Comprehensive Analysis and Assessment of the Role of Hard-to-Handle Factors in the Reasons of Methane and Coal Dust Explosions in Mines in Russia

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The authors made a detailed analysis of the circumstances and reasons of accidents caused by explosions of gas and dust in the period from 1990 till present. The results of the assessment of accidents reasons made using statistical methods and methods of technical analysis have been shown. The research has shown that currently there is a steady trend towards stabilization of the number of accidents, despite the high level of technological infrastructure at enterprises and improvement of the main methods of fighting methane, i.e., venting and degassing widely used in mining enterprises. The reason for this, in the opinion of the authors, is the fact that the factors that influence gas situation in working areas can be classified as those manageable and those hard to manage. Factors have been proposed that make it possible to classify the factors provided for by the work practice as the manageable ones. It was shown that the impact on the manageable factors in strict compliance with occupational safety and working methods minimizes the danger to the level of acceptable risk. It is proposed to classify as hard-to-manage those factors that affect the sustainability of the ventilation process and have natural or mixed natural and technogenic nature. Additional accounting and classification of hard-to-manage factors in conjunction with other reasons will make it possible to assess more comprehensively, during investigation the place, the circumstances and the structure of their relationships, ways of development and nature of accidents, and to identify the maximum number of violations in case of accidents. The probability of complete detection during investigation of accidents increases in the whole time and space chain of reasons, from facilitating and accompanying to the main and immediate ones. Safety management in mining production may only be improved by means of a differentiated approach to the role of each factor, including the hard-to-manage one that can affect emergence and development of an accident.

Key words: gas and dust explosions, methane, coal dust, underground accidents, explosion reasons, accident analysis.

The problems of ensuring safety in mining operations become particularly significant when these are performed in the conditions of combustible gases products emission into the atmosphere and the presence of explosive dust accumulation in the working areas. Flammable gases mission is observed at almost all currently operated coal and potash deposits in Russia, as well as in the mines of Germany, Poland, France, USA, and China (Petrosyan, 1998). In Russia the majority of the currently operated coal and potash mines are gas-bearing (Plontikov, 1992). Explosions of gas and coal dust are dangerous in over 86 % of coal mines, out of which over 50% of coal mines belong to over-classified in terms of methane

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content and are prone to sudden outbursts (Paleev et al., 2011).

Explosions of methane and dust are the most severe and complex in terms of accident consequences. By their location, they most often occur in cut faces of preparatory and room excavations, and by the severity of consequences the most dangerous are explosions of methane-dust-air mixture in excavation sites (Paleev et al., 2011). The reasons of such accidents are often complex and cannot be effectively eliminated with individual measures.

The problem of improving work safety in terms of gas and dust factors can only be solved on the basis of comprehensive analysis of all reasons, circumstances, and conditions of occurrence and development of accidents. Special attention should be paid to identifying structural pattern of accident occurrence with establishing elements that can be managed by the means and methods of ensuring safety used in modern mining enterprises. Based on the results of the analysis of the structure and the relationships between the reasons, measures may be developed that are most aimed at preventing the combination of conditions and circumstances that cause a certain accident.

In this regard, a careful analysis is required of the entire chain of the general and direct reasons that contribute to and are related to accidents, in order to develop a system of scientifically-based measures for ensuring work safety in the conditions of dust and gas regime with regard to numerous natural, technical, organizational factors.

The statistics for the last two decades shows that on the average in coal mines in the world there is one major accident every year, when the number of fatalities is one hundred people or more, and several smaller-scale accidents, where several people are killed (Romanchenko and Vasilevski, 2005). The statistical data in relation to specific conditions are very conditional, if one takes into account the fact that in developed countries that account for a significant share of the global production, no explosions of gas and dust occurred with severe consequences over the last forty-eight years, and the number of killed miners is relatively small. This is because in some developed countries, underground coal mining is almost completely or partially terminated, in other countries, large-scale reconstruction and amalgamation of companies occurs, in other countries - unprofitable and dangerous enterprises are massively closed. The last two trends in development of the mining industry have been actively implemented in the mines in Russia since the 90s of the last century (Lebetski and Romanchenko, 2012).

