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# Substantiating the parameters of quickly erected explosion-proof stopping

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### Abstract

The objective of this paper is to substantiate the method of construction and design parameters of explosion-proof stoppings for the quick and safe remote sealing-off of the sources of complex fires and explosions in coal mines. A new method was designed for the remote erection of explosion-proof stoppings in mine workings and a mathematical model of mass transfer through the body of a stopping made of discrete material. Tactics were improved for the containment of underground fires and explosions due to rapid remote erection of explosion-proof stoppings. The technology of the quick erection of stoppings made of rocks crushed by an explosion for sealing-off of the emergency sections of the mine has been proposed. A computational model and a method for calculating the parameters of explosion-proof stoppings erected by the method of directed explosion have been created. The results of the calculations open the possibility to prepare the means of containment of dust explosions in advance and to improve the tactics of safe containment of explosions and fires.

### Keywords:

underground fire; explosion; explosion-proof stopping; crushed rocks; filtration; gas pressure

## 1. Introduction

In recent years, the situation with the emergencies in Ukraine's coalmines has remained complicated, with underground fires, especially endogenous ones, and explosions of mixtures of air with methane and coal dust being the most difficult in terms of consequences and elimination works. According to the State Paramilitary Mine Rescue Service in the Coal Industry (SPMRS), the annual number of underground fires in 2014-2019 ranged from two to six. In 2015-2017, the frequency of explosions of methane-air mixture (the number of explosions per 1 million tons of coal) increased from 0.025 to 0.08 (2015: 1 explosion per 21 million tons of coal; 2017: 1 explosion per 12.5 million tons of extracted coal) (**Kostenko et al., 2022; Zavialova et al., 2021**). The main part of the time spent on fire and explosion suppression is from 200 to 1,100 hours, which is 50 to 60% of the total time loss of SPMRS. Furthermore, the material values of enterprises that were threatened with destruction in accidents and emergencies amounted to about UAH 4.5 to 5 billion annually. According to statistics for the last three years, the average damage from one accident or emergency is about UAH 2.6 million. Among the 21 accidents and emergencies that occurred in 2020 at the serviced enterprises, the average amount of total damage was about UAH 3.3 million (2019: UAH 3 million).

The accidents related to the elimination of fires in hard-to-reach places (i.e. the mined-out area of longwalls, filled stope development workings, areas of geological disturbances, etc.) are the most difficult in terms of operational and technological state. In such conditions, active fire extinguishing is inefficient; therefore,

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the mine rescuers are forced to switch to the sealing-off method or associated combined methods. An important task is the fastest possible transition to the blockage of airflow to the source of the fire, otherwise an accident develops and becomes protracted (**Zavialova et al., 2021**).

The sealing-off methods of accident elimination are characterized by the greatest labour and material intensiveness and duration. An essential component of such methods is the erection of sealing-off structures. There are many types of stoppings, which differ in materials (wood, stone, plaster, concrete, metal), structure (cutting, non-cutting), method of erection (manual, mechanized), purpose (explosion-proof, waterproofing, ventilation), etc. Common to all types of sealing-off is the need to develop a design, purchase of materials and equipment with their delivery to the mine and to the accident site for the erection, and the erection of the stopping itself. Ventilation manoeuvres, such as local reversal of the direction of ventilation, which requires additional time and may complicate the course of the fire, are performed to erect stoppings in the workings with a ventilation stream coming from the fire source. In modern conditions, the described actions take from one to several days, while the fire continues and develops. To reduce the time of transition to the sealing-off of the emergency section of the mine network, some processes are performed in parallel (**Mineev, 2019**). For instance, the delivery of materials is carried out together with the preparation of cuttings; however, this does not significantly reduce the period of fire containment.

Furthermore, the risk factor is the lack of information on the possibility of complicating the fire by explosion, which threatens those who directly participate in the accident elimination, therefore there is a need to make stoppings explosion-proof. Such structures, which are erected in order to prevent the destruction of mine workings by the explosion wave generated by the explosion of mine gases or dust, require much more materials and, accordingly, time for their construction. The process of erection of explosion-proof stoppings shall be such as to ensure not only reliable sealing-off of the combustion source from the air, but also to eliminate the threat of impact of explosive factors on people involved in the fire fighting.

