

DARIUSZ OBRACAJ¹*, KRZYSZTOF SOROKO², MAREK KORZEC¹**CONDITIONS FOR DECIDING WHETHER TO TERMINATE A FIRE RESCUE OPERATION
IN AN UNDERGROUND MINE – A SYSTEMIC DECISION-MAKING APPROACH**

Fires in underground metal mines primarily occur as open fires. Due to technological factors, these fires are mostly linked to heavy mining vehicles and conveyor belts. This article focuses on determining when to end fire rescue operations and when it is safe to resume mine operations. Complex mine ventilation systems, especially in areas with extensive operations, can delay the clearing of smoke and pollutants toward upcast shafts. While it is economically important to minimise downtime, safety must remain the top priority when deciding to restart operations. To aid this decision-making process, the article presents a new method for identifying danger subzones within a larger affected zone. Simulation software can model smoke dispersion in the ventilation network, and remote measurement techniques can monitor gas concentrations during fire incidents. This article demonstrates how to estimate the clearing time for smoke pollutants using actual mine data and introduces a decision algorithm for terminating fire rescue operations. The aim is to provide practical insights for mine engineers managing fire operations, supporting informed decisions about eliminating the danger zone and restoring mine operations safely and effectively.

Keywords: Underground mine fire; vehicle fire; fire rescue operation; danger zone; pre-incident planning

1. Introduction

Underground mine fires pose challenges to both operations and safety, as they can occur as concealed or open fires. Concealed fires occur when coal, sulphide ores, oily rags, paper, or timber combust spontaneously, usually from self-heating when oxidation heat is trapped. Open fires start when flammable materials, machinery, or equipment ignite, often in areas affected by the mine's active ventilation system.

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Underground fires expose mine personnel to open flames, high temperatures, toxic or asphyxiating gases, and reduced visibility. While prior research has focused on rescue operations [1-4], new challenges emerge when determining safe restoration of normal mine operations after extinguishing a fire. As a result, clear criteria for the resumption of mine operations become essential. Without them, poor decisions can prolong downtime and increase costs. Recognising this need, it is crucial to develop structured, evidence-based procedures for efficient post-fire mining activities to ensure both safety and operational effectiveness.

The principles for starting and carrying out fire rescue operations are well-defined in mining regulations across individual countries [5-8]. However, despite the clarity of these operational procedures, regulations provide less specific guidance on how to define and remove danger zones during and after a fire. A danger zone refers to a section of the mine that may be affected by smoke, fire, and other hazardous conditions or may become compromised due to reversed intake air or the rollback effect. For example, Polish mining regulations [9] require that, even with ongoing mine personnel self-rescue training, extra personnel be posted to block entry to areas adjacent to the danger zone during rescue operations. However, it is not specified what to do after the fire is extinguished in order to cancel the fire rescue operation and resume mining operations.

The danger zone stays in place until the incident commander ends the fire rescue operation. Although confirming fire extinguishment is simple, it's unclear when and how to remove safety posts and resume normal mine work. Hazardous gases can linger after the fire is out, and there are no clear guidelines for ending fire rescue operations.

A common approach to determining when to conclude firefighting operations involves identifying specific locations for monitoring mine atmosphere parameters. This method has become increasingly challenging in mines with extensive ventilation systems, despite the use of advanced systems for monitoring both wired and wireless ventilation environments in underground mines [8,10,11]. Only rescue teams can enter the danger zone until it's safe, which makes measurements and safety costly and difficult. Often, the average time for airflow from the fire site to the upcast shaft is used to determine the waiting period after extinguishing the fire. While this approach is effective in simple ventilation systems, its reliability decreases as system complexity increases and fire gases persist for longer durations. Fires in intake airways near downcast shafts pose the greatest risk.

To address limitations in fire termination decisions, pre-incident planning with computer modelling of mine fire evolution is useful. The quality of a mine's ventilation network representation is crucial for predicting fire impact. The complexity of the ventilation network is also important due to numerous active roadways and intricate network connections, including multi-line systems with parallel ventilation lines linked by cross-cuts. Additionally, mining operations in large areas with distant downcast and upcast shafts further complicate the analysis. As roadway layouts and ventilation connections change during mining, accurately modelling fire and smoke propagation in hard rock mines using a room-and-pillar system requires consideration of all relevant factors.

Due to the complexity of fire rescue operations in metal mines, a systematic approach to decision-making is necessary. Evaluating factors that affect whether to continue rescue operations after extinguishing a mine vehicle fire is especially important in complex ventilation networks. Advanced software tools that predict the spread of smoke and fire gases can support decisions on when to end rescue operations and resume normal activities.

Based on the analyses presented, a new method divides a large danger zone into smaller subzones, allowing mining to resume in stages. An algorithm for implementing this method has been introduced. A real mine case study shows how this helps make decisions about ending fire rescue, considering both fire behaviour and changing mine conditions.

The study emphasises the importance of considering not only fire behaviour but also the temporal and spatial changes in the mine's environment.

2. Metal mine ventilation network

2.1. Complexity of the ventilation network

Metal mines feature complex ventilation systems, often utilising room-and-pillar mining methods. These methods require substantial air supply due to multiple active mining rooms, leading to the construction of multi-threaded access roadways for both airflow and transportation routes. Depending on the geological structure, ventilation networks may be single- or multi-level, with varying flow velocities and potential changes during fire incidents. The complexity, as categorised by Wang et al. [12], complicates the control of pollution spread in the network. Additionally, operations such as drilling and hauling involve mine vehicles. In such a mine, a vehicle fire is highly likely and can pose a real threat to mine personnel and to the directed smoke flow from the fire site to the upcast shafts. A simplified model in Fig. 1 illustrates airflow distribution from the downcast shaft to mining areas, highlighting the complex network of multi-lane roadways.

During and after a fire, roadways can fill with smoke and hazardous gases, creating danger zones for personnel, particularly those leading to upcast shafts or areas at risk of reversed airflow.

