

**MINE VENTILATION MODELLING AT FIRES:
DYNAMIC SIMULATION OF TOXIC GASES AND HEAT
TRANSFER,
AND ESCAPE ROUTES ESTIMATION**

by
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ORIGINALITY STATEMENT

I, Zhengis Moldakhmet hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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ABSTRACT

This thesis explores the dynamics of mine ventilation systems in underground fire incidents using Ventsim Visual software dynamic simulation on the Maleevsky mine ventilation model. The fire sources is a load-haul-dump (LHD) loader, with 340 kg of diesel fuel, 306 kg of hydraulic oil, 2,200 kg of rubber tyres, and 2,000 kg of plastics, which represents a total fire load of 163 GJ.

Four fire scenarios are tested during a three-hour simulation: an LHD fire where all ventilation fans are running (Scenario 2), and the same fire but the main underground fan fails at 60 minutes after ignition (Scenario 3). Six movable monitors measure CO concentrations, temperature, and velocity of airflow in the affected part of production. A further scenario (Scenario 4) involves the same fire, but with the main fan failing at 30 minutes (in the growth phase, not after the fully developed phase) to determine the impact of the timing of the fan failure on exposure to toxic gases. A fifth scenario (Scenario 5) is considered in which the main fan fails at the time of ignition ($t = 0$ min), and an additional seventh monitor is placed in Airway 4934 near the source of fire to capture the local response of the fire-source to this monitor.

The findings indicate that in both cases the highest CO concentrations of about 2,300 ppm were recorded at the nearest monitor, which is almost two times more than the Immediately Dangerous to Life or Health (IDLH) of 1,200 ppm. An important counterintuitive result appears: the failure of fans at 60 minutes decreases the severity of the fire in general, as it restricts the oxygen supply, resulting in the fire switching to oxygen-restricted burning, instead of sustained combustion by flaming. Scenario 2 has a sustained plateau of CO above IDLH during 60-90 minutes; Scenario 3 has a peak and a rapid decrease, halving or decreasing by half the duration of IDLH. Peak CO at the farthest monitor is reduced to 350 ppm (Scenario 3) - a 74% decrease compared to 1,350 ppm (Scenario 2). In Scenario 4 (fan failure at 30 minutes), the effect is even more pronounced: maximum CO at the nearest monitor is limited to about 550 ppm (76 % less than Scenarios 2 and 3), the IDLH level is not exceeded in any location in the production section, and the cumulative CO exposure is reduced by 87 % compared with the baseline of all fans operating. In Scenario 5 (loss of the fans at $t = 0$ min) the local CO at the fire source is peaked at the highest level in any scenario (approximately 3,300 ppm in the fire airway, measured at the new Airway 4934 monitor) but the lateral spread through the rest of the production section is severely constrained: 12 of the 14 candidate escape destinations register a route-maximum CO of 0.0 ppm and full visibility, and all

14 routes remain viable, indicating that the pre-ignition fan loss produces the hazard footprint which is intense locally but spatially confined.

Analysis of 14 evacuation destinations escape routes indicates that the spatial relationship between evacuation pathway and the fire gas transport corridor determines the viability of routes with routes passing through the fire plume recording lethal CO values of 1,919,193 ppm and parallel routes recording only 178 ppm. Failure of the fans provides a second evacuation window which is not available under sustained ventilation and is created after about 90-120 minutes. These results are quantitative measures to the fan shutdown dilemma, which proves that controlled fan management can be used as an active fire suppression means in underground mines emergencies.

DEDICATION

My family is dedicated to this thesis because they have been the pillars of my academic life through their uncompromising support, patience and encouragement. Dear parents, thank you, because of your sacrifices, your faith in me and your love that kept me going through all the difficulties.

To my friends and classmates - thank you, the struggles we faced together, the laughter when we are in tough situations, a reminder that we are not all alone in this journey.

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1. INTRODUCTION

1.1 Background

Fire in underground mines is one of the most disastrous and complicated risks in the mining sector across the world. Contrary to surface fires, which enjoy the advantages of natural ventilation and easy access to suppression, underground fires are found in closed and geometrically complex airways networks in which the effect of combustion propagation is rapid and unpredictable. The fact that mine fire incidents produce toxic gases, heat and heavy smoke is a direct cause of danger to the life of underground workers as well as worsening the structural integrity of the ventilation systems and the provision of the established evacuation routes (McPherson, 2009). The historical background of mine fire disasters highlights the seriousness of this risk, with the examples of the Sunshine Mine fire in Idaho (1972), which took the lives of 91 miners mostly due to carbon monoxide inhalation, the Westray Mine explosion in Nova Scotia (1992), and the Soma mine disaster in Turkey (2014), which claimed the lives of 301 miners,

Load-haul-dump (LHD) vehicle fires are among the most prevalent and impactful sources of fires in contemporary mechanized underground mining. LHD machines are diesel-powered, hydraulically operated heavy machinery that work around the clock in the production areas of underground mines. A fully loaded 17 tonne payload LHD vehicle has a large amount of combustible materials within it: about 340kg of diesel fuel, 306kg of hydraulic oil, 2,200 kg of rubber tyres and another 2,000 kg of plastics and flammable materials, which equates to a combined fire load of about 163GJ (Hansen, 2010?). This amount of fuel when ignited releases high rates of heat which may reach up to 30 MW at peak combustion causing huge amounts of carbon monoxide, carbon dioxide, hydrogen cyanide due to rubber burning, and black thick smoke with very low visibility (Brake, 2013).

Carbon monoxide (CO), carbon dioxide (CO₂) and nitrogen oxides (NO₂) are the main products of LHD vehicle combustion, as well as hydrogen cyanide (HCN) of rubber pyrolysis, sulfur dioxide (SO₂), and dense particulate matter. Of particular interest is carbon monoxide because of its colorless and odorless character and its ability to bind hemoglobin, which has a greater affinity to it than oxygen (more than 200 times). CO causes headache and confusion at 400 ppm and incapacitation within 30 minutes at 1,200 ppm, which is the IDLH level set by NIOSH and death within a few minutes at 3,000ppm (Hansen, 2010). Burning of rubber tyres and materials that

contain polyvinyl chloride (PVC) produce other toxic species such as hydrogen chloride (HCl) and HCN that further increase the respiratory risk than the one caused by CO alone (Litton, 2009).

The transfer of heat in underground fires occurs by convection, radiation and conduction. Convective heat transfer moves hot gases in the direction of ventilating routes, making the thermal hazard zone extend well beyond the immediate fire site. Perturbations in airflow caused by buoyancy due to interaction between hot combustion gases and cooler mine air can change the pre-existing ventilation patterns, and possibly reverse the direction of airflow in return airways and push the toxic gases toward the intake headings where mine personnel are located (Gillies et al., 2004). This ventilation reversal phenomenon invalidates the very premise of directional movement of airflow on which evacuation plans are based.

One of the most complicated and hotly contested questions in the management of underground mine fires is whether or not to continue running the primary ventilation fans in the event of a fire. Continued operation of the fans keeps the fire fed with oxygen and maintains the directional airflow pattern, which allows evacuation to be controlled. In contrast, fan shutdown lowers oxygen supply and can cause a decrease in fire intensity, though it causes unpredictable and stagnant atmospheric conditions and removes the controlled airflow, on which the tenability of escape routes relies (McPherson, 2009; Gillies et al., 2004). This paradox has been widely discussed yet not completely resolved, in part because it is hard to get quantitative data under controlled conditions.

Computational simulation models like Ventsim™ Visual allow the airflow behavior, thermal interactions and contaminant transport to be modeled under steady-state and transient fire conditions (Stewart, 2014; Cheng et al., 2020). The current work fills the research gap in the quantitative analysis of fire shutdown of fans by performing a systematic, simulation-based research on the dynamics of LHD vehicle fires in the real ventilation network of the Maleevsky underground mine. This thesis presents quantitative evidence by modelling a realistic 163 GJ LHD fire conditioned to full-ventilation and fan-failure to inform the fan shutdown decision and also to provide actionable information to the emergency response planning.

The interplay between the buoyancy forces caused by fire and mechanical ventilation forms nonlinear dynamics that are complex and depend on the rate of heat release of the fire, the geometry of the airways that are affected, and the overall resistance properties of the ventilation circuit. A

failure in a fan of a multi-fan system causes redistribution of air throughout the network depending on the relative location and strength of the remaining fans and the distribution of resistance in the network (Hartman et al., 2012). Such redistribution may lead to unforeseen outcomes, such as the increase of airflow in certain branches and its decrease in other ones, and it is critical to consider simulation tools that would simulate the entire network. Of particular interest is the critical velocity concept, the lowest velocity that prevents the upward movement of the gas; for large LHD fires (2030 MW) the critical velocity can exceed 34 m/s, higher than the design velocity in most production headings, so that even in normal ventilation backlayering can happen.

1.2 Problem Statement

LHD vehicle fires continue to be one of the most hazardous and least predictable risks in mechanized underground mining despite major improvements in mine ventilation engineering. The lack of adequate assessment of emergency conditions with high fire loads of over 160 GJ per vehicle, the formation of multiple toxic species due to mixed fuel combustion, and the complicated interaction between fire behavior and response of ventilation systems all result in emergency conditions that cannot be properly assessed through traditional methods of a static analysis (De Souza, 2013).

The dilemma of the mine emergency managers when a fire event occurs on the nature of the management of the ventilation fans, either to sustain them, or to close them, has far-reaching effects on the fire behavior and survival of the personnel. Existing regulatory advice and industry practice offer inconsistent advice and the decision is often made under severe time constraints with incomplete information (Brady et al., 2010). Evidence-based emergency response measures can only be developed through simulation-based analysis, with realistic fire loads, and industrial-scale mine models.

Moreover, planning of the escape routes in most underground mines is based on fixed designations that are not based on the time-dependent changes in the atmospheric conditions during fire incidents. What could be a safe route in the beginning, might not hold safe in a few minutes as toxic gases spread in the mine. Lack of dynamism and scenario-specific analysis of escape routes is a major weakness of the existing mine safety practices (Adjiski et al., 2019). The current study satisfies these needs by thoroughly simulating both ventilation conditions based on the Maleevsky mine model.

1.3 Objectives of the Thesis

1.3.1 Main Objectives

The main objective is to dynamically simulate the performance of the Maleevsky mine ventilation system during an LHD vehicle fire to test how fan failure affects the fire behavior and the atmospheric conditions and to estimate the viability of the escape routes with time under both ventilation conditions using the Ventsim Visual software.

1.3.2 Specific Objectives

Literature review to define suitable methodologies for our case

- 1) To determine a steady-state ventilation model with a baseline of the Maleevsky mine, to verify the airflow distribution, pressure differentials and velocity profiles throughout the mine ventilation network.
- 2) To model an LHD car fire with a 163 GJ fuel mass (diesel, hydraulic oil, rubber tyres, plastics) with all ventilation fans running during 3 hours, CO concentrations, temperature, and airflow were monitored at six strategic sensor points.
- 3) To replicate the same LHD fire with the main underground fan failure at 0, 30 and 60 minutes after ignition, the effect of the reduction of oxygen supply on the intensity of the fire, the production of toxic gases, heat release, and the recovery rates in the atmosphere.
- 4) To assess the time-varying tenability of various escape routes in both cases, with the Emergency Escape Route module of Ventsim, to determine viable evacuation periods and efficient escape routes.
- 5) To present quantitative data that can be used to inform the fan shutdown dilemma, comparing fire severity data, cumulative exposure to gas and the viability of the escape route in full-ventilation and fan-failure conditions.

1.4 Hypotheses

Hypothesis 1: Controlled Fire Intensity through ventilations. The LHD vehicle fire will exhibit a ventilation-controllable combustion regime, where the intensity of the fire and the rate of CO generation directly depends on the amount of oxygen supplied by the ventilation system. Therefore, the failure of fans will not increase the risk but decrease the rate of heat release in the

fire and production of CO since the fire will no longer be maintained in the sustained flaming combustion but will be limited by oxygen, resulting in burning.

Hypothesis 2: Divergence in Temporal Exposure Profile. The two ventilation scenarios will result in two fundamentally different temporal profiles of exposure to toxic gases: Scenario 2 (all fans) will result in a sustained plateau of high CO concentrations because of the continued supply of oxygen, whereas Scenario 3 (fan failure) will result in a shorter, sharper CO peak followed by faster atmospheric recovery as the oxygen supply to the fire is cut off.

Hypothesis 3: Fan Failure and Escape Route Paradox. In contrast to traditional expectations, escape route conditions during the post-failure period in Scenario 3 will be similar or even more favorable than the same time periods in Scenario 2, as the less intense fire after the failure of the fans will result in the production of less cumulative toxic gases and a faster atmospheric recovery process along the evacuation routes.

1.5 Justification of the R&D

The study addresses a critical gap in quantitative evidence, which is simulation-based, to address the dilemma of fan shutdown in managing underground mine fires. Probably the most significant operational choice in mine fire response is whether or not to keep ventilation fans running during a fire, but it is currently an operationally significant choice made more on the basis of qualitative judgement than quantitative evaluation (McPherson, 2009). This study offers the kind of comparative, evidence-based, and data-driven evidence that has been lacking in the mine ventilation literature by simulating both scenarios using the actual ventilation network of a working mine with a realistic LHD fire load.

This model of the Maleevsky mine, which is a real operational underground mine, is an important improvement over the simplified, hypothetical mine geometries that are usually employed in academic fire simulation studies. The industrial scale makes the outcomes reflect the entirety of airflow redistribution, pressure interactions, and contaminant transport that take place in actual mine ventilation networks during fire events (Cheng et al., 2020). Moreover, 163 GJ LHD fire load is a realistic worst-case scenario and has direct applicability to the mine emergency planning within the global mining industry (Brake, 2013). It is integrated with the escape route tenability analysis to offer a comprehensive fire safety evaluation that can be immediately applied to emergency preparedness and regulatory development (Nehrii et al., 2022).

