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IMPROVEMENT OF METHODS OF ANALYSIS AND ESTIMATION OF EMERGENCY RISKS OF COAL MINES

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Abstract. There are very different interpretations of the term "risk" in the scientific literature. Common to all definitions is that risk involves uncertainty – will an undesirable event occur or not? According to modern concepts, industrial risk is usually interpreted as a probability measure of the occurrence of man-made phenomena, accompanied by the emergence, formation and action of hazards, and the resulting social, economic, ecological and other types of damage. Thus, in a simplified view, risk is a combination of the probability of harm and the severity of this harm. Emergency risk is the probability of such damage caused by occurred accident.

The definition of the theory of emergency risks and their classification are provided. The ratio of risk objects and undesirable events allows us to distinguish five main types of risks: individual, technical, environmental, social and economic risks. The emergency risk of mining enterprise includes all these components. Using the considered types of risk allows us to search for optimal solutions for ensuring safety both at the level of the coal mine and at the macro level. A functional model of emergency risk development is presented. The process of hazard identification and risk assessment is analyzed. Emphasis is placed on risk analysis as a basis for the preparation of risk management measures, and requirements for risk analysis are formulated. The main methods of risk analysis are briefly described. The method of assessing the degree of risk is presented, and the final degree of danger is determined. Recommendations are made for the selection of risk analysis methods at various stages of the operation of hazardous production facilities, namely, for pre-design work, design, commissioning, operation, reconstruction.

It is noted that in order to properly assess any type of risk, it is necessary to move from risk standard definition to risk assessment by indirect factors

All methods of analysis and assessment of emergency risks of coal mines can be used in individually or complementing each other, and qualitative analysis methods can include quantitative risk criteria (mainly based on expert assessments). A full quantitative risk analysis should use the results of a qualitative hazard analysis.

Keywords: mine accidents, emergency situations, impressive factor, emergency risk, methods of risk analysis and assessment.

1. Introduction

There are very different interpretations of the term "risk" in the scientific literature. Common to all definitions is that risk involves uncertainty – will an undesirable event occur or not? According to modern concepts, industrial risk is usually interpreted as a probability measure of the occurrence of man-made phenomena, accompanied by the emergence, formation and action of hazards, and the resulting social, economic, ecological and other types of damage. Thus, in a simplified view, risk is a combination of the probability of harm and the severity of this harm. Emergency risk is the probability of such damage caused by an accident that has occurred.

As already noted in [1], there are no standards in Ukraine for defining the terms and concepts of accidents and emergency situations, except for a small document [2] and scattered information in industry documents. Therefore, we will list some of them in order to improve the perception of the further presentation of the material.

Accident - destruction of structures and/or technical equipment used at dangerous production facilities of the coal industry, explosions of gas and dust, sudden emissions of coal, rock, gas, mining impacts, collapse of rocks, fires etc.

Incident – failure or damage of technical devices used at a dangerous production facility, deviation of the technological process from the regulatory regime.

A hazardous production facility (HPF) for the coal industry is a facility where mining operations are conducted, as well as underground operations.

The existing classification includes 31 types of accidents, the liquidation of which requires the involvement of additional human resources (fire brigades, paramilitary mining rescue units, etc.) and 18 incidents investigated by the enterprise. The most complex, requiring maximum attention and the use of means of ventilation, are the following (by severity of liquidation and consequences):

a) sudden emissions of coal, rock and gas;
b) mining strikes;
c) explosions, flashes, burning of gas and dust in underground workings;
d) endogenous fires (including recurrences of extinguished endogenous fires);
e) gas breakthroughs from fire areas, sudden release of gases;
f) explosions and fires in warehouses of explosive materials and in other places of their storage, as well as on vehicles transporting munitions. Combustion of explosives during blasting, which caused serious consequences;
g) exogenous fires in underground mining workings;
h) fires and explosions in over-mine buildings and structures;
i) gassing of mine workings and violation of dust explosion protection systems.

When an accident occurs, an ***emergency situation*** (ES) is a state in a certain area that is developed as a result of an accident that can cause or has caused human casualties, damage to human health and/or the environment, significant material losses and violations of people's living conditions. Emergencies are divided, according to the "Procedure of classification of emergency situations by their levels" [3], into state, regional, local or object level situations. The criteria are:

a) territorial distribution and volume of technical and material resources necessary to eliminate the consequences of the emergency;
b) the number of people who died or were injured as a result of the impact factors of the ES;
c) the amount of damages caused by impressive factors of the source of the ES.