At the same time, in recent years, the mining industry in underdeveloped countries has been intensively developed, where the share of major accidents has always remained high, and with the introduction of new intensification methods of production it increased to such an extent that there has appeared a global trend to increasing the number of considerable accidents. People's Republic of China has become a kind of a leader in accidents; its share in the world's coal production is about 35%, but it accounts for 80% of all accidents and deaths among miners, a large portion of which falls on gas and dust explosions (Federal Service for Ecological, Technological and Nuclear Supervision, 2006).

At the same time, the share of minor accidents caused by gas and dust explosions remains almost constant in all mining countries of the world. The reasons for such statistics are fairly well studied: episodic action of natural or technical factors in developed countries, and organizational factors on the background of the impact of natural and technical factors in developing countries (Paramilitary mine rescue troops in mining enterprises of the metallurgical complex, 2006).

According to the statistics of gas and dust explosions within the last two decades, Russia in the current conditions takes a middle position between the developing and developed countries. Currently, in the mines in Russia, one group accident with multiple casualties occurs once a year on average, being caused by methane and dust explosions, and three or four minor accidents (Federal Mining and Industrial Inspectorate of Russia, 2004).

METHODS

In order to obtain reliable results of studying the reasons of accidents that would make it possible to develop specific measures aimed at improving safety of mining operations with regard to the gas factor, a comprehensive implementation of both statistical and detailed technical analysis is required.

Methods of statistical analysis are based on studying quantitative indicators from report data about accidents at enterprises and in organizations. They consist in studying documents about traumatism: reports, acts, logbooks. This makes it possible to group the cases and reasons of accidents by certain indicators: professions, jobs of the injured, experience, age, related reasons, equipment that caused the injury. Varieties of statistical methods of analysis are: tabular or graphical analysis, analysis by indicators of injuries, topographic method, paired correlation and multiple analysis. Statistical analysis in studying cases of gas and dust explosions can be implemented by the following methods.

1) Frequency tables are the simplest method of analyzing categorical variables. Frequency tables are also used for studying quantitative variables. This type of statistical research is often used as a procedure of exploratory analysis in order to see how various observed groups are distributed in the sample, or how the characteristic value is distributed between the minimum and the maximum values. Frequency table can be graphically illustrated with histograms.
2) Cluster analysis is a method of the classification analysis; its primary purpose is the decomposition of a set of studied objects and characteristics into somewhat uniform groups, or clusters. This is a multivariate statistical method, it assumes that the source data may be of significant value, i.e., both the number of research (observations) objects, and the characteristics of these objects may be significantly greater. With that, the objects belonging to the same cluster must be homogeneous (similar), and the objects belonging to different clusters are to be heterogeneous.

Often, in assessing an emergency situation related to dust and gas explosions, a simple statistical method is used, the purpose of which is to obtain data by distribution of frequencies and probabilities of accidents occurrence in certain groups (clusters) in the space of the mines, and in time (Medvedev, 2009).

Technical methods of analysis are aimed at finding the relationship between the reasons and technical factors that caused the accident, and developing preventive measures for avoiding such events. As a results, a qualitative picture of events development is found, and quantitative indicators determining factors are defined. Kinds of methods of technical analysis are: the monographical method, questionnaires, method of expert assessment.

The monographical method stipulates multilateral analysis of the reasons for accidents at workplaces. With that, the organization and working condition of equipment, fixtures and tools are studied. This method is also effective in statistical analysis of working conditions. The monographical method consists in detailed examination of the working conditions, technological process, workplace equipment, work methods, sanitation, and means of collective and individual protection. In other words, this method relates to analyzing hazardous and harmful production factors that are specific to a particular production (mono) area, equipment, or a technological process. This method stipulates in depth an examination of all circumstances of the accident, and appropriate research and testing is made, if necessary. Subjects of the study are: workshop, working area, technological process, main and auxiliary equipment, labor practice, personal protective equipment, state of the production environment, aerological conditions in the excavation, illumination, fumes level, dust concentration, noise, vibration, radiation, reasons of accidents that had occurred earlier in this workplace. Thus, circumstances and reasons of an accident are studied comprehensively.