## 2. Overview of recent studies and publications

Underground accidents remain a serious problem in many coal-mining countries, such as the United States, China, and others, which have environmental and economic problems on an international scale (**Zhanget al., 2022**).

In order to ensure the safety of mine rescue operations in the containment of fires in the event of a potential threat of explosion of methane and air mixtures, the analysis of explosion protection in the containment of fires has been performed, the patterns of explosive environment from the epicentre of the explosion have been studied, the methods and techniques of explosion suppression in fire containment have been substantiated (**Ageev et al., 2012**). However, the proposed ways remain conventional with only their parameters being improved, while the requirements for quickly erected stoppings have not been resolved.

The attempts to speed up the process of containing fires by eliminating the need to perform cutting, as well as the execution of the body of the stopping of the fast-setting compounds (**Nurgaliyevet al., 2018**) and remote erection of stoppings through wells in the mine workings drilled from the surface by injecting a concrete solution with a plasticizer additive (**Maslenkov et al., 2011**) or the use of foam concrete (**KeKuoet al., 2020**) also do not address these issues radically.

It is proposed to erect the embedded stopping by creating a rock mound in workings from large pieces of rock, covered with a layer of smaller rock or sand. Pneumatic cylinders connected to the compressed air supply are installed on the rock mound (**Ovcharenkoet al., 2015**).

To contain the explosions, it is proposed to use water barriers along the path of shock wave propagation (**Pejic et al., 2017**). The disadvantage of this method is its response delay: with the high speed of the shock wave, the water curtain does not have time to form completely, and the fire front passes the liquid barrier.

Extinguishing fires in the workings equipped with belt conveyors is associated with great difficulties and labour consumption. Therefore, it was proposed to form a rock plug by explosive collapse of rocks in the zone of inelastic deformations by blasting the fasteners. After the installation of pressure charges with a cumulative effect on the mounts of the steel arch, its destruction is achieved. The number of sections to be destroyed is determined by calculations based on the required amount of destroyed rock. However, the sealing-off effect is not achieved because the volume of settled rocks does not overlap the cross-section of the working, and the spatial structures of the conveyor prevents fire suppression on the belt (**Shwager et al., 2018**).

The quickly erected anti-explosion set used in the industry is designed to dampen the pressure in front of the explosion wave in the mine workings. It is a parachute-like device made of a material treated with a flame-retardant formulation. Under the influence of air shock wave, generated at the emergency section from the explosion of gas and coal dust, the quickly erected anti-explosion set installed in the working reduces the excess pressure in the front of the air shock wave, catches the objects transferred by an air shock wave (timber, coal fines, rock). However, the protective capabilities of the quickly erected anti-explosion set are limited by the low strength of the product materials. The device is not effective enough to stop coal dust explosions that are continuously distributed in the working. Excess pressure can reach several MPa, and the speed is close to Mach number, the temperature exceeds 1,500°C (**Tutaket al., 2017; Romanchenko et al., 2018**).

A device for the containment of explosions of coal dust is known, which contains suspended supports holding the tanks, where the suspended supports have the form of two-arm brackets that cover the upper fasteners, and the tanks with water or inert dust are executed as seamless polyethylene spheres having holes at the edges with a flexible cord with rings inserted, used to suspend the tanks on the arms of the bracket, and the arms of the brackets are bent at an angle of 5° upward. This device is characterized by the response delay of the mechanical cycle 'extinguishing agent – tank – two-arm bracket – compressed air front'. It takes a relatively long period of time to move the heavy tank from the bracket, to disturb the extinguishing agent and to distribute it to the extinguishing concentration in the cross section of the working. Due to the high velocity of propagation of coal dust explosion along the working, this period of time is insufficient for the timely creation of a reliable barrier to the fire front (**Kostenko et al., 2020**).

