ANALYSIS OF METHANE AND DUST EXPLOSIONS IN MODERN COAL MINES IN RUSSIA

Valery V. Smirnyakov
Ph.D., Associate Professor, Department of Industrial Safety, Saint-Petersburg Mining University, Russian Federation, 199106, Saint- Petersburg, 21 Liniya, 2

Victoria V. Smirnyakova
Ph.D., Associate Professor, Department of Industrial Safety, Saint-Petersburg Mining University, Russian Federation, 199106, Saint- Petersburg, 21 Liniya, 2

Danil S. Pekarchuk
Postgraduate Student, Department of Industrial Safety, Saint-Petersburg Mining University, Russian Federation, 199106, Saint- Petersburg, 21 Liniya, 2

Fedor A. Orlov
Postgraduate Student, Department of Industrial Safety, Saint-Petersburg Mining University, Russian Federation, 199106, Saint- Petersburg, 21 Liniya, 2

ABSTRACT
The authors conducted a detailed analysis of accidents circumstances associated with explosions of gas and dust during the period from 1991 to the present day. The assessment results of emergency situations causes carried out by statistical methods and methods of technical analysis are provided. The conducted researches showed that currently there is a steady trend towards stabilization of accidents number, despite the high technical equipment of the enterprises and enhancement of the main direction of methane control - ventilation and draining-out of gases - widely used in mining enterprises. The reason for this, in the opinion of the authors, is the fact that the factors affecting the gas situation within the excavation site can be classified as manageable and difficult-to-control. The signs making it possible to attribute factors to manageable ones, provided by the technology of works performance have been proposed. It is shown that the affect on the controllable factors with strict occupational health and safety and technology of works compliance minimizes the risk to the magnitude of the acceptable risk. The factors affecting the stability of the process of ventilation and having a natural or mixed natural and anthropogenic character are advised to qualify as the difficult-to-control ones. In the process of investigation, the additional accounting and classification of difficult-to-control
factors in combination with other causes will allow you to evaluate more completely, the places, circumstances and structure of their interrelationships, the ways of development and nature of accidents, identify the maximum number of violations in case of accidents. The probability of complete detection increases when investigating the accidents across spatial and temporal chain of causes. The improving safety management in mining practice is only possible at the differentiated approach to the role of each factor that may affect the accident emergence and development.

**Keywords:** causes of explosions, coal dust, explosions of gas and dust, methane, underground accidents.

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1. **INTRODUCTION**

Problems of ensuring safety of mining operations acquire special significance when they are conducted in conditions of combustible gases release to the atmosphere and the presence in the operating areas of the explosive dust accumulations. The release of combustible gases is observed in almost all currently operating coal and potash deposits in Russia and in the mines of Germany, Poland, France, USA, China [1-15]. In Russia, the majority of coal mines and potash mines that are currently operated, are gas-bearing [16, 17]. More than 86% of coal mines are dangerous with regard to explosion of gas and coal dust, among them more than 50% of coal mines belong to extra-categorical on methane and dangerous on sudden emissions [18-21].

Explosions of methane and dust are the most severe and complex consequences of an accident. According to their localization they occur most frequently in the development openings and stopes of faces, and as for consequences severity, the most dangerous are explosions of methane-dust-air mixture in the working areas developments [22, 23]. The causes of such accidents often are of complex nature and cannot be effectively eliminated by certain measures.

The problems solution of improving safety of conducting works in conditions of gas and dust factors is possible only on the basis of comprehensive analysis of all the causes, circumstances, conditions of accidents occurrence and development. Special attention should be paid to identifying the structural diagram of accident occurrence with the establishment of elements manageable by those means and methods of safety provision that are in operational service with modern mining enterprises. Based on the results analysis of the structure and interrelation of causes, it is possible to develop measures, the maximally focused on preventing the combination of those conditions and circumstances at the confluence of which there is one or the other accident takes place [17, 24-26].

In this regard, a thorough analysis of the entire chain of causes, general and direct, contributing and accompanying the accidents is required with the aim of developing a system of scientifically substantiated measures to ensure the safety in conducting works under conditions of dust-gas mode, given the multitude of natural, technical, organizational factors [27, 28].