1.6 Scope of Work

The research work is carried out in the framework of the Ventsim 3D Visual model of the Maleevsky underground mine, a production area that is where LHD activities are concentrated. Three conditions of operation are considered: (1) steady-state ventilation at the base; (2) LHD fire with all fans running 180 minutes; and (3) LHD fire with main fan failure at 0, 30, 60 minutes 180 minutes. The source of the fire is used to represent full combustion of a 17 tonne payload LHD vehicle of 163 GJ (Heat Energy?). There are six moving monitors which record CO, temperature and airflow after every minute. Escape route analysis analyses various evacuation routes. The research is silent on the performance of fire suppression, structural failure, or damage of electrical infrastructure.

1.7 Practical Importance

The practical importance lies in the fact that the fan shutdown dilemma is solved by using quantitative data. The discovery that the failure of fans can potentially cause a reduction in the severity of a fire by limiting oxygen supply has an immediate consequence: controlled shutdown of fans or slowing down of their speed can potentially be a valid fire management tool under certain conditions, as long as escape routes tenability is ensured throughout the transition phase. In the case of mine operators the simulation methodology offers a repeatable approach to testing fire scenarios with site specific models. To the regulatory agencies, the results would be used to provide evidence-based recommendations on how to handle the fans during fire incidents (MSHA, 2018; Nehrii et al., 2022). A second evacuation window identified in the post-failure atmospheric recovery period is a practical contribution that may directly save lives in the emergencies of mine fires in the future.

2. LITERATURE REVIEW

The literature review focuses on fire hazards in underground mining, paying special attention to LHD vehicle fires, the fan shutdown dilemma, and computational fire simulation and escape route analysis methodologies.

2.1 Underground Mine Fires: Causes, Characteristics, and Types.

There are underground mine fires which are exogenous (equipment, cables, conveyor belts, etc. ignite underground mine fires) or endogenous (coal or sulfide ore spontaneously ignites

underground mine fires) (McPherson, 2009). The most prevalent fire risk in hard rock mining that is mechanized is exogenous fires, especially those involving mobile diesel equipment. According to De Souza (2013), vehicle fires represent a large percentage of underground fire incidents, and LHD machines are particularly susceptible to them because of the large fuel stores, constant working in small spaces, and being exposed to environments that may damage fuel and hydraulic lines.

Hansen (2010) explained fire development as an incipient, growth, and full-developed stage, with the transitions as a critical factor depending on the ventilation conditions. Fires in well-ventilated areas have adequate oxygen levels to sustain combustion and continuous flaming. Fires under oxygen-deprived conditions can switch to smoldering combustion, resulting in disproportionately high CO concentrations compared to heat production as a result of incomplete combustion. This is the ventilation-combustion interaction that is key to the fire behavior in the conditions of fan failure. Stracher and Taylor (2004) and Singh et al. (2018) reviewed endogenous fire hazards. Yuan and Smith (2012) proved that the CO emitted by fires could rise to dangerous levels even at 2+ km of the source in 20 minutes. Zhou et al. (2019) found that heat release rates vary significantly with air velocity.

The mixed fuel nature of LHD vehicles presents an extra complexity to single-material fires due to the combustion behavior of the mixed fuel sources. In cases where diesel fuel, hydraulic oil, rubber, and plastics are burned together, the initial burning of the material with the lowest ignition temperature controls the dynamics of the combustion, followed by the successive entry of the material with a higher ignition temperature into the fire. Liquid fuels, diesel fuel and hydraulic oil, due to their relatively low flash points, normally start burning and offer the initial source of heat which then burns the solid rubber and plastic components (De Souza, 2013). Once lit, the rubber tyres provide the highest percentage of the total fire load, as they are massive (2,200 kg in a typical 17-tonne LHD) and moderate calorific value (32 MJ/kg). Their burning results in the most toxicologically complex emission profile, not only of CO and CO₂, but also of hydrogen cyanide due to the decomposition of nitrile rubber compounds, sulfur dioxide due to vulcanized rubber additives, and thick black carbonaceous particulate matter with the particle sizes in the respirable range of less than 10 micrometers.

The time-dependent heat release rate of an LHD fire is not simply related to the t -squared growth curve that is often used in fire engineering calculations. Rather, the simulated presence of

various fuel packages generates a multi-peaked, multi-modal heat release profile. As reported by Brake (2013), the primary ignition of diesel fuel creates a quick, yet comparatively weak flame (around 250 MW), which consequently increases at the involvement of hydraulic oil and tyre material, reaching the highest levels of heat release of 2030 MW in the full involvement phase when all the fuel components are burning simultaneously. This peak period can take 30 to 90 minutes based on the ventilation conditions, after which the rate of heat release decreases as the more easily burning fuel substances burn out, and the slower burning rubber and structural materials are left to keep the fire going at a lower and lower rate. The ventilation simulation implication is that the fire model needs to capture this time dependence in the heat release and gas production, to generate realistic atmospheric predictions.

2.2 Airflow Perturbations and Ventilation Reversal due to Fire.

The thermal energy produced by fire reduces air density to generate buoyancy forces which may counter the pressure of mechanical ventilation and result in a reversal of airflow (McPherson, 2009). Gillies et al. (2004) established that the reversal likelihood was determined by the rate of heat release, airway resistance, elevation differences, and fan operating characteristics. Inclined or vertical airways produce especially high buoyancy effects due to fires. Wala et al. (2001) demonstrated that even small fires (5 MW) cause a large scale redistribution of flows in room-and-pillar layouts with airflow velocities decreased by more than half in certain branches.

Adjiski et al. (2019) created time-dependent tenability mapping approach with Ventsim™ Visual, which presented the systematic analysis of atmospheric conditions along escape routes at consecutive time steps. Stewart (2014) found that the most practical method of mine-scale fire analysis is network-based simulation because full CFD simulations are computationally infeasible due to the complexity of a typical mine network. The fan failure phenomenon further complicates the situation, with the lost ventilation pressure increasing toxic gas concentration in certain places and potentially decreasing fire severity through oxygen deprivation (Brake, 2013).

2.3 Generation and Dispersion of Toxic Gases During mine fires.

The main reason behind fire-related deaths is toxic gas production (NIOSH, 2020). Litton (2009) gave some background data on emission rates: rubber generates CO (0.05-0.15 g/g) under various conditions of ventilation and diesel fuel burning generates CO (0.04-0.08 g/g). The pyrolysis of PVC-containing substances produces both CO and hydrogen chloride, and rubber tyre

pyrolysis produces hydrogen cyanide in addition to CO, and Cheng et al. (2020) used Ventsim to model the multi-gas dispersion, and the ratio of CO/CO₂ changes spatially and temporally in relation to the availability of oxygen, which is directly applicable to the study

Advection by the ventilation airstream, turbulent diffusion and stratification by gravity controls gas dispersion (Hansen, 2010). Gas concentrations quickly rise to fatal levels in dead-end headings or locations where fire has caused airflow stagnation, which is primarily poorly ventilated (Egan, 2017). Menezed et al. (2022) underlined that even in active ventilation systems, local airflow differences form toxic gas pockets because of directional change, change in pressure, or geometrical limitations.

The toxicological effects of CO are based on well-defined dose-response relations that are imperative in deciphering the simulation outcomes. Carbon monoxide attaches to hemoglobin and has a binding affinity of about 210-250 times more than that of oxygen to form carboxyhemoglobin (COHb). COHb reaches about 25-30 percent at 200 ppm, one hour later, causing headache, dizziness, and poor judgment. COHb at 800 ppm is 4050 percent in 60 minutes of time and the person becomes confused, loses control and may collapse. At 1,500 ppm, COHb concentrations become 60-70 percent in 20 minutes leading to unconsciousness and death when exposures are continued (Hansen, 2010). These dose-response relationships allow the direct translation of the concentration-time profiles measured at each monitor to estimates of physiological effect.

Cumulative exposure, which is a time-product of the concentration ($C \times t$, in ppm-minutes) gives a more significant measure of toxic hazard compared to peak concentration. Peak concentration of a short duration could be less dangerous than moderate concentration of a longer duration. This difference is directly applicable to the comparison between Scenarios 2 and 3 in this experiment: the cumulative $C \times t$ exposure between the two scenarios is significantly different as a result of variations in the temporal profiles, despite the similarity in the peak CO concentration at proximal monitors. The extended plateau in Scenario 2 creates a greater cumulative exposure than the steep rise and then fall in Scenario 3, with significant implications on relative probability of survival.

2.4 Heat Transfer in an Underground Fire Environment.

The main mode of thermal energy propagation in mine ventilation systems is convective heat transfer (McPherson, 2009). Edwards and Hwang (2006) established a roughly exponential

decay of temperature in the ventilation airways which is dictated by the heat transfer coefficient, airway perimeter, and the velocity of airflow. Thermal attenuation Conductive heat transfer to nearby rock offers thermal attenuation that diminishes with time as rock surfaces heat up (Danko, 2013). Radiative heat transfer is important at close proximity to the fire, but decays quickly with distance (Wala et al., 2001). According to Tutak et al. (2024), proper thermal modeling is critical to predicting the ventilation changes induced by fire since temperature differences cause the buoyancy forces that cause reversal of the airflow.

2.5 Mine fire modeling Simulation tools.

Network-based models (Ventsim Visual, MFIRE, VnetPC) describe the mine as a network of branches and nodes, and they offer computationally efficient analysis of the mine on a mine-scale (Stewart, 2014). One of the most popular platforms is Ventsim™ Visual, which includes modules to simulate fire, dispersion of gases, heat transfer, and escape routes (Cheng et al., 2020). CFD models (ANSYS Fluent, FDS) are three-dimensional and have limited computation capabilities to small sections of the mines (McGrattan et al., 2013). Brake (2013) suggested the integration of Ventsim, with CFD of fire zones. Semin and Kormshchikov (2024) have reviewed the use of AI with mine ventilation systems, and Rahimi et al. (2022) have shown the usefulness of CFD to detect areas of gas entrapment that cannot be detected by other traditional analysis tools.

2.6 Escape Route Estimation and Tenability Analysis.

The viability of an escape route must be assessed regarding the atmospheric tenability along the possible escape routes: concentration of toxic gases, temperature, and visibility (Purser, 2008). The fractional effective dose (FED) model is a model of quantitative toxic hazard assessment of which an FED value of 1.0 is expected to result in incapacitation. Conti et al. (2005) established that in most fire situations, the traditional escape routes are unsustainable in 10-30 minutes, which is far shorter than the time that it takes the personnel to get to the surface. Adjiski et al. (2019) created simulation-based evaluation of escape routes based on Ventsim with time-step analysis of CO, temperature, and visibility along candidate paths. Osunmakinde (2013) proved scalable wireless sensor network designs of real-time gas monitoring in favor of dynamic escape route evaluation.

2.7 Underground Mining LHD Vehicle Fires.

LHD vehicle fires are a very dangerous risk because of a high amount of combustible inventory in one machine. Hansen (2010) reported that a typical underground LHD holds 300-500 liters of diesel fuel, 200-400 liters of hydraulic oil, four or six rubber tyres of 400-600 kg weight each, and large amounts of plastic and rubber parts. The total fire load of 150-200 GJ can be compared to a large structural fire. Brake (2013) established that peak heat release rates of LHD fires can be more than 30 MW when fully involved. The fire tends to undergo a growth phase (15-30 minutes), full involved phase (30-90 minutes) and decay phase as fuel is used up. The rate and severity of progression is highly dependent on the ventilation situation: fires in well-ventilated burn at a higher rate and intensity in shorter periods, whereas oxygen-limited fires burn less intensely but can last longer.

According to Kim et al. (2020), a review of fire detection technologies in vehicle fires reveals that the high intensity and the rapid occurrence of LHD fires puts intense pressure on fire detection and response systems. Ignition to lethal atmospheric conditions can take as little as 2-5 minutes, which is why early detection and timely evacuation is of paramount importance.

2.8 Fan Shutdown Dilemma.

Whether to keep ventilation fans running during underground fires or not is one of the most controversial issues in mine ventilation engineering. The main conflict as expressed by McPherson (2009) is the tension between keeping the fans running to supply oxygen to sustain the fire but keeping the predictable, directional airflow pattern, which evacuation plans rely on. Fan shutdown decreases the oxygen supply and can lower the intensity of fire but results in unpredictable atmospheric conditions and can lead to reversal of flow caused by buoyancy and deflection of products of combustion into safe zones.

Gillies et al. (2004) reviewed historical mine fire accidents and discovered that in several accidents, premature turnoff of fans was a factor that led to fatalities due to the migration of toxic gases into the intake airways. Nevertheless, they also found instances where the further operation of fans made the fires worse by providing a continuous supply of oxygen. Brady et al. (2010) discovered that there was considerable variation in the international regulatory guidance with some jurisdictions suggesting continuation of fans and others suggesting shutdown. This confusion has not allowed the establishment of universal guidelines and the operators have to depend on their professional judgment when faced with extreme circumstances.

The time-dependence of fire behavior also complicates the fan shutdown decision. During the initial phases, it might be suitable to keep the area well ventilated since the oxygen requirement of the fire is minimal compared with the amount of air available and directional airflow facilitates evacuation. When the fire gets into the fully involved stage, ventilation supplies oxygen supporting peak combustion and toxic output might outpace dilution capacity. In this phase, it can be helpful to minimize ventilation. During the decay stage, clearing of residual gases is enhanced by restoring full ventilation. This time-dependent optimization of fans has not been conducted in a systematic manner, and the current study adds quantitative data.