Summarizing the above data from literature, we can conclude that currently the main problem of such means is the inability to quickly, safely, remotely, and preferably automatically, erect stoppings in fires, especially in explosions of coal dust. At the risk of complication of fire by explosions of methane and air-dust mixture explosion-proof stopping shall be highly resistant to shock. However, the existing technologies provide for their time-consuming construction for several days, which is deadly for workers.

Thus, the issue of improving the tactics and design of means of extinguishing underground fires and explosions of methane and dust mixtures with air remains very relevant.

The objective of this study is to substantiate the method of construction and design parameters of explosion-proof stopping for quick and safe remote sealing-off of the sources of complex fires and explosions in coalmines.

The object is the technology of quick remote erection of an explosion-proof construction sealing off an underground fire.

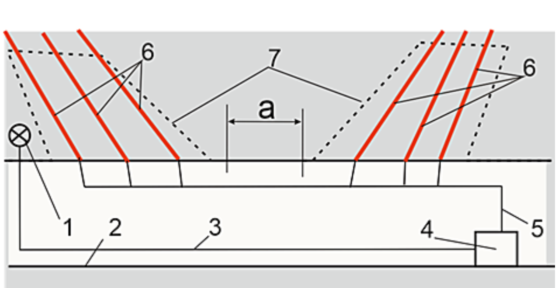
The subject of research includes the processes and patterns of suppression of the shock waves and ventilation streams by the sealing-off structure.

## 3. Results and discussion

It is proposed to ensure the quick erection of the stopping using the rock of the roof of the development working exploded and transferred by the explosion. The resulting mass of crushed rocks has both sealing-off and shock-inhibiting properties.

The device proposed by the authors (**Kostenko et al., 2021**) for the construction of a stopping in the mine workings (see **Figure 1**) consists of seismic sensor 1 walled in rocks, mine working 2 with a height h and an average width b; seismic sensor 1 is connected by electric cable 3 with amplifier 4 with built-in means of light and sound alarm; firing line 5 is laid from amplifier 4 to each of explosive-charged wells 6, which are arranged in groups in the surrounding rocks; a gap with a length a exists between groups of wells. The charge of explosive in each group of wells is calculated for the release of rocks in the volume determined from the expression W1= W2= h2•b, the parameters of well groups are designed for directed counter-release of rock mass in case of blasting.

In the presence of an explosion of dust-air mixture in the mine working, an explosive process is initiated, which is a shock airwave and a fire front, which move through the mine working at a speed close to the speed of sound in the air. The seismic waves propagate in the rocks surrounding the mine working, with a velocity two to three times the velocity of the shock wave. Seismic sensor 1 reacts to the energy transmitted by seismic waves and transmits a signal to amplifier 4 by means of electric cable



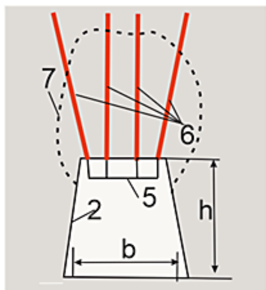




**Figure 1:** Longitudinal (A) and transverse (B) sections of the mine working where the equipment for containment of fires or explosions is arranged in the initial state: 1 – seismic sensor; 2 – mine working outlines; 3 – electric cable; 4 – amplifier with built-in means of sound and light alarm; 5 – firing line; 6 – group of explosive-charged wells; 7 – outline of separation from the array of blasted rock; h,b– height and average width of the working, respectively; a– distance between the groups of wells.

3. The built-in means of light and sound alarm alert people who may remain inside the working about the need to leave the area of wells 6 immediately. With a delay of a few seconds, amplifier 4 produces a momentum to blast charges in wells 6. The blasting of wells 6 occurs until the shock front approaches the location of the group of wells 6. As a result of the explosion of wells, the crushed rock mass transferred by the energy of explosive gases fills the mine working area between the groups of wells in the section with a length of a. The dimensions of the section are selected so that the rock separated from the first group of wells has a volume of W1, and from the second –W2; after settling on the sole of the working and increasing the stacked volume by the coefficient of loosening m, a solid rock-fall is generated at the section of working with a length of 'a' (see **Figure 2**).