The statistics of the last two decades shows that in the world, at average, one major disaster takes place annually in coal mines and mining plants, when the death toll is a
hundred people or more, and several smaller-scale incidents when several people die. The statistics in relation to specific conditions is very conditional, if you take into consideration that a significant proportion of global production over the past forty-eight years accounts for the developed foreign countries where there were no explosions of gas and dust with heavy consequences, and the number of dead miners was relatively small. This is due to the fact, that in some developed countries the underground coal mining is almost completely or partially terminated, in others - the extensive reconstruction and the companies enlargement, in the thirds - the mass closure of uneconomic and hazardous enterprises. The latter two trends in the development of the mining industry was actively introduced in the mines of Russia starting from 90-ies of the last century.

At the same time, in the world in recent years, the mining industry in underdeveloped countries vigorously developed, where the proportion of major accidents remained always high, and with the implementing new methods of production intensification it has increased to such an extent that there has been a global trend to increasing in the number of major accidents. The People's Republic of China has become a so-called leader in accidents, producing about 35% of the world's coal production, but along with this, it accounts for 80% of all accidents and deaths among miners, the significant proportion of which is due to gas and dust explosions

At the same time, the proportion of minor accidents associated with explosions of gas and dust remains almost constant in all the mining countries of the world. The reasons of such statistics has been well studied: episodic effect of natural or technical factors in developed countries and organizational effects at the background of natural and technical factors of developing countries [29].

According to the statistics of gas and dust explosions, in the last two decades, under current conditions Russia took the intermediate position between the developing and developed countries. Currently, in the Russian mines, at average every 2 years, a group accident with numerous casualties caused by explosions of methane and dust, and three to four accidents of smaller scale and consequences (Federal Service for Ecological, Technological and Nuclear Supervision) take place [30].

2. METHODS
To obtain reliable results of the accidents causes investigation making it possible to develop specific measures aimed at improving the gas factor safety of mining operations, the comprehensive implementation of both statistical and detailed technical analysis is required.

Statistical methods of analysis are based on the study of data quantitative indicators of accident reports at enterprises and organizations. They consist of traumatism study according to the documents: reports, acts, registration logs. This allows you to group the cases and causes of accidents according to certain characteristics: occupation of injured or aggrieved persons, work places, experience, age, respective reasons and equipment resulting in injury. Varieties of statistical methods of analysis are as follows: tabular or graphical analysis, injury rate analysis, topographic method, correlation paired and multiple analysis. The statistical analysis when investigating the cases of gas and dust explosions can be implemented with the following methods.

1) The frequency array tables represent the simplest method for the analysis of categorical variables. The frequency array tables are also used for study of quantitative variables. This kind of statistical study is often used as one of the procedures of exploratory analysis to see how different groups of observations are distributed in the sample, or how the characteristic
value is distributed in the interval between the minimum and the maximum value. The frequency array tables are illustrated graphically using histograms.

2) Cluster analysis is a method of classification analysis; its main purpose is the separation of the set of investigated objects and characteristics into uniform, in some sense, groups or clusters [31, 32]. It is a multidimensional statistical method, so it is assumed that the source data can be of a considerable amount, i.e. essentially big could be both the number of research objects (observations) and features characterizing these objects. With this, the objects belonging to one cluster should be homogeneous (similar), and the objects belonging to different clusters - heterogeneous.

Most often, when assessing the emergency situation associated with gas and dust explosions, the simplest statistical method is applied the purpose of which is obtaining data on the distribution of accidents frequencies and probabilities per certain groups (clusters) in the mine space and per time.

The technical methods of analysis are carried out for establishing the interrelations of causes and technical factors resulted in the accident and for developing preventive measures for preventing such events as well. According to the result, the qualitative picture of the events development is established and the quantitative indicators of the determining factors are determined. Varieties of technical methods of analysis are as follows: monographic method, questionnaire method, method of expert assessments.