Effects of natural ventilation pressure (NVP) should also be taken into account. NVP can maintain airflow in mines where the difference in elevation between intake and return airways are large and mechanical fans are off. The Maleevsky mine model incorporates the effects of NVP and the redistribution of the post-failure airflow is based on the joint effect of residual mechanical pressure, NVP, and buoyancy caused by the fire, instead of assuming that the airflow would cease entirely on failure of the fan.

2.9 Regulatory Systems and Safety standards.

The MSHA regulations of 30 CFR Parts 75 and 57 provide the requirements of the fire prevention, suppression, atmospheric monitoring, and escape route provision with at least two independent escape routes (MSHA, 2018). The international standards have similar provisions but with regional differences (Brady et al., 2010). Olczak et al. (2023) found a high degree of inter-jurisdictional regulatory stringency variation. Asfaw et al. (2013) established that the economic viability correlates with stronger safety performance. Although thorough frameworks exist, most jurisdictions do not explicitly require dynamic simulation-based fire analysis and fan shutdown decision support.

2.10 Future Directions and Gaps in Research.

Ongoing gaps consist of a lack of empirical validation data of fire simulation models (Litton, 2009), no standardised fan shutdown decision criteria based on quantitative analysis, untried potential of machine learning in fire prediction (Wu et al., 2024; Sharma and Maity, 2024), and the lack of application of simulation tools to industrial-scale mine models with realistic fire loads. The most influential trend in the future is the combination of simulation and real-time monitoring in dynamic fire response (Nehrii et al., 2022). To fill a few gaps identified in this thesis,

dynamic fire simulation is used on an industrial scale mine model with a realistic 163 GJ LHD fire load and used to give comparative evidence on the decision to shutdown the fans.

Lit rev summary (one paragraph)

3. METHODOLOGY

3.1 Research Design

The study simulates a LHD vehicle fire in the Maleevsky mine ventilation system in Ventsim Visual in three scenarios: (1) steady-state ventilation in the mine without fire; (2) LHD fire with all fans running 180 minutes; (3) LHD fire with failure of the main underground fan 60 minutes after ignition. Transport of the gases is the passive scalar dispersion. The equation of Atkinson is used to compute the airway resistance. The length of the simulation of three hours reflects the entire combustion process of the 163 GJ LHD fuel load: growth (0-30 min), sustained burning (30-120 min) and decay (120-180 min). Scenario 3 injects failure of fans in the sustained burning stage to isolate the impact of reduction in oxygen supply to fire behavior.

The source of fire is located in the production area where LHD machines work. The reason why this point is chosen is that it is the most likely origin of fire in mechanized underground mines and injects combustion products into the airflow of the active production zone, maximizing the contamination of occupied areas. CO concentration (ppm), dry bulb temperature (°C) and airflow velocity (m/s) are measured at one-minute intervals at six dynamic monitors at increasing distances of the fire source. The spatiotemporal resolution required to conduct an escape route tenability assessment is obtained in the monitor data.

3.2 The Maleevsky Mine Model

Maleevsky mine is simulated in Ventsim Visual as follows: The network characteristics of the Maleevsky mine are as follows, as illustrated in Figure 1: 4,938 airways with a total length of 134,405.1 m; total airflow intake of 556.1 m³/s and exhaust of 562. The model considers compressible airflow and takes into consideration natural ventilation pressure (NVP).

NETWORK SYSTEM SUMMARY	
Модель создана по плану, без проверки на факте.	
Compressible Airflows	Yes
Natural Ventilation Pressure	Yes
Fan Pressure Simulation Type	Total Pressure Method
Stage	0: Stage 1
Airways	4938
Current Stage Segments	2424
Total length	134,405.1 m
Total airflow intake	556.1 m ³ /s
Total airflow exhaust	562.4 m ³ /s
Total massflow	582.43 kg/s
Mine resistance (excluding duct)	0.01041 Na ² /m8
Mine resistance (including duct)	0.01046 Na ² /m8
POWER SUMMARY	
AIR (friction loss) Power	1,829.5 kW Total
	385.6 kW Shaft
	1,436.0 kW Drive
	7.9 kW Vent Duct
Refrigeration Power Input	0.0 kW
INPUT Power Electrical	3,322.6 kW
Network Annual Power Cost	\$ 2,910,631
Network Efficiency	55.1 %

Figure 1. Baseline Ventilation Network System Summary(Ventsim).

Figures 2-4 depict the three dimensional topography of the mine in various viewpoints, demonstrating the multi-level design with ramp accesses between production levels, primary shafts and ventilation systems.

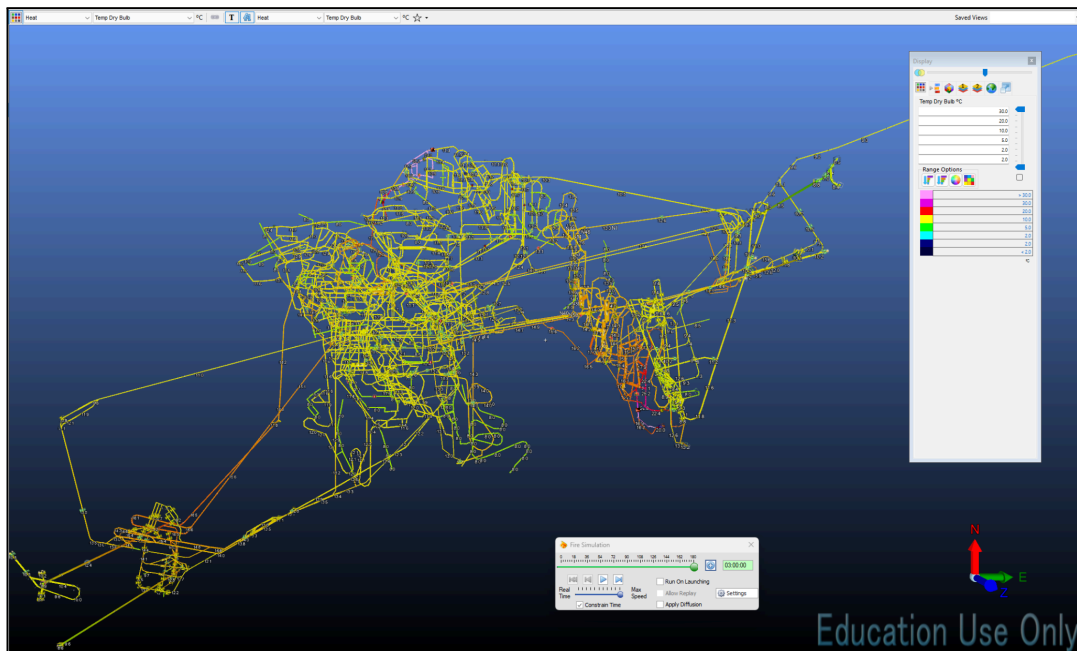


Figure 2. Mine layout - overview.

Legend (Ventsim default colour convention applied throughout Figures 2-4): blue airways = fresh-air intake; red airways = return / exhaust; green airways = ventilation ducts and auxiliary branches; yellow markers = primary intake and exhaust shafts. Numerical labels next to airways indicate airflow rate (m³/s). Numbers used in further CO-distribution figures: 0-50 ppm dark blue (safe), 50-125 ppm cyan, 125-250 ppm green, 250-500 ppm yellow, 500-1,000 ppm orange, > 1,000 ppm magenta (above NIOSH IDLH).

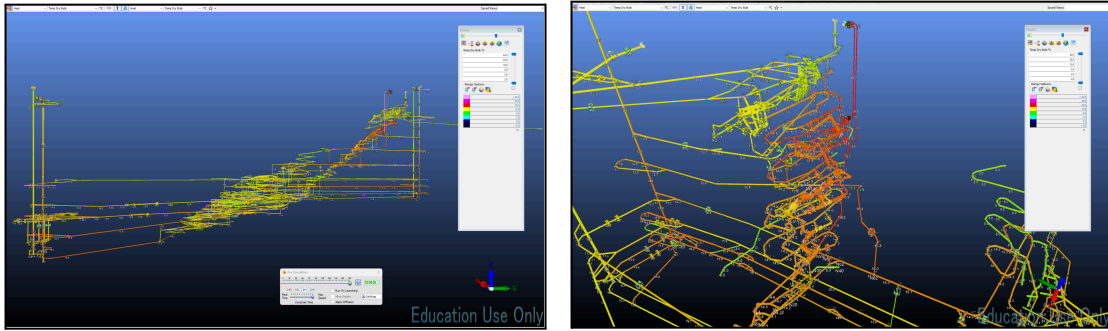


Figure 3–4. Mine layout perspectives showing multi-level geometry and airway connectivity.

3.3 Characterization of Fire Source of LHD.

The fire source is a 17 tonne payload LHD. The 163 GJ of total fire load is based on the fuel inventory of an average underground LHD, which is reported by Hansen (2010) and Brake (2013). The data on fire load used in the simulation are presented in Figure 5 and obtained through empirical combustion research. The fuel composition - diesel fuel (340 kg, 45 MJ/kg), hydraulic oil (306 kg, 45 MJ/kg), rubber tyres (2,200 kg, 32 MJ/kg), and other flammable plastics (2,000 kg, 32 MJ/kg) - generates a mixed combustion profile producing CO, CO₂, HCN from rubber pyrolysis, hydrogen chloride (HCl) from polyvinyl chloride (PVC) decomposition, and dense particulate matter.

Table 2. Fuel stock and fire load of a 17 tonne payload LHD vehicle (163 GJ total).

Fuel	Quantity	Calorific value	Heat released
Diesel fuel	400 L = 340 kg (~70 % of full tank)	45 MJ/kg	15,300 MJ
Hydraulic oil	360 L = 306 kg	45 MJ/kg	13,770 MJ
Rubber tyres	550 kg each = 2,200 kg (allowing for wear and non-combustibles)	32 MJ/kg	70,400 MJ
Other plastics and flammable materials	2,000 kg (5 % of 40-tonne tare weight)	32 MJ/kg	64,000 MJ
Total	~ 4,846 kg of combustible material	-	163,470 MJ ≈ 163 GJ

Source: Adapted on Hansen (2010) and Brake (2013); values are the same as the fuel inventory used as input to the Ventsim fire-source model in Section 3.6.

The fire is modelled in Ventsim as a fire simulation module with fuel-specific heat release rate profiles as in Figure 6. The LHD fire location within the production section is shown in Figure 7.

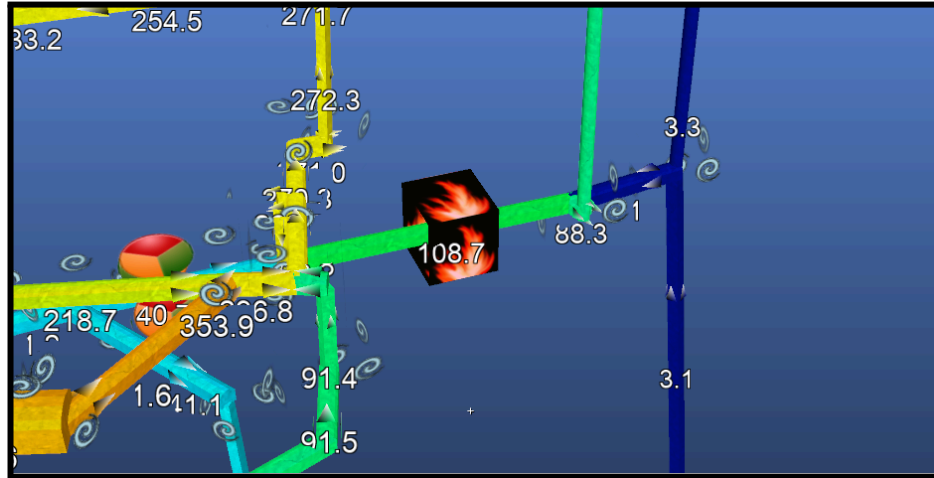


Figure 6. LHD fire source configuration in Ventsim™.

3.4 Ventilation System and Fan Set-up.

There are several fans that supply ventilation to the mine. The operating parameters and the main fan configuration are displayed in Figure 8. In the case of Scenario 3, the primary underground fan will fail at 60 minutes with the event scheduling feature of Ventsim (Figure 9). The most severe failure mode is the failure of the fan which is modelled as an instantaneous complete shutdown. The other fans are still running, and they keep on ventilating partially using the network.

The main underground fan considered in the fan-failure scenarios in this thesis is a Russian-designed, two-stage axial fan of the VOD series, model VOD-30 (“ТБВ БОД 30”), with a rotor-blade angle of 25° (Figure 8a). These fans (VOD-16P, VOD-18, VOD-21M, VOD-30, VOD-40, VOD-50, produced by AMZ Ventprom on the basis of licensed designs of KB AeroVent) are the prevailing choice for primary ventilation of large coal and metal mines in Kazakhstan, Russia and other former-Soviet republics. The VOD-30 has an aerodynamic scheme K1 + HA + K2 + CA (two impellers - first-stage K1 and second-stage K2 - with an inlet guide vane in between (HA) and a straightening vane (CA) at the outlet). Twelve blades are installed on each impeller and are secured in the hub by split conical bushings; the blades are reset in the casing through hatches to set the operating point of the mine. The fan offers a rotor diameter of 3,000 mm, a weight of around 35 tonnes (with motor), is motorised by an asynchronous 6,000 V motor of power 800-1,600 kW

(depending on selected blade angle and rated point), and operates at 500-600 rpm. It is force-lubricated from a hermetic oil station, and has radial and radial thrust supports with duplicate temperature alarms. The installation also includes a second (standby) fan, a requirement under Kazakhstan industrial-safety regulations to ensure that ventilation can be restored within the specified time limit in case of a failure of the operating fan.