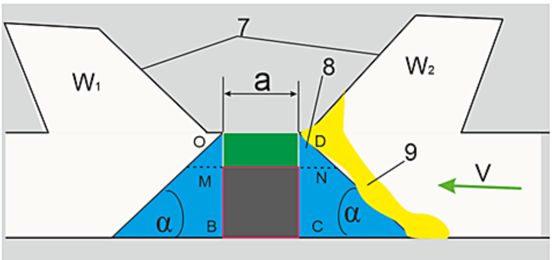



**Figure 2:** Longitudinal section of the mine working, where a stopping was erected to contain fires in the mine working: 8 – transferred mass of loose rocks formed by the explosion; 9 – layer of hardening foam; α – angle of natural slope of the crushed rock mass; B, C, N, D, O, M – points of the fragment of the stopping where the process of mass transfer is considered; the rest of the designations see in **Figure 1**.

There are two possible uses of the sealing-off structure, depending on the type of accident, namely fire and explosion. Sealing-off erection is possible both in automatic mode, in case of explosion of coal dust, and remotely in case of fire. The remote erection of stopping is possible using a separate line connected to amplifier 4, in a situation where the emergency site personnel are taken out of the location of the wells of directed explosion 6 (see **Figure 1**), preferably to fresh air.

This determines the various parameters of the stopping, especially the distance between the groups of directed wells, the value of 'a'. The weakest parameter, in terms of gas permeability, is the smallest linear size of the upper part of the stopping. The parameter 'a' depends on the strength of the rocks lying in the roof, the parameters of blasting, the size of the working height 'h', as well as other factors. It is a trapezoid in longitudinal section. The marginal areas of crushed and exploded rocks are placed in the workings at an angle of natural slope α. It depends on the size of the pieces of rock, the density of their stacking and a number of other factors, most often the value of the angle is within 25 to 35°.

To study the movement of air through the mass of crushed rocks, it is preferred to make the equations of air flow, state, continuity and energy for an artificially isolated fragment BCDO of the stopping (see **Figure 2**). The joint solution of the equations will determine parameters such as air velocity, pressure, density and temperature.

Given the flat relative to the central vertical plane nature of the motion of gases, the physical parameters of the problem are averaged over the width of the mine working, thus, the above equations are written for the two-dimensional region of BCDO (see **Figure 2**). If in this mathematical model we assume that the value of DO, namely the size 'a', is equal to or greater than the height of the working 'h', the system of differential equations can be significantly simplified by transitioning to a one-dimensional model.

In the two-dimensional setting, the system of differential equations, which describes the motion of heated air in the working rocks collapsed by artificial explosion, has the following form, which is described by **Equation 1**:

$$
\begin{cases}
\dfrac{\partial Vx}{\partial t} = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial x} - \dfrac{gVx}{K_f} \\
\dfrac{\partial Vz}{\partial t} = -\dfrac{1}{\rho}\dfrac{\partial P}{\partial z} - \dfrac{gVz}{K_a} - g \\
\mathrm{m}\dfrac{\partial \rho}{\partial t} + \dfrac{\partial (Vx\rho)}{\partial x} + \dfrac{\partial (Vz\rho)}{\partial z} = 0 \\
\rho = \dfrac{P}{RT} \\
\rho_n C_n \dfrac{\partial T}{\partial t} = \lambda divgradT - \rho C_p div\left(T\bar{V}\right) - \dfrac{K\tau}{h}(T - T_n)
\end{cases}
\quad (1)
$$

where:

$V_x$, $V_z$ – components of air filtration rate [m/s],
$x$, $z$ – horizontal and vertical spatial coordinates [m],
$P$ – air pressure [Pa],
$\rho$ – density of air [kg/cu.m],
$g$ – acceleration of free fall [m/sq.s],
$K_f$ – filtration coefficient [m/s],
$T$ – air temperature [K],
$\rho_n$ – density of collapsed rock [kg/cu.m],
$C_n$ – specific heat capacity of rocks [J/(kg*K)],
$R$ – gas constant [J/(kg*K)],
$\lambda$ – coefficient of thermal conductivity [W/(m*K)],
$C_p$ – specific heat of air [J/(kg*K)],
$t$ – time [s],
$\bar{V}$ – air velocity vector [m/s],
$K_\tau$ – coefficient of non-stationary heat exchange of rocks with filtered air [J/(sq.m*cK)],
$T_n$ – temperature of pieces of rock of porous medium [K].