The striking factor of the source of the ES is a component of a dangerous phenomenon or process characterized by physical, chemical, biological or other action (impact) and exceeding normative indicators.

According to [3], the vast majority of accidents of types a)–i) refer to the local level.

The formation of ES is the result of a certain set of risk factors generated by relevant sources. With regard to the problem of life safety, it can be the deterioration of health or the death of a person, an accident or catastrophe of a technical system, the death of a group of people, material damage from hazards that have realized, etc.

2. Methods

Each undesirable event can occur in relation to a certain risk object. The ratio of risk objects and undesirable events allows us to distinguish five main types of risks: individual, technical, environmental, social and economic. The emergency risk of a mining enterprise includes all these components (Table 1).

Table 1 – Characteristics of emergency risk components

Type of risk	Object of risk	Source of risk	Unwanted event
Individual	Man	Living conditions	Illness, injury, disability, death
Technical	Technical systems and objects	Technical imperfection, violation of operating rules, external factors	Accident, explosion, disaster, fire, destruction
Ecological	Ecological systems	Technogenic ES	Anthropogenic ecological disasters
Social	Social groups	ES	Group injuries, diseases, deaths
Economic	Material resources	Increased production risk	Increased safety costs, damage from insufficient safety

Individual risk R_{ind} – the frequency of an individual person's impression due to the influence of the accident hazard factors under investigation

$$R_{ind} = \frac{P(t)}{L(f)},$$

where P – the number of victims per unit of time t from a certain risk factor f;. L – the number of people exposed to the corresponding risk factor f per unit of time t.

Technical risk R_{techn}– the probability of failure of technical devices with consequences of a certain level (class) for a certain period of operation of the HPF.

$$R_{techn} = \frac{\Delta T(t)}{T(f)},$$

where ΔT – the number of accidents per unit of time t on identical technical objects (systems); T – the number of identical systems and objects subject to a common risk factor f.

Ecological risk expresses the probability of an environmental disaster as a result of the impact of man-made disasters. For the types of accidents that we consider, it consists in the entry of methane into the earth's atmosphere (short-term emissions of other gases do not significantly affect ecological systems). For accidents at the local level, its impact is noticeably felt only on the territories adjacent to the mine.

Social risk is a risk for a group or association of people. For ES, such a risk is usually not considered, since it is more related to the safety of the population of territories adjacent to objects of potential danger or those subject to the influence of natural disasters or dangerous natural factors.

For emergency risk, the indicator of ***economic risk*** R_{econ} is the ratio of benefit and damage received by society from the type of activity under consideration

$$R_{econ} = \frac{D}{K} \cdot 100\%,$$

where D – damage to society from the consequences of an emergency situation, $D=B_{ls}+D_a$; B_{ls} – costs to achieve the required level of safety; D_a – direct expenses for liquidation of the accident, cost of lost equipment and coal, etc.; K – net benefit from the normal flow of the production process $K=D_i-B_c-B_{lc}-D_a > 0$; D_i – total income from coal production; B_c – basic production costs.

Then the formula of economically justified life safety has the form

$$D_a < D_i-(B_c+B_{lc}).$$

Using the considered types of risk allows you to search for optimal solutions for ensuring safety both at the level of the coal mine and at the macro level. For this, it is necessary to choose the value of the ***acceptable risk*** - such that, given the existing social values, can be considered acceptable in this situation.

It is noted that in order to properly assess any type of risk, it is necessary to move from risk standard definition to risk assessment by indirect factors. The selection of such indirect factors is the goal of solving the problem of improving the assessment of emergency risks.

The process of beginning and development of accident risk is most strongly influenced by a variety of factors and conditions characteristic of the industrial system (Fig. 1). And these are not only probabilistic and quantitative indicators. Acquaintance with this scheme makes it possible to identify a number of root causes of risk: failure of nodes and equipment due to their design flaws or violation of maintenance rules: personnel errors; external influences, etc. As a result of the possibility of these causes, dangerous production facilities are often in an unstable state, which in relation to the safety of production becomes especially critical in the event of emergency situations.

