boreholes [*Black,* 2017; *Clarke,* 1994; *Gosgortechnadzor,* 2000; *Yu,* 1992; *ZAO NTTs PBp,* 2019]. The application of these methods requires halting the works in a face that can influence negatively on the mining rate. So, they can be named quazi-continuous methods. Moreover, due to the halting of the works in a face, the determined danger depends on the time period between the halting and making the prediction. Only automated informational system constructed with the application of geophysical methods for continuous control of the gas-saturated coal massif geo-mechanical state can provide the prediction in a working face.

The veracity of the prediction methods is defined by the overall covering of the basic outburst danger factors [*Black,* 2019; *Fan et al.,* 2017; *International...,* 1995; *Khodot,* 1961; *Nedra,* 1978; *Yu et al.,* 2015].

Thus, as the fulfilled analysis shows, each, presently applied geophysical method cannot cover all these factors independently. That is why, lately, it is offered to fulfill the prediction applying several methods simultaneously. An example for organizing such type of prediction is a Marco company system of dynamic phenomena prediction. In this system the prediction of a rock burst manifestation is based on analyzing the creep of rocks in the vicinity of the stope. The program for analyzing the convergency in a face by the system of Marco electrohydraulic control "Digital mine" allows controlling the creep of rocks and instability stages of the massif by means of measuring the pressure in prop supports and further analysis of the captured data. The speeding of the creep of rocks indicates the transition into unsteady condition. An important criterion of a rock-burst danger is a simultaneous transition into instability, registered in several neighboring sections of supports [*Reuter et al.,* 2018]. To increase the prediction veracity the creep of rocks control is accompanied by acoustic emission monitoring [*Reuter et al.,* 2015]. However, this system does not take into account gas presence and its pressure.

The analysis proved that all known geophysical means and methods of outburst danger prediction, taken separately, did not provide high veracity of prediction due to incomplete coverage of the basic outburst danger factors. This was the reason why the task to determine the basic requirements to continuous prediction method and to substantiate the informational system which would satisfy these requirements was set.

The purpose of this paper is in substantiating the informational system for continuous prediction of coal seam outburst danger where the veracity of the result is higher than in other well-known methods.

The Requirements to the Informational System for Continuous Prediction of Coal Seam Outburst Danger

Based on the performance analysis of the outburst danger prediction methods the following requirements to the informational system for continuous prediction of coal seam outburst danger were formed:

- Informational system shouldn't interfere with the mining works except for the time given to periodical "tuning" procedures. Only systems based on geophysical methods of controlling stress state in a gas-saturated stressed coal-bearing massif can do it.
- Informational system should be based on controlling basic outburst danger factors.
- Informational system should have scientifically grounded technique for on-the-spot definition of the critical value of the outburst danger indicator at the intended for excavation zone of a mining seam. The techniques which are at hand nowadays do not meet the requirements to the full extent and insufficient reliability of the prediction performed by geophysical methods proves it.
- Prediction method which will become a ground for informational system should have scientifically grounded value for "sensitivity depth" of the danger ahead of the working face. At present, the explored zone depth of the instrumental and geophysical methods for the current outburst danger predication makes several meters. And this value does not have rather strict scientific grounding [*ZAO NTTs PBp,* 2019].
- Informational system should be computerized to be able to process large volumes of information.

- Informational system should have infrastructural subdivision for supporting operation of the unit: installing and carrying the hardware parts, controlling their operation, interpreting the obtained prediction results and activating the action plan should there be a prediction with the mark "Dangerous". As far as the acoustic or electromagnetic signal can be often used for sounding the rock massif the specialists of this subdivision must know the bases of wave processes, their generation conditions, and the condition of their propagation along hard, nonhomogeneous, gas-saturated, fractured body which contains other failure characteristics. Nowadays the major part of mining universities do not prepare such specialists (geophysical engineers). We believe, with the growth of applying geophysical methods in underground coal mines it is expected to see the growth of preparing such specialist in colleges and universities as it happened before with mine surveyors, mechanic engineers, electrical engineers, and information and communication technology specialists.

The Structure of Outburst Danger Prediction Subsystem

As any classical informational system for automated control, the informational system (IS) for outburst danger prediction, for its effective operation, should include two parts: functional and supportive.

The functional part of IS for outburst danger prediction should analytically and experimentally substantiate the algorithm for solving the problem of continuous prediction of sudden coal and gas outburst for a certain face. As far as the advancing of the mining face takes place, continuous fulfillment of the following procedures should be included in this algorithm [*Shadrin,* 2020]:

1. Defining a current value of the outburst danger indicator which covers all basic outburst danger factors.
2. Defining a critical value of the outburst danger indicator for a given position of the mine working at each current moment in time.
3. Comparing current and critical values of outburst danger indicators with further definition of the danger degree. The danger degree can be qualitatively characterized by three or four danger levels, for example, "no danger", "weak threatening", "threatening" and "danger".
4. Should "danger" degree arise the actions on informing and providing safety measures, if necessary, must be activated.

The supporting part of IS for outburst danger prediction should create conditions for operation of its functional part. For this purpose it should consist of: technical support, software, organizational support, regulatory support, methodological support, information support, linguistic support etc. [*Shadrin and Teleguz,* 2020].

The Model of Rock Massif Loss of Stability During Dynamic Phenomena Initiation

Past decades saw the tendency to creating a unified theory of different dynamic phenomena development.

The similarity of dynamic phenomena fundamental features gives the ground for that [*Petukhov and Linkov,* 1978]. These features are:

- Large reserves of potential energy (elastic strain, pressurized gas) and limited ability of a material to irreversible absorption of potential energy;
- Preliminary (the first) stage of the process that is finalized by loss of equilibrium stability (dynamic phenomena initiation);
- Propagation of a destruction wave from the wall of the working (the second stage);
- The movement of the material (and gas) into the mined-out space (the third stage);
- Stopping the destruction wave and ending the dynamic phenomenon (the fourth stage).

All theoretical models for dynamic phenomena initiation are built on the bases of solid-state mechanics regularities. And these models can be nominally divided into force-based and energy-based ones.

In the force-based model active forces which bring about the loss of stability of the massif and passive forces which prevent the instability act. The loss of stability takes place when the active forces prevail over the passive ones. As a rule, two events are considered as the loss of stability of the massif: it's crashing due to cracks propagation and outsqueezing of the coal into the working.

An example of the force-based model for the massif stability loss caused by the outburst triggered by the crack propagation is the problem of defining the criteria for initial crack propagation under the influence of ground pressure and gas pressure in the vicinity of the destruction wave front [*Petukhov and Linkov,* 1983]. According to this model the process of crack propagation takes place under the influence of the active forces such as compressive loads – vertical and horizontal components of the ground pressure and the gas pressure in the crack. Strengths properties of coal presented by compressive properties and tensile strengths prevent the propagation.

An example of the force-based model for the massif stability loss caused by squeezing of the coal is a coal outsqueezing into the mined-out space [*Murashev,* 1978]. The concept of the process is in following. In the process of coal excavation due to heterogeneity of a coal seam and the presence of different defects of different size and forms in it (the largest ones appear as a result of cleavage) the disintegration of a coal massif into blocks takes place in a face space. Squeezing of several coal blocks out of the mouth of the initiated outburst cavity takes place when the pushing(active) force starts prevailing over the obstructive (passive) force. As an active force, a sum of the lateral pressure force (horizontal component of the normal stresses), gas pressure in a crack force and the gravity force of the outsqueezed layer (if it is not a horizontal working) can be taken. As an obstructive force the cohesion force and the force of inner friction of coal in a massif conditioned by shear stresses acting upon the lateral surface of the outsqueezed layer can be taken.

The advantage of the force-based models of dynamic phenomena development is in the point that the condition of losing stability in a certain space area can be described rather accurately.

The disadvantage of the force-based model is in the point that the defined condition for losing the stability of the massif in a certain small area may not definitely cause the initiation of dynamic phenomenon. The condition of losing the stability should be fulfilled in a rather large face space zone but the force-based model cannot take it into account.

According to the energy-based theory of dynamic phenomena "...in the vicinity of the mine working such volume of rock potential and kinetic energy and non-associated gas inner energy should be released that it would be enough for disintegrating coal and its shifting towards mine working within a certain period of time" [*Khodot,* 1961].

To initiate and develop a sudden outburst, energy is needed. This energy disintegrates coal into fractions and gives them kinetic energy to move along the cavity of the outburst and the working. To do this work, a certain amount of coal and enclosing rock elastic strain energy together with the potential energy of the in-situ high gas pressure should be concentrated in a crashing area of a rock massif.

The amount of this energy should exceed the amount required for disintegrating coal and delivering it into the working as a part of this energy would be consumed in the form of heat by the environment and spent on electromagnetic and seismic vibrations from the crashing area through the rock massif and on acoustic radiation in the mine working atmosphere [*Petukhov and Linkov,* 1978].

The advantage of the energy-based model for dynamic phenomena development is that energy components which the energy balance contain are taken into account integrally on the whole volume of the face space.