Monographic method provides for a multianalysis of accidents causes at the workplaces. With this, the organization and working conditions, equipment, inventory items, and tools conditions are studied. This method is also effective in statistical analysis of the labour conditions. Monographic method involves more thorough examination of the whole complex of working conditions, manufacturing process, workplace equipment, working practices, sanitary-hygienic conditions, means of collective and individual protection. In other words, this method consists in the analysis of dangerous and harmful production factors inherent to only one or the other (mono) production area, equipment, manufacturing process. According to this method, all the circumstances of the accident are investigated in-depth, and if necessary, the appropriate examinations and tests are performed. Study subjects: workshop, site, manufacturing process, main and auxiliary equipment, labor methods, personal protective means, conditions of the workplace environment, aerological conditions in digging, illumination, gas content, dust content, noise, vibration, radiation, causes of accidents that happened earlier at this workplace. Thus, the accidents circumstances and causes are studied comprehensively.

The questionnaire method consists in the fact that the questionnaire are developed for workers interrogation in which safety-related issues are considered. On the basis of questionnaire data (answers to questions), the accidents circumstances are determined and precautions to prevent the accidents causes are developed.

The method of expert evaluations is based on expert conclusions (evaluations) of working conditions, on the compliance identification of the process equipment, devices, tools, manufacturing processes compliance with standards and ergonomic requirements relating to machines, mechanisms, equipment, tools, and control panels.

The technical investigation is intended to establish maximally possible accuracy of the accident cause, to define measures on eliminating its consequences and the suffered object restoration, to define material damage, develop the necessary measures and proposals to prevent similar accidents at this and other related objects and enterprises. Technical investigation of accident causes is carried out by a special Commission in composition and order determined by normative documents.
3. RESULTS

Statistical methods for evaluating the accidents frequencies distribution and probabilities of their occurrence per certain groups (clusters) made it possible to obtain the following data [19, 33].

The analysis of change dynamics in number of explosions of gas and dust in coal mines over the period from 1991 to 2016 allowed establishing the following picture. During this period, there were 209 explosions, 26 consequences of which can be referred to catastrophes. The maximum number per year was 17 explosions (1992). All recorded explosions happened at 60% of the total number of mines. With this, more than 80% of the explosions took place at 30% of the total number of mines. 1580 person injured, including 811 persons were fatally injured (Federal Service for Ecological, Technological and Nuclear Supervision. Information bulletin. 2002-2016).

Data analysis per regions showed that the largest number of explosions - at average of more than 76% per year - took place at the Kuzbass mines, in certain periods the figure was 100% (1999). The results are shown in Figure 1.

**Figure 1** The distribution of gas and dust explosions per regions of Russia

The conducted statistical data processing of accidents researches aimed at tasks and objectives determination showed that currently there is a steady trend towards stabilization of accidents number, despite the high technical equipment of the enterprises and enhancement of the main direction of methane control - ventilation and draining-out of gases - widely used in mining enterprises.

Although the observed trend indicates a decrease in the number of accidents, however, the average number of accidents tends to a constant value different from zero that now can be assessed as 4 explosions per year, that generally corresponds to the global trend.

The relevance of the problem is confirmed by the fact that the relative indices of accidents caused by gas and dust explosions at the Russian mines, after production shut down and more than 100 of the most dangerous mines liquidation, given to the number of operating mines, remain virtually unchanged over the past two decades (Figure 2).

**Figure 2** The distribution of explosions by mine categories

The most significant number of explosions - 83% happened at the mines referred to extra-categorical and methane outburst-prone. In general, the number of explosions can be
considered proportional to the mines category by methane. Cases of coal dust explosion in non-gaseous mines were observed - 1% [20, 21].

Analysis of the gas and dust explosions epicenters allowed us to establish that most often the explosions take place in the goafs (27%) and at the working areas that work out the areas of flat dip (25%). A significant number of explosions observed in blind workings (23%) and at working areas working out the areas of flat dip (20%).

The analysis results of the ventilation schemes of different types of workings is shown in Figure 3. The basic number of explosions was observed in the areas ventilated by return flow schemes, as well as on the areas of steep dip. With these schemes, this is accounted for significant amounts of abandoned workings, that are the main sources of gas ingress in the working areas.