The fan operating curve imported into Ventsim Visual is in Figure 8b. At 25° blade angle the fan total pressure (FTP) curve drops from about 5,100 Pa at 40 m³/s to 1,500 Pa at 160 m³/s, with a maximum static efficiency of about 0.81 in the middle of the curve and a maximum shaft power of about 800 kW (at 100-110 m³/s). The fan was tabulated in Ventsim by ten data points along the FTP curve (40.0, 53.3, 66.7, 80.0, 93.3, 106.7, 120.0, 133.3, 146.7, 160.0 m³/s with corresponding pressures of 5,100, 4,889, 4,729, 4,600, 4,315, 4,144, 3,800, 3,236, 2,427, and 1,500 Pa). The curve type of interpolation was linear. The steady-state baseline in Section 4.1 has the operating point of the main fan in the range of 100-110 m³/s, which is located on the most efficient part of the curve and is consistent with the total mine intake of 556.1 m³/s being split between the main fan and the other fan circuits (auxiliary fan) shown in Figure 1.

In Scenario 3, the main fan is stopped by an instantaneous, full-stop failure at 60 minutes after the fire is ignited (using the Ventsim VentFIRE Events Manager preset, Figure 9). All other fans (development, haulage, stope-exhaust, surface and U/G large fan circuits) continue operating, so the residual ventilation in the post-failure stage is a combination of the residual mechanical pressure, the natural ventilation pressure (NVP) of the multi-level network, and the fire buoyancy. In the supplementary Scenario 4 described in Section 3.6.4 the same VOD-30 unit is taken offline at 30 minutes (Figure 9b) - the only difference between Scenarios 3 and 4 is the time of failure, which is enough to draw conclusions about the impact of pre-peak and post-peak fan failure on the fire dynamics.

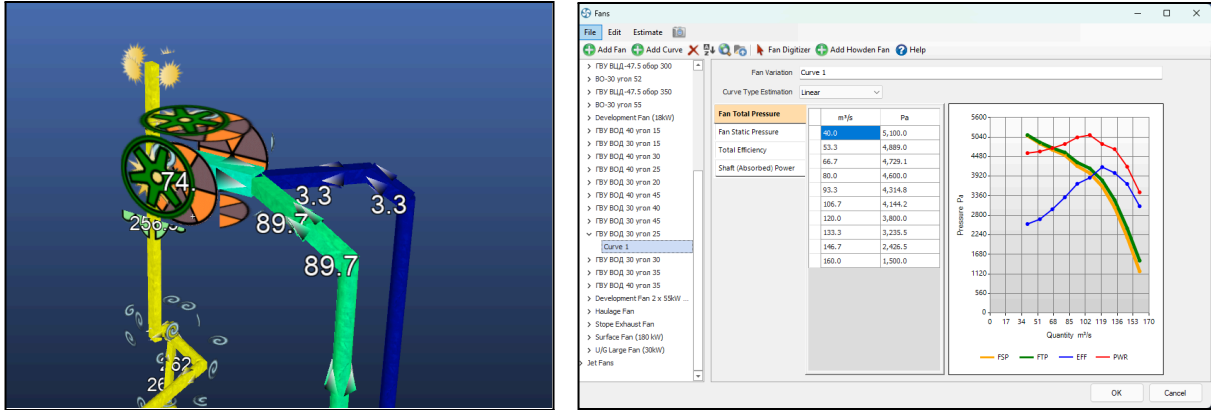


Figure 8. Main fan configuration (left) and fan operating parameters (right).

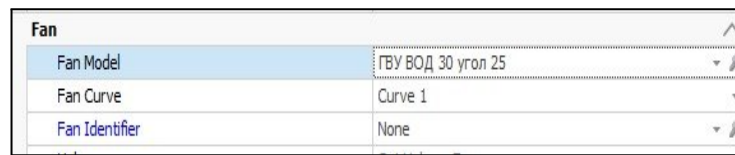


Figure 8a. Ventsim main-fan model name - VOD-30 (ГВУ БОД 30), 25° blade angle, Curve 1.

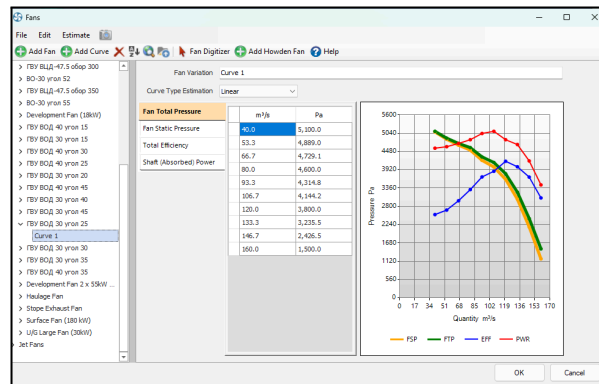


Figure 8b. VOD-30 fan operating characteristic (blade angle 25°)

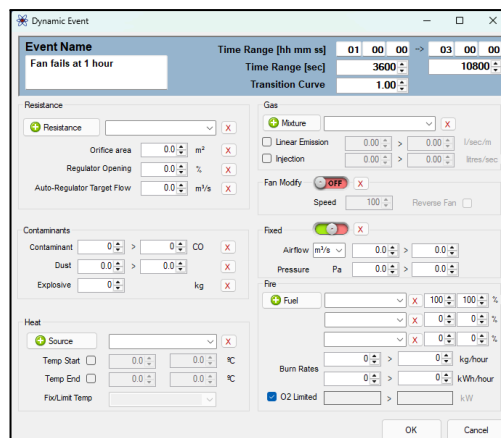


Figure 9. Fan failure event settings — main fan shutdown at 60 minutes.

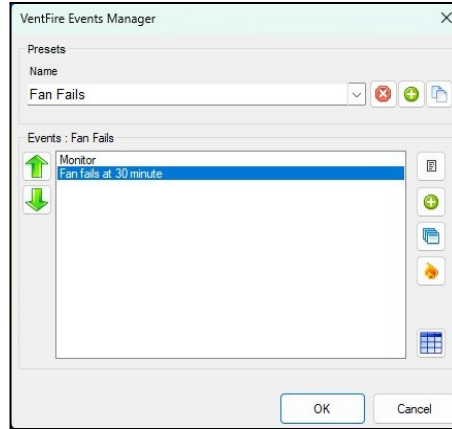


Figure 9b. VentFIRE Events Manager - main fan failure at $t = 30$ min (Scenario 4).

3.5 Section and Monitor Placement Production.

The fire simulation targets a particular part of the production area in the Maleevsky mine where LHD activities are concentrated (Figure 10). In this section, there are several points of junction (N33, N40, N63) at which the airflow divides and combines, forming a geometrically complex sub-network. The spatial resolution of the gas dispersion can be done in detail by analyzing this section instead of the complete mine, but the complete mine model has realistic boundary conditions and network-wide pressure interactions.

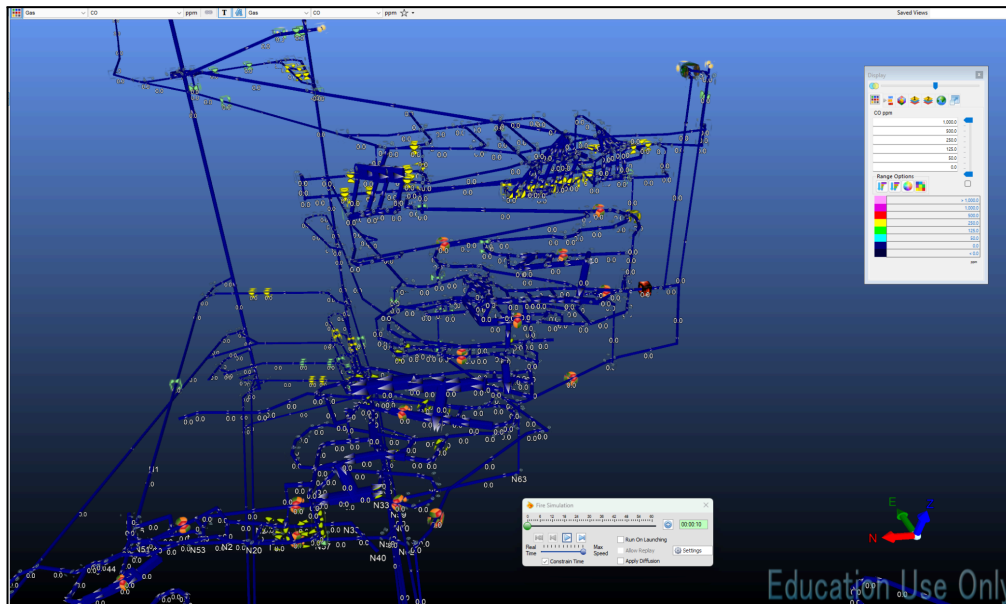


Figure 10. The production section under simulation - before fire (top) and during fire showing CO spread (bottom).

To measure three spatial areas of the atmospheric effect of the fire, six monitors are installed (Figure 11). Proximal monitors (Monitor 1 at Airway 8381 and Monitor 2 at Airway 8397) are the closest to the fire source in the main path of downstream airflow. These intermediate monitors (Monitor 3 at Airway 9901 and Monitor 4 at Airway 8124) are placed at crossroads where fire gases are combined with cleaner air of parallel entries. The distal monitors (Monitor 5 at Airway 14483 and Monitor 6 at Airway 13281) are those that record conditions at the farthest distance to the fire source, which reflects how far the network is contaminated. Such a setup allows the assessment of CO attenuation with range, transport delay times, and escape route tenability over the entire evacuation range.

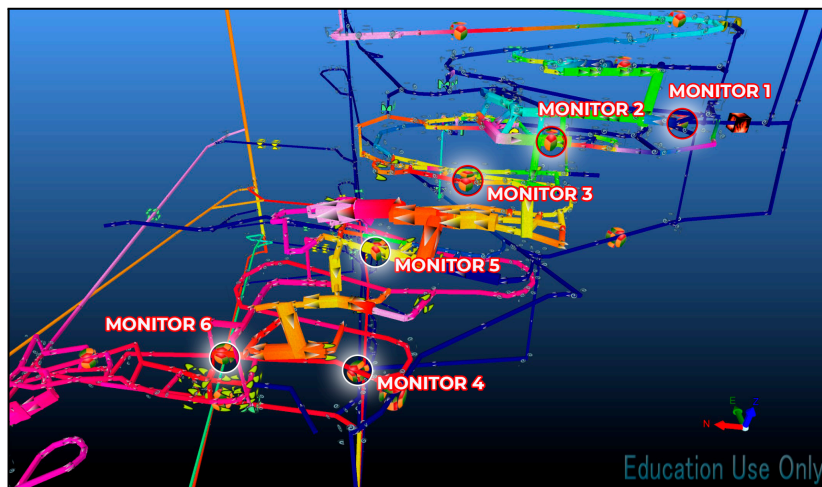


Figure 11. Monitor locations within the production section.

The fire source settings in Ventsim™ are shown in Figure 12. The software estimates the rate of heat release, gas emission rates and thermal output, depending on the type of fuel, quantity and the conditions of ventilation of the fire site.

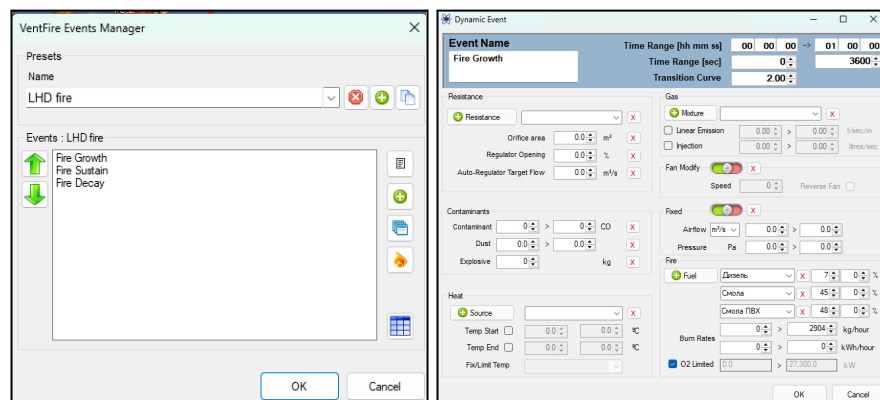


Figure 12. Fire source parameters in Ventsim™.

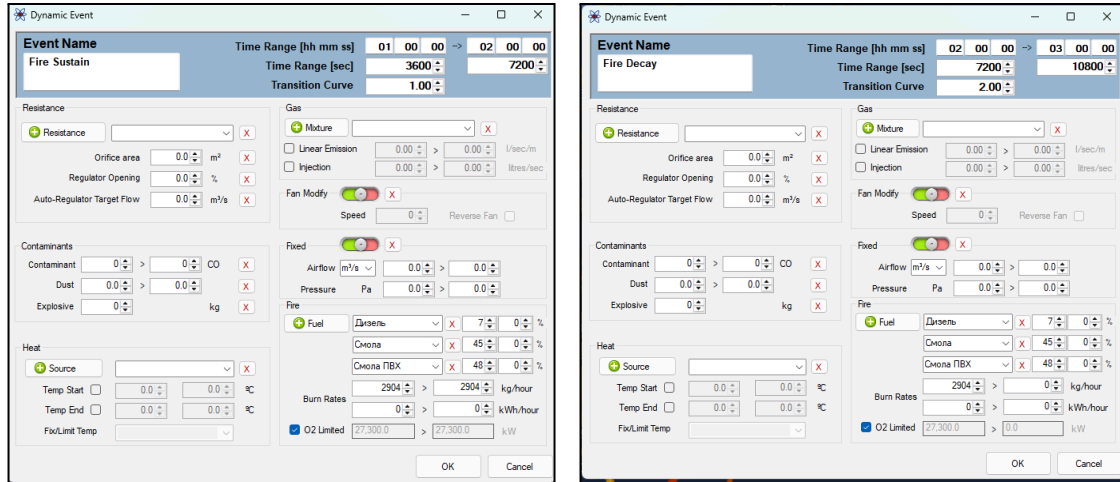


Figure 12b. Additional fire configuration settings.