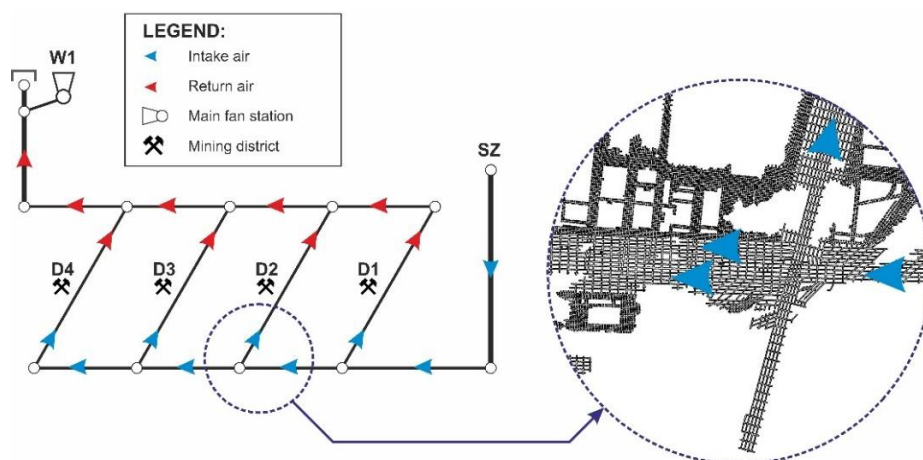


Fig. 1. Simplified model of complex ventilation network

2.2. Mine ventilation network during fire occurrence

Three operational states of mine ventilation systems during a fire can be identified:

- pre-incident ventilation (Fig. 1), when the mine atmosphere is determined by ongoing technological processes (mining, loading, hauling, etc.);
- ventilation during a fire (Fig. 2a), when fire gases flow towards upcast shafts
- post-fire ventilation (Fig. 2b), when fire gases are still present in the return airways.

During and after a fire, roadways can fill with smoke and hazardous gases, creating danger zones for mine personnel, particularly those leading to upcast shafts or areas at risk of reverse airflow. Fig. 2a highlights the danger zone during the fire, while Fig. 2b shows the paths of lingering fire gases after extinguishment.

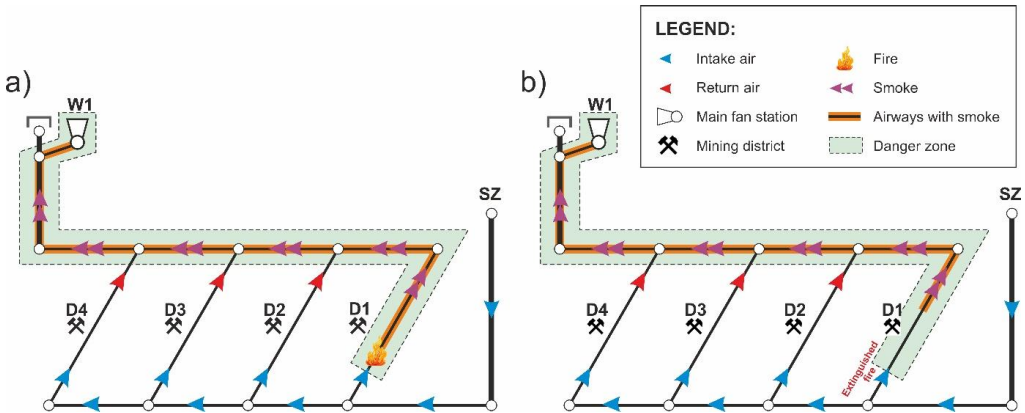


Fig. 2. Designated danger zone in the mine ventilation system:
a) during a fire; b) after the fire has been extinguished

The following section discusses decision-making concepts for terminating fire rescue operations using a simplified ventilation network.

3 Decision support method for terminating a fire rescue operation

3.1. Fire suppression time

The incident commander can end a fire once two basic criteria are met: confirmation that the fire is out and the danger zone roadways are clear of fire gases. Fire suppression services usually report when the fire is out. Pre-incident plans can also use data on burn and extinguishing times of vehicles and load-haul-dump (LHD) vehicles in metal mines. The type of fire, flammable materials, and ventilation conditions affect its duration.

There are two primary types of fires in metal mines.

- 1) Linear Fires: These fires, such as those occurring in conveyor belts, last longer, and their duration depends largely on ventilation and the extinguishing method used.
- 2) Point Fires: These occur in fixed locations, like vehicle or transformer station fires, like vehicle or transformer station fires, where the flammable material and airflow determine how long they will last.

Published studies include fire characteristic curves that show the development of mine vehicle fires over time, with research focusing on the heat release rate (HRR) curve, essential for

numerical modelling. For LHD vehicles, including off-road vehicles, fire development curves show how the HRR changes during combustion. The ISO/TS 16733-2:2021 standard [13] provides an example of such a curve (Fig. 3). According to the graph, the fire intensity reaches its maximum after a certain time. The self-extinguishing phase lasts significantly longer than the fire's growth phase. By analysing the curves, it is possible to estimate the duration of vehicle burning without fire extinguishing intervention.

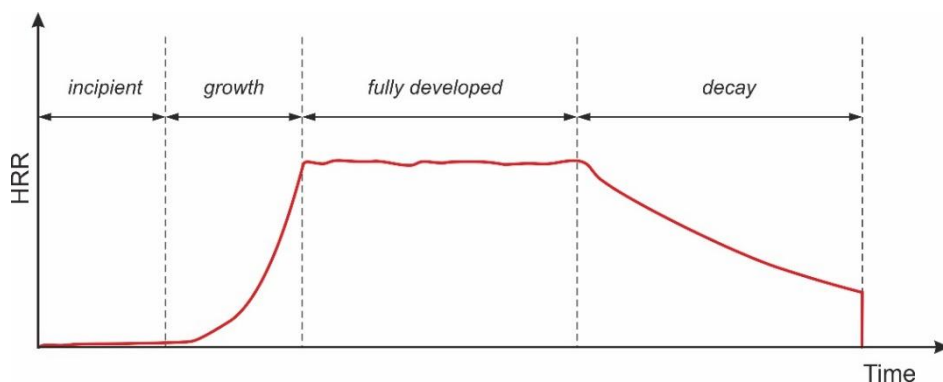


Fig. 3. Phases of development of a road vehicle fire according to standard ISO/TS 16733-2:2021 [13]

The topic of mine vehicle fires in mine workings is rarely discussed in international literature. Even less frequently are actual experiments conducted in underground workings. Investigations by R. Hansen [14-18] highlight different fire curves for vehicle fires in Australian underground mines, revealing that maximum power can be reached within 10 to 20 minutes. This time largely depended on the ignition source in the vehicle and the manner in which the fire spread to subsequent vehicle components. The presented research results indicate that the fire duration from its onset to the decay phase varied between 110 and 300 minutes (the fire progressed to the decay phase more quickly when there were no further increases in fire intensity). The nature of the HRR curve also varies from the reference curve (Fig. 3). In such fires, more than one fire intensity peak may occur. Between these peaks, there may be periods of pause, manifesting themselves as a decrease in fire intensity followed by a rebound. This is due to the burning of various components of mine vehicles.