There is a clear similarity between the accidents. Usually, an accident is preceded by a deviation from the normal course of processes. The duration of this phase is uncertain. These deviations do not yet lead to an accident, but lay the foundations for it.

The user of the monitoring system usually does not notice this phase due to the uncertainty of the incoming information, so user does not have a sense of danger. In the next phase, an unexpected event occurs that significantly changes the situation. Users try to restore the normal course of the technological process, but due to the uncertainty of the incoming information, they can only worsen the development of the accident.

At the third stage, another unexpected event, sometimes quite insignificant, can become an impulse that causes a person to disobey the situation and the emergence of an emergency situation.

Risk is an inevitable, objective concomitant factor of industrial activity. Risk management may include monitoring, assessment (reassessment) of risks and actions aimed at ensuring compliance with the decisions made. The basis for determining acceptable risk criteria is: norms and rules of industrial safety; information on accidents and incidents that occurred and their consequences; practical experience; socio-economic benefit from the operation of a dangerous production facility.

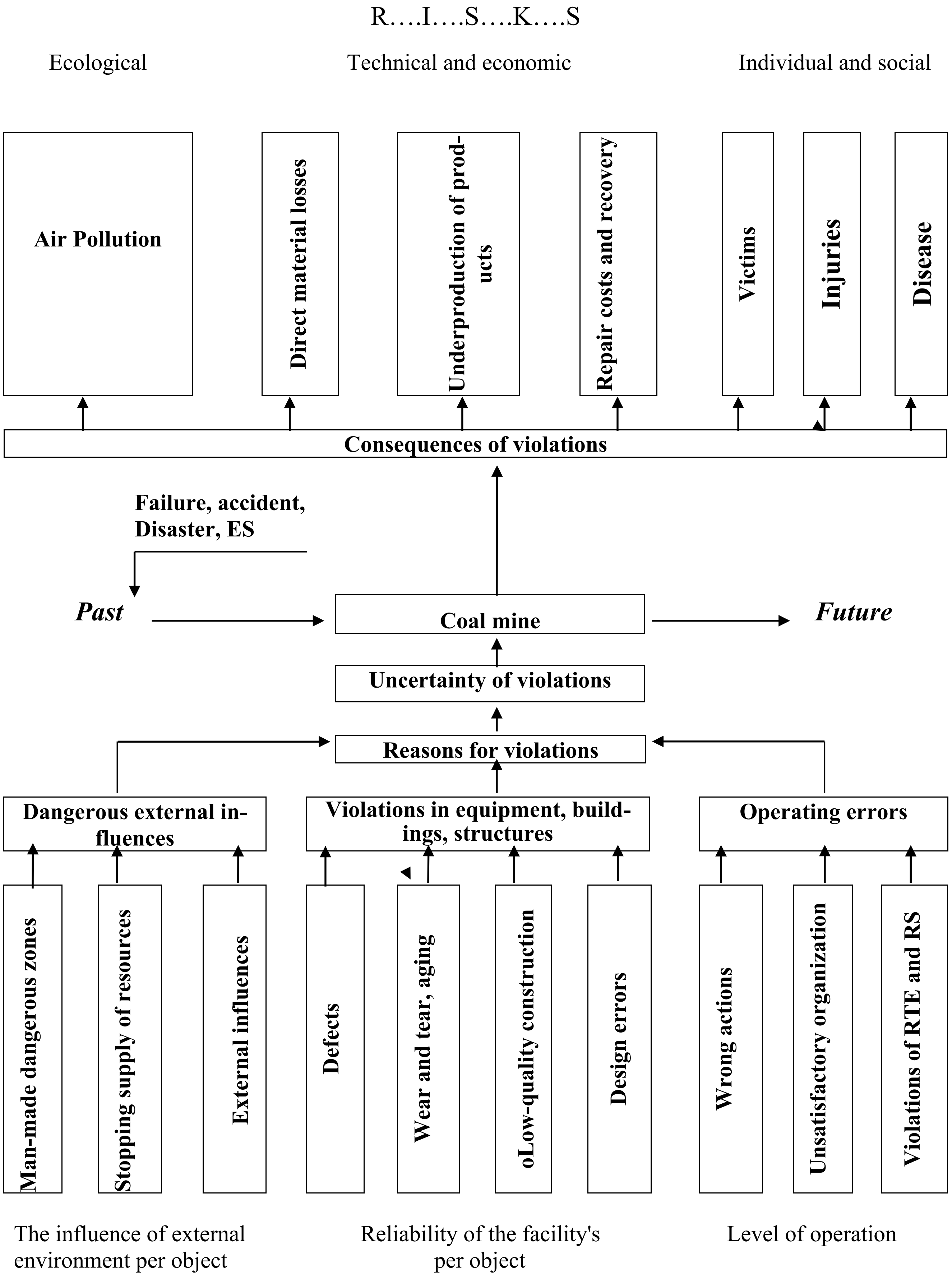

Figure 1 – Functional model of emergency risk development

The process of hazard identification and risk assessment is simplified in Fig. 2 We will consider only blocks 1–5.

Determining the sources of danger is not difficult. For this, it is only necessary to analyze the table. 1 and fig. 1 and adapt their general provisions to the conditions of a specific mine (list of possible accidents, incidents, etc.).

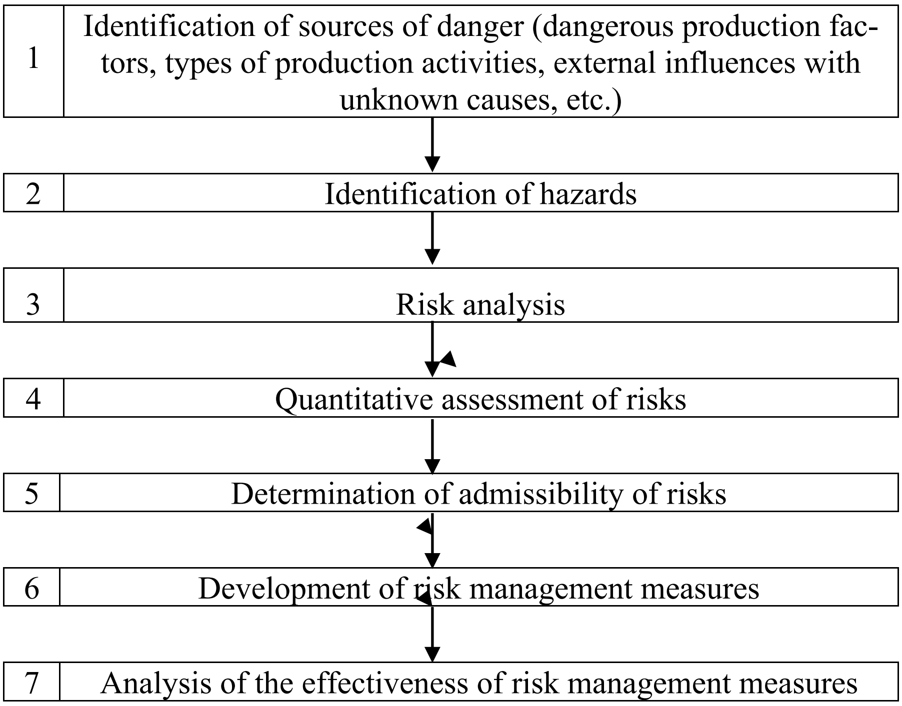

Figure 2 – Structure of the hazard identification and risk assessment process