The questionnaire method consists in developing questionnaires for workers who deal with security issues. On the basis of personal data (answers to questions), the circumstances of accidents are determined, and preventive measures are developed, in order to prevent the reasons that caused them.

The method of expert assessments is based on expert findings (assessments) of working conditions for finding compliance of the process equipment, fixtures, tools, processes, to the requirements of standards and ergonomic requirements related to machines, mechanisms, equipment, instruments and control panels.

Technical investigation is intended to establish the causes of the accident with the greatest possible accuracy, to identify measures for eliminating its consequences and restoring failed object, to determine the damage, to develop necessary measures and suggestions for preventing similar accidents at this and other related facilities and enterprises. A technical accident investigation is done by a special Committee in the manner determined by regulating documents.

RESULTS

Statistical methods for assessing distribution of frequencies and probabilities of accidents occurrence in certain groups (clusters) made it possible to obtain the following data (Tarazanov, 2001 - 2014; Rosstat, 2013).

The dynamics of changes in the amount of explosions of gas and dust in coal mines between 1991 and 2014 are shown in Figure 1. The data shows that during this period there were 207 explosions, 25 of which may be classified as disasters by their consequences. The maximum number per year was 17 (1992), and the minimum was 2 (2008). All reported explosions occurred in 60 % of the total number of mines. With that, in 30% of the total number of mines, over 80 % of explosions occurred. 1,542 persons were injured, out of which 773 persons had fatal injuries.

Analysis of the data by regions showed that the greatest number of explosions - an average of over 76 % per year - occurred in the mines of Kuzbass, in certain periods this figure reached 100 % (1999). The results are shown in Figure 2.

The performed statistical data processing for setting tasks and investigation has shown that currently there is a steady trend towards stabilization of the number of accidents, despite the high level of technological infrastructure at enterprises, and improvement of main methods of

Table 1. Results of ignition sources technical analysis

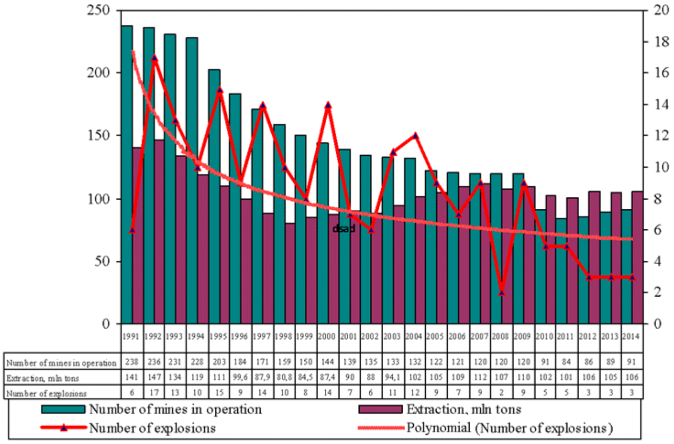
Factors	Ignition source
Natural	1) Faults of electric equipment and damages of the cable networks from external natural causes
	2) Spontaneous combustion processes (endogenous fires)
	3) Roof rock collapse during interaction of rocks
Technical	1) Faults of electric equipment and damages of the cable circuits from external natural causes
	2) Exogenous fires
	3) Blasting operations, including:
	- detonating explosive charge
	- burning out charge
	- sparking in explosive circuit
	- other sources
	4) Heated bodies, including:
	- from friction
	- from faults in electric circuits
	- welding operations
	- smoking (as a source of ignition)
	5) Frictional sparking, including:
	- interaction between equipment and rock
	- interaction of parts of equipment
	6) Discharges of static electricity
	- during operation of equipment
	- during clothes interaction
	7) Ignition of self-contained self-rescuers
	8) Damage of cap lamps
Organizational	1) Violations of the rules of operation and equipment repair
	2) Violation of discipline in the workplace (facts of smoking, welding)
	3) Unsatisfactory control over the state of equipment and excavations