The system of differential equations (1) is so complex that it is impossible to obtain an analytical solution of this system. Therefore, to obtain a numerical solution, the system of equations (1) must be translated into a finite-difference scheme, obtain an algorithm for calculating the functions of $V_x$, $V_y$, $\rho$, $P$ and $T$ and make a program for calculating these parameters on a computer according to the obtained algorithm.

For a system of differential equations (1) to be closed, it must be supplemented by contour boundaries and initial conditions. It is necessary to proceed from the condition of such a physical model where the MBCN and OD contours are impermeable.

According to the imposed restrictions on the properties of the OMBCND contour, the boundary and initial conditions are as follows, which is described by **Equation 2**:

$$\begin{cases} V_x|_{G2} = V_0; V_z|_{G2} = 0; T|_{G2} = T_{oc}; P|_{G2} = P_h; \\ \rho|_{G2} = \rho_n; \\ \dfrac{\partial V_x}{\partial n}|_{G1} = \dfrac{\partial V_z}{\partial n}|_{G1} = 0; T|_{G1} = T_n; \dfrac{\partial P}{\partial n}|_{G1} = 0; \\ \rho|_{G1} = \dfrac{P}{RT}|_{G1}; \\ V_x|_{G3} = V_1; V_z|_{G3} = 0; T|_{G3} = T_k; P|_{G3} = P_{norm} + \alpha; \\ \rho|_{G3} = \dfrac{P}{RT}|_{G3}. \end{cases} \tag{2}$$

In the OMBCND area, the initial-time conditions have the form:

$$V_x|_{t=0} = V_z|_{t=0} = 0; P|_{t=0} = P_{norm}; T|_{t=0} = T_n,$$

where:

- $V_0$ – heated air velocity [m/s],
- $T_{oc}$ – temperature of the air heated in a fire in the working [K],
- $P_h$ – heated air front pressure [Pa],
- $\rho_n$ – density of heated air in front of the curtain in the form of a porous medium [Pa],
- $V_1$ – air velocity at the exit of the porous medium [m/s],
- $T_n$ – air temperature at the exit of the porous medium [K],
- $P_{norm} + \alpha$ – air pressure, which is permissible Safety Rules for Mine Workings [Pa].

To substantiate the parameters of the stopping, the dependence of the pressure of gases moving along the length of the mass of crushed rocks shall be considered. To do this, let us proceed to a one-dimensional model in **Equation 3** and significantly simplify the system (1):

$$\begin{cases} \dfrac{\partial V(x,t)}{\partial t} = -\dfrac{1}{\rho}\dfrac{\partial P(x,t)}{\partial x} - \dfrac{gV(x,t)}{K_f} \\ \dfrac{\partial V(x,t)}{\partial x}\rho = 0 \\ \rho C_n \dfrac{\partial T(x,t)}{\partial t} = \lambda \dfrac{\partial^2 T(x,t)}{\partial x^2} - \rho C_p \dfrac{\partial T(x,t)}{\partial x} - \dfrac{K\tau}{h}(T - T_n) \end{cases} \tag{3}$$

We consider the initial conditions only with (**Equation 4**):

$$V(0,t) = V_0, T(0,t) = T_0, P(0,t) = P_h \tag{4}$$

The solution of the problem (3), (4) refers to a BC segment of the mine working filled with pieces of rock collapsed because of explosion. We consider only the pressure function and analyse its behaviour depending on the change in the filtration coefficient.