Figure 3 The distribution of explosions depending on the type of ventilation scheme of the site working

Common causes of accidents in mine workings resulted in the violation of ventilating mode, and as a consequence, to the explosions given in the investigation materials, can be represented as the following list [27, 34]:

1) Uncontrolled redistribution of air between the workings.
2) Changes of the mining machines operation mode and the organization of work in the direction of acceleration, without taking the appropriate measures on increasing air supplied to the mine face.
3) Mining and geological conditions change.
4) Poor strata control.
5) Poor isolation of goaf, the presence of voids, large air leaks.
6) Malfunction of ventilation at end cuts.
7) Low speed of air movement along the roadway.
8) Intensive release of methane from the broken-down coal, the free array, wall face and workings in the process of post-explosion works.
9) Sudden emissions of coal and gas, bleeding.
10) Wrong degassing of the earlier sealed workings
11) Scheduled shutdown of main and auxiliary fans
12) Restriction of air supply in the mine or workings (including by the managers instruction).
13) Use of imperfect schemes of strata drilling in, preparation and extraction, development systems.
14) Absence of mines degassing, when it is impossible to ensure the methane concentration in the atmosphere of some mines within the permissible limits by means of ventilation.
15) Poor state of the main fans and ventilation network.
16) Engineering errors in calculations and measurements of air, including when operating the main fans.
17) Incorrectly selected mode of ventilation when eliminating accidents, caving, blockages.
18) Thermal drop of ventilation pressure arising from fires.
19) Poor control of the ventilated mine workings.
20) Natural and associated with them factors.

These data provide an idea about the causes nature of the mine ventilation malfunction but do not reflect their quantitative ratio and the structures of interrelations between them. Often, in one general formulation of the cause, several different in nature factors is hidden. To determine all the circumstances of the probable causer, as well as the accident nature, such classification is not sufficient. Such information is also unsuitable for statistical processing.

The most complete and reliable information about places, circumstances, ways of development and nature of accidents also enabling to identify the maximum number of malfunctions, can be obtained during their investigation, in course of which the methods of technical analysis and expert evaluations are used. The main task of such accidents circumstances study is to identify causes and sources: first, the appearance of explosive concentration of gases and dust in mine workings, and secondly, their ignition and explosion.

With this purpose, to systematize all the causes that led to accidents, their cluster division was accepted according to the major factors - natural, technical, organizational - inherent in mining operations.

Comparative results of common statistical and technical methods of the analysis of ignition sources causes that resulted in gas and dust explosion are shown in Figure 4 and in Table 1.

![Figure 4 Results of the general statistical analysis of ignition sources](image-url)

Methods of statistical analysis can give primarily quantitative assessment on the causes of ignition and gas content composition but do not allow you to track the entire cause-effect chain of events that led to the accident, i.e., does not reflect the structure of interrelations between them.

Comparative results of general statistical and technical methods for analyzing the causes of combustible gases presence in the workings atmosphere that resulted in explosions are shown in Figures 5-7 and in Table 2.
**Table 1** Results of the technical analysis of ignition sources

<table>
<thead>
<tr>
<th>Factors</th>
<th>The source of ignition</th>
</tr>
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</table>
| Natural            | 1) Malfunctions of electrical equipment, and damages in cable networks from external natural causes.  
2) Processes of spontaneous combustion (breeding fires).  
3) Roof rocks caving during the rock pieces interaction between each other.                                                                                     |
| Technical          | 1) Malfunctions of electrical equipment, and damages in cable networks from the external technical causes.  
2) Freely burning fires.  
3) Blasting operations, including: detonating charge of the explosive, burnout charge, sparking in the blasting circuit and other sources.  
4) Hot bodies, including: from the process of friction, from the faults in electrical networks, welding works and smoking (as a source of ignition).  
5) Frictional sparking, including: under the interaction of equipment and rocks and under the interaction of the equipment parts.  
6) Discharges of static electricity: under the equipment operation and under clothing interaction.  
7) Ignition of oxygen self-rescuers.  
8) Damage of cap lamps.                                                                                                                                 |
| Organizational     | 1) Violation of operation and equipment repair rules.  
2) Violation of labor and production discipline (facts-finding of smoking, welding works).  
3) Poor monitoring of the equipment and workings state.                                                                                                         |

**Figure 5** The results of general statistical analysis of the natural causes of gassed air in workings

**Figure 6** The results of general statistical analysis of the technical causes of gassed air in workings
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Figure 7 The results of general statistical analysis of the organizational causes of gassed air in workings