Table 3. Ventsim Dynamic Event configuration exhibited in Figure 12b (fire-decay phase) translated into English.

Parameter	Value	Meaning
Event Name	Fire Decay	Decay phase of the LHD fire event
Time Range	02:00:00 → 03:00:00 (7,200 → 10,800 s)	Hours 2-3 of the simulation
Transition Curve	2.00	Quadratic decay (exponent = 2)
Fuel - Дизель (Diesel)	7 %	Diesel fuel mass fraction
Fuel - Смола (Rubber)	45 %	Rubber tyres mass fraction
Fuel - Смола ПВХ (PVC plastics)	48 %	PVC and other plastics mass fraction
Burn Rate	2,904 kg/hour	Mass consumption rate of all fuels combined
O ₂ Limited	27,300 kW	Maximum HRR allowed by available O ₂

Note: Figure 12b depicts the user-interface labels in Russian because the simulation was run on a localised Ventsim installation localised to Kazakhstan. The English equivalents are given in Table 3. The energy-balance outputs of the Ventsim solver to the decay phase are the fuel-mass fractions (7% diesel, 45% rubber, 48% PVC plastics), the burn rate (2,904 kg/h) and the O₂ limited limit (27,300 kW).

3.6 Simulation Scenarios

3.6.1 Scenario 1: Baseline

Fire-free steady-state simulation. Fans are all rated. Outputs: CO concentration (should be zero), airflow velocity distribution, pressure field, and temperature field. This forms the basis on which changes caused by fire are measured.

3.6.2 Scenario 2: LHD Fire, Fans in Operation.

180-minute dynamic fire simulation. The fire is initiated at time $t = 0$ in the LHD. All the fans are kept on, which supplies oxygen to the fire zone. CO, temperature, and airflow are monitored at 1-minute intervals. CO distributions at the mines are taken as snapshots at intervals of 20, 30, 45, 60, 80, 100, 120, 150, 180 minutes to monitor the spatial gas propagation.

3.6.3 Scenario 3: 60 Minute Fan Failure, LHD Fire.

The same as Scenario 2 during the first 60 minutes. At $t = 60$ min the main underground fan is switched off. The other fans keep on running. The simulation lasts the entire 180 minutes. Snapshots of mine layouts are taken at 30, 45, 60, 80, 120, 150 and 180 minutes with special focus on the transition at 60 minutes. The pre-failure interval (0-60 min) is an internal check; the difference that appears after 60 minutes can be attributed to the failure of the fans.

3.6.4 Scenario 4: 30 Minute Fan Failure, LHD Fire.

Scenario 4 is the same as Scenario 2 for the first 30 minutes. At $t = 30$ min the main underground fan (VOD-30, blade angle 25°) is instantaneously shut down using the same VentFIRE Events Manager preset as Scenario 3, except that the trigger time is changed to 30 minutes (Figure 9b). All other fans remain on. The simulation continues for the entire 180 minutes. The CO concentration, dry-bulb temperature, and airflow velocity are measured every minute at the same six monitors as in Scenarios 2 and 3, and the CO distributions in the layout of the production section are captured at 0, 15, 30, 40, 60, 80, 120 and 180 minutes. The purpose of this scenario is to see if the positive fan-failure response seen in Scenario 3 is maintained - or even enhanced - if the fan fails prior to the fire reaching its peak heat-release and CO-emission rates. In Scenario 3 the fan fails at 60 minutes, when the fire has already reached its peak rate of heat release and CO production of about 2,300 ppm at Monitor 1. In Scenario 4 the fan loss occurs at 30 minutes when the fire is still in its growth stage and the fuel-involvement rate is a small fraction of its peak. This allows us to study the influence of the time of fan failure on the cumulative exposure to toxic gases and on the second-evacuation-window concept (see later in the results section).

3.6.5 Scenario 5: 0 Minute Fan Failure, LHD Fire.

Scenario 5 is the most extreme time when the main underground fan (VOD-30, blade angle 25°) will be turned off: it is turned off at $t = 0$ min, i.e. at the same time when the LHD fire ignites. The preset of the VentFIRE Events Manager used is the same as Scenario 3 and 4, with the trigger

time set to 0 minutes. The rest of the auxiliary fans will be left on throughout the 180 minutes of the simulation. The CO concentration, dry-bulb temperature and airflow velocity are measured at a rate of one minute at the same six monitors used in Scenarios 2, 3 and 4. To further measure the local fire-source response in the immediate vicinity of the LHD, an additional seventh monitor was added in Airway 4934 (Figure 9c) to measure the local fire-source response in the immediate vicinity of the LHD, since the airflow field downstream of the fire is fundamentally different than the preceding scenarios with the main fan unavailable since ignition. CO distributions in the production section are sampled at 20, 30, 60, 90, 120, 150 and 180 minutes. The goal of this scenario is to test the limit case of the oxygen-limitation hypothesis: should the main fan never run after ignition, does the fire grow to be a fully ventilation-controlled fire at the start, and is the spatial diffusion of toxic gases lessened proportionally to the lessened air supply? Scenario 5, then, completes a monotonic series of fan-failure times (60 min 30 min 0 min) which allows the effect of the moment of fan loss on cumulative toxic exposure, and on the feasibility of escape routes, to be quantified in a systematic manner.

Table 1. Simulation configuration summary.

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Type	Steady-state	Dynamic (180 min)	Dynamic (180 min)	Dynamic (180 min)	Dynamic (180 min)
Fire	None	LHD (163 GJ)	LHD (163 GJ)	LHD (163 GJ)	LHD (163 GJ)
Fan status	All ON	All ON	Main fan OFF at 60 min	Main fan OFF at 30 min	Main fan OFF at 0 min
Monitors	N/A	6 sensors, 1-min interval	6 sensors, 1-min interval	6 sensors, 1-min interval	7 sensors, 1-min interval
Snapshots	1 (final state)	9 time points	7 time points	8 time points	7 time points

Table 2. Regulatory exposure limits applied in the analysis.

Contaminant	TWA (8-hr)	STEL	IDLH
CO	50 ppm (OSHA)	200 ppm	1,200 ppm (NIOSH)

CO ₂	5,000 ppm	30,000 ppm	40,000 ppm
Temperature	N/A	60°C dry bulb	N/A
Visibility	N/A	3–5 m minimum	N/A

The thesis uses a two-tiered approach to determine the tenability of the mine environment. The first tier is the regulatory limits for the routine operation of underground ore mines in the Republic of Kazakhstan, which is the governing legal standard for the Maleevsky mine as it is a polymetallic (zinc-lead-copper) underground mine under the jurisdiction of Kazakhstan industrial-safety regulations. The second tier is the international short-term and acute-exposure limits used in the global mine-fire literature (OSHA, MSHA, NIOSH, ACGIH) that become the controlling limits in fire emergencies when the routine working-zone limits are exceeded. The extended set of regulatory limits is shown in Table 2b below, which combines the two sets so that the results of the simulations in Section 4 can be compared against the standard that the mine operator (RK) needs to comply with and the international mine-fire-safety standard.

Table 2b. Enhanced regulatory exposure limits - Kazakhstan and international.

Parameter	Kazakhstan (RK Tech. Reg. P09-2207 §75)	International (NIOSH / OSHA / Purser)
Oxygen (O ₂)	≥ 20.0 vol % in active workings	≥ 19.5 vol % (MSHA); < 12.5 % IDLH
Carbon monoxide (CO)	MAC = 20 mg/m ³ ≈ 17 ppm	OSHA TWA 50 ppm; STEL 200 ppm; IDLH 1,200 ppm
Carbon dioxide (CO ₂)	≤ 0.5 vol % workplaces; ≤ 1.0 % in repair workings	OSHA TWA 5,000 ppm; IDLH 40,000 ppm
Nitrogen dioxide (NO ₂)	MAC = 5 mg/m ³ ≈ 2.6 ppm	OSHA ceiling 5 ppm; IDLH 20 ppm
Sulfur dioxide (SO ₂)	MAC = 10 mg/m ³ ≈ 3.8 ppm	OSHA TWA 5 ppm; IDLH 100 ppm

Hydrogen sulfide (H ₂ S)	MAC = 10 mg/m ³ ≈ 7 ppm	OSHA ceiling 20 ppm; IDLH 100 ppm
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Note: The Kazakhstan MAC values listed above (CO = 20 mg/m³ ≈ 17 ppm; H₂S = 10 mg/m³ ≈ 7 ppm; SO₂ = 10 mg/m³ ≈ 3.8 ppm; NO₂ = 5 mg/m³ ≈ 2.6 ppm) are taken from the public summary of RK Tech. Reg. P09-2207, Article 75 and the corresponding Order on Occupational Hygiene Standards. These values must be compared and contrasted with the latest published version of the regulation before submission, as different versions list slightly different MAC ceilings (in particular to H₂S, where some sources give 10 mg/m³ as the ore mine ceiling and 3mg/m³ as the general work place ceiling).

Under routine mining conditions the KZ limits apply: the maximum CO concentration in the working zone is about 17 ppm (20 mg/m³), the minimum oxygen concentration is 20 vol % and the maximum CO₂ concentration at workplaces is 0.5 vol %. These limits are three orders of magnitude lower than those commonly used as IDLH in the international literature on the fire safety of underground mines, because the routine standard is designed to protect against long-term occupational exposures while the IDLH is a 30-minute "immediately dangerous to life or health" limit for acute exposures. In the fire scenarios simulated in Section 4, the routine KZ workplace limits are exceeded everywhere in the production section within 5-10 minutes of the fire, so the relevant tenability criteria in the emergency are the OSHA STEL (200 ppm CO), the NIOSH IDLH (1,200 ppm CO), the Purser (2008) thermal limit of 60 °C dry bulb, and the Purser visibility limit of 3 m. These four values are the criteria that are used in Section 3.7 and Section 4.4 to classify segments of the escape route as safe, moderate, or lethal; the KZ routine limits are reported here to quantify the gap between the law and compliance that any underground fire creates and to provide justification for the regulatory recommendations of Section 6.2.

3.7 Escape Route Estimation

The escape-route analysis is solved with the Emergency Escape Route module of Ventsim Visual Dynamic, which post-processes the time-resolved CO, temperature, visibility and airflow fields generated on the VentFIRE solver and calculates the tenability of every accessible path between any chosen starting airway and every surface exit and refuge bay in the network. Each of the four fire scenarios (Scenarios 2, 3, 4 and 5) is run at the moment of maximum hazard along each

candidate route, such that the resulting tenability classification is representative of the worst conditions that personnel would encounter when traversing the route, not the conditions at a single point in time. The initial airway is held constant in all four scenarios in order to be able to attribute the differences in the route-tenability outcomes to the differences in the fan-failure timing between scenarios.

3.7.1 Ventsim Emergency Escape Route Module

Each candidate destination is then computed to give a complete set of route measures: total walking distance (m); total travel time decomposed into walking time (along sub-horizontal airways) and climbing time (along ramps and inclined airways); peak CO concentration encountered along the path (ppm); cumulative time above the OSHA Short-Term Exposure Limit (STEL = 200 ppm) and above the Time-Weighted Average limit (TWA = 50 ppm); equivalent 8-hour TWA exposure of the entire traversal (ppm); the minimum visibility of the path (m); and the number of distinct airway segments comprising the route. Each segment is further broken down into one of four travel modes - walking in clear air, walking in smoke, climbing in clear air, climbing in smoke - and the module assigns a different walking speed to each mode (1.0-1.5 m/s in clear air, 0.3-0.5 m/s in smoke) so that the travel-time estimate already includes slow-down due to visibility.

The output of the module is a colour-coded route map (green = viable, yellow = degraded but passable, red = non-viable) superimposed on the 3-D ventilation network and a parallel spreadsheet that lists, in each case, the numerical values of all route measures. This work uses the colour-coded map to give a qualitative snapshot of how each scenario redefines the evacuation landscape, with the spreadsheet providing the quantitative basis of the route-by-route comparisons of Section 4.6.

3.7.2 Tenability Criteria

The tenability thresholds used to categorize route segments are based on Purser (2008) and are consistent with the limits adopted in Section 3.6 to analyze the in-airway monitor results. A segment is said to be safe (green) when all four of the following conditions are met simultaneously throughout the period the personnel are estimated to be in that segment: (i) the CO concentration is less than the OSHA STEL of 200 ppm and the cumulative dose is less than the NIOSH IDLH equivalent of 1,200 ppm in 30 minutes; (ii) the dry-bulb temperature is lower than the Purser thermal-incapacitation limit of 60 °C; (iii) the visibility is at least 3 m, the minimum value at which

the smoke-irritation factor of Purser allows controlled walking; and (iv) the oxygen concentration is at least the MSHA minimum of 19.5 vol %. A segment is considered to be degraded (yellow) when one of the criteria is violated temporarily (less than 5 minutes) but the accumulating dose is below the NIOSH IDLH equivalent. A segment is considered non-viable (red) when the CO peak is above 1,200 ppm at any point along the segment, when the visibility is below 0.5 m, when the dry-bulb temperature exceeds 60 °C more than 5 minutes, or when the segment is overlapping the fire airway itself. The path can only be considered a complete route when all of its segments are considered to be safe or degraded; a single non-viable segment makes the entire route non-viable.

3.7.3 Application Across the Four Fire Scenarios

The module is implemented in the same manner as each of the four fire scenarios in order that the results of the route-tenability can be compared in a like-for-like manner. The initial airway remains the same in all the runs and the candidate destinations remain the same fourteen accessible exits and refuge points. The four scenarios are only differentiated by when the main fan failed compared to ignition, which determines how the toxic-gas envelope would evolve and thus how the tenability of each candidate route would change over the course of the 180-minute simulation.