Table 2. Results of technical analysis of the reasons of gas concentration in excavations

Factors	The reason and source of gas emission
Natural	1) Changes in geological conditions (rock massif)
	2) Intense methane emission from broken coal, bare massif, wall face, sides of the excavation, and goafs
	3) Sudden outbursts of coal and gas, feeders (rock massif)
	4) Changes in barometric pressure (goaf)
	5) Collapse of the roof rocks (goaf, rock massif)
	6) Thermal depression that occur in case of endogenous fires (goaf)
Technical	1) Violation of the ventilation regime due to air redistribution between excavations (all sources)
	2) Unsatisfactory insulation of goaf, presence of voids, significant air leakages (goaf, rock massif)
	3) Disturbance of ventilation in blind mind workings (bottom-hole area)
	4) Low air speed across the excavations (all sources).
	5) Planned shutdown of main and auxiliary ventilation blowers (all sources)
	6) Limitation of air flow to the mine or to the work site (all sources)
	7) Use of imperfect schemes for opening, preparation and coal extraction, systems of development (all sources).
	8) Absence of degassing in mines, if it is impossible to ensure concentration of methane in the atmosphere of some mines within the permissible limits by means of ventilation (goaf, rock massif).
	9) Unsatisfactory state of main blowers and ventilation network (all sources).
	10) Thermal depression arising from exogenous fires (goaf, rock massif)
	11) Unsatisfactory roof control (goaf, rock massif)
Organizational	1) Changes in the mode of production and work organization towards acceleration without increasing the volume of air fed into work faces (all sources)
	2) Violations during degassing of previously locked out workings (all sources)
	3) Engineering errors in air calculating and measuring (all sources)
	4) Incorrect ventilation mode in liquidation of accidents (all sources)
	5) Unsatisfactory control over the ventilation of mine workings (all sources)

Table 3. Results of technical analysis of the reasons for formation and occurrence of explosive accumulation of dust

Factors	Reason and sources of dust formation and dust emission
Natural	1) With increasing depth of exploitation, coal humidity decreases, which leads to increasing of dust explosive properties.
	2) With increasing depth of exploitation, dust formation during destruction of coal massif increases.
Technical	1) With the use of combined machines of high productivity, the amount of dust per unit of mass of extracted coal increased, and dust formation sharply increased around the whole working face
	2) Intensive ventilation causes distribution of dust far beyond the working face and the extraction area.
	3) Increasing speed of the air stream along the conveyorways contributes to spreading dust throughout the mine.
	4) Use of complete conveyorization for delivering rock mass contributes to secondary dust formation
Organizational	1) Imperfect methods of dust prevention
	2) Absence of automatic instrumental monitoring of suspended and deposited dust.
	3) Unsatisfactory control over dust explosion safety at excavations



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Number of mines in operation	238	236	231	228	203	184	171	159	150	144	139	135	133	132	122	121	120	120	120	91	84	86	89	91
Extraction, mln tons	141	147	134	119	111	99,6	87,9	80,8	84,5	87,4	90	88	94,1	102	105	109	112	107	110	102	101	106	105	106
Number of explosions	6	17	13	10	15	9	14	10	8	14	7	6	11	12	9	7	9	2	9	5	5	3	3	3

Fig. 1. The number of gas and dust explosions in coal mines in Russia between years 1991 and 2014