Table 2 The results of technical analysis of the causes of gassed air in workings

<table>
<thead>
<tr>
<th>Factors</th>
<th>Cause and source of gas release</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural</td>
<td>1) Change in mining and geological conditions (mine mass).</td>
</tr>
<tr>
<td></td>
<td>2) Intensive release of methane from the loose coal, wall face, working side walls and mined-</td>
</tr>
<tr>
<td></td>
<td>out space.</td>
</tr>
<tr>
<td></td>
<td>3) Sudden outbursts of coal and gas, bleeders (mine mass).</td>
</tr>
<tr>
<td></td>
<td>4) Changes in barometric pressure (mined-out space).</td>
</tr>
<tr>
<td></td>
<td>5) Caving of roof rocks (mined-out space, mine mass).</td>
</tr>
<tr>
<td></td>
<td>6) Thermal drop of ventilation pressure arising at breeding fires (mined-out space).</td>
</tr>
<tr>
<td>Technical</td>
<td>1) Breakdown of ventilation mode due to air distribution between workings (all sources).</td>
</tr>
<tr>
<td></td>
<td>2) Poor insulation of mined-out space, presence of caving, large air leaks (mined-out space,</td>
</tr>
<tr>
<td></td>
<td>mine mass).</td>
</tr>
<tr>
<td></td>
<td>3) Malfunction of ventilation at end cuts (borehole zone).</td>
</tr>
<tr>
<td></td>
<td>4) Low air speed in workings (all sources).</td>
</tr>
<tr>
<td></td>
<td>5) Scheduled fans shutdown of the of the main and local ventilation (all sources).</td>
</tr>
<tr>
<td></td>
<td>6) Restriction of air supply to the mine or on site (all sources).</td>
</tr>
<tr>
<td></td>
<td>7) Use of imperfect schemes of strata drilling in, preparation and extraction, development</td>
</tr>
<tr>
<td></td>
<td>systems (all sources).</td>
</tr>
<tr>
<td></td>
<td>14) Absence of mines degassing, when it is impossible to ensure the methane concentration in</td>
</tr>
<tr>
<td></td>
<td>the atmosphere of some mines within the permissible limits by means of ventilation (mined-out</td>
</tr>
<tr>
<td></td>
<td>space, mine mass).</td>
</tr>
<tr>
<td></td>
<td>9) Fans poor state of the main ventilation and the ventilation network (all sources).</td>
</tr>
<tr>
<td></td>
<td>6) Thermal drop of ventilation pressure arising at breeding fires (mined-out space, mine mass).</td>
</tr>
<tr>
<td></td>
<td>5) Poor strata control (mined-out space, mine mass).</td>
</tr>
<tr>
<td>Organizational</td>
<td>1) Changes in mining mode and the organization of work in acceleration without the increase</td>
</tr>
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<td></td>
<td>of air feed in faces (all sources).</td>
</tr>
<tr>
<td></td>
<td>2) Violations during the degassing of the earlier sealed workings (all sources).</td>
</tr>
<tr>
<td></td>
<td>3) Engineering errors in calculations and air measurements (all sources).</td>
</tr>
<tr>
<td></td>
<td>4) Wrong mode of ventilation during accident elimination (all sources).</td>
</tr>
<tr>
<td></td>
<td>5) Poor ventilation control in mine workings (all sources).</td>
</tr>
</tbody>
</table>

Technical analysis of the relationship between factors of the mining operations and the causes for formation and appearance of dust explosive concentrations in mine workings allowed us to obtain the results given in Table 3.
Table 3 The results of the technical analysis of the causes for formation and appearance of dust explosive concentrations

<table>
<thead>
<tr>
<th>Factors</th>
<th>Cause and sources of dust formation and release</th>
</tr>
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</table>
| Natural      | 1) With increasing mining depth, the coal humidity is reduced resulting in increase of dust explosive properties.  
2) With increasing mining depth, the dust formation at the destruction of unmined coal increases.                         |
| Technical    | 1) Using the mining machines with high performance has dramatically increased the amount of dust per unit of loose coal mass and dust formation all over the stope.  
2) Due to the intensive ventilation, dust spreads far beyond the stope and the working area.  
3) Increase in the speed of air jet along the conveyor workings contributes to dust spreading almost throughout the mine.  
4) The use of continuous conveyerisation for mined rock delivery contributes to secondary dust generation |
| Organizational | 1) Imperfect methods for dust prevention.  
2) Absence of automatic instrumental control of suspended and settled dust.  
3) Poor monitoring of the mine workings dust explosion prevention state.                                                      |