To describe the indicated-above energy components in energy balance of the outburst it is necessary to know their distribution in the formation area and the influence of elastoplastic, strength, thermal and physical, acoustic and other characteristics of the massif on them. Thus, the disadvantage of the energy-based model is that it is difficult, nearly impossible, to set down in space the distribution of the parameters which define the components of the energy balance accurately.

The majority of sudden outburst models employ the ground pressure, the in-situ gas pressure conditioned by high gas-bearing property of a seam and low filtering coefficient of coal in outburst danger zone and its strength as the basic factors for initiating gas-dynamic phenomena [*International...,* 1995; *Nedra,* 1978].

As far as it is not known beforehand what outburst danger factor prevails during the development of a gas-dynamic phenomenon it is important to choose such a sudden outburst model that takes into account all basic factors over the whole period of the dangerous situation appearance. To substantiate the model, it is important to study all basic outburst danger factors.

Basic Parameters (Factors) of a Rock Massif Necessary for Controlling Outburst Danger Prediction by Informational System

Studying the reasons for causing sudden coal and gas outbursts it was defined that outburst danger of coal seams depended on a large number of parameters. They are: the ground pressure, the in-situ gas pressure, filtering-reservoir and strength characteristics of a coal seam, its structure, presence of the dislocations, coal humidity, employed excavation technology etc. [*Chernov and Puzyrev,* 1979; *Fan et al.,* 2017; *International...,* 1995; *Korol and Skobenko,* 2013; *Nedra,* 1978; *Yu,* 1992]. So, it was admitted that the prediction should be multifactorial [*Chernov and Puzyrev,* 1979; *Nedra,* 1978; *Yang et al.,* 2015; *Zhang and Li,* 2005].

The more accurate the basic factors that influence on outburst danger are taken into account, the higher the veracity of the prediction method is. So, for example, in one research it was suggested to consider 26 parameters [*Zykov,* 2010]. However, in a current outburst danger prediction it is impossible to control such a large number of parameters simultaneously. That is why informational system for outburst danger prediction should control only basic parameters which define outburst danger and allow doing it applying nondestructive methods (avoiding drilling and probing) i.e. geophysical methods. It is advisable that a number of, necessary for prediction, parameters have already been controlled by separate sub-systems included into multi-functional safety system of a mine.

The analysis of the well-known models for preparing sudden coal and gas outbursts shows that the basic factors that bring about the initiation of this gas-dynamic phenomenon are: the ground pressure, the in-situ gas pressure conditioned by a high gas-saturation of a coal seam and a low coefficient of coal filtering in an outburst danger zone and its strength [*Nedra,* 1978]. The most dangerous values these factors takes being in the vicinity of disjunctive and plicative dislocation in the rock massif structure [*Chernov and Puzyrev,* 1979; *Cheng et al.,* 2013; *Fan et al.,* 2017; *International...,* 1995; *Nedra,* 1978; *Olkhovchenko,* 1982; *Xue et al.,* 2014 *Zykov,* 2010].

It is also known that apart from the above-mentioned factors an employed technology of a seam excavation and so called “human factor” also have a great impact on dynamic phenomena manifestation [*ZAO NTTs PB,* 2018a, 2018b]. Coal humidity is a factor that lessens the sudden outburst danger. It is empirically proved that if the coal humidity prevails 6 per cent the outbursts never take place as the liquid blocks gas in micro-pores and the coal starts to be plastic and the zone of high rock pressure gradually shifts far into the depth of the massive for starting an outburst [*Chernov and Puzyrev,* 1979].

While analyzing the basic factors that initiate dynamic phenomena the question of priority influence of a gas factor or a ground pressure on the development of different dynamic phenomena arises. It is widely admitted that elastic-strain energy is determinative in low gas-bearing seams and dynamic phenomena take place in the form of rock-bursts [*Petukhov and Linkov,* 1978]. Rock-bursts can also take place in gas-bearing coals in case their strength is high and they are able to generate elastic energy of sufficient magnitude for its destruction. It is a distinctive characteristic of thin seams as even sudden coal and gas outbursts in them starts from local rock bursts at the wall of a working which further shifts into an outburst.

However, in the majority of cases, in the seams with medium or large thickness, gas energy has a significantly greater influence on preparing and developing the outburst then the elastic-strain energy. [*Khodot,* 1961; *Petukhov and Linkov,* 1978]. It is connected with the notion that outburst dangerous coal seams have low strength and do not allow generating elastic energy of a great value. Simultaneously, such coal seams have a low gas permeability that leads to accumulating great volumes of potential energy of pressurized gas.

The analysis of the above studied force-based models for cracks propagation in a face space and/or outsqueesing of the coal into mined-out space so as energy-based model for massif destruction in the process of dynamic phenomena manifestation prove that dynamic phenomena can take place under the influence only of a single factor: whether it is ground pressure factor or gas pressure factor. The experiment can prove it. It is well-known that degasified coal sample can be broken only under the force of a press. And, vice versa, while simulating sudden outburst on specially designed testing unit coal was saturated by gas in a rectangular tube. When opening the cover on the tube-end, an outburst took place under the influence of gas, though there was no mechanical pressure on the coal [*Polevshchikov,* 2003]. It should be also noted that, in first theoretical works of professor S. A. Khristianovich, devoted to the mechanism of preparing and flowing of a sudden outburst, the ground pressure wasn't taken into account [*Khristianovich,* 1953a, 1953b]. As it is not known beforehand what outburst factor prevails during the development of gas-dynamic phenomena it is important to choose such an outburst model which would take into account all basic factors during the occurrence of the dangerous situation. So as such, a model of two-stage sudden outburst preparation was chosen.

Two-Stage Model of Preparing the Outburst Danger Situation

The given model was built on the bases of taking into account basic features of outburst danger [*ZAO NTTs PBp,* 2019]. They all can be nominally divided into two groups. The first group includes cracks and bumps appeared in a massif conditioned by the crack (fracture) propagation in it and it is only a feature of a stress state dynamic change. The second group that includes the peeling and outsqueezing of a face with increasing gas release shows the preparation of a final stage which causes prompt destruction of a small coal area at the fore-breast of the face forming the mouth of the initiated outburst cavity.

In the result of the given outburst danger signs analysis the above-mentioned model was offered [*Shadrin and Diyuk,* 2019]. According to this model at the first stage in the face space of a working a forming of a coal block structure due to the propagation of the cracks under the influence of ground and gas pressures takes place. At the second stage, the failure of a relatively thin coal layer in the mouth of the outburst cavity and outsqueezing of the formed coal blocks into the working take place. After that the sudden outburst starts. That is the disintegration of coal by the influence of ground and gas pressures and its pushing out into the working by emitted gas according to a standard mechanism [*Black,* 2019; *Fan et al.,* 2017; *International...,* 1995; *Khodot,* 1961; *Khristianovich,* 1953a, 1953b; *Nedra,* 1978; *Yu et al.,* 2015].

The advantages and the novelty of two-stage model of sudden coal and gas outburst preparation are in the following:

1. The model describes the process of sudden outburst preparation from the start – from starting of the cracks propagation to the end – breaking and outsqueesing of the "stopper" (the coal layer) from the mouth of the initiated outburst cavity.
2. The model takes into account basic outburst danger factors: the ground pressure; the gas factor conditioned by high values of gas-saturation and in-situ free gas pressure; low strength of coal, characterized by high sorption capacity and low coefficient of gas filtering.
3. It is empirically proved that
   – the occurrence of a "jump-like" growth of the cracks is registered by acoustic-emission method or/and electromagnetic emission method;
   – after unloading the thrown out during dynamic phenomena fine dust, which is called by Kuznetsk coal basin miners "violent flour", on the soil under the mouth of the working large coal lumps formed after the bursting and squeezing the "stopper" out of the mouth of the cavity were found.
4. Both stages have a mathematical description for criterion of their flowing expressed through basic parameters of gas-saturated coal massif which define its stability: the ground pressure, methane concentration in the atmosphere of the working at the face (functionally connected with in-situ free gas pressure), strength properties of coal. It allowed working out a complex outburst danger prediction method and a possible variant of the current outburst danger technique [*Shadrin,* 2019].

However, the given model is an approximate one as it doesn't take into account "delicate" coal structure in outburst danger zone of a seam. The peculiarity of the coal structure is in the point that it consists of compressed conglomerate of individual small particles surrounded by different-sized pores with occluded and partially free gas inside. After sharp loss of the coal seam stability in the mouth of the initiated outburst cavity these particles are separated from each other easily. Herewith, front surface of the stability loss moves continuously into the depth of the massif forming so called coal disintegrating wave (the term offered by S. A. Khristianovich) [*Khristianovich,* 1953b]. As a result the volume of desorbed gas which forms the rejection wave of "dissipated" coal particles into the working increases sharply [*Khristianovich,* 1953a].