In Scenario 2 (all fans on throughout the simulation) the primary fan is continuously used to sweep down the design ventilation circuit the long, narrow contaminated plume that closely follows the design ventilation circuit. The escape-route analysis of Scenario 2 is therefore the worst case scenario in terms of the spatial extent of the contaminated zone: routes that cross the major return corridor are exposed to peak CO that exceeds the IDLH and to a visibility that is less than 0.5 m, whereas routes that do not cross the major return corridor are largely tenable. The module is run at $t = 60$ min, when the plume has reached its maximum spatial extent under sustained ventilation.

In Scenario 3 (main fan failure at $t = 60$ min), the analysis is done at $t = 75$ min, that is, fifteen minutes after the failure, which is the time when the post-failure flow reversal has stabilised and the residual buoyancy-driven plume has reached its new (smaller) steady extent. Scenario 3 decreases the spatial extent of the contaminated zone than Scenario 2 because the loss of advective transport limits the downstream propagation, so a number of routes that were non-viable under Scenario 2 become degraded-but-viable under Scenario 3. Section 4.6 also reports a separate run of the module at $t = 60$ min (the moment of failure itself) to capture the transient peak that occurs whilst the airflow is reversing.

In Scenario 4 (main fan failure at $t = 30$ min, during the fire growth phase) the analysis is carried out at $t = 45$ min, which is fifteen minutes after the failure and corresponds to the same post-failure stabilisation interval, as in Scenario 3 - chosen in this way so that the two fan-failure scenarios are compared at the same dynamic states rather than at the same absolute clock times. Since the fire is in its growth stage when the fan fails, the highest rate of CO emission has not yet been reached, and the geographic extent of the contaminated zone in Scenario 4 is the lowest of any of the ventilated scenarios; a significantly greater fraction of the candidate routes is classified as fully viable in Scenario 4 than in Scenarios 2 or 3.

In Scenario 5 (main ventilation circuit fails at $t = 0$ min, at the same time as ignition) the situation is qualitatively different than the other three situations because the main ventilation circuit never operates when the fire is active. The module is operated at $t = 60$ min, the time at which Monitor 7 in Airway 4934 records its peak CO of about 3,300 ppm and its peak dry-bulb temperature of about 190 °C. This seventh monitor was added specially to provide this scenario with a local reading of the fire-airway tenability that the six previously-deployed monitors (configured to provide a local reading of the ventilated scenarios) cannot capture in a buoyancy-dominated, low-flow regime. The escape-route analysis in Scenario 5 reflects two conflicting effects: locally, the airway containing the LHD and the vertical airway directly above it are non-tenable at any point in time, and so globally, the absence of forced ventilation means that the contaminated plume never advects into the rest of the production section, so the majority of the candidate routes are at tenable conditions at any point in time. The outcome is a route-tenability topology dominated by one, well-defined no-go region around the fire and which leaves the rest of the network largely intact.

The combination of the four scenarios gives a systematic examination of the effect of the timing of fan-failures on the evacuation landscape of the Maleevsky mine. The trade-off between the locally severe but spatially confined hazard of Scenario 5, and the locally moderate but spatially extensive hazard of Scenario 2, and the intermediate behaviour of Scenarios 3 and 4, is quantified by the route-by-route comparison reported in Section 4.6. This trade-off is the empirical grounds of the regulatory and operational recommendations that have been elaborated in Section 6.2.

3.8 Evaluation Metrics

The following measures are used to assess the simulation outputs: peak CO concentration at each monitor and the time to peak, which gives fire intensity and transport delay data; duration above IDLH (1,200 ppm), STEL (200 ppm), and TWA (50 ppm) at each monitor, which quantifies the severity of the exposure; the shape of Available safe egress time (ASET) is compared with required safe egress time (RSET) of a route, with RSET consisting of detection time (2-5 min), pre-movement time (3-5 min), and travel time depending on distance of route and walking speed (1.0-1.5 m/s in clear air, 0.3-0.5 m/s in smoke).

4. RESULTS

4.1 Baseline Ventilation Analysis

The operational readiness of the Maleevsky mine ventilation network was checked by the baseline steady-state simulation. The system had a balanced airflow in all production headings, delivering 556.1 m³/s at 55.1% efficiency. The airflow velocity and pressure distributions at the baseline are presented in Figure 13 and 14.

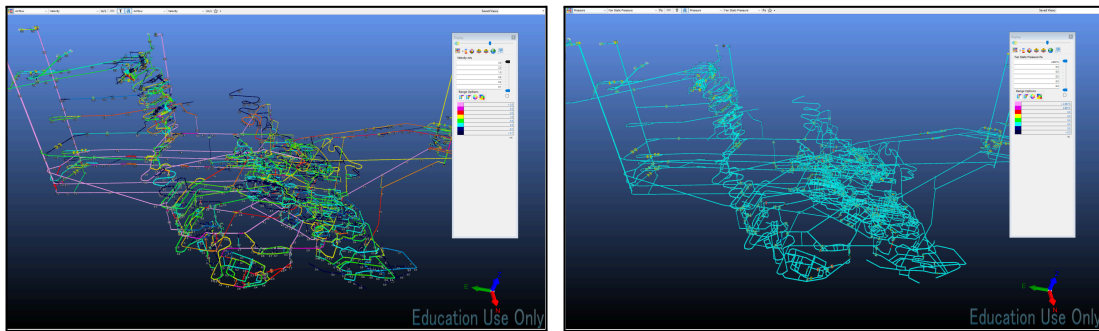


Figure 13–14. Airflow velocity distribution (left) and pressure distribution (right) under baseline conditions.

Main intake and return drifts were between 2 and 5 m/s and production headings had velocities of more than the minimum 0.5 m/s needed to have significant contaminant dilution. Directional airflow integrity was ensured in the network by the pressure gradient between intake and exhaust. Dead-end headings were found to be peripheral, with velocities less than 1.0 m/s- these low velocity zones are the most susceptible to gas buildup during fire incidents since low velocity restricts the ability to dilute and the rate of gas transport.

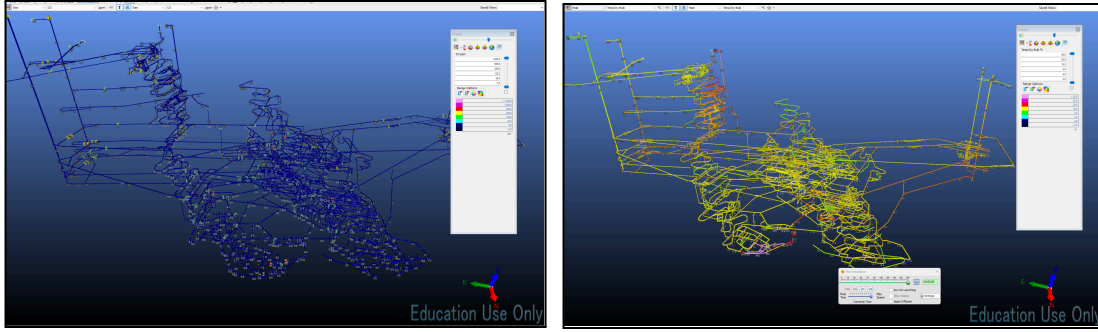


Figure 15–16. CO concentration (left, zero confirmed) and temperature distribution (right) under baseline conditions.

All six monitors have zero CO concentrations (Figure 15), indicating that there are no spurious sources of gases in the model. At ambient temperature, temperature was spatially homogeneous (Figure 16). These baseline values set the quantitative point of reference of all future analysis of fire scenarios: any non-zero CO reading, increase in temperature, or a change in airflow velocity in Scenario 2 and Scenario 3 can be directly linked to the fire event.

4.2 Scenario 2: LHD Fire with Full Ventilation

4.2.1 Spatial CO Propagation

Figures 17-22 monitor the spatial development of CO in the production section at six time intervals throughout the 180-minute simulation. The color scale is based on the dark blue (0 ppm), green (50,125 ppm), yellow (125,500 ppm), and red (>1,000 ppm) color, which allows visually evaluating the progress of the contamination front.

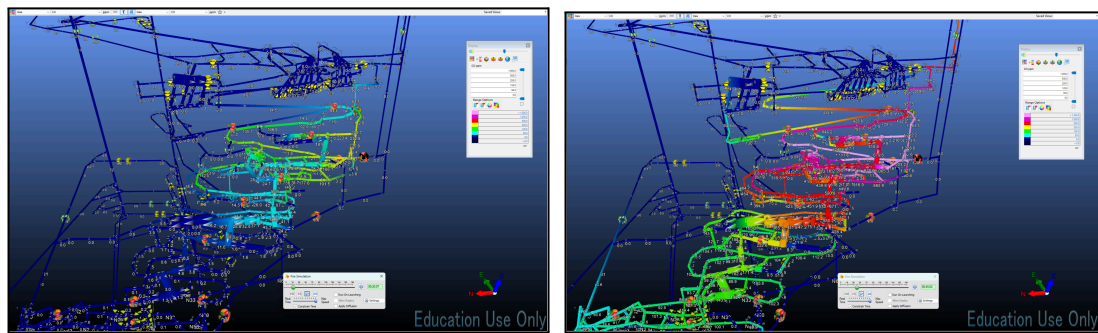


Figure 17–18. CO distribution at 20 minutes (left) and 45 minutes (right).

At 20 minutes (Figure 17), the CO is restricted to the immediate fire zone and immediate downstream airways with concentrations of 50-200 ppm in the closest headings and most of the section at zero. This initial stage is indicative of the bulk transport of combustion products along the main downstream airways at the local airflow velocity (approximately 2-3 m/s) which is equivalent to a

contamination front traveling at a rate of approximately 120-180 m/min., at 45 minutes (Figure 18) where the green and yellow coloration (50-500 ppm) is present across half of the area studied. The fire has reached a fully involved stage and the constant supply of oxygen supports the maximum CO production.

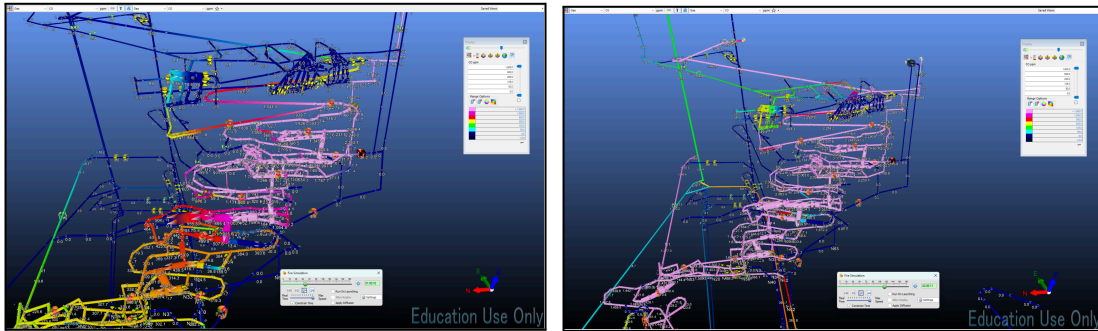


Figure 19–20. CO distribution at 60 minutes (left) and 120 minutes (right).

At 60 minutes (Figure 19), the contamination by CO has nearly covered the whole production section. The proximal zone is found to be higher than 1,000 ppm (red), whereas the intermediate and distal are 250-500 ppm (yellow-green). This establishes that the whole production area (over 1,000 meters) is contaminated above the OSHA TWA of 50 ppm in less than an hour of a well-ventilated LHD fire. The highest spatial extent of contamination is achieved at 120 minutes (Figure 20). The continuous supply of oxygen has also ensured maximum combustion of up to 90 minutes leading to extensive CO levels of 500 to 2,000+ ppm throughout the section. The red and orange areas have grown to take most of the airways on the direct ventilation pathway.

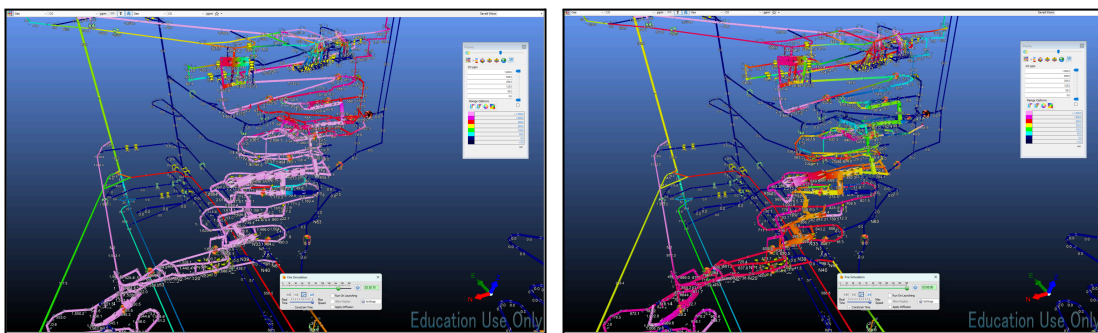


Figure 21–22. CO distribution at 150 minutes (left) and 180 minutes (right).

At 150 minutes (Figure 21) the fuel consumption has started to decrease the intensity of the fire and the CO concentrations are now decreasing in the proximal zone and still high in the distal zone, a spatial lag due to the delay in transport. At 180 minutes (Figure 22), the CO levels are decreasing across the board although not completely yet, the distal airways still indicate a level of

200-600 ppm. This continuous contamination at the end of the simulation shows that it takes over 180 minutes to completely clean the atmosphere in Scenario 2, which is to say that miners in the far zones are exposed to risky conditions throughout the three-hour simulation.

4.2.2 Monitor Analysis

The six monitor graphs give quantitative time profiles to the above spatial snapshots. All monitors show the time of arrival, growth rate, maximum concentration, plateau and decay of the CO front at a certain location.