4. DISCUSSION

According to the comprehensive analysis of the interrelation between the provided data concerning the explosions causes and sources, the conclusion can be made about the complex nature of the interrelation structure of such accidents causes like gas and dust explosions in mine workings. Under the investigation results, none of the causes can be accepted as the only one in the result of which the accident took place. For example, the organizational cause such as unsatisfactory ventilation control (state) in mine workings, is often a consequence of a number of technical and natural factors. Therefore, the current classification of all the causes in the form of list, separated per factors of mining operations, in our view, does not fully reflect its specificity. The so-called "human factor" as the main cause presents directly or indirectly in 98 % of all accidents and incidents. However, the human capacity to manage the situation aimed at preventing the accidents occurrence and development is limited and do not exceed in some cases 30 %.

The reason for this, in our opinion, is the fact that the factors affecting the gas atmosphere within the working area can be further classified as manageable and difficult-to-control, in other words, they are difficult to be control and managed by the available means.

All factors provided for by the organization and technology of conducting the works belong to manageable ones. Their main feature is the presence in the work schedule of measures able to control their influence. Mine workings ventilation and degassing of mass can be the example. The affect on the controllable factors with strict occupational health and safety and technology of works compliance minimizes the risk to the magnitude of the acceptable risk.

The factors affecting the stability of the process of ventilation and having a natural or mixed natural and anthropogenic character belong to the difficult-to-control ones. These includes: natural factors - change in barometric pressure; natural and anthropogenic factors - unsustainable redistribution of air due to changes in the magnitude of leaks into the caving area; geomechanical factors – changes in the structure of the caving area, the caving of the roof rocks in the mined-out space; anthropogenic factors - formation of local accumulations of methane in stagnant spaces.
Analysis of accidents causes showed that due to the affects of only difficult-to-control factors there have been 13.7% of the total number of accidents occurred over the past 25 years, and their partial effect was observed in more than 51% of the total number of accidents. Thus, although for the overwhelming number of accidents the organizational and technical violations in people's actions are recognized as the main reasons, difficult-to-control factors can not be discounted classifying them as contributing or associated, and under certain conditions as the main or direct components of the accident causes.

5. CONCLUSION
Additional accounting and classification of difficult-to-control factors in combination with other causes will allow us to more fully assess the places, circumstances and structure of their interrelations, the accidents ways of development and nature, to identify the maximally number of violations in case of accidents, and, consequently, to reveal temporal and spatial chain from contributing and associated to the main and immediate causes. In our opinion, it is possible to improve safety management in mining practice at the differentiated approach to the role of each factor that may affect the accident occurrence and development. With this, it is necessary to evaluate the possibility of changing influence of each factor in time and in space workings of the mining enterprise. For example, such natural factor as barometric pressure change that is practically out of control, is able to influence the gas situation of the working area for a long time - up to several days [35]. On its background, the other difficult-to-control, natural-anthropogenic factor - caving of the main roof rocks, can dramatically and for a short period of time affect the gas emission from the mined-out space. The result of the combined effect of these factors can be assessed as the reasons for deterioration of the gas situation in the working area, i.e. the probability of gas content in the working zone, and as a consequence - the accident occurrence. To normalize the atmospheric composition in the workings in similar conditions, it is necessary to provide for additional technical and organizational measures, for example to increase air supply to the area and improve monitoring over the equipment of automatic gas protection.

Thus, a comprehensive analysis of safety violations cases and causes of accidents during mining operations, conducted according to the results of the accidents investigation associated with dust and gas explosions, has allowed us to determine the existence of factors, the control and management of which is difficult in the process of mining activities. Timely consideration of these factors will significantly enhance the aerial safety of the mining.

REFERENCES
Analysis of Methane and Dust Explosions in Modern Coal Mines in Russia