It should be emphasised that the research indicates that fires involving mine vehicles last significantly longer than those involving passenger cars in tunnels, highlighting the need to consider this in mine fire scenarios. The duration of a fire involving a mine vehicle in an underground roadway is influenced by the airflow velocity to the burning vehicle. Most studies focus on airflow below 1 m/s, but the heat release rate (HRR) can increase several-fold at speeds above 3 m/s, nearing ten-fold above 10 m/s [19-21].

Natural outflow of fire gases from a ventilation network through upcast shafts is an inevitable consequence of a mine ventilation design. As demonstrated by [22-24], low ventilation intensity in some airways “deep” in the ventilation network can extend cleanup duration.

The presented literature studies indicate that knowledge of a fire curve of a mine vehicle is important and should be strictly considered, for example, during training, simulations of various

fire scenarios, and preparation for fire rescue operations. Additionally, a numerical representation of the complex ventilation network is necessary to analyse the distribution of smoke or fire contaminants.

To develop a method for deciding when to terminate fire rescue operations, it can be assumed that the active extinguishing time should not exceed the duration it takes for the vehicle to burn freely. Furthermore, the overall duration of the fire rescue operation must surpass this free-burning time.

3.2. Fire rescue operation termination criteria

As demonstrated in the previous section, the duration of fire rescue operations must exceed the time required to extinguish a fire. The criteria to extinguish a fire in mines exploiting non-flammable deposits, including ores, can be summarised as follows:

1. Active fire extinguishing until no visible signs of burning, glowing, melting, or smoke remain.
2. Complete clearance of the ventilation system (danger zone) from harmful gases.
3. An additional waiting period as a safety margin.

The first criterion is typically satisfied because rescue teams report directly on fire suppression activities. Once active extinguishing is complete and the absence of smoke and visible fire indicators is confirmed, the fire can be officially declared extinguished. To verify that the danger zone can be removed after extinguishing a vehicle fire, it is necessary to measure concentrations of harmful gases in the leeward area immediately behind the fire site. However, this does not ensure that roadways in the danger zone are safe for personnel. The next step is to determine whether hazardous gases are present in the roadways within this zone. In mines covered by Polish mining regulations, the gas that should be measured in the context of determining fire hazard is carbon monoxide. However, in the case of heavy diesel vehicle fires in mines, this may also include measurements of HCl and HC, which also dominate vehicle fire gases, as reported by [25].

The second criterion, related to the availability of information on air quality in previously designated danger zone roadways, is difficult to obtain. The integration of wireless sensor networks [26-27], fuzzy logic [28], IoT technologies [29], remote sensing [30], and fiber-optic monitoring systems [31] presents a multifaceted approach to monitoring fire gases in underground mines. Their effective use in large, extensive, and complex mine ventilation networks can be challenging. Furthermore, traditional wired or wireless systems may struggle to accurately detect gas concentrations during a fire due to high temperatures and smoke.

Therefore, direct measurement of gas concentrations in a danger zone requires mine rescuers to enter the mine with breathing apparatus. In extensive ventilation networks, this approach is impractical due to the number of entrances and teams needed. Remote gas measurement via unmanned aerial vehicles could effectively monitor atmospheric conditions [32].

Another supporting solution to this technical problem is the use of software to simulate the spread of pollutants in mine ventilation networks. In case of complex networks, such as those found in mines with room-and-pillar systems and multiple intake and ventilation shafts, fire gases can travel longer distances through the mine's underground workings. Such simulations must consider factors like fire-induced buoyancy forces (natural ventilation pressure), choking effects, flow reversals and smoke rollback, all of which complicate the analysis of fire product propagation [33-35].

Various tools are available for simulating the propagation of smoke and gas in mine ventilation networks [36]. These software packages can verify that airways are clear of harmful gases after a fire is extinguished. By quantifying the time needed to clear roadways, computer simulations support decision-making regarding danger zone removal and help transition from monitoring to allowing mine personnel to re-enter.

3.3. Concepts for removing a danger zone

Four concepts are considered in search of criteria enabling the fire incident commander to decide to end a fire operation and remove the previously designated danger zone:

- Conservative concept: considers maximum time for smoke or contaminants to reach upcast shafts;
- Danger zone concept: uses airflow and dilution to clear subzones one by one;
- Dynamic concept: removes subzones based on previous data and airflow;
- Analytical concept: uses simulation and other factors to predict contaminant reductions, such as carbon monoxide, over time.

Each concept offers a distinct transition mechanism from fire suppression to the restoration of normal mine activities.

The first of the proposed concepts is the simplest method to consider for determining the moment of termination of firefighting and rescue operations and the announcement of the removal of a danger zone. This method involves the ventilation engineer determining the time it takes for smoke to flow from the fire origin through all airways to the upcast shafts, taking into account airflow velocities in each airway. This time can be referred to as smoke extraction time t_{cle} and is assumed to be the longest time required for smoke to flow through all roadways in the danger zone. To ensure a safety margin, it is assumed that the acceptable time for the end of firefighting operations, t_{term} must be greater than smoke extraction time: $t_{term} > t_{cle}$. The drawback of this solution is that it takes time for the roadways to be completely cleared of fire contaminants (Fig. 4) before a danger zone can be removed. This zone can be very large in extensive ventilation networks.