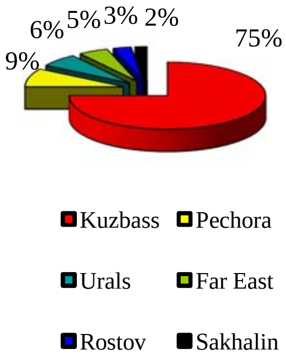
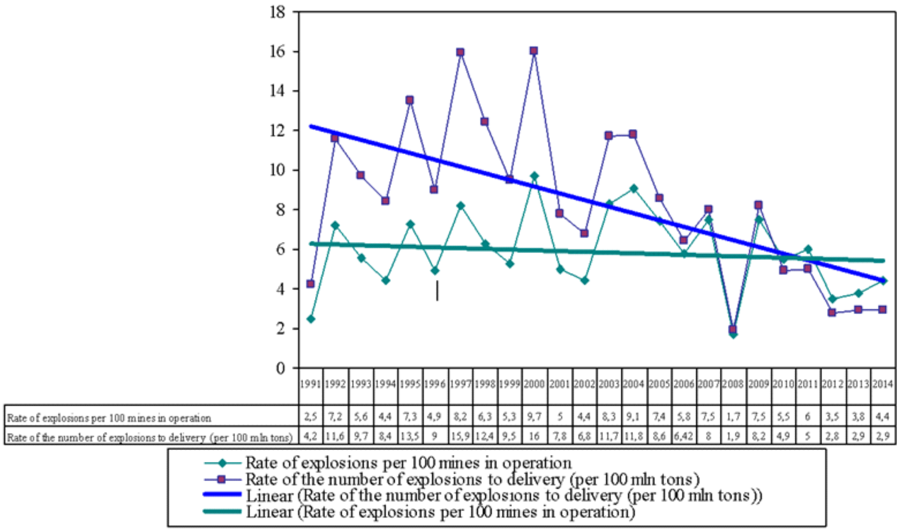


Fig. 2. Distribution of gas and dust explosions in regions of Russia

fighting methane, i.e., venting and degassing that are widely used at mining enterprises.

These statistical data can generally be characterized as positive, since the trend indicates a decrease in the number of accidents. However, the average number of accidents tends to be a constant different from zero, which can currently be assessed as 4 explosions per year, which is in line with the global trend.

The urgency of the problem is confirmed by the fact that the relative number of accidents caused by gas and dust explosions in mines in Russia, after termination of production and elimination of over 100 most dangerous mines,



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Rate of explosions per 100 mines in operation	2,5	7,2	5,6	4,4	7,3	4,9	8,2	6,3	5,3	9,7	5	4,4	8,3	9,1	7,4	5,8	7,5	1,7	7,5	5,5	6	3,5	3,8	4,4
Rate of the number of explosions to delivery (per 100 mln tons)	4,2	11,6	9,7	8,4	13,5	9	15,9	12,4	9,5	16	7,8	6,8	11,7	11,8	8,6	6,42	8	1,9	8,2	4,9	5	2,8	2,9	2,9

Fig. 3. Relative indicators of trends in changing the number of gas and dust explosions

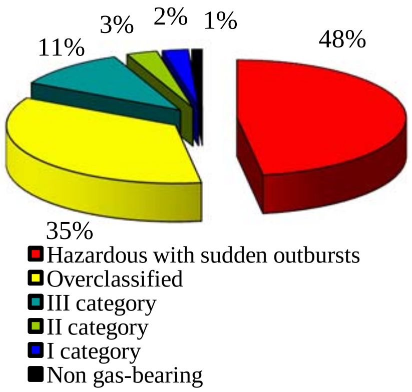
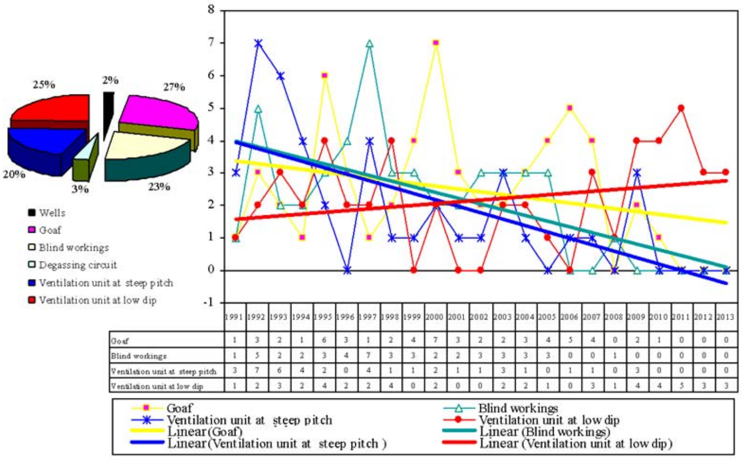


Fig. 4. Distribution of explosions by the categories of mines

reduced to the number of operating mines, has remained virtually unchanged over the past two decades (Figure 3).