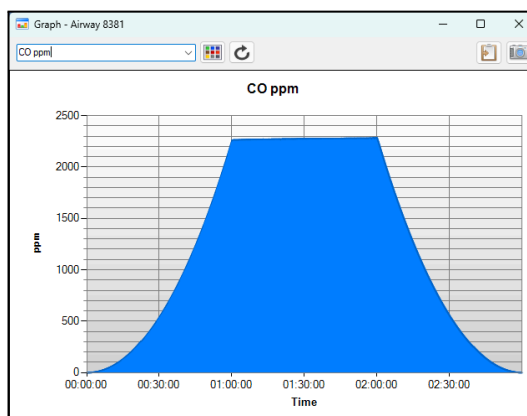


Figure 23. Monitor 1 (Airway 8381) - CO concentration, Scenario 2.

The CO exposures were most intense at Monitor 1 (Figure 23), which was nearest to the fire source. CO starts increasing at about 15 minutes, which means the delay in transporting the gas to the sensor between the ignition of the fire and the arrival of gas. The concentration rises gradually at about 40- 50 ppm/min at the growth stage (15-45 minutes) indicating the increasing heat transfer of the fire as more and more fuel components are involved. The profile to about 2,300 ppm is achieved at around 60 minutes and levels off until around 120 minutes. This plateau of 2,300 ppm - almost twice the IHLD of 1,200 ppm - lasts about 60 minutes. It is the long-lived nature of this plateau which is the hallmark of a well-ventilated fire, the constant flow of oxygen keeps the combustion process at full intensity, and the ventilation carries the products of combustion away at a constant rate past the sensor. CO decreases after 120 minutes due to the use of fuel and reaches about 200 ppm in 180 minutes but fails to revert to zero within the simulation time.

Exposure to 2,300 ppm over 60 minutes would result in carboxyhemoglobin (COHb) levels higher than 70 percent in 15-20 minutes- a level at which a person is not conscious. All the staff in this area who have not evacuated after the first 15 minutes of the fire are incapacitated and killed.

Already the growth phase concentration of 500-1,500 ppm (20-50 minutes) leads to confusion and impaired coordination, impairs the cognitive processes involved in making decisions on navigation and evacuation.

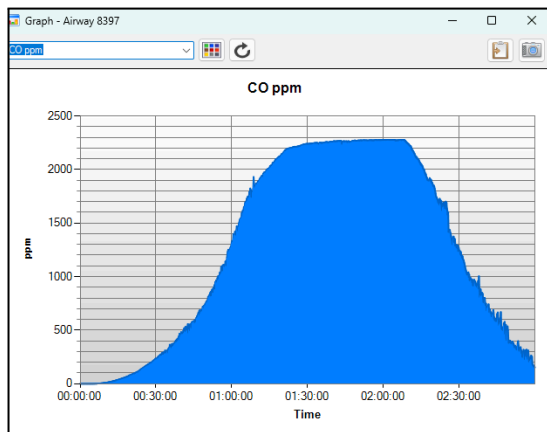


Figure 24. Monitor 2 (Airway 8397) - CO concentration, Scenario 2.

Monitor 2 (Figure 24) will have almost the same profile as Monitor 1 with a peak at about 2,300 ppm with a plateau at 75-120 minutes. The delay of the 10-15 minutes in comparison with Monitor 1 is equal to the distance of advective transport between the two sensors. The fact that the peak concentrations of Monitors 1 and 2 are similar, shows that the airway between them is a direct gas transport conduit with little dilution by crosscut entries. This result is important to escape route planning: airways down the direct downstream of the fire are fully exposed to the full, undiluted concentration, and do not provide any attenuation benefit as the distance between the fire source and the airway increases.

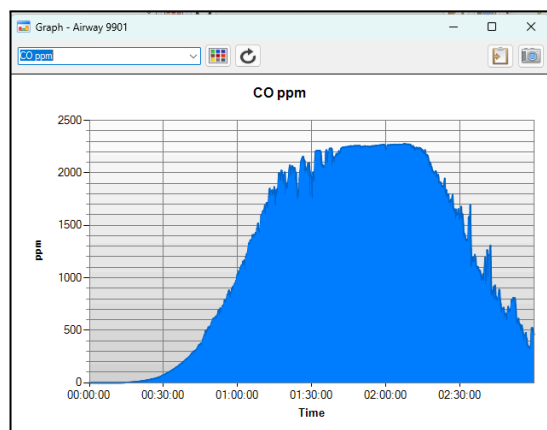


Figure 25. Monitor 3 (Airway 9901) - CO concentration, Scenario 2.

Monitor 3 (in Figure 25) is a junction point where the fire gases are mixed with cleaner air entering parallelly. The highest concentration of about 2,200 ppm is only slightly less than Monitors

1-2 (4% lower) indicating that the junction mixing is not a significant source of dilution at this point. The concentration profile however is more variable in the plateau stage- observable in the less smooth and noisier curve than Monitor 1- that indicates the turbulent mixing processes occurring at the intersection between the gas laden air in the fire zone and the cleaner air in parallel headings. The peak is delayed around 25 minutes compared to Monitor 1.

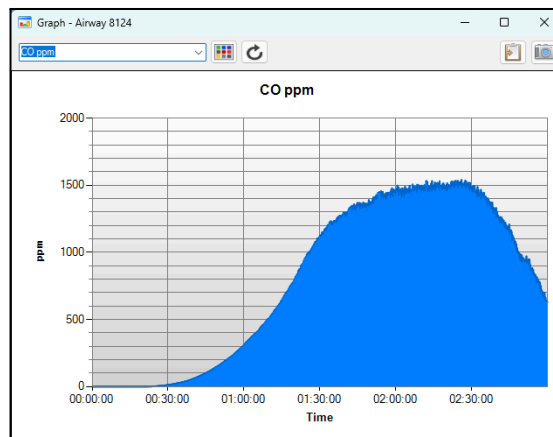


Figure 26. Monitor 4 (Airway 8124) - CO concentration, Scenario 2.

Figure 26 (Monitor 4) indicates a rather distinct profile. Its highest concentration is about 1,500 ppm- a 35-percent decrease compared to Monitor 1. The maximum is reached at about 105120 minutes which is 4560 minutes later than Monitor 1. The low peak shows that a significant amount of dilution has taken place due to crosscut connections with Monitor 4 being located in a heading that is fed by the lateral migration of gas and not by advection. Monitor 4 is over the IDLH during a period of about 30-40 minutes and over the TWA of 50 ppm during a period of about 120 minutes, although the peak is lower. The increased time to peak also implies that the atmospheric conditions at Monitor 4 continue to worsen at 120 minutes and proximal monitors have already started to decline- a time-lag that makes it difficult to time evacuation of people in this area.

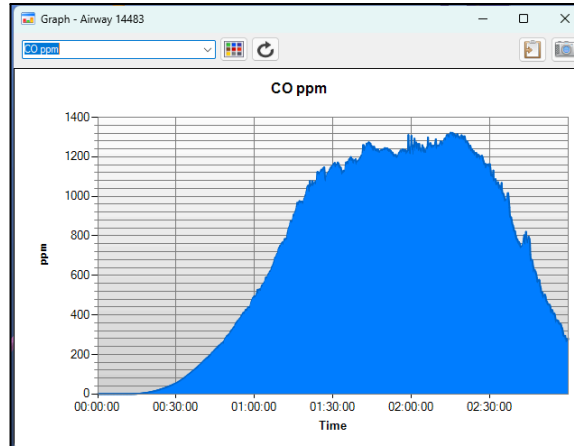


Figure 27. Monitor 5 (Airway 14483) - CO concentration, Scenario 2.

Monitor 5 (Figure 27) peaks at about 1,300 ppm at about 90-135 minutes. The profile depicts a wide, rounded peak with a high concentration noise which means that there are varying gas transport conditions at this point. The peak is just slightly above the IDLH level, and it was in the 1,100-1,350 ppm range about 60 minutes. At 180 minutes, CO remains at around 700-800 ppm, and it is clear that atmospheric clearance has not occurred completely at this distance.

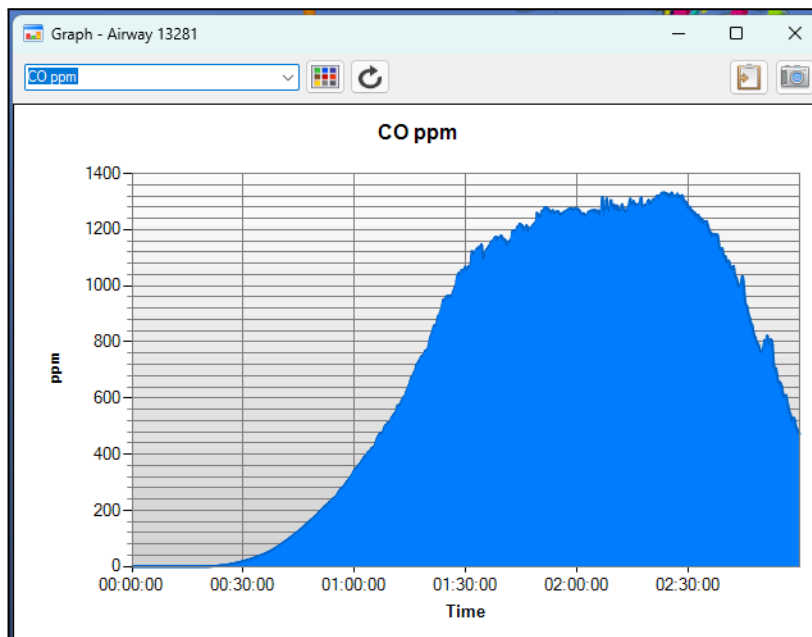


Figure 28. Monitor 6 (Airway 13281) - CO concentration, Scenario 2.

Monitor 6 (Figure 28), which is the farthest sensor, gives the most significant information regarding the extent of contamination over the network. The initial appearance of CO is at about 30 minutes which validates the presence of a transport delay of about 30 minutes between the point of fire and this point. The concentration increases slowly reaching its peak at about 1,350 ppm in the

range of 120-150 minutes. It is interesting to note that the peak of Monitor 6 is delayed by about 90 minutes compared to Monitor 1, but it exceeds IDLH. CO shows the highest residual at the end of the simulation; it is still above 600 ppm at 180 minutes. This is due to the fact that the gas front comes late and the ventilation system has not had enough time to clear up the contamination when the simulation is completed. The practical implication is harsh: the distal location staff are exposed to CO exceeding IDLH, reaching them around 90 minutes after ignition, and no atmospheric recuperation in the three-hour simulation period. Any evacuation out of this area should be done prior to the arrival of the gas front or the people should take shelter permanently.

Table 3. Summary of CO concentrations across monitors (Scenario 2).

Monitor	Airway	Peak CO (ppm)	Time to Peak	Duration >IDLH	CO at 180 min(ppm?)
1	8381	~2,300	~60 min	~60 min	~200
2	8397	~2,300	~75 min	~55 min	~150
3	9901	~2,200	~80 min	~50 min	~250
4	8124	~1,500	~110 min	~35 min	~500
5	14483	~1,300	~115 min	~30 min	~750
6	13281	~1,350	~135 min	~25 min	~600

There are two important trends identified in Table 3. To begin with, the level of CO is lower at further distances to the fire of the monitors along the sideways pathways (Monitors 45: 1,3001,500 ppm) but is high at the monitors along the direct ventilation route (Monitors 13: 2,2002,300 ppm). This implies that the main airflow channel offers minimal dilution- gases move along the main airflow channel at almost full strength- and crosscut migration offers 30-40% attenuation. Second, the distance to peak is distance-dependent (60-135 minutes) and the distance to residual CO at 180 minutes (200-750 ppm) is distance-dependent (distal areas are contaminated later, but slower to recover).

4.2.3 Temperature and Airflow

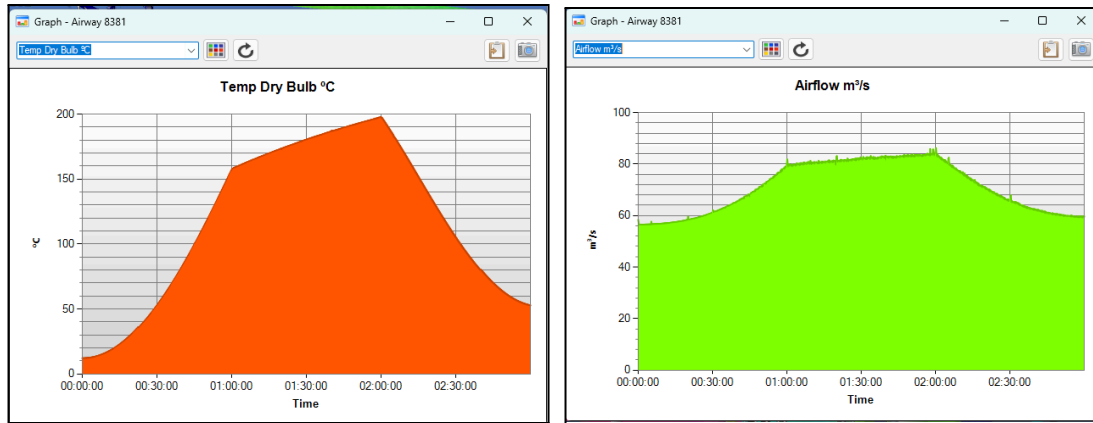


Figure 29–30. Monitor 1 temperature (left) and airflow velocity (right), Scenario 2.

Figure 29 of the Monitor 1 temperature profile indicates a thermal response that is correlated with the CO concentration profile: the temperature increases with the growth stage of the fire, reaches its peak in the sustained burning stage, and drops in the decay stage. Figure 30 of the airflow velocity reveals measurable distortions due to the thermal buoyancy of fire, proving that the 163 GJ fire load is adequate to produce thermal energy to alter local ventilation patterns despite the entire system of fans running.