The second concept considers the inflow of fresh air and the dilution of harmful gases in mine airways between the fire source and the upcast shafts, enabling the cyclical removal of danger

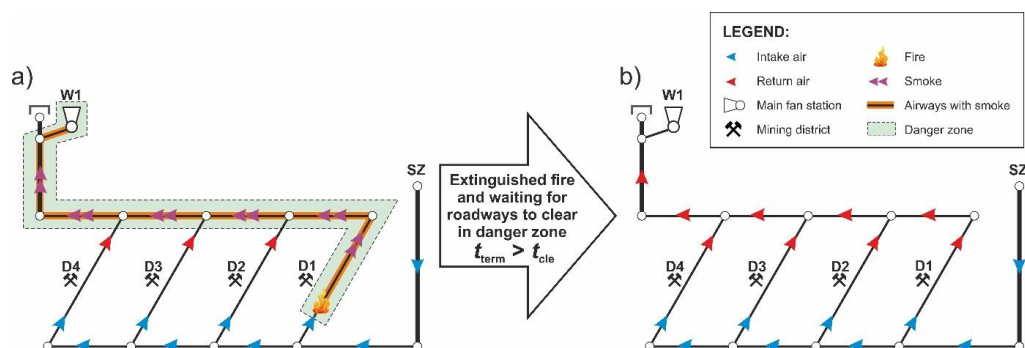


Fig. 4. Conservative concept of removing a danger zone, a) danger zone during a fire, b) ventilation network cleared of fire contamination

subzones after the gases have passed through each subzone. As the harmful gases in a given subzone dilute, the incident commander can cyclically remove a danger subzone, allowing personnel to enter parts of the zone, despite the continued presence of gases in subzones located closer to the upcast shaft. Fig. 5 shows the concept, which involves narrowing the danger zone by cyclically removing subzones as time passes after the fire source is extinguished.

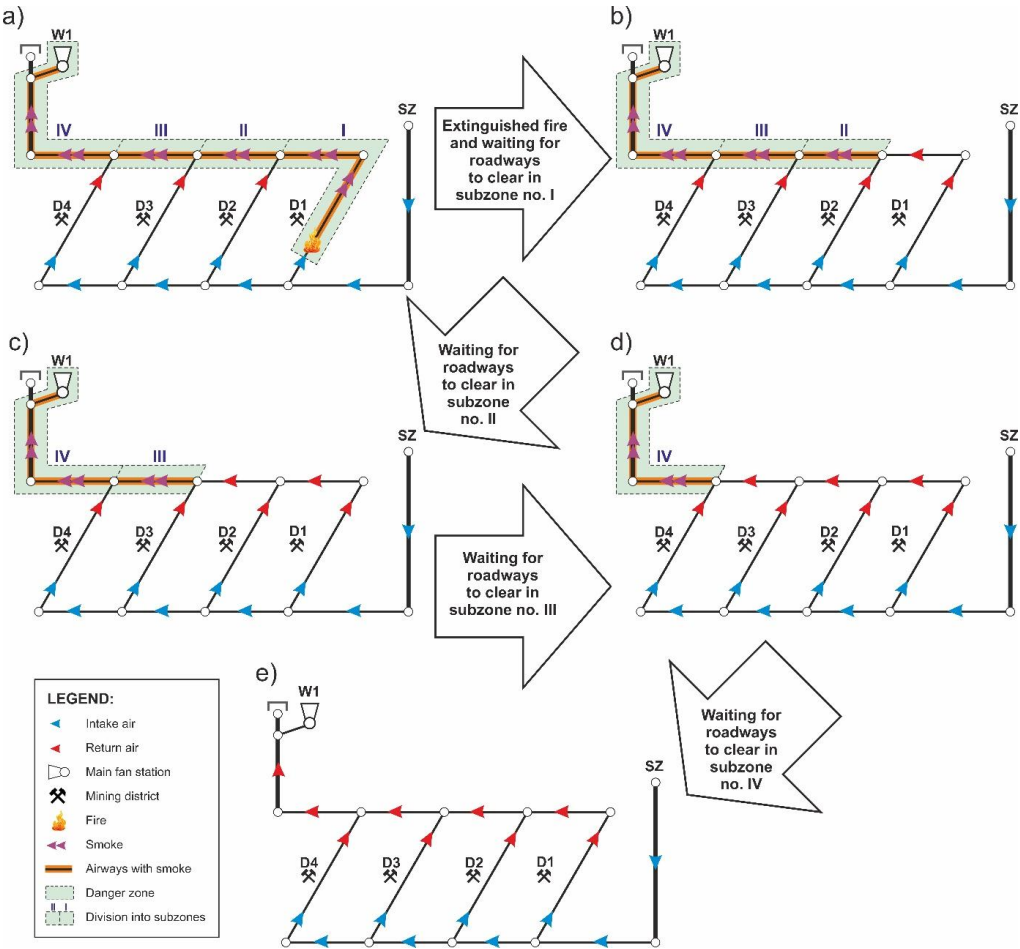


Fig. 5. Concept of cyclically removing danger subzones, a) danger zone divided into four subzones, b) cleared roadways of subzone I, c) cleared roadways of subzones I and II, d) cleared roadways of subzones I, II and III, e) cleared all subzones

The next concept is the most extensive decision-making tool. In this concept, the incident commander decides to partially remove subzones and adjust the extent of the danger zone, similar to the previous concept. However, the subzones will not necessarily be removed in a cyclical order based on the direction of airflow toward the upcast shaft. With extensive ventilation networks in specific subzones, it may turn out that the gases “dilute” or “flow” more quickly, allowing the subzone to

be cleared for safe operation. Fig. 6 illustrates the dynamic concept, which involves reducing the danger zone by removing subzones in any order over time after the fire has been extinguished.