Under the given initial conditions, the pressure function has the following form (**Equation 5**):

$$P(x,t) = P_h - \frac{V_0 g \rho x}{K_f} \tag{5}$$

Taking the depression of the air front equal to the depression of the extraction section $P_h$ = 981 Pa, the initial velocity of its movement $V_0$ = 3 m/s, the air density $\rho$= 1.185 kg/cu.m (at a temperature of 25°C), the acceleration of free fall $g \approx 10$ m/sq.s, using the obtained expression for pressure (5), at different filtration coefficients, we can easily determine the distance at which the pressure is zero, i.e. the movement of air is absent (see **Table 1**).

These results show that the length of a few centimetres of densely filled crushed rock to the working section is sufficient to reduce the filtration of gases coming from the combustion source to zero values. Unfortunately, the mass of the rock separated by the explosion, as usual, contains the elements of fasteners, pipes, cables, etc., which lead to a significant increase in the permeability of the environment. It is advisable to take the minimum size of the stopping not less than the height of the mine working a≥h, which is guaranteed to eliminate the flow of air through the stopping.

**Table 1:** Effect of filtration coefficient ($K_f$) on the minimum size of the distance (a) required to neutralize the loss pressure

| **$K_f$, m/day** | 50 | 100 | 150 | 200 |
|---|---|---|---|---|
| **a, m** | 0.02 | 0.03 | 0.05 | 0.06 |

It should be noted that the penetration of gases into discrete media is not only due to filtration, but also due to turbulent and Knudsen diffusion, therefore additional measures of sealing-off shall be implemented, such as film or foam coating, etc. (see **Figure 2**, item 9).

The use of stoppings created by directed explosion to contain coal dust explosions is due to the presence of other properties of such a technical solution. The required parameters of explosion resistance of the stopping differ significantly from the sealing-off due to the initial conditions of the shock front.

During the movement of the explosion, the gases that have high pressure and temperature gases, including flammable and explosive ones, shall not penetrate the containing obstacle. The effect of the barothermal effect of the explosion, high pressure and temperature of the explosion front is short and lasts less than a second. It takes a few seconds for the gases to seep through the gaps between the pieces of crushed rock. Moreover, there is an intensive cooling of gases in contact with the relatively cold mine environment. Behind the obstacle, they lose the negative properties causing the explosion. Furthermore, at the site of the explosion, the gases cool rapidly, and there is liquefaction, which is accompanied by the suction of air from the undamaged part of the mine working to the site of the explosion through the obstacle.

However, when used as an anti-explosive barrier created by a directed explosion of the stopping, its qualitatively new properties act additionally. When the explosive is blasted in the wells and the crushed rock is transferred, an additional void of volume W is formed above the primary contour of the working; the total cross-section of the void is approximately doubled.

The shock wave of the explosion moves along the working having a cross-sectional area S with an average velocity V1. When the shock front approaches the point of expansion of the working, where the cross-sectional area is approximately 2S, the flow is inhibited and the velocity is reduced to V2, which is inversely proportional to the ratio of the cross-sectional planes. In our case, this ratio is S/2S = 0.5, i.e. the velocity of the shock wave is reduced by half. Thus, given that the mass transferred by the explosion of air remains unchanged, the momentum from the explosive shock to the stopping is reduced by half.

The next factor that positively affects the stability of the stopping is its shape. The shock wave strikes the inclined surface formed by the mass of rocks crushed by the explosion, which is located relative to the sole of the workings at an angle of α = 25 to 35°. When interacting with an inclined surface, a vector of movement of air is deviates and velocity is reduced to V3 (see **Figure 3**). Some of the energy is reflected towards the roof and the rest of the reduced shock momentum is spent on sealing off the discrete medium of the stopping.

When the device for the containment of coal dust explosion is triggered automatically, a series of explosive-charged wells is detonated, which is several seconds ahead of the dust explosion front. One of the results of the blast is the release of significant amounts of explosive gases and rock dust. The gases remain near the stopping due to blockage of the ventilation flow. The oxygen content is sharply reduced in the volume filled with explosive gases, which prevents the combustion of coal dust and helps to suppress the fire front.