The largest number of explosions - 83 % occurred in the mines referred to as «over-classified» and methane-outburst hazardous. In general, the number of explosions can be considered proportional to the category of mines in terms of methane concentration. The number of cases of coal dust explosion in non-fiery mines was 1% (Figure 4).

The results of the analysis of the locations where explosions of gas and dust occurred are shown in Figure 5 (Ruban, 2011). Most frequently, the explosions occurred in the goaf (27 %), and in



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Goaf	1	3	2	1	6	3	1	2	4	7	3	2	2	3	4	5	4	0	2	1	0	0	0
Blind workings	1	5	2	2	3	4	7	3	3	2	2	3	3	3	3	0	0	1	0	0	0	0	0
Ventilation unit at steep pitch	3	7	6	4	2	0	4	1	1	2	1	1	3	1	0	1	1	0	3	0	0	0	0
Ventilation unit at low dip	1	2	3	2	4	2	2	4	0	2	0	0	2	2	1	0	3	1	4	4	5	3	3

Fig. 5. Distribution of explosions by the location of occurrence in coal mines

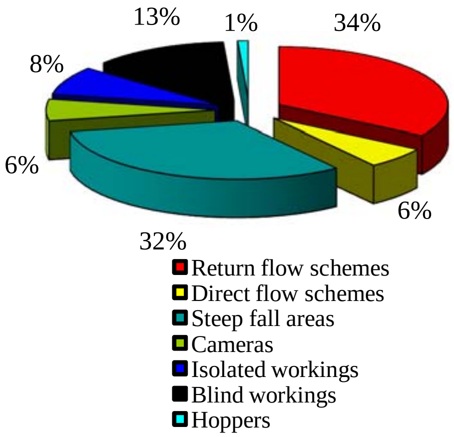


Fig. 6. Distribution of explosions depending on the type of the ventilation scheme of the excavations on site.

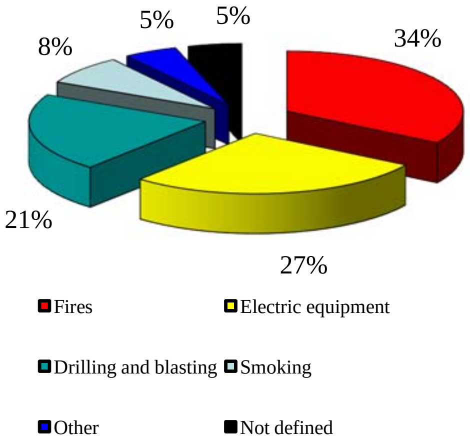


Fig. 7. The results of general statistical analysis of ignition sources

the mining areas in the flat dip strata (25 %). A significant number of explosions were observed in blind workings (23 %) and in the mining areas in the flat dip strata (20 %).

The results of the analysis of ventilation schemes in various types of excavations are shown in Figure 6 (Ruban et al., 2011). Most of the explosions are marked in the areas ventilated by return flow, and in the areas of steep dip. This is explained by the presence of significant amounts of goafs in such schemes, which are the main sources of gas in the working area at excavation sites.