The main tasks of the *hazard identification* stage are a clear description of all sources of hazards and ways (scenarios) of reducing their harmful effects. It is necessary to determine which elements and processes in the technological system require a more serious analysis.

The results of hazard identification are:

a) list of undesirable events;

b) description of sources of danger, risk factors, conditions for occurrence and development of undesirable events and scenarios of possible accidents;

c) preliminary assessments of dangers and risks.

Options for further actions can be:

a) the decision to stop further analysis due to the insignificance of dangers or the sufficiency of the obtained preliminary assessments;

b) a decision to carry out a more detailed hazard analysis and risk assessment;

c) development of preliminary recommendations for reducing hazards.

Risk analysis is the process of identifying hazards and assessing the risks of adverse events for individuals or groups of individuals, property, or the environment. The main goal of risk identification and analysis is the formation of decision-makers, a holistic picture of risks that threaten the safety of the enterprise, the life and health of workers. That is, at this stage, first of all, a *qualitative risk* assessment is carried out. Indirect risk factors are determined, which do not have a probabilistic form, but contribute to the further *quantitative assessment of the risk.* The general task is to determine the acceptable level of risks, safety standards of workers, which is already in a certain way a quantitative measure of assessment. It should be taken into account that the determination of the acceptable level of risk is carried out in conditions of insufficient information. In addition, during the analysis, it is necessary to solve probabilistic problems, which can lead to significant discrepancies in the obtained results.