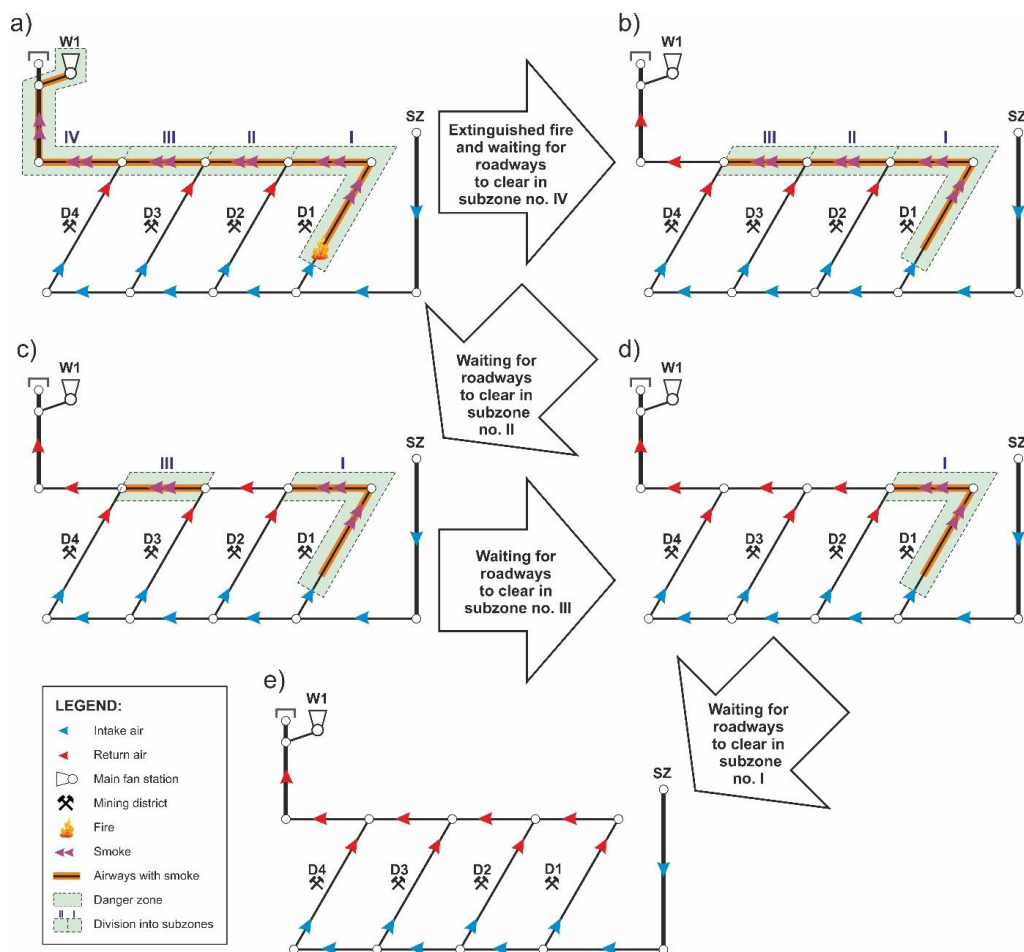


Fig. 6. Dynamic concept of removing danger subzones arbitrarily, a) danger zone divided into four subzones, b) cleared roadways of subzone IV, c) cleared roadways of subzones IV and II, d) cleared roadways of subzones IV, II and III, e) cleared all subzones

In the most advanced analytical concept, decisions can be made by additionally taking into account the results of flow simulations of harmful gases spreading in the ventilation network, achieved through computer programs. This approach requires knowledge of the HRR curve and the carbon monoxide emission curve. The simulation results can help determine the time it takes for CO concentration to decrease in individual roadways. However, due to the uncertainty regarding the accuracy of these simulations and their correlation with actual occurrences in roadways, this concept should be considered complementary to the previously described methods, which involve measurements within a mine ventilation network.

3.4. Algorithm for terminating firefighting operations

For the proposed concepts of making decisions to terminate fire rescue operations and to remove a danger zone, a decision-making algorithm was developed and is presented in Fig. 7.

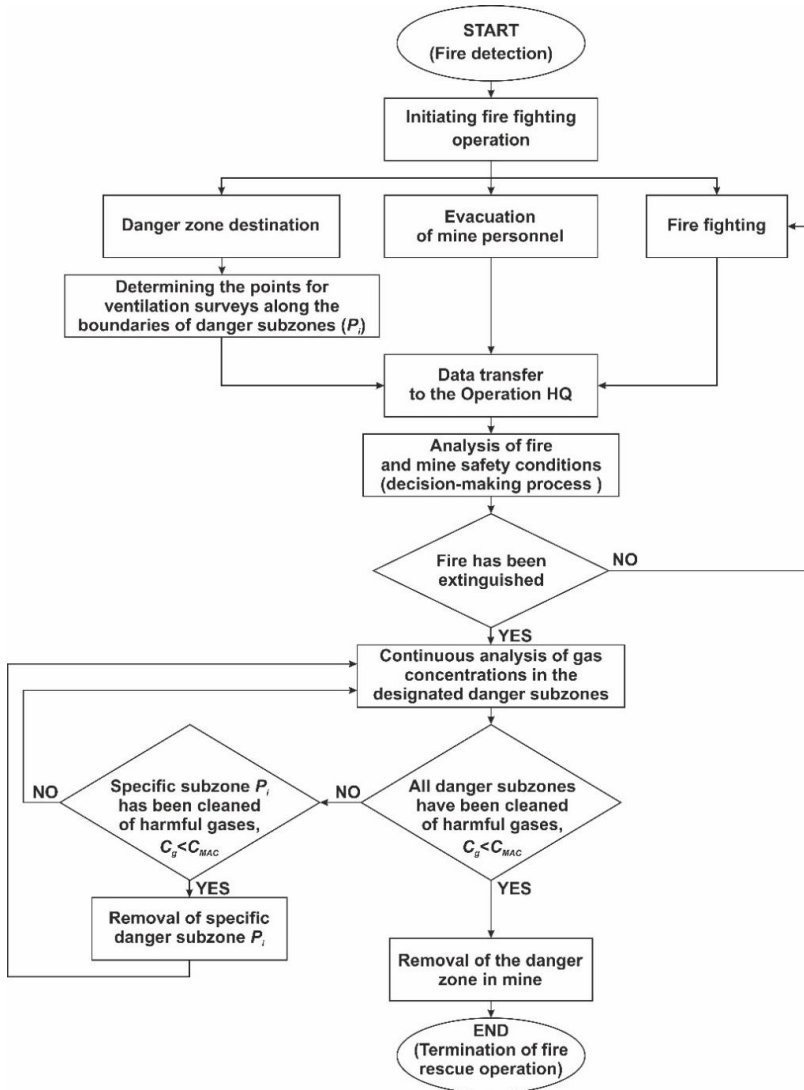


Fig. 7. Decision-making algorithm to terminate fire and rescue operations in a mine based on the subzones concept

The schematic diagram of the ventilation network with the location of sample remote measurement points in subzones is presented in Fig. 8.