In addition, together with explosive gases, a significant mass of rock dust is formed, which floats in the air and partially settles on the surface of the mine working. It is known that the addition of rock dust to coal significantly reduces the explosive potential of the obtained mixture. Filling of the working sections adjacent to the stopping with the products of the explosion of well charges significantly reduces the conditions for the continuation of a self-sustaining explosion of coal dust.

Thus, when using the device, an effective barrier is created in advance to reliably suppress barothermal factors of coal dust explosion, as well as to provide conditions for reducing negative explosion factors for the personnel in the working network behind the accident containment system.

It is expedient to use a quickly erected explosion-proof stopping when working out methane-rich layers prone to spontaneous combustion and posing risks of coal dust explosions by automated high-performance complexes. Fires and explosions at such mine working sections lead to significant losses of expensive equipment as well as production. Furthermore, there are significant environmental consequences in the form of long-term release of fire gases and heat emissions.

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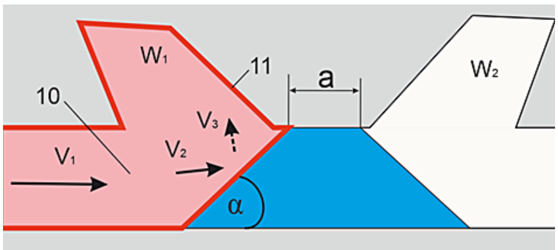


**Figure 3:** Schematic of the stopping for containment of coal dust explosions in mine workings: $V_1$, $V_2$, $V_3$ – vectors of the velocity of the explosion shock front, respectively, at: linear and extended sections of the working reflected from the surface of the stopping, 10 – volume of the working filled with explosive gases; 11 – surface of the working covered with dust products of the explosion; the rest of the designations see in **Figure 1**

As an example, the schematic of fire and explosion protection of the excavation site is given (see **Figure 4**).

It is recommended to place the equipment for the containment of fires or explosions, namely explosive-charged wells to create stoppings with directed explosion, in the pillars that protect the main workings from the rock pressure effects. The seismic sensors are placed toward the projected explosion front and installed in an array of rocks containing the working. It is expedient to install sensors in the layers of rocks that are least prone to cracking, such as sandstone or limestone. Based on the scheme of ventilation of the section, it is necessary to block both the workings that supply fresh air, and those that are used for its removal.

As a disadvantage, we can note the need to provide additional safety measures when handling explosive-charged wells during their arrangement, maintenance and discharge after working out the section.

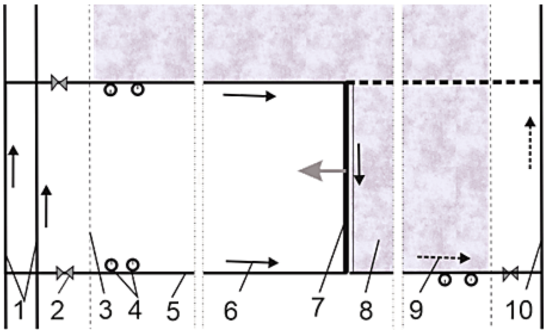


**Figure 4:** Location of the equipment for containment of fires in the workings of the excavation section: 1 – main workings; 2 – groups of explosive-charged wells; 3 – boundary of the protective pillar; 4 – seismic sensors; 5 – section working; 6 – stream of fresh air; 7 – longwall; 8 – mined-out area; 9 – stream of outgoing air; 10 – boundary working

The use of explosive technology for the construction of sealing-off structures opens up the possibility of qualitatively improving the tactics of extinguishing complex fires in the mining sections of coalmines. The ability to create stoppings remotely and quickly allows for the focus to be turned towards the urgent evacuation of the personnel caught by an accident to safe places, with simultaneous accelerated delivery of the equipment and materials to suppress combustion sources. There is no need to wait a few days for emergency ventilation manoeuvres and long-lasting operations for the delivery and erection of sealing-off facilities. This contributes to the acceleration of counteraction of the development of the combustion source and its elimination and, accordingly, decrease in material and labour costs and reduction of time of emergency response.