At the stage of hazard identification and preliminary risk assessments (hazard analysis), it is recommended to use methods of qualitative analysis based on special aids (questionnaires, instructions, etc.). Qualitative methods are not suitable for the analysis of accident risks, because a full-time worker does not have enough information to assess the accident risk, and the management staff, whose job duties include assessments of accident risks, are able to perform it, relying only on their own practical experience.

Practice shows that conducting a full quantitative risk assessment is more effective for comparing sources of danger or different options for safety measures than for drawing a conclusion about the degree of safety of the object. Quantitative risk assessment methods are always useful, and in some situations only permissible, in particular for comparing hazards of different origins (various indirect factors), assessing the consequences of major accidents or for illustrating the obtained results.

However, due to the lack of statistical data in practice, it is recommended to use expert assessments and risk ranking methods based on simplified methods of quantitative risk analysis. In such approaches, the events or elements under consideration are divided into several categories by the magnitude of probability, severity of consequences and risk. A high level of risk may be considered (depending on the specifics of the object) *unacceptable* (or requiring special consideration), an intermediate level of risk requires the implementation of a program of work to reduce the level of risk, a low level is considered acceptable, and a minor level may not be considered at all.

When choosing and using risk analysis methods, it is recommended to observe the following requirements:

a) the method must be scientifically based and corresponds to the hazards under consideration;

b) it should give results in a form that allows a better understanding of the forms of realization of dangers and outline the ways of reducing the risk;

c) it must be repeatable and verifiable.

This is the novelty of the proposed approach. If the standard methods of risk assessment are not always sufficiently justified (it is difficult to explain to the average user the difference in the probability of danger of 10^{-6} and 10^{-5} - both are simply small; the aging of the mechanism and the erroneous actions of the operator who uses it will be much clearer). That is, the use of indirect risk factors is more justified.

At the same time, it is necessary to take into account the stages of operation of the object, the purpose of the analysis, the criteria of acceptable risk, the type of dangerous production object and the nature of the danger, the availability of resources for the analysis, the experience and qualifications of the performers, the availability of the necessary information, etc. At the stage of hazard identification and preliminary risk assessments, it is recommended to use methods of qualitative analysis and risk assessment based on special aids (questionnaires, forms, survey sheets, instructions) and practical experience of the executors. They will determine the weight of indirect factors.

3. Results and discussion

Since 2016, the National Standard of Ukraine DSTU IEC/ISO 31010:20 "Risk Management" has been in force in our country. Methods of general risk assessment", coordinated with the European standard IEC/ISO 31010:2009 "Risk management - Risk assessment techniques". It provides information on the concepts of general risk assessment, the processes of general risk assessment and risk analysis. General information on the methods of risk assessment accepted in the world, the factors of their selection are presented.

The variety of methods, the European specificity, the varying degree of difficulty of their application and the relatively short period of implementation of this DSTU at Ukrainian enterprises currently limit their implementation, with rare exceptions, to the following:

a) methods of ***the check sheet*** and ***"What if?"***;

b) method of ***analysis of types and consequences of failures*** (***ATCF***);

c) method of ***analysis of species, consequences and cry failure rate (ASCCFR)***. The disadvantages of ***ATCF*** and ***ASCCFR*** methods can be considered the time-consuming nature of collecting information and the narrow focus of the methods on the failure (not an emergency state!) of the technical system. The complete picture of risks at the enterprise cannot be obtained by these methods;

d) the method of ***analysis of danger and operability*** is similar;

e) large accidents, as a rule, are characterized by a combination of random events that occur with different frequency at different stages of the occurrence and development of the accident (equipment failures, human errors, unforeseen external influences, destruction, release, ignition, explosion, fire, etc.). ***Logical-graphic analysis methods of "failure trees" and "event trees"*** are used to identify cause-and-effect relationships between these events.