The presence of the given "delicate" structure is proved empirically by the fact that in the result of a sudden outburst the volume of emitted gas is higher than it is expected due to the gas-bearing capacity known previously for this coal seam (measured, possibly, on non-outburst-dangerous area). It was also empirically proved that a transitive layer between outburst dangerous and non-dangerous zones could be thin: from 1 to 2 meters. It conditioned the importance of continuous current prediction of outburst danger.

The described "delicate" structure of the outburst danger zone coal is apparently conditioned by the peculiarities of its structure, reservoir and strength properties. This peculiarity is expressed in its local high sorption capacity. However, the character of this peculiarity due to its complexity is not taken into account in two-stage outburst danger preparation model. Nevertheless, this model allows analyzing the influence of basic outburst danger factors on prediction veracity of both instrumental and geophysical methods. We'll demonstrate it. Herewith it will be taken into account, that the defined functional dependences of the outburst danger indicators and criteria on the controlled parameters, studied in this paper, are true only if the specific type of the indicated equipment is used for measuring the speed of the initial gas emission out of the drill, coal strength and outburst danger indicator of the method "on parameter of artificial acoustic signal".

The Influence of the Basic Outburst Danger Factors on the Instrumental Prediction Methods Veracity

Making the analysis we take only those instrumental outburst danger methods which can be done quite rapidly in a mine working. The following methods can be referred to this type [*Chernov and Puzyrev,* 1979; *Clarke,* 1994; *ZAO NTTs PBp,* 2019]: the method "on the coal seam structure"; the method "on the initial gas emission rate" and the method "on the initial gas emission rate and the drilling fine output". These methods are used in Russia.

The method "on coal seam structure" estimates only the potentiality of sudden outburst grounding on two outburst danger factors: on a coal strength and indirectly – on a gas factor. The later statement is conditioned by the capacity of a broken coal to adsorb large volumes of gas which in its turn can quite fast be desorbed into initiated during the first stage of outburst preparation cracks of different size and bring about high pressure in them. However, the real presence of gas in a coal seam, the quantitative value of its pressure and the gas-saturation are not taken into account by the method.

The criterion of this prediction method in Russian mines is the presence of coal plies with total power over 0.2 m and medium strength $q < 75$ c.u., measured by strength-measuring device P-1 designed by Skochinskiy Mining Institute [*ZAO NTTs PBp,* 2019]. The given criterion does not have strict analytical ground and is basically applied in the areas which, according to the corresponding technique, are referred to outburst dangerous zones, where the outburst hasn't taken place in them or they have been registered in the underdeveloped form of a weak force, for example, in the form of sudden out-squeezing with high gas emission etc. The advantage of the method is the simplicity and promptness of its performance.

As this criterion has only approximate estimation character of the influence of the coal strength on the outburst danger and does not qualitatively take into account the gas factor and does not consider the ground pressure factor at all, it is taken with "a reliability margin" (amply) it causes low reliability of the prediction.

The next prediction method – "on the initial gas-emission rate", supplementary to estimating coal strength on the presence of low-strength ply quantitatively estimates outburst danger gas factor on initial gas-emission rate with interval borehole drilling (in 1 m distance and to 6.5 m depth) on the less robust coal ply. The outburst danger criterion for this method at the Russian mines is the exceeding, at any interval of drilling, the initial gas emission rate 4 liters per minute except of the Donetsk Basin where this parameter can be from 4.0 to 5.0 liters per minute depending on volatile content in coal samples [*ZAO NTTs PBp,* 2019].

The given criterion is based on the data received during multiple experimental researches in the mines of all coal basins of Russia. According to these researches when initial gas-emission rate is less than 4.0 l/min the outburst doesn't take place [*Chernov and Puzyrev,* 1979]. Moreover, this method considers that the gas factor prevails over the ground pressure factor and it is not always justified. Thus, for example, in deep underground mines of Donbass coal seams with low power in a face space are too squeezed and there is a relatively low level of free gas in this zone. That is why sudden outbursts there start mainly with the local rock-bursts which cause the pressure relief of a certain gas-saturated coal seam zone. Due to this the intensive gas desorption takes place and the ground pressure shifts into a sudden coal and gas outburst. Thus, under the described conditions ground pressure factor has a significant value.

The influence of the ground pressure factor on outburst danger in the prediction method "on initial gas-emission rate" isn't taken into account and this fact causes the lack of prediction veracity. The fact of not taking into account the influence of this factor will be estimated quantitatively after studying the method of current prediction "on initial gas-emission rate and drilling fines output".

This method was created as a result of analyzing the experimental data about sudden outbursts in Russian mines. According to the data if the initial rate of the gas-emission while drilling control boreholes is $i_{\max} < 4.0$ l/(min m), sudden outbursts never take place, but if it is $i_{\max} >$ 8 l/(min m) the outbursts practically always take place. (Here a non-system unit of 1 liter is used. 1 liter = 0.001 m^3). For the range of values from 4.0 l/(min m) to $i_{\max} \leq 8$ l/(min m) the outbursts may or may not take place. Professor V. N. Puzyrev explained this ambiguity by the influence of the stress state, strength and other coal characteristics on outburst danger. To take them into account he offered the outburst danger indicator R, based on statistic processing of a large number of experimental data about initial gas-emission rate and drilling fines output under interval drilling of control boreholes, received in zones where the outbursts took place [*Chernov and Puzyrev,* 1979]. Owing to the fact that this method takes into account the basic outburst danger factors the given instrumental method is still suggested to use in the mines of Russia.

The measured parameters control basic outburst danger factors i.e. with the ample certainty it can be considered, that the initial gas-emission rate characterizes the gas factor of the outburst danger, and the drilling fines output does it with a stress state of a seam and a residual coal strength (the higher the ground pressure and the lesser the coal strength are the larger the drilling fines output from a meter-long interval of a borehole).

The criterion of this method is given by the following expression [*ZAO NTTs PBp,* 2019]:

$$R = (S_{\max} - 1.8)(i_{\max} - a) - b = 0, \qquad (1)$$

where $S_{\max}$ – is a maximal value of the drilled fines output, l/m; $i_{\max}$ – is a maximal value of the initial gas-emission rate, l/(min m); $a = 5$ – for Vorkuta deposit; and $a = 4$ – for other coal basins and deposits of eastern regions of Russia; $b = 21$ – for Vorkuta deposit; $b = 6$ – for other coal basins and deposits of eastern regions of Russia.

The dependency graph of type (1) where $a = 4$ and $b = 6$ is shown in Figure 1.

To estimate the influence of failure to take into account the ground pressure and the coal strength factors on the prediction veracity in a prediction method "on the initial gas-emission rate" we'll divide the area under the curve of type (1) into two zones with the area correspondently D_1 and D_2. Here: D_1 – is a rectangle area, limited by axis of abscissas and straight lines, parallel to coordinate axis and cutting the values on them off: $S_{\max} = 2.2$ l/m, $S_{\max} = 20.0$ l/m, $i_{\max} = 4$ l/(min m); D_2 – the figure area, limited by the curve R and straight lines, parallel to coordinate axis and cutting the values on them off: $S_{\max} = 2.2$ l/min, $i_{\max} = 4$ l/(min m) (see Figure 1).

The whole area under the curve corresponds to non-dangerous value of the outburst danger indi-

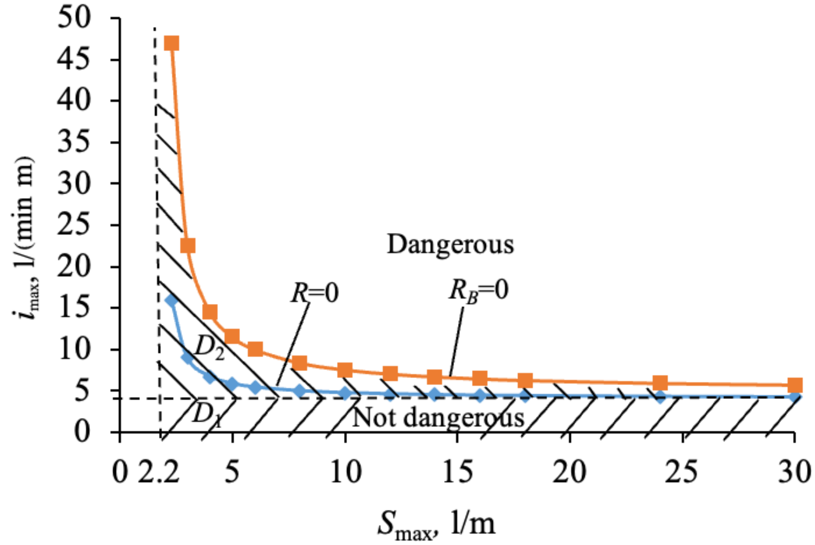

Figure 1. The dependence of the outburst danger indicator $R = 0$ on the initial gas-emission rate i_{max} and the drilling fines output S_{max} when $a = 4$ and $b = 6$.

cator. Area D_1 when $i_{max} < 4.0$ l/(min m) corresponds to a non-dangerous value share of outburst danger indicator defined only according to a gas factor i.e. controlled by the method "on initial gas-emission rate". D_2 area corresponds to a non-dangerous value share of the outburst danger indicator defined with the consideration of ground pressure and coal strength factors.