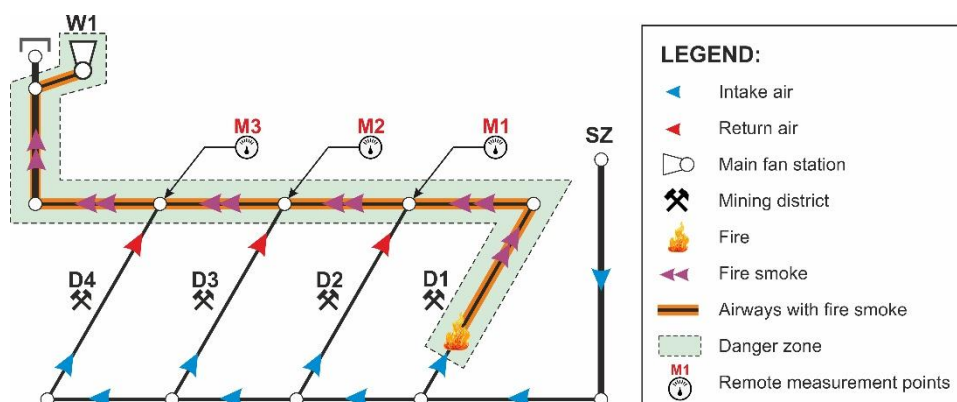


Fig. 8. Sample locations of remote measurement points in danger subzones

4. Example of analytical concept application in the ore mine

4.1. Numerical model of the mine ventilation network

Various simulation tools are used to model the distribution of smoke and harmful gases in mine ventilation networks. These tools represent a ventilation network as branches, corresponding to roadways, and nodes, corresponding to intersections. To create a realistic network model, it is necessary to incorporate elements such as fans, ventilation doors, stoppings, and air crossings. Additionally, it is necessary to account for mass and energy transfer phenomena within branches, as these influence air densities. Software packages such as Ventgraph, MFire, Ventsim (VentFire module), and Vuma-network provide fire and smoke behaviour simulation capabilities for ventilation systems [36–38]. For localised fire and smoke spread, such as in a single mining district, computational fluid dynamics (CFD) tools are commonly used. Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology, is among the most widely adopted CFD tools for this purpose [39].

Vuma-network software was selected to illustrate the possibilities of using computational tools to simulate transient gas flows in mine ventilation networks, due to its ease of creating ventilation networks for mines with a room-and-pillar mining system. In this context, the ventilation model from the S-P copper ore mine, which utilises such a mining system, was used to demonstrate the feasibility of determining fire duration and smoke distribution. The ventilation model for modelling the transient state of fire development simulation was reproduced in Vuma-network. Vuma-network uses the open-source MFire 4.0 code [38].

The model of S-P mine's ventilation network, containing four downcast shafts and two upcast shafts, is shown in Fig. 9. The figure illustrates the ventilation network in a plan view. The figure indicates the location of the fire involving a vehicle and five designated danger zones. According to the presented assumptions, the zones include roadways through which smoke and harmful gases can flow to two upcast shafts, W1 and W2. Fig. 9 also indicates eight measurement points for monitoring CO concentration during the simulation of the spread of harmful gases through the network.

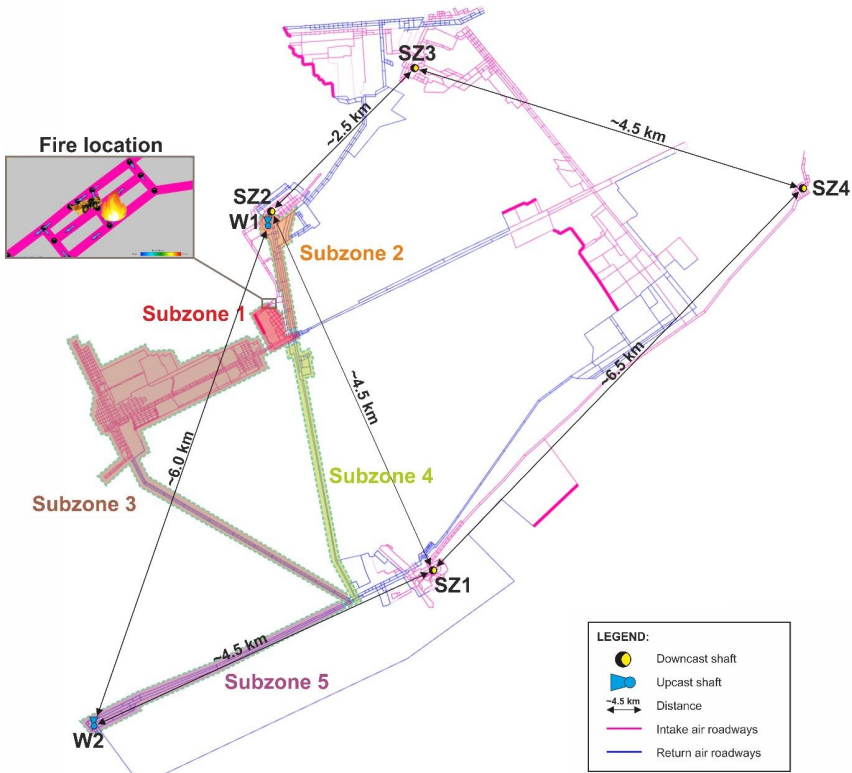


Fig. 9. Fire site and danger subzones in the ventilation network of the S-P mine

4.2 Simulation of CO spread in the ventilation network

Fig. 10 shows the parameters of the fire development curve for a burning loader with a maximum heat release rate of 25 MW. During the growth and decay periods of the fire curve, the fire output is approximately proportional to the square of time. A quadratic function is assumed for the fire growth period (from $t_0 = 2$ minutes to $t_1 = 4$ minutes), then, for simplification, a constant value is assumed during the full fire development period (from $t_1 = 4$ minutes to $t_2 = 25$ minutes) and a decreasing quadratic character is assumed during the decay period (from $t_2 = 25$ minutes to $t_3 = 60$ minutes). The time period from 0 to t_0 is referred to as the ignition delay period, which spans from ignition to the onset of flame. A 2-minute ignition delay period was assumed. The firefighting scenario involves extinguishing the loader for up to 54 minutes without the need to restrict airflow to the area. After 54 minutes, the fire was extinguished, and gas emissions were therefore assumed to have stopped.