The analysis of "failure trees" reveals combinations of equipment failures, incidents, personnel errors, uncalculated external man-made influences that lead to an emergency situation. The method is used to analyze the possible causes of an emergency situation and calculate its frequency based on knowledge of the frequencies of individual events. Moreover, in this case, it is not difficult to move from the mathematical definition of risk to the assessment of the influence of implicit risk factors;

The "event tree" analysis is performed based on the main event (emergency situation) and is used to analyze its development. At the same time, the frequency of the emergency situation is calculated by multiplying the frequency of the main event by the conditional probability of the final event.

f) methods of ***quantitative risk analysis***, as a rule, are characterized by the calculation of several indicators of accident risk components (Table 1). For example, indicators of technical risk are determined by appropriate methods of reliability theory. Indicators of individual risk are the qualification and readiness of an individual to act in a dangerous situation, his security. Social risk is characterized by the scale and probability (frequency) of accidents and is determined by the damage distribution function (Farmer's curve). Accordingly, the criterion of *acceptable risk* will no longer be determined by a number for a separate event, but by a curve built for various accident scenarios taking into account their probability (influence of implicit factors).

Methods of quantitative risk analysis - the general name of a set of methods a)–d), the consecutive use of which can rely on the results of each other. These methods can be used effectively:

a) at the stage of design and placement of the HPF;
b) during justification and optimization of safety measures;
c) during the assessment of the danger of major accidents at HPF;
d) during a comprehensive assessment of the danger of accidents to people, property and the environment.

When assessing the ***degree of risk*** of identified hazards, the risk present in most manufacturing operations is assessed. The degree of risk is determined by the formula $R=P\times N\times M$, where P is the probability of danger; N – the probability of the consequences of the danger (seriousness of the consequences); M is the personal opinion of the workers who assess the risk. Coefficients are determined conditionally with a mandatory survey of workers at a given workplace, and are rated from 1 to 5. It is at this stage that the influence of implicit factors can be effectively calculated - because a person operates with such concepts, not probabilities. The final degree of danger is conditionally distributed among five risk categories (see Table 2).

Table 2 - Determination of the final degree of danger

The final degree of danger	Degree of risk R	Control measures required to reduce risk
A	$R>100$ unacceptable risk	There is always the possibility of an injury, a serious accident. Work cannot be started or continued until the risk has been reduced. It is necessary to reassess the risk and take additional measures.
B	$51<R<100$ unwanted (significant) risk	It is necessary to take measures to reduce the risk to an acceptable level. To reduce the risk, it is necessary to allocate the necessary funds.
C	$11<R<50$ medium risk	It is necessary to take safety measures.
D	$4<R<10$ permissible (acceptable) risk	The risk is acceptable with the consent of the management of the enterprise. It is necessary to constantly monitor this risk, and develop additional safety measures.
E	$1<R<3$ minor risk	The risk, due to its insignificance, does not require special control measures (but it is not absolute safety!).

The interval of blocks roughly expresses the urgency of measures to reduce the degree of risks and the priority of adopting safety measures. The final degree of danger depending on the degree of risk *R* is determined according to the table. 2.

Pay attention: in the course of the assessment, probabilities do not appear anywhere, implicit factors are in the foreground!

According to our research, it is advisable to choose risk analysis methods for various types of activities and stages of operation of dangerous production facilities according to the table. 3. This choice can be explained as follows. At the stage of preliminary design studies, there is no mine yet, and no information about possible situations, so the most suitable is the analysis method 6, which operates on the information that exists for future use by other methods.

Table 3 - Recommendations for the selection of risk analysis methods

Method	Activity				
	Pre-project works	Designing	Commissioning	Operation	Reconstruction
1. "What if?"	*L*	*R*	*R*	*R*	*S*
2 Check sheet	*L*	*R*	*R*	*S*	*R*
3. Analysis of danger and performance	*L*	*S*	*R*	*R*	*R*
4. Analysis of types and consequences of failures	*L*	*S*	*R*	*R*	*S*
5. Analysis of "failure trees" and "event trees"	*L*	*S*	*R*	*R*	*S*
6. Quantitative risk analysis	*S*	*S*	*L*	*R*	*S*

The following designations are used in the table: *L* – the least suitable method of analysis; *R* is the recommended method; *S* is the most suitable method of analysis.