When determining D_1 and D_2 areas, the area positioned to the left from the straight line with abscissas $S_{max} = 2.2$ l/m were not taken into account. It is conditioned by the fact that to measure the drilling fines output less than this value is practically impossible. It happens because if the drilling rod cutter diameter is 42 mm and the degree of the coal crushing ratio equals to 1.3, the minimal value of the intended drilling fines output from one long meter of a bore-hole $S_{l,\min} = 1.8$ l/m [Zykov, 2010]. Due to the imbalance of the cutter in the borehole and irregularity of its walls this value can increase on 20 per cent more [Zykov, 2010]. and it makes approximately 2.2 l/m. Thus, this value is a minimally possible value of the parameter S_{max} in calculating outburst danger criterion without considering the influence of gas on the drilling fines output and the ground pressure. We'll name it $S_{l,\max}$. Due to the influence of the gas pressure and especially the ground pressure and decreasing of the coal strength, the parameter S_{max} can significantly exceed the value $S_{l,\max}$ and reach the value of 100 l/m [Zykov, 2010]. However, as it can be seen in Figure 1, the curve R with the growth Smax asymptotically approaches to a straight line $i_{max} = 4$ l/(min m). That is why the area D_2 with the values of $S_{max} > 20.0$ l/m can be neglected.

Out of (1) we have:

$$i_{max} = \frac{b}{S_{max} - 1.8} + a. \qquad (2)$$

Then the area of non-dangerous values of R indicator lays lower than the curve $R = 0$ when changing the value S_{max} in the limits of (2.2–20.0) l/m and its area equals $D_1 + D_2$:

$$D_1 + D_2 = \int_{2.2}^{20.0} i_{max} dS_{max}. \qquad (3)$$

Substituting (2) into (3) for $a = 4$ and $b = 6$ option, it we'll get, $D_1 + D_2 = 94.12$ l^2/(min m^2). It is obvious that $D_1 = (20.0-2.2)\times 4 = 71.2$ l^2/(min m^2). Then $D_2 = 22.92$ l^2/(min m^2). Shifting from the current outburst danger prediction on the initial gas-emission rate and the drilling fines output while drilling control boreholes method to outburst danger prediction on a coal seam structure and initial gas-emission rate out of controlling borehole method, D_2 area was excluded from the area of non-dangerous values of the outburst danger indicator. The relative value of this "simplified prediction method" Δ equals:

$$\Delta = \frac{D_2}{D_1 + D_2} = \frac{22.92}{94.12} \cdot 100 = 24.35\%. \qquad (4)$$

After making similar calculations for Vorkuta coal deposit conditions when $a = 5$ and $b = 21$ it appeared that relative accuracy for defining non-dangerous values area of outburst danger indicator due to simplifying the prediction method made $\Delta_v = 57.92\%$.

Thus, the veracity of the prediction method "on initial gas-emission rate and drilling fines output out of the borehole" is significantly higher than the method "on initial gas-emission rate" due to the decreasing of so called "reliability margin" on 25–60%.

The Influence of the Basic Outburst Danger Factors on the Veracity of Continuous Geophysical Prediction Methods

The performed review of literature sources revealed the following. At present, new geophysical methods for predicting dynamic phenomena are being developed, improved and applied. The basic methods are: the acoustic emission method, the electromagnetic emission method, spectral analysis of operating mining equipment "noise" method (one of its variants is called "on artificial acoustic signal parameters"); method of analyzing the data registered by aero-gas monitoring.

Acoustic emission method as far as electromagnetic emission method are based on monitoring the process of a "jump-like" growth of the cracks under the influence of ground and gas pressures. Both methods are applicable as in the process of a "jump-like" growth of a crack its sides emit both acoustic and electromagnetic waves. However, acoustic emission method is preferable due to energy datum and it will be demonstrated further.

The work [Ivanov, 1994] studies thermodynamics of a rock destruction centre considering the kinetics of cracks generation in it. The problem is formulated as the following: in the center of rock destruction with the volume V with the surface of the outer boundary Σ, at the first stage of its forming the micro-cracks are scattered around the volume of this centre rather evenly. Thus, the possibilities of micro-cracks appearance in this or that part of the volume V are even and the average rate of crack-formation under constant stress inside the centre and at its boundary Σ is also constant. It is also assumed that the temperature in different parts of the destruction centre is constant and does not depend on the coordinates.

Under these conditions, on the bases of the energy conservation law, the following expression for defining the total destruction energy of a crack normalized to the unit surface of the crack, W_t, expressed through similar normalized components was obtained [Ivanov, 1994]:

$$W_t = W_0 + W_{\text{def}} + W_{\text{eld}} + W_{\text{kin}}, \tag{5}$$

where: W_0 – is a theoretical value of destruction surface energy, defined by the interatomic binding strength; W_{def} – is a deformation component that defines thermal heat loss; W_{kin} – a kinetic component that defines acoustic emission.

The performed quantitative estimation of the components of total modified destruction surface energy gives the following values [Ivanov, 1994]:

$$\left.\begin{array}{l} W_t \sim 10^3 \div 10^5 \text{J/m}^2;\ W_0 \sim 1\ \text{J/m}^2; \\ W_{\text{def}} \sim 10^2 \div 10^4\ \text{J/m}^2; \\ W_{\text{eld}} \sim 10^{-1} \div 10^2\ \text{J/m}^2; \\ W_{\text{kin}} \sim 10^2 \div 10^3\ \text{J/m}^2. \end{array}\right\} \tag{6}$$

As it is seen, the largest part of the outerly fed to the center of destruction energy (to $90 \div 99\%$) dissipates in the form of heat and acoustic emission and only $1 \div 10\%$ dissipates in the form of electromagnetic emission. Moreover the share of acoustic emission is close to a half of the total energy and on $\sim 1 \div 2$ orders of magnitude larger than electromagnetic one. It is important to take into account that in rocks, the electromagnetic emission attenuation rate is significantly higher than acoustic one. Presumably, this is the reason why acoustic emission method or micro-seismic method is wider applied than electromagnetic emission method.

To analyze the potentiality of these methods for predicting dynamic phenomena we'll show the influence of outburst danger factors on the crack growth criterion.

In paper [Petukhov and Linkov, 1983] a calculation scheme of an isolated crack propagation with a typical size $2l$, situated at the distance of x_{cr} from the working face is presented (Figure 2).

The face zone of the rock massif is introduced in the form of homogeneous half-space positioned in the ground pressure forces field with main stresses $\sigma_1(x) - -\sigma_3(x)$ (to be easy understood the case of planar loading is taken) and weakened by cracks

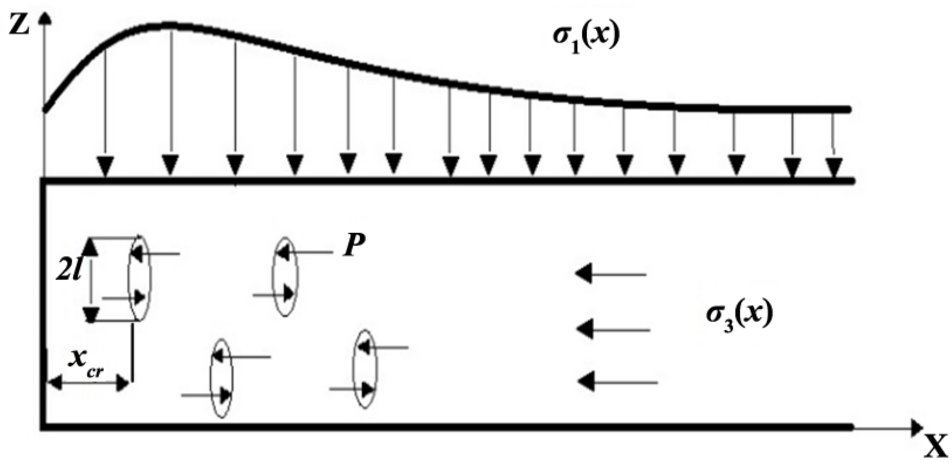

Figure 2. The coal seam ahead of the working face in the stress field $\sigma_1(x) - \sigma_3(x)$, weakened by the cracks filled with gas under pressure P.

filled with gas under pressure P. For this scheme the following expression for defining crack stability criterion [*Petukhov and Linkov,* 1983]:

$$\psi_{cr}\frac{P-|\sigma_3|}{\sigma_s}+\frac{|\sigma_1|}{\sigma_p}=1, \tag{7}$$

where $\psi_{cr}(x_{cr}/l) = k_1/k_1^{\infty}$; k_1 and k_1^{∞} – are the stress intensity coefficients correspondently in the point of observing and out of the working zone influence; σ_p and σ_s – are the compression strength and tensile strength correspondently.