The proposed method of automated operation of directed explosions for the erection of explosion-proof stoppings is also a qualitatively new tactical method of termination of self-supporting explosions of coal dust. The use of seismic waves as an indicator of the explosion, in contrast to the existing slow-response means, increased the reliability of the termination of the explosion front and limit the area where the miners are exposed to negative explosion factors.

The explosive method of sealing-off also has a significant environmental effect due to the reduction of burned materials and, consequently, release of heat and greenhouse gases.

## 4. Conclusion

The analysis of accidents in Ukraine's mines shows that underground fires in hard-to-reach places, especially complicated by the threat of explosions, are the most difficult in terms of negative results and the severity and duration of elimination. The protracted nature of the containment and elimination of this type of accident is due to the significant duration of the erection of sealing-off structures, the stoppings.

An improved version of the erection of explosion-proof structures by filling the cross-section of the working with discrete material, the rocks loosened and transferred by counter-directed explosions, has been proposed.

Preparation of explosive-charged wells in advance allows for remote and even automatic operation of the device for the erection of the stopping.

Based on the mathematical modelling of mass transfer tools through a discrete medium, the parameters of arranging groups of wells that determine the thickness of the stopping, i.e. its sealing-off characteristics, have been substantiated. A linear relationship between the distance between groups of wells and the ability to stop mass transfer has been established.

The structures erected by the method of directed explosion on the path of the coal dust explosion front have increased containment properties. This is due to the presence in the space in front of a stopping of explosive gases that phlegmatize the combustion of methane and coal dust; furthermore, the rock dust generated after the explosion reduces the explosive properties of coal dust agitated by seismic waves.

The results of the research open the possibility to prepare the means of containment of dust explosions in advance and to improve the tactics of containment of explosions and fires. The tactics of elimination of complex fires in hard-to-reach places, especially complicated by the threat of methane and coal dust explosions, are qualitatively changing. The main efforts of mine rescuers shall be aimed at the urgent evacuation of the personnel from the emergency section with the simultaneous delivery of combined fire suppression means based on sealing-off.

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## SAŽETAK

### Utvrđivanje parametara brzo uspostavljene protueksplozijske brane

Cilj je rada utvrditi način konstrukcije i projektnih parametara protueksplozijske brane za brzo i sigurno daljinsko izoliranje izvora složenih požara i eksplozija u rudnicima ugljena. Dizajniran je nov način daljinskoga uspostavljanja protueksplozijskih brana u rudarskim radovima i matematički model prijenosa mase kroz tijelo brane od materijala u rasutome stanju. Poboljšan je način za suzbijanje podzemnih požara i eksplozija zahvaljujući brzomu daljinskom uspostavljanju protueksplozijskih brana. Predložena je tehnologija brzoga postavljanja brana od kamena usitnjenoga usmjerenom eksplozijom za izoliranje interventnih dionica rudnika. Izrađen je numerički model i metoda za proračun parametara protueksplozijskih brana uspostavljenih metodom usmjerene eksplozije. Rezultati proračuna otvaraju mogućnost da se unaprijed pripreme sredstva za zadržavanje eksplozivne prašine te da se poboljša metoda sigurnoga suzbijanja eksplozija i požara.



**Ključne riječi:**
podzemni požar, eksplozija, protueksplozijska brana, drobljeni kamen, filtracija, tlak plina


## Author’s contribution

**Viktor Kostenko** (doctor of technical sciences, professor) initialized the idea, developed a methodological approach, managed the whole process and supervised it from the beginning to the end; **Olena Zavialova** (PhD, associate professor) analyzed problematic situations, review of literary sources; **Yuliia Novikova** (PhD, associate professor) created a calculation model and a methodology for calculating parameters; **Olha Bohomaz** (PhD) completion of the literature review; **Yaroslav Krupka** (mag.ing.) calculated parameters; **Tetiana Kostenko** (doctor of technical sciences, professor) participated in all stages of work, submission and review of the paper, analyzed results.