Characteristic common causes of accidents in mines that led to violation of their ventilation regime, and, consequently, to explosions shown in the materials of the investigation, can be represented in the following list (Kolesnichenko et al., 2013; Klishin et al., 2011; Oganesyan, 2004):

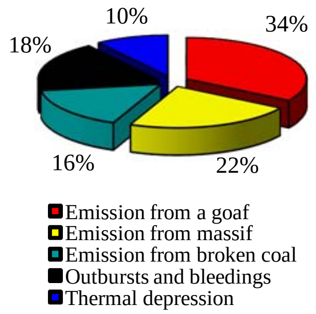


Fig. 8. Results of general statistical analysis of natural reasons of gas concentration in excavations

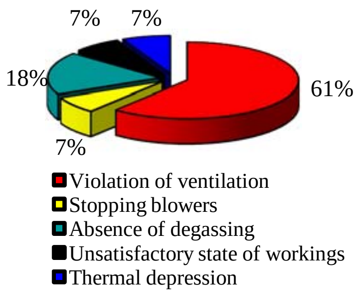


Fig. 9. Results of general statistical analysis of technical reasons of gas concentration in excavations

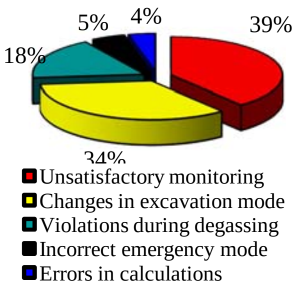


Fig. 10. Results of general statistical analysis of organizational reasons of gas concentration in excavations

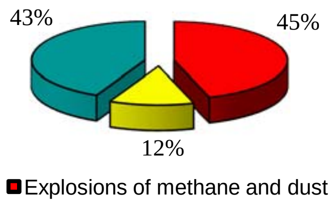


Fig. 11. The results of general statistical analysis of cases of gas and dust explosions

1) Uncontrolled air redistribution between excavations.
2) By changing the mode of mining machines operation and organization of work towards acceleration, non-acceptance of appropriate measures for increasing the flow of air fed into the excavation.
3) Change in geological conditions.
4) Non-satisfactory roof management.
5) Non-satisfactory insulation of the worked out space, presence of voids, large air leaks.
6) Disturbance of ventilation in blind mind workings.
7) Low air speed across the excavation.
8) Intense methane emission after blasting from the broken coal, bare massif, wall face, and sides of the excavation.
9) Sudden outbursts of coal and gas, methane bleedings.
10) Improper degassing of previously locked out workings.
11) Planned shutdown of main and auxiliary blowers.
12) Limitation of air flow into the mine or into

the working (including as instructed by managers).

13) Use of imperfect schemes for opening, preparation and coal extraction, systems of development.
14) Absence of degassing in mines, if it is impossible to ensure concentration of methane in the atmosphere of some mines within the permissible limits by means of ventilation.
15) Unsatisfactory state of main blowers and ventilation network.
16) Engineering errors in calculations and air measurements, including during main fans operation.
17) Incorrectly chosen ventilation mode in liquidation of accidents, breakdowns, blockages.
18) Thermal depression, including the one due to fires.
19) Unsatisfactory control over the ventilation of mine workings.
20) Natural and associated factors.

These data make it possible to get an idea of the nature of the reasons of violations of mine ventilation, but do not reflect their quantitative relationships and patterns of relationships between them. Often one general wording contains several factors different in their nature. Such a classification is not enough for establishing all the circumstances, probable contributors, and the nature of the accident development. Such information is also unsuitable for statistical processing.

Most complete and accurate information about locations, circumstances, ways of development and the nature of accidents, which also make it possible to identify the maximum number of violations, can be obtained during their investigation, with the use of the technical analysis and expert estimates (Ludzich and Kulakov, 1999). The main challenge in studying circumstances of such accidents is to identify the reasons and sources: first, appearance of explosive concentrations of gases and dust in mines, second, their ignition and explosion. With this purpose of systematizing all the reasons that caused the accident, they are clustered by main factors inherent to mining - natural, technical, organizational (the Government Labor Inspectorate in the Kemerovo region, 2008).

These materials show that methods of statistical analysis first of all can provide quantitative assessment of the composition of causes of ignition and gas concentration, but does not make it possible to monitor the entire cause-effect chain of events leading to an accident, i.e., does not reflect the structure of interaction between them (Tuleyev, 2008).