At the design stage, an analog method of expert evaluations based on a questionnaire survey of a team of experts is recommended. In the presence of the necessary design documentation, all other methods are the most suitable. At the commissioning stage, the "What if?" method is most suitable, since the project exists, the mine is built, but experimental data on its condition are not yet available. Therefore, the complex method is the least suitable. At the stage of operation, expert evaluation methods are the most suitable, as technologists can evaluate the effectiveness of their own design solutions in this way. It is recommended to use all other methods on the basis of real information about the state of the mine (and if there are statistics on its emergency state - and on its basis).

At the stage of reconstruction, all information about the mine is real, so all methods of risk analysis are suitable, and expert assessments (methods 1-2, tabl. 3) fall into the recommended category and are used only in the absence of this or that information.

We have considered several examples of taking into account implicit accident risk factors. Thus, work [5] considered such an implicit risk factor as an incorrect calculation of the probable number of people to be evacuated from emergency sections of the ventilation network. The paper [6] analyzes the ratio of various implicit factors that provoke the occurrence of an exogenous fire. In [7], the implicit factor of gassing of mine workings with gaseous emission products is considered. The more visible and at the same time the most universal BOW-TIE method stands apart, the extended characteristics of which are given in [5].

4. Conclusion

It can be concluded that all methods of analysis and assessment of accident risks of coal mines can be used in isolation or complementing each other, and methods of qualitative analysis can include quantitative risk criteria (mainly, according to expert assessments using, for example, the matrix (Table 3) of ranking danger). A complete quantitative risk analysis should use the results of a qualitative hazard analysis.

A more in-depth study of implicit factors in the assessment of accident risks at various HPF can be considered a research perspective, since the assessment of accident risks with their help can be considered simpler and more understandable for the user, while maintaining the rigor of the statements and the validity of the results obtained.

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ВДОСКОНАЛЕННЯ МЕТОДІВ АНАЛІЗУ ТА ОЦІНКИ АВАРІЙНИХ РИЗИКІВ ВУГІЛЬНИХ ШАХТ

Кокоулін І.Є.

Анотація. У науковій літературі зустрічаються вельми різні трактування терміну «ризик». Загальним в усіх визначеннях є те, що ризик передбачає невизначеність – виникне небажана подія чи ні? Згідно сучасних уявлень виробничий ризик звичайно інтерпретується як імовірнісна міра виникнення техногенних явищ, що супроводжуються виникненням, формуванням та дією небезпек, і нанесеного при цьому соціального, економічного, екологічного та інших видів збитків. Таким чином, у спрощеному уявленні ризик – це сполучення імовірності нанесення шкоди і тяжкості цієї шкоди. Аварійний ризик – імовірність нанесення такої шкоди аварією, яка виникла.

Наведено визначення теорії аварійних ризиків та їх класифікацію. Співвідношення об'єктів ризику і небажаних подій дозволяє розрізнити п'ять основних типів ризиків: індивідуальний, технічний, екологічний, соціальний та економічний. Аварійний ризик гірничого підприємства включає всі ці складові. Використовування розглянутих видів ризику дозволяє виконати пошук оптимальних рішень щодо забезпечення безпеки як на рівні вугільної шахти, так и на макрорівнях. Наведено функціональну модель розвитку аварійного ризику. Проаналізовано процес ідентифікації небезпек і оцінки ризиків. Зроблено акцент на аналізу ризику, як основи для підготовки мір з керування ним, та сформульовано вимоги до нього. Коротко охарактеризовано основні методи аналізу ризиків. Наведено метод оцінки ступеню ризику, та визначено кінцевий ступінь небезпеки. Вироблено рекомендації щодо вибору методів аналізу ризиків на різних етапах функціонування небезпечних виробничих об'єктів, а саме – до передпроектних робіт, проектування, введення до експлуатації, експлуатація, реконструкція..

Відзначено, що для правильної оцінки будь-якого типу ризику необхідно відійти від його стандартного визначення, переходячи до оцінки ризику за непрямими чинниками.

Всі методи аналізу та оцінки аварійних ризиків вугільних шахт можуть використовуватись ізольовано чи доповнюючи один одного, причому методи якісного аналізу можуть включати кількісні критерії ризиків (в основному, за експертними оцінками). Повний кількісний аналіз ризику повинен використовувати результати якісного аналізу небезпек.

Ключові слова: шахтні аварії, надзвичайні ситуації, вражаючий чинник, аварійний ризик, методи аналізу і оцінки ризику.