Introducing the notion of the massif stress state indicator in the vicinity of a crack on gas factor – I_g, and similar on the ground pressure factor – I_p and the indicator of critical stress state value – I_{cr} we'll define them by the expressions:

$$\left.\begin{array}{l} I_g=\psi_{cr}\sigma_p; \\ I_p=\sigma_s\,|\sigma_1|-\psi_{cr}\sigma_p\,|\sigma_3|\,; \\ I_{cr}=\sigma_s\sigma_p. \end{array}\right\} \tag{8}$$

Then the criterion in (7) is modified as:

$$\frac{I_g}{I_{cr}}+\frac{I_p}{I_{cr}}=1. \tag{9}$$

As it is seen from (9) the influence of the ground pressure and of a gas factor on the crack stability bears additive character. Consequently, increasing the indicator I_g on a number of per cents the crack growth is possible under the lesser value of I_p on the same number of per cents and vice versa. Moreover, the maximal values I_g and I_p are defined by coal strength characteristics σ_p and σ_s. The critical stress value indicator – I_{cr} strongly depends on these characteristics. To estimate this dependence we'll use approximate relationship for defining σ_p and σ_s through coal strength coefficient q, measured by a strength measuring device P-1 [*Shadrin and Diyuk,* 2019a]:

$$\sigma_p \approx \frac{4q}{110-q},\ \text{MPa};\ \sigma_s \approx \frac{0.3q}{110-q},\ \text{MPa}. \tag{10}$$

The calculations reveal that under changing the coal strength from 90 c.u. to 70 c.u. the value of the indicator I_{cr} lessens in 6.6 times.

As it is seen from (8) and (9) the distance of the crack from the wall of the working, due to the dependence of ψ_{cr} parameter on x_{cr} influences on the parameters that define stress state indicators I_g and I_p. This dependence is such that when approaching to the side of the workings on 0.1–0.3 m out of the depth of the massif, parameter ψ_{cr} increases approximately from $\psi_{cr} \le 1.2$ to $\psi_{cr} \ge 5$ [*Petukhov and Linkov,* 1983].

Thus, all three basic outburst danger factors influence on crack growth criterion. However, the dependence of this criterion on the distance from the side of the working is one of the reasons for low reliability of the outburst danger prediction made by the acoustic emission method. Another reason is indefiniteness of the crack growth influence on a working face stress state as it can bring about both to its dangerous state (a bearing pressure zone approached to the face) and to its discharge caused by the shifts of the bearing pressure maximum into the depth of the massif.

The prediction method "on the parameters of artificial acoustic signal" is based on the influence of a stress state on amplitude frequency characteristic of a wideband acoustic "noise" produced by the operating mining equipment and which passed the controlled zone of the massif to the receiver (geophone). This influence is conditioned by the fact the attenuation coefficient in a solid body is directly proportional to the sound frequency and inversely proportionate to the acting medium stresses [*Shadrin,* 2019]. That is why the current value of the outburst danger indicator K_c, defined as the ratio of high frequency and low frequency components of the "noise", characterizes the relation of the current and limit stresses (i.e. the danger degree) according to the equation [*Shadrin and Diyuk,* 2019b]:

$$K_c = \frac{A_h}{A_l} = \exp(-C\frac{\sigma_l}{\sigma_c}d), \tag{11}$$

where: A_h and A_l – are acoustic noise of the operating equipment amplitudes, measured correspondingly at high and low frequencies, B; σ_l and σ_c – are, correspondingly, medium limit stress and current stress at the given point of the massif and at the present moment, Pa; d – is the distance between the source of the noise that influence on the face and geophone which is installed into the side (wall) of the workings, m; parameter C is defined according to the equation [*Shadrin and Diyuk,* 2019b]:

$$C = \frac{\alpha_0 \beta (f_h - f_i)}{f_0}, \mathrm{m}^{-1} \tag{12}$$

where f_h and f_i – correspondingly, are the characteristic frequencies from the ranges of high and low operating frequencies of the acoustic signal, Hz; α_0 – the attenuation at a certain frequency f_0, which belongs to the registered frequency range, m^{-1}; β – non-dimensional proportionality coefficient defined by the features of the massif in a controlled zone.

The outburst danger indicator reaches the limit value K_l when $\sigma_c = \sigma_l$. Then this value is equal to:

$$K_l = \exp(-Cd). \tag{13}$$

It is seen from (11) and (13) that a significant disadvantage of this prediction method is the dependence of the outburst danger indicator and its limit value on the distance d. In practice, it reveals itself in a "jump-like" growth of the K_c indicator value when switching a communication link (with the data processing ground unit) from a distant geophone to a closer to the face one.

The acoustic vibrations propagate in fractured-porous coal and gas media on a solid frame. That is why the value of the gas pressure in coal cracks and pores has no influence on their attenuation coefficient. Hereof the second disadvantage of the prediction method "on the parameter of artificial acoustic signal" follows. It controls only the ground pressure factor. That is why it gives rather high accuracy in predicting dynamic phenomena in thin coal seams (for example, in Donbass Coal Basin mines). And, probably, it doesn't give accurate prediction in medium and hard power coal seams.

The prediction method based on analyzing the data registered by the systems of aero-gas control is fulfilled in the mines of Russia during downward development workings mining by drill and blast tunneling method on the steep-lying coal seams [*ZAO NTTs PBp,* 2019]. According to the received data the volume of the emitted from the face space methane is estimated. By its nature this method controls only a gas factor of the outburst danger and does not have high prediction veracity, a priori.

The reviewed geophysical prediction methods appeared due to so called phenomenological approach to their substantiation. To be exact, the experiments with registering acoustic emission in the process of destruction of different material samples gave the ground for appearing of prediction method "on acoustic emission". During the experiments it was revealed that when compressive or tension stresses reached the value equaled to about 70 per cent from the corresponding stress the acoustic emission activity started growing and reached its maximum [*Greshnikov and Drobot,* 1976]. Then the final stage of a short-time decrease in the acoustic emission activity followed ending up with destruction of the sample. That is why the abnormal growth of the acoustic emission activity is the feature for the beginning of the sample destruction. However, a face space of a working, in contrast to the tested sample that has finite dimensions, moves continuously. So, here, the acoustic emission behavior laws differ. Partially, the disadvantages of this method are reviewed above.

The basis for appearing of the method "on the parameters of artificial acoustic signal" was the results of acoustic emission impulses spectral analysis

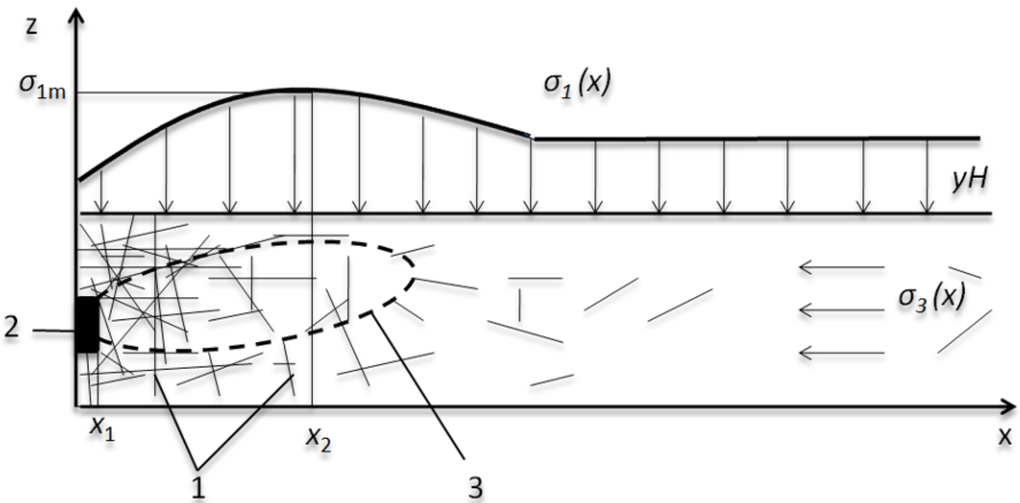

Figure 3. Squeezing the coal block out of the outburst cavity mouth.

registered while using the acoustic emission method for prediction at several Donbass mines. Relatively high veracity of the prediction at those mines gave a ground for some researches to assume that defining outburst danger indicator using (11) would be true for any coal mine. However, further experimental researches proved such conclusions wrong.

Similarly, the prediction method "on the data registered by aero-gas control systems" didn't get deep scientific substantiation.

In contrast to the phenomenological approach the "two stage preparation of a sudden outburst" method provides rather strict substantiation to the outburst danger factors influence on the veracity of geophysical prediction methods. Their influence at the first stage, at the stage of the crack propagation is reviewed above. The second stage, the stage of squeezing the coal out of the mouth of the initiated outburst cavity will be reviewed further.

The physical model of the given process is shown in Figure 3 [*Shadrin and Diyuk,* 2019a].