The results of general statistical analysis of the cases of gas and dust explosions are shown in Figure 11. The figure shows that the total share of explosions with simultaneous participation of gas and dust, and explosions with possible or partial participation coal dust prevails.

Technical analysis of the relationship between the factors of mining industry and the reasons for formation and occurrence of explosive accumulation of dust in mines made it possible to obtain results shown in Table 3.

DISCUSSION

Based on comprehensive analysis of the relationship between the presented facts about reasons and sources of explosions, a conclusion can be made about the complex nature of the structure of the relationship between the reasons of accidents, such as gas and dust explosions in excavations. By the results of investigation, no reason may be considered as the only one that caused the accident. For example, the organizational reason such as unsatisfactory monitoring of ventilation (state) of excavations is often a consequence of a number of technical and natural factors. Therefore, the existing classification of all reasons in the form of a list grouped by factors of the mining industry, in our opinion, does not fully reflect its specificity. The so-called "human factor" is present, directly or indirectly, as the primary reason, in 98% of all accidents and incidents. However, human ability to control the situation for preventing occurrence and development of accidents is significantly limited, and does not exceed 30 % in some cases.

The reason for this, in our opinion, is the fact that the factors that influence the gas situation in working areas may be classified as manageable and hard to manage, in other words, hard to control and manage by the means available in production.

Manageable factors include the factors provided by the organization and work practices. Their main characteristic is the schedule of work containing activities that make it possible to control their influence. An example is ventilation of excavations and degassing of the massif. The influence on manageable factors in strict compliance with safety rules and technologies minimizes the danger to the level of acceptable risk.

Problematic factors include the factors that affect sustainability of the ventilation process and have natural or mixed natural-and-technogenic nature. These include: natural factors, i.e., changes in barometric pressure; natural and anthropogenic factors, i.e., unstable air redistribution due to changes of leakage into the caving zone; geomechanical factors - changes in the structure of the caving zone, roof rocks collapsing in the goaf; technogenic factors, i.e., formation of local methane accumulations in the no-flow areas.

The analysis of accidents reasons made it possible to state that for reasons of influence of only problematic factors within the last 25 years 13.7% of the total number of accidents occurred, and their partial effects were observed in more than 51 % of the total number of accidents. Thus, although for many accidents the main reasons were considered organizational and technical violations, the hard-to-manage factors cannot be disregarded and are to be classified as contributing or related, and under certain conditions, as the major or direct components of the reason of an accident.

CONCLUSION

Additional recording and classification of problematic factors in conjunction with other reasons make it possible to assess, during the investigation, more comprehensively the location, the circumstances and the structure of their relationships, ways of development and the nature of accidents, to identify the maximum number of violations in case of accidents, and, consequently, to identify all time and space chain from contributing and related to the basic and direct reasons. Safety management in mining production may be improved, in our opinion, by means of a differentiated approach to the role of each factor that can affect emergence and development of an accident. It is necessary to assess the possibility of changing the influence of each factor in time and in space of the excavations of a mining enterprise. For example, the virtually immune to influence natural factor, such as change of barometric pressure, can affect the gas situation in an excavation of a site for a long time - up to several days. In its background, another unmanageable natural and technogenic factor - collapse of main roof rocks - can dramatically and in a short time to affect gas emission from the goaf. The result of the joint influence of these factors can be assessed as the reasons contributing to deterioration of the gas situation in the excavation site, i.e. the probability of increased gas concentration in the working area grows, and, consequently, accident occurrence grows as well. In order to normalize the composition of the atmosphere in goafs in such conditions, it is necessary to provide for additional technical and organizational measures, for example to increase air supply to the site, and to enhance monitoring of automatic gas protection equipment operation.

Thus, comprehensive analysis of security violations and reasons of accidents in mining operations performed on the basis of the results of the investigation of accidents due to dust and gas explosions made it possible to establish existence of factors, monitoring and management of which is difficult in the mining process. Timely consideration of such factors will considerably improve aerologic safety of mining operations.

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