4.3. Simulation results of concentrations in the ventilation network

In accordance with applicable fire safety regulations, entrance control posts were placed along the potential path of smoke flow to the upcast shafts. The mining district where the fire

Fig. 10. Assumed model of vehicle fire development curve (HRR) – window of Vuma-network software

originated is affected by the main fan stations at shafts W1 and W2. This results in the main return airflow being split towards these shafts. It means that for safety reasons, five danger sub-zones are designated, as shown in Fig. 9. Entrance control posts are placed at the boundaries of roadways within the zones and other areas of operation. During the simulation, the distribution of gas concentration in the danger subzones is checked at eight points. CO concentration control is assumed. The results for fire temperature, CO concentration, and airflow in the branch where the fire originated are shown in Fig. 11. The range of smoke flow in the ventilation network after 54 minutes is shown in Fig. 12. Fig. 13 shows changes in CO concentrations in eight branches with designated measurement points.

Analysing the CO concentration distribution results in Fig. 11, it can be concluded that at a developed fire temperature of 1200°C in the downwind airflow, the CO concentration was 8000 ppm. The concentration decreased to 3000 ppm after 30 meters along the roadway due to free inflow of air into the mining district.

At the analysed measuring stations, CO concentrations remained under 150 ppm, with higher readings near the W1 upcast shaft. At other stations, values did not exceed 100 ppm. Notably, in mines with a room-and-pillar system, significant gas dilution occurs as smoke flows toward upcast shafts. This results from air leaks at stoppings between intake and return airways and fresh inflow from smoke-free districts.

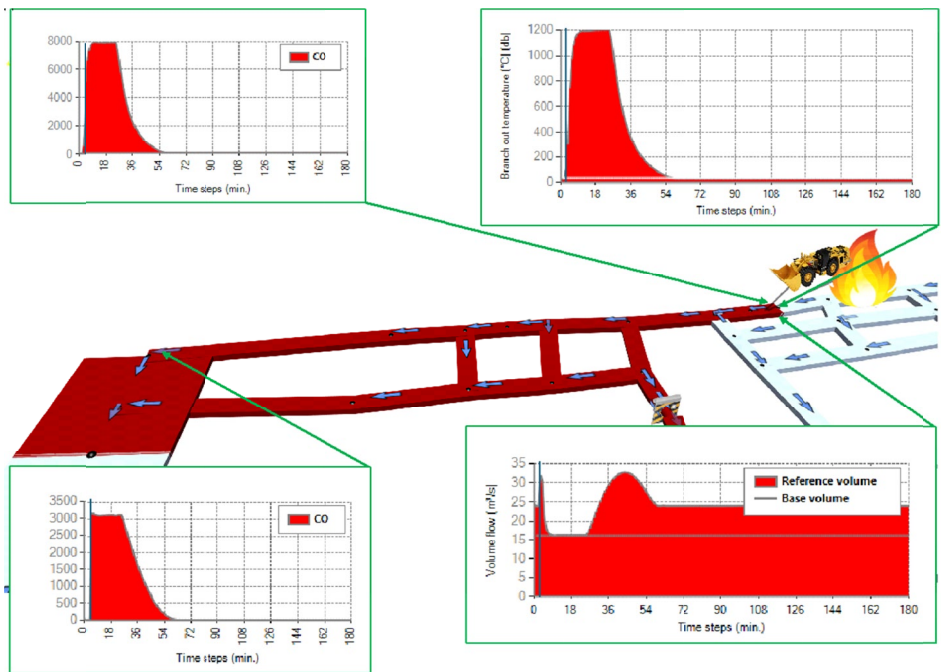


Fig. 11. Smoke spread, fire temperature, airflow through the fire site, and CO concentration distributions – simulation results after 5 minutes of a loader fire

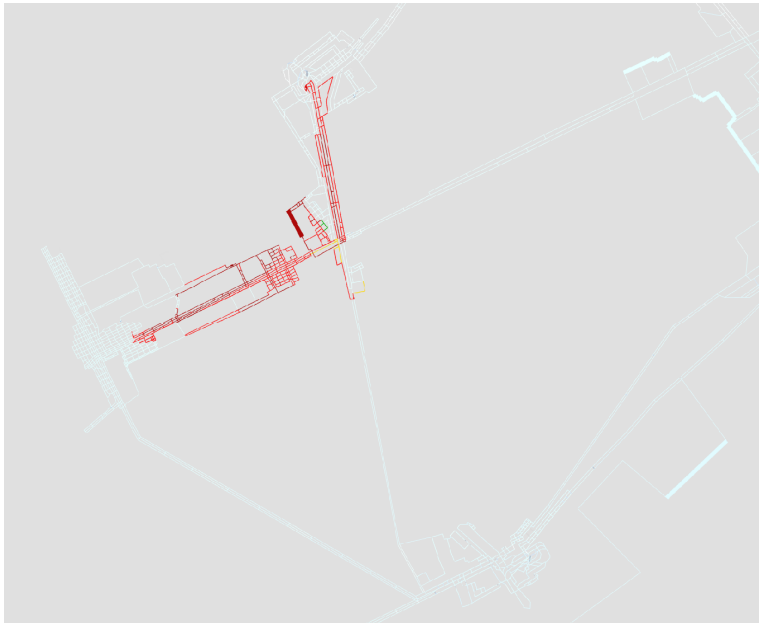


Fig. 12. Smoke spread in ventilation network – simulation results after 54 minutes of a loader fire