Here the following values are introduced: $\sigma_1(x)$ and $\sigma_3(x)$ – are vertical and horizontal components of normal stresses, correspondingly; 1 – cracks with the under pressure free gas, P; 2 – the outsqueezed coal block; γH – the stresses, out of the coal working influence zone (γ – the specific gravity of the overlaying rocks; H – occurrence depth from the ground surface); 3 – outburst cavity; σ_{1m} – is a maximal value of normal stresses vertical component in the zone of the heightened ground pressure; x_1 – is a critical distance from the face working, where a coal block stability condition is broken; x_2 – the distance from the working face to the maximum of the normal stresses vertical component.

At the mouth of the future outburst cavity active force f_a influences on the mine working side zone. This force consists of the stresses horizontal component σ_3 that acts on the surface of the contacting with the massif coal blocks, the free gas pressure P in cracks with the non-contacting sides. Gravity force of the squeezed out coal block is not taken into account due to little value [*Shadrin and Diyuk,* 2019a]. As a rule, in the future outburst cavity the coal is less hard and broken. That is why reaching the stresses of a certain limit value outsqueezing of this coal block starts.

The coal block is kept at place by a passive force f_p. Such force is a friction force of the outsqueezed area side surface on the neighboring more hard coal. Herewith it is assumed that the contact of the outsqueezed area along its perimeter with the non-outsqueezed part of coal goes along the whole surface of the area.

The condition for squeezing the coal block out into the coal working is given by the following expression [*Shadrin and Diyuk,* 2019a]:

$$\frac{f_a}{f_p} = \frac{F_1 + F_2}{f_p} \geq 1. \tag{14}$$

Here F_1 corresponds to the lateral pressure force (a horizontal component of normal stresses), F_2 – is a gas pressure in a crack force, f_p corresponds to the cohesive force and the internal friction force of coal in a massif.

As it is seen from (14) the influence of the ground pressure and the gas pressure on the stability of the outsqueezed block bears adaptive character as in case with the crack (see (9)).

The analysis of the stability criteria of both outburst preparation stages showed that three basic outburst danger factors are simultaneously significant. However, the traditional prediction method "on the parameters of artificial acoustic signal" takes into account, as it is said above, only the ground pressure. To take into account the gas factor and the coal strength it was offered to define medium stresses limit values σ_l using (7) and (14) and according to (13) it was also offered to calculate the outburst danger indicator critical value. As far as measuring the gas pressure in a seam continuously was impossible the decision was taken to use a well-known connection between the in-situ gas pressure and its concentration in the coal working atmosphere at the face [*Khodot,* 1961]. As a result, the following expression for defining the current critical value of the outburst danger indicator, simultaneously for both stages of outburst preparation was received [*Shadrin and Diyuk,* 2019b]:

$$K_{c,l} = \exp\left\{-Cd\left[\frac{P_1}{0.1\left(\frac{q}{110-q}\right)P_1 - \delta N\sqrt{\frac{Q\Omega}{\xi_i}}}\right]\right\}, \quad (15)$$

where $P_1 = 1$ MPa – is a normalizing factor conditioned by defining the coal strength limits through non-dimensional coal strength indicator q (d.u. – dimensionless unit) by the strength measuring device P-1; Q – air consumption of a booster fan that delivers the air to the workings, m^3/s; Ω – is a current value of methane concentration at the face working, measured by a sensor of the aero-gas control apparatus, %; ξ_i – the coefficient that takes into account the influencing degree (the share of freshly exposed area of a face) of i-th type equipment (a combined machine, a drilling rig etc.) on the face, $0 < \xi_i < 1$.

In (15) parameter N is defined as follows [*Shadrin and Diyuk,* 2019b]:

$$N = m(k_0 \eta P_{at})^{1/2} \times x_{cr}\exp\left(-\frac{x_{cr}}{x_{st}}\right)(100S_f)^{-1/2}, \mathrm{Pa\,s}^{1/2}\ \mathrm{m}^{-3/2}, \quad (16)$$

where m – is a constant value characterized by coal porosity; k_0 – is a coefficient that characterizes a coal seam gas-permeability, m^{-3}; η – is a dynamic methane viscosity, Pa s; P_{at} – is a gas pressure in the working face cavity equal to the atmospheric pressure, Pa; x_{cr} – is a critical distance from the face working, in the plane of which the crack is initiated or started propagating (for the first stage), or the outsqueezing of a coal layer takes place (x_1 – for the second stage of the outburst preparation), m; x_{st} – is the distance from the face to the massif area where gas pressure stabilizes, m; S_f – surface area of the development heading face, m^2.

Parameter δ in (15) is taken for that stage of the outburst preparation where it has a maximum value and equals [*Shadrin and Diyuk,* 2019b]:

$$\delta = \max\left\{\frac{\psi_{cr}}{3},\ (1-\varphi)\,10^{-2}\frac{r_e}{x_1}\right\}, \quad (17)$$

where φ – is a coefficient that defines the share of the outsqueezing coal layer area along which, the crack sides that separate this layer from the rest of the massif, tightly contact; r_e – is an effective radius of the outsqueezed coal layer.

The analysis shows that the real value area of both function arguments δ is in the limits from some tenth of a unit and close to 2, and they are comparable in values. That is why we can approximately take it as $\delta \approx 2$.

Parameter N for different stages of the outburst preparation differs with a multiplier $B = x_{cr}\exp(-x_{cr}/x_{st})$ as at the stage of a crack propagation x_{cr} corresponds to the distance from the working face to the top of the growing crack, and at the stage of the outsqueesing, the value x_{cr} equals to the thickness of the outsqueezed coal layer x_1. The performed estimations prove that the numeric values of this parameter equal correspondingly: for the stage of the crack $B \approx 0.1 - 20.0$ m; for the stage of the outsqueezed coal layer of the initiated outburst $B \approx 0.1 - 0.2$ m.

Thus, parameter N, that characterizes the outburst danger gas factor, for the stage of the crack development, changes in a rather larger value range than for the stage of a coal layer outsqueeezing. It results in the fact that the current limit value of the outburst danger indicator $K_{c,l}$, for the stage of the crack development distanced from the working face surface, in most cases is significantly lesser (in ten or hundred times) than for the stage of outsqueezing into the working of the coal layer into the mouth of the future outburst cavity. However, at a small distance from the working face this parameter is practically similar for both stages of the outburst preparation. That is why the registered growth of the acoustic emission activity is an important (the process of the block coal structure forming) but insufficient condition for initiating the outburst, as only at the edge of the face working side the criteria of the crack development are close to each other in values. Apparently this is the reason why despite of the application and improvement of the micro-seismic method during the last 70 years the veracity of the prediction of the dynamic phenomena is rather low. It can be supposed that the acoustic emission method will have a high level of a rock bump predication veracity in the left coal pillar. As in this case the controlled rock object is under the condition similar to the items controlled by the acoustic flaw-detection method.

Spectral-Acoustic Method of Outburst Danger Prediction

The method of current outburst danger prediction where the current value of the outburst danger indicator is defined using the parameters of an artificial acoustic signal, and its critical value is defined on the bases of measuring the gas concentration, using gas control apparatus, and the coal strength is defined using the strength measuring device P-1 will be further called spectral-acoustic one.

Thus, only the spectral-acoustic outburst danger prediction method, out of all geophysical methods, takes into account the basic outburst danger factors along the whole process of preparing sudden coal and gas outburst.

To show qualitatively how the gas factor influences on the critical value for the outburst danger indicator of the spectral-acoustic method in (15) it is necessary to estimate parameter N and assume that in the controlled coal seam the ground and the gas pressure factors that define outburst danger criterion are nearly equal. It is possible if in (9) $I_g \approx I_p$, and in (14) $F_1 \approx F_2$. Under this condition the summands, in the denominator of the fraction in (15) should also be close to each other on values:

$$0.1\left(\frac{q}{110-q}\right)P_1 \approx \delta N\sqrt{\frac{Q\Omega}{\xi_i}}. \qquad (18)$$

Assume, that before the dynamic phenomenon, when the current outburst danger value $K_c \approx K_{c,l}$, defined using (15), the methane concentration in the atmosphere of the working reaches the value $\Omega = 1\%$. Then, out of (18) under the $\Omega = 1\%$, $\delta = 2$ and $\xi_i = 0.1$, $P_1 = 1$ MPa we have:

$$N \approx 0.5\cdot 10^{-2}\left(\frac{q}{110-q}\right),\ \mathrm{s}^{1/2}\,\mathrm{m}^{-3/2}\,\mathrm{MPa}. \qquad (19)$$

The dependence of (15) type should be true under all possible coal strength values. That is why we define, using (19) the value $N_{\max}$ for $q_{\max} \approx$ 107 c.u., and get: $N_{\max} = 0.178$, $\mathrm{s}^{1/2}$ $\mathrm{m}^{-3/2}$ MPa.

In Figure 4 the dependency graphs of (15) type, when $\delta = 2$, $P_1 = 1$ MPa; $Q = 10$ m^3/s, $N_{\max} =$ 0.178 $\mathrm{s}^{1/2}$ $\mathrm{m}^{-3/2}$ MPa, $\xi_i = 0.1$, $d = 10$ m for different coal strength q. Coefficient C is taken under the following values of the parameters that define it: f_h, f_l and f_0 equal correspondingly 800, 300 and 500 Hz; $\alpha_0 = 1.3$ m^{-1}; $\beta = 0.07$.

It is seen from Figure 4 that with increasing the coal strength the critical value of outburst danger indicator grows up and with the methane concentration growing in the vicinity of the face working it decreases. Provided that when changing the coal strength and the methane concentration in the indicated limits the indicator $K_{c,l}$ changes nearly in 2 times. Hence, the conclusion follows that under the acceptable value of error of the second kind it is impossible to define the unified value $K_{c,l}$ for all possible conditions even in the limits of one mining seam.

We shall show that the connection between the parameters which define the gas factor and the complex factor that defines the stress state and the coal strength for instrumental and spectral-acoustic prediction methods has a similar nature. For instrumental method this dependence is defined by (2) and is introduced in Figure 1. In the instrumental method the gas factor defines the parameter $i_{\max}$, and the complex factor defining the stress state and the coal strength defines the parameter $S_{\max}$. For the geophysical criterion, the parameter Ω is set into one-to-one correspondence with the parameter $i_{\max}$ and the parameter $S_{\max}$ is set to one-to-one correspondence with the parameter ω, which is opposite to the coal strength q, since this parameter like the drilling fines output parameter is larger if the coal is less strong and the stresses are higher.

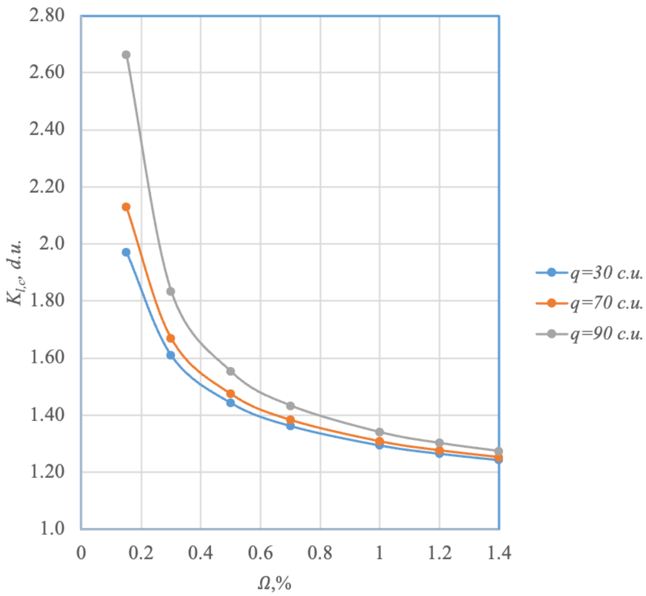

Figure 4. The dependence of the limit current outburst danger indicator $K_{c,l}$ on the methane concentration Ω (%) for different coal strength values q (c.u.).

We introduced the notation:

$$q = 1/\omega, \text{ c.u. (conditional unit).} \tag{20}$$

Then, out of (15) we get the expression for defining the family of curves for different values $K_{c,l}$ bounding the methane concentration with the value opposite to the coal strength:

$$\Omega = \frac{\xi_i P_1^2}{Q\delta^2 N^2}\left[0.01\left(\frac{1}{110\omega - 1}\right)^2 + 0.2\left(\frac{1}{110\omega - 1}\right)\frac{Cd}{\ln K_{c,l}} + \frac{C^2 d^2}{\ln^2 K_{c,l}}\right], \% \tag{21}$$

The family curves graph of (21) type under the same parameters that the graph in the Figure 4 is introduced in Figure 5.

Comparing the curves depicted in Figure 1 and Figure 5 which are described correspondingly by (2) and (21) the following can be seen. The geophysical outburst danger criterion of the spectral-acoustic method set for two-stage model of a sudden outburst preparation bears the same hyperbolic type of dependency from the gas factor and the coal strength that the instrumental method on initial gas-emission rate and drilling fine output during drilling the boreholes. Consequently, the geophysical spectral-acoustic method has approximately the same high prediction veracity as the instrumental method "on initial gas-emission rate and drilling fine output during drilling the boreholes".

However, if for the instrumental prediction method the critical values for outburst danger indicator for basic coal basins are known then for the spectral-acoustic method it is not known. It will be demonstrated further that comparing the prediction results of the instrumental and the spectral-acoustic methods applied simultaneously in one and the same face working it is possible to define the critical value for outburst danger indicator for the spectral-acoustic method.

Experimental Definition for the Critical Value of the Spectral-Acoustic Method Outburst Danger Indicator

The technique for defining is based on the comparison of prediction results obtained by the spectral-acoustic and the instrumental methods (on initial gas-emission rate and drilling fines output from the borehole). The methods should be performed simultaneously in one and the same face working. Notably, the instrumental method is used as the reference one as it proved to have high veracity of prediction during a long period of time.

The selection of the reference method should satisfy the similarity conditions. In this case these

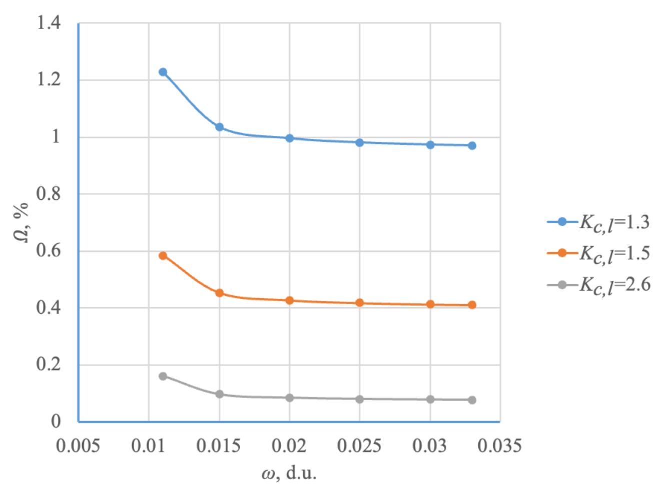

Figure 5. The family of dependences for current values of outburst danger criteria $K_{c,l}$ on the methane concentration in the vicinity of the face working and the value ω, opposite to the coal strength.

conditions are as follows. Both methods should take into account basic outburst danger factors. The outburst danger indicators and the criteria should be substantiated on the bases of the unified model of a sudden outburst preparation, in this case it is the force-based one. Outburst danger indicators range of values for both methods is in the interval of $(0; 1)$. The variant of the instrumental method described in [*Zykov,* 2010] satisfies these conditions. The outburst danger indicator for this method, in case of applying it in a development heading is marked as B_p, the critical value of this indicator is $B_{p,l}$.

The coefficient of relative outburst danger B_{rd} of the instrumental method we define as a ratio of experimentally measured value $B_{p,e}$ and the critical value of the outburst danger indicator:

$$B_{rd} = B_{p,e}/B_{p,l}. \tag{22}$$

Defining the experimental current value of the outburst danger indicator for spectral-acoustic method K_{ce}, when the combined machine is the source of sounding acoustic signal we write down the relative outburst danger coefficient K_{rd} as a ratio of the current experimental value K_{ce} and the current limit value (for the given moment and the given position of a face working) of the outburst danger indicator:

$$K_{rd} = K_{ce}/K_{cle}. \tag{23}$$

Assuming that the relative outburst danger coefficients of the instrumental and the spectral-acoustic methods are equal, i.e. $B_{rd} \approx K_{rd}$, and taking into account that $B_{p,l} = 1.0$ [*Zykov,* 2010], we find, experimentally defined for the given coal face working area, the current limit value of the outburst danger indicator for the spectral-acoustic method

$$K_{cle} = \frac{K_{ce}}{B_{pe}}. \tag{24}$$

This limit value of the outburst danger indicator can be used when applying the simplified variant of the spectral-acoustic method which is called the method "on the parameters of artificial acoustic signal" (not taking into the account the gas factor and the coal strength) during further development of the face working. However, the accuracy of the result will be reached under the condition if there is no aggravation of the outburst danger situation: a significant growth of methane concentration in the atmosphere of the working doesn't take place, the power of the broken coal layer doesn't increase or the coal strength doesn't lessen.

The given method was tested at JSC "Pervomayskaya" Coal Mine in Kuzbass at the air-heading face 370bis along the coal seam XXVII.

The research was done consequently by two methods of current outburst danger prediction, firstly, by the instrumental method "on the initial gas-emission rate and drilling fines output" and then by the geophysical method "on the parameters of artificial acoustic signal".