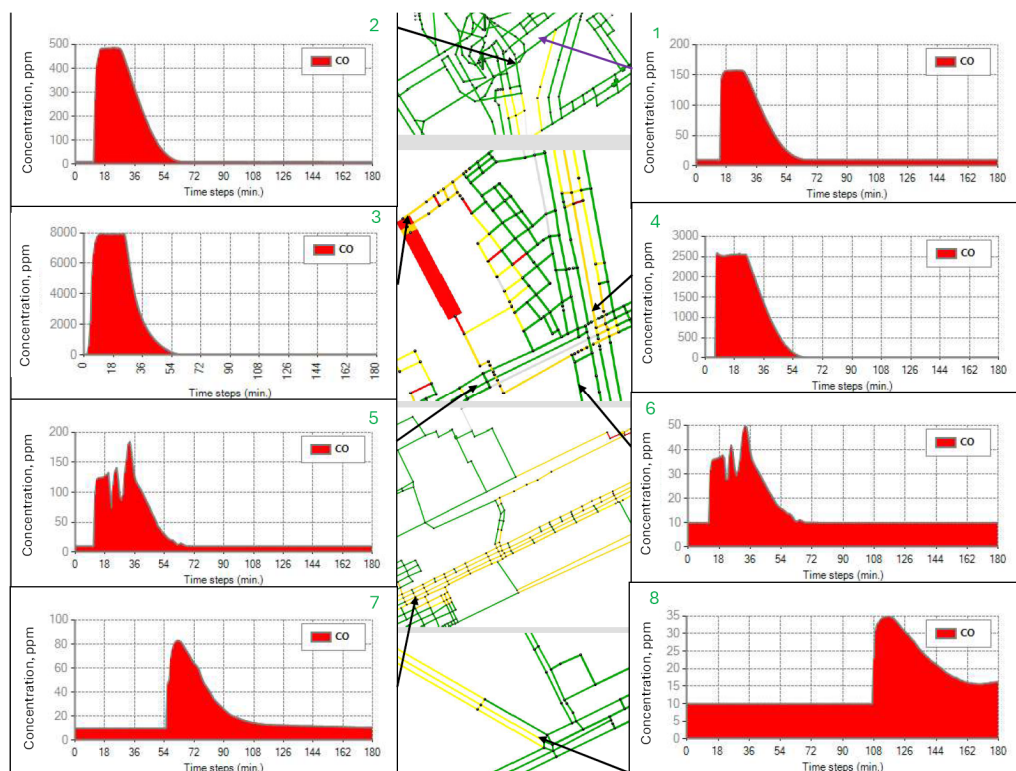


Fig. 13. CO concentration distributions – simulation results after 20 minutes of a loader fire

4.4. Discussion of CO concentrations in a danger zone after extinguishing the fire

The main exhaust fans at shaft W1 primarily affect the site of the loader's fire. Smoke flows into the shaft briefly. About 10 minutes after extinguishing the fire, smoke and fire gases are cleared from roadways in subzones 1 and 2. In contrast, in subzone 3, fire gases move more slowly. Harmful gases reach their peak CO concentration several minutes after the fire is out. At point eight, CO begins to decrease 110 minutes after the fire starts, i.e., 56 minutes after the fire goes out. It is assumed that roadways will be cleared of contaminants when the CO concentration drops to background levels, i.e., the gas concentration before the fire starts.

The simulation results indicate that it is not necessary to maintain all danger subzones for an extended period after the fire is extinguished. Subzone 1 can be eliminated within minutes of extinguishing the fire. The elimination of subzones 2 and 4 can be completed after approximately 10 minutes. Subzones 3 and 5, which discharge gases to shaft W2, should be maintained the longest. Subzone 3 can be eliminated 50 minutes after the fire is extinguished, and subzone 5 after an hour.

In summary, the duration of fires involving a loader depends on the specific component of the vehicle that ignited the fire. The published research into experimental vehicle fires in

underground mines indicates that fire duration can range from several dozen to several hundred minutes. Estimating the time required for fire gases to reach distant upcast shafts necessitates current fire information and the adaptation of the fire development model to simulate both fire duration and post-extinguishment smoke flow. Accurate modelling of complex mine ventilation networks enables the estimation of the total fire rescue operation duration, including the time required for return mine airways to clear fire gases.

However, it should be emphasised that numerical simulation depends on the quality of the mapping of the ventilation network's structure in the given software. The accuracy of numerical simulations relies on the precise representation of the ventilation network structure in the software. In steady-state calculations, heat and mass transfer must mirror actual mine ventilation conditions. Therefore, simulation results should be validated with underground measurements. In mines with extensive ventilation networks, it is recommended to install remote, continuous CO concentration measurement devices at selected points within the network, particularly at the boundaries of the established subzones [40]. The data from these devices would facilitate the verification of numerical calculations.

5. Conclusions

Various decision-making approaches to terminating operations are compared, leading to the formulation of principles and the development of an algorithm for identifying danger zones after a fire and safely removing those zones once the fire has been extinguished. Analyses and simulations performed on a model of a real mine ventilation network indicate that using fire gas concentration calculation results supports a rational decision-making process and allows for the gradual removal of danger subzones based on a dynamic approach. Key conclusions are as follows:

1. Making a decision to remove the danger zone and entrance control posts is a challenging and highly responsible task for the rescue incident commander.
2. In complex ventilation networks of underground metal mines, after a fire is extinguished, smoke and fire gases can continue to flow towards the upcast shaft for an extended period after the fire has been extinguished.
3. Because harmful gases or smoke can linger, extinguishing the fire should not mean that rescue operations are supposed to end immediately. The rescue operation should only be deemed complete once the danger zone has been cleared of harmful gases or smoke.
4. The knowledge of the predicted smoke extraction time in the roadways, along with the verification of this time through underground measurements, can serve as a criterion for the rescue incident commander's decision to terminate the operation.
5. In mines with extensive and complex ventilation networks, devices for remote and continuous measurements of gas concentrations should be installed at selected points in the network, at the boundaries of established subzones. Readings from such devices can validate the results of numerical calculations.
6. Smoke extraction ("clearance") time does not need to encompass the entire dangerous zone. Instead, it can be determined for specific subzones, which can be removed progressively based on the flow of harmful gases toward the upcast shaft. Implementing such an approach requires mine ventilation services to be prepared to analyse various fire scenarios. Simulation software can model smoke dispersion in the mine ventilation network during vehicle fires.

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