Measuring initial gas-emission rate in the controlling boreholes was fulfilled by standard equipment for performing instrumental method of outburst danger prediction. Simultaneously with the instrumental method the control of outburst danger gas factor was done by the methane control apparatus according to the readings of the sensor installed into the vicinity of a face working. The coal strength was estimated by the strength measuring device P-1. To air the face working the booster fan with 10 $\mathrm{m}^3/\mathrm{min}$ capacity was used. To control the outburst danger applying the method "on parameters of artificial acoustic signal" AK-1 device was used. The peculiarity of the readings of this device is that for convenient measuring results indication the value range of the outburst danger indicator is multiplied by a scale coefficient M. That is why, the indicated by the device, experimental value $K_{c,e} = M \cdot K_{c,e,r}$, where $K_{c,e,r}$ is a real experimental value of the outburst danger indicator. As a result the value range $K_{c,e}$ goes beyond the limits of the interval $(0; 1)$. According to the results of the measuring, the value of the outburst danger indicator for the instrumental method $B_{pe} = 0.74$ was defined.

After that, the place driving by the combined machine in cycles of 2 meters in length was started. During the excavation the maximal value of the methane concentration in the vicinity of the face working $\Omega_{\max}$, the maximal value of the outburst danger indicator received using the prediction method "on the parameters of artificial acoustic signal" $K_{e,\max}$ and the coal strength q were registered. The data is presented in the Table 1.

Further on, with the help of these results, using the technique introduced in [*Shadrin and Diyuk,* 2019b] the following coefficients C and N included into (15) were calculated. As a result, the following expression for calculating the current limit value of the outburst indicator for spectral-acoustic method was received:

$$K_{c,l} = \exp\left\{-0.0089d \times \left[\frac{P_1}{0.1\left(\frac{q_c}{110-q_c}\right)P_1 - 0.2\sqrt{Q\Omega_c}}\right]\right\}. \quad (25)$$

For each driving cycle, according to (24) the current experimental limit value of the outburst danger indicator for the prediction method "on the parameters of artificial acoustic signal" $K_{c,l,e}$ and according to the (25) for the spectral-acoustic method $K_{l,c}$, as if it is realized hardwarily, was defined.

The results of the calculations made as far as the face working advances are introduced in Figure 6.

As it is seen from Figure 6 if the methane concentration increases the limit values of the outburst danger indicator for both variants of prediction methods decreases. However, in the variant of the spectral-acoustic method with taking into account the gas pressure and the coal strength this dependence is much stronger. Consequently, for this variant the error probability of the first kind is less than for the method of prediction "on the parameters of artificial acoustic signal".

Results and Discussions

A zonal character of the coal seam outburst danger brings about the need in prediction systems that have high veracity of the obtained results. It is caused by the fact that the error in the prediction of the first kind may bring about the accidents and the error of the second kind causes unjustified expenses of time and resources on outburst preventive measures. So, high tempo of mining encouraged the development of geophysical prediction methods that did not interfere with the excavation process.

Early prediction methods were based on the phenomenological approach towards the substantiation of the controlling parameters. That is why, the simplified models of the sudden coal and gas outburst which took into account mainly one outburst danger factor were used. The acoustic emission method (or micro seismic one) took these factors into account in the fullest extent possible. It is based on controlling the process of a "jump-like" crack growth under the influence of the rock pressure and the in-situ gas pressure. However, seventy-year experience of applying this method in a numerous modifications demonstrated the lack of the prediction veracity. Also other methods showed the lack of the prediction veracity: the temperature method, the method "on the parameters of artificial acoustic signal generated by the operating mining equipment"; the method "on the data registered by aero-gas control systems".

The application of the two-stage model of the outburst allowed qualitatively and, in some cases quantitatively, estimating the influence of failing to take into account the certain outburst danger factors on the prediction veracity of the instrumental and the geophysical methods. As a result, it was demonstrated that the criterion of initiating the "jump-like" crack growth depends on the distance of the crack from the side of the working. In this connection the crack growth criterion is commensurable to the criterion of squeezing the coal out of the mouth of the initiated outburst cavity only if the crack is situated near the side of the working. As far as the distance between the crack and the side of the working grows the criterion of initiating the crack growth may be in ten or hundred times lower than the coal outsqueezing criterion. That is why the micro seismic prediction method witnesses about the performance of the necessary condition of the outburst preparation that is the initiation of the crack propagation but not about the sufficient condition of the coal outsqueezing.

The application of the spectral-acoustic method for controlling the whole process of outburst preparation from the stage of initiating the development of a crack to the stage of squeezing a coal block out into the working from the side of the face working was substantiated. It fulfills the control of the ground pressure by the method "on the parameters of the artificial acoustic signal of the operating equipment", the gas factor by the method "on methane concentration in the atmosphere of the working", the coal strength is measured with the help of the strength measuring device. Thus, the outburst indicator is defined by the method "on

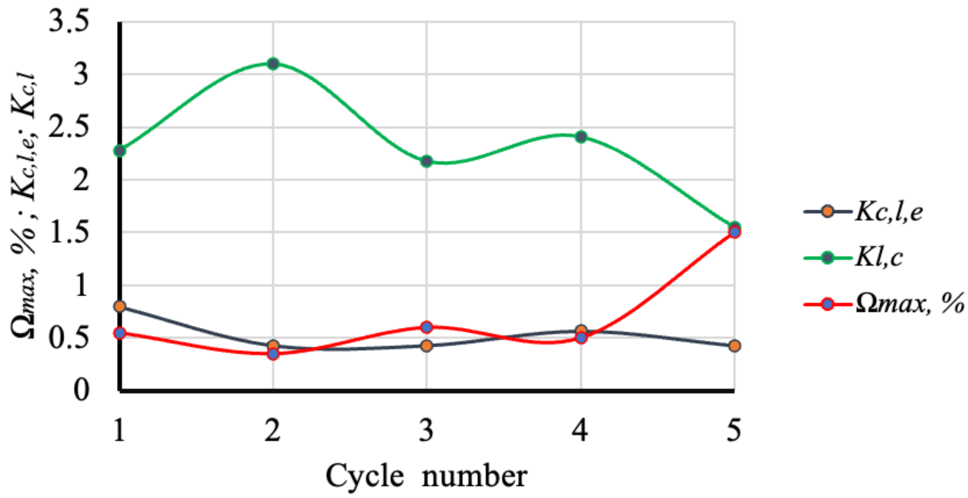

Figure 6. The dependence of the critical values of $K_{c,l,e}$ and $K_{l,c}$, indicators and methane concentration in the atmosphere of the working $\Omega_{\max}$ on the number of the face working driving cycle.

Table 1. Prediction Parameters of the Face Working Gas-Dynamic State While Carrying Out of the Experiment

Current time of day	Type of work	$\Omega_{\max}$, %	$K_{e,\max}$	q, c.u.
12:00	Prediction made by instrumental method	0.45		
14:20–15:45	Advance cycle 1	0.55	0.75	60
16:40–17:50	Advance cycle 2	0.35	0.4	60
20:30–21:20	Advance cycle 3	0.60	0.4	60
23:00–24:00	Advance cycle 4	0.50	0.53	60
06:10–08:40	Advance cycle 5	1.5	0.4	55

the parameters of the artificial acoustic signal" and its limit (critical) value is calculated according to the data on methane concentration and the coal strength.

Geophysical methods control the outburst danger factors only indirectly. That is why the outburst danger criterion for them should be set according to the prediction results made by the instrumental methods that control the processes which directly prepare the outburst. Thus, both methods should satisfy the similarity principles.

As such the prediction method "on the initial gas-emission rate and drilling fines output" was substantiated.

The idea of "tuning" the geophysical method is in experimental definition of the limit value for the outburst danger indicator during the development of a certain working. The "tuning algorithm" is in the consequent fulfillment of the instrumental and geophysical prediction methods, in comparing the outburst danger indicators and in defining firstly, the limit value of the outburst danger indicator for the spectral-acoustic method in a zone of the experiment and secondly, in defining the coefficients that are included into the calculation of the outburst danger indicator limit value for the spectral acoustic method taking into account the methane concentration in the atmosphere of the working and the coal strength. With the help of this expression the limit value of the outburst danger indicator can be defined continuously during mining.

At the modern coal mines, as a rule, several independent automated subsystems for controlling separate technological parameters of the mining methods are being applied. The systems for controlling the face working atmosphere parameters, for predicting dynamic phenomena by different methods together with the location of the microseismic phenomena with defining their coordinates and acoustic emission impulse parameters; the electric plants operating mechanisms temperature; the pressure of the supports etc. are referred to them. Totally these subsystems form a multifunctional safety system of the mine. As it is demonstrated in this paper to get the accurate current outburst danger prediction, the data, which are received by the method for controlling ground pressure "on the parameters of artificial acoustic signal" and the mine atmosphere aero-gas control equipment which gives the data on methane concentration and the coal mine booster fan capacity are needed.

In the perspectives, for improving the veracity of the prediction, the prediction system can be completed by other data. This subsystem as any other classical informational system of the automated control should include functional and supporting parts. It is substantiated that outburst danger prediction subsystem should be connected with the aero-gas control subsystem.

Conclusion

All the above-given data serve as a substantiation for the development of the continuous outburst danger prediction informational system of high result veracity. And this system can be included into a multifunctional safety system of a coal mine.

Acknowledgments. The reported study was funded by RFBR and Kemerovo region, project number 20-45-420014.

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