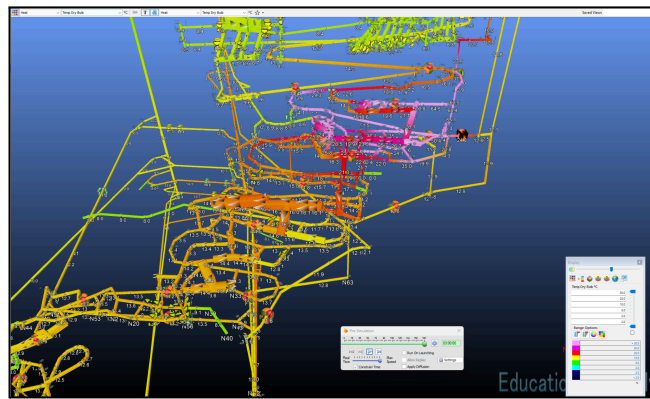


Figure 31. Heat distribution after 180-minute fire simulation (Scenario 2).

The heat distribution map (Figure 31) shows the thermal footprint at the end of the simulation. The maximum temperatures are located in the immediate fire zone and decreasing along the ventilation routes as heat is taken up by the rock mass. The wide range of the thermal anomaly, which includes several levels and headings, suggests that the continued fire in Scenario 2 produces a considerable thermal footprint that stretches far outside the combustion area.

4.3 Scenario 3: LHD Fire with Fan Failure at 60 Minutes

4.3.1 Spatial CO Propagation

Figures 32-36 indicate the CO distribution at some significant time points and the main focus is at 60 minutes when the main fan collapses.

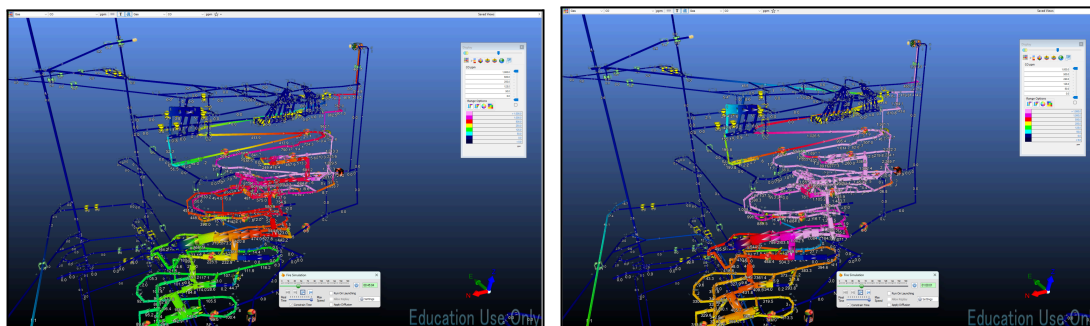


Figure 32–33. CO at 45 min before failure (left) and 60 min at moment of failure (right).

The distribution of CO at 45 minutes (Figure 32) is the same as Scenario 2 at the same time since the fan has not failed yet. This is the internal control that will ensure that any further deviation can be explained by the failure of the fans alone. The main fan is switched off at 60 minutes (Figure 33). The CO levels at this point in time indicate the highest levels of contamination as in Scenario 2 because the fire has been burning under full intensity and fully ventilated in an hour.

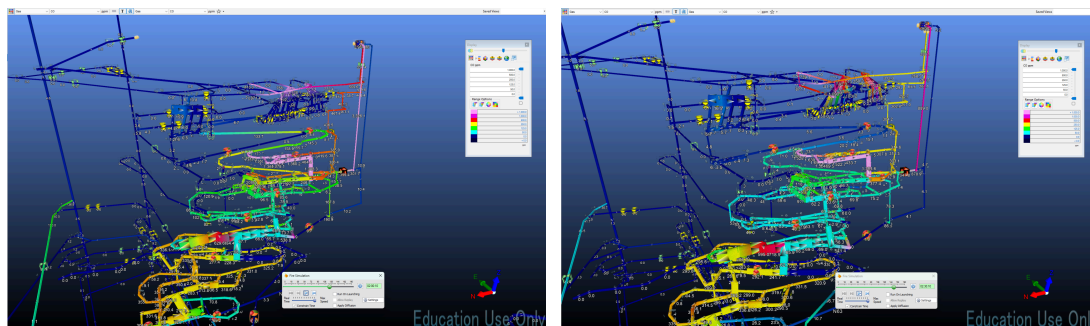


Figure 34–35. CO at 120 min, 60 min after failure (left) and 150 min (right).

The CO distribution at 120 minutes (Figure 34) 60 minutes after the fan failure is drastically different than Scenario 2 (see Figure 20). The section indicates significantly less concentrations in the section with big spots that were red (>1,000 ppm) in Scenario 2 now green-yellow (<500 ppm) in Scenario 3. The lower oxygen supply in the fire has limited the production of CO and the remaining ventilation due to the remaining fans has started to clear the contamination that has already been produced. After 150 minutes, the section has mostly cleared, and there are only some small spots of moderate contamination (Figure 35).

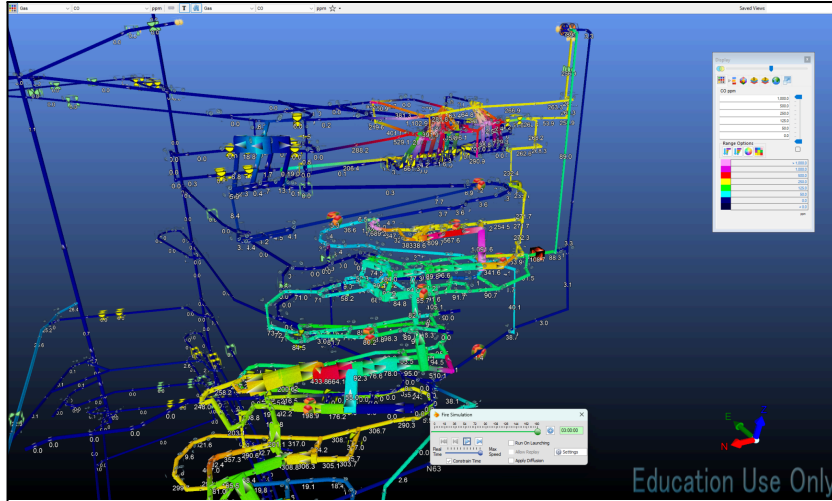


Figure 36. CO distribution at 180 minutes (Scenario 3 - final state).

The mine section (Figure 36) demonstrates a close to full recovery of the atmosphere at 180 minutes (Scenario 3). This is a contrast to Scenario 2 at 180 minutes (Figure 22) where there was still a great deal of residual contamination remaining. The most striking evidence to the oxygen limitation effect is the visual comparison of the two end-state snapshots: the same fire, the same fuel load, the same mine geometry but a radically different atmospheric outcome caused by the fan failure just 60 minutes.

4.3.2 Monitor Analysis

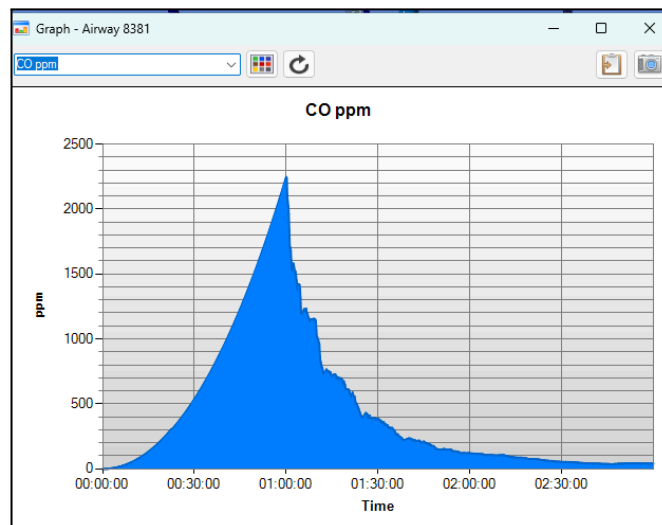


Figure 37. Monitor 1 (Airway 8381) - CO concentration, Scenario 3.

The critical finding is shown in Monitor 1 in Scenario 3 (Figure 37). The CO profile within the initial 60 minutes is the same as in Scenario 2: the concentration increases to about 2,300 ppm, which is the same as the maximum in Figure 23. But rather than a plateau as in Scenario 2, the

concentration commences to fall as soon as it reaches its peak at about 60 minutes, which is exactly at the moment of the fan failure. CO decreases to about 1,000 ppm at 75 minutes (15 minutes after failure), 500 ppm at 90 minutes and nearly goes to zero at 150 minutes. The period of the IDLH exceedance is around 25-30 minutes, which is 50-58 percent less than the period of the IDLH exceedance in Scenario 2 (60 minutes).

The principle is simple: the failure of the main fan at 60 minutes reduces the flow of air to the fire zone significantly. The fire that had been burning at full intensity and with plenty of oxygen changes to oxygen-limited combustion. As the oxygen supply is insufficient to maintain flaming conditions, the rate at which the fire releases heat slows down, the rate of CO production slows in the same proportion, and the remaining fuel combusts much more slowly or extinguishes itself. The remaining fans residual ventilation keeps on carrying and diluting the already produced CO and gives rise to the observed decline. The fire does not suddenly cease- the slow decrease instead of a sudden cut-off indicates the gradual exhaustion of oxygen in the fire area and the thermal inertia of the combustibles.

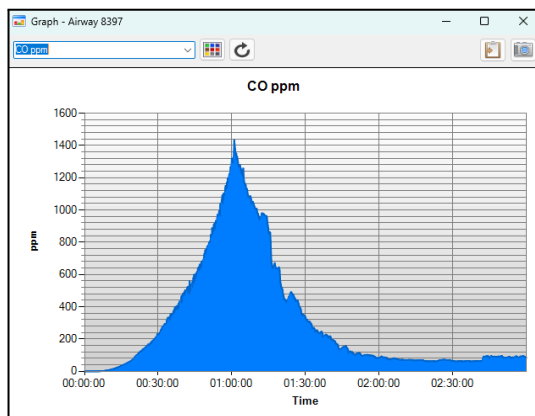


Figure 38. Monitor 2 (Airway 8397) - CO concentration, Scenario 3.

In Scenario 3 (Figure 38), Monitor 2 shows a peak of only about 1,450 ppm, 37 per cent less than the peak of 2,300 ppm in Scenario 2. The profile indicates that there is a sharp spike and then it drops at a rapid rate as compared to a sustained plateau in Scenario 2. This 37 percent decrease at Monitor 2 is more than the insignificant decrease at Monitor 1 (where both cases have the same maximum of 2,300 ppm), showing the distance dependence of the oxygen limitation effect. The readings of Monitor 2 indicate the gas produced in the pre-failure peak phase and the post-failure declining phase, the time-averaging of the two regimes gives a lower effective peak when compared to the Monitor 1, which records the undiluted peak emission before the fan failure fully develops.

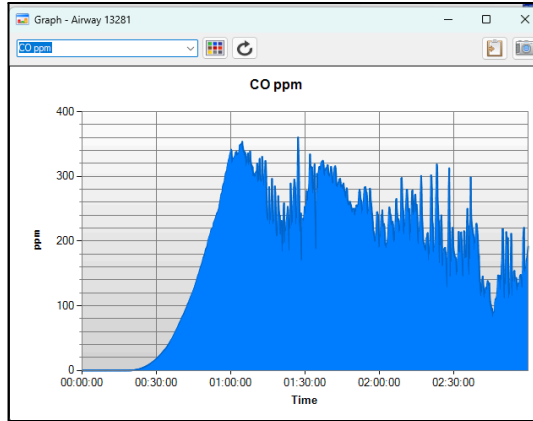


Figure 39. Monitor 6 (Airway 13281) - CO concentration, Scenario 3.

The most dramatic evidence of the oxygen limitation effect is in monitor 6 in Scenario 3 (Figure 39). The maximum concentration is just about 350 ppm, which is 74% less than the 1,350 ppm peak at the same point in Scenario 2 (Figure 28). Monitor 6 does not reach the IDLH of 1,200 ppm at any time during the simulation at 350 ppm. The concentration profile indicates that the concentrations start increasing at about 30 minutes (identical transport delay as in Scenario 2), with the 350 ppm peak at about 6075 minutes, and the concentrations decrease slowly with strong oscillation. The oscillations are indicative of the perturbed, less stable airflow patterns after the fan failure, and the turbulent mixing results in concentration variations at this remote site.

The 74 percent decrease at Monitor 6 and the 0 percent decrease at Monitor 1 indicate the presence of a crucial relationship that is dependent on the distance. The closer to the source of fire, the more similar are the two scenarios (since the fire is at its maximum before the fan fails). The more remote the source of the fire, the more advantageous is fan failure (since remote monitors will mostly record emissions during the post-failure, oxygen-limited phase). It is this gradient that is desired to optimize evacuation safety: the regions where miners must traverse in the evacuation process, intermediate and distal zones, see the largest atmospheric enhancement.

Table 4. Scenario comparison: peak CO at each monitor.

Monitor	Airway	Scenario 2 Peak	Scenario 3 Peak	Reduction	
1	8381	~2,300 ppm	~2,300 ppm	0%	Yes (~30 min)
2	8397	~2,300 ppm	~1,450 ppm	37%	Yes (~10 min)

3	9901	~2,200 ppm	~1,200 ppm*	~45%	Borderline
4	8124	~1,500 ppm	~800 ppm*	~47%	No
5	14483	~1,300 ppm	~500 ppm*	~62%	No
6	13281	~1,350 ppm	~350 ppm	74%	No

The attenuation effect with distance is quantified in table 4. The decrease is increasing and monotonically increasing with a value of 0% at Monitor 1 and 74 percent at Monitor 6. This gradient can be explained by physical causes based on transport delay, gases measured at remote monitors were emitted 30-90 minutes before the recording time. In Scenario 3, the fan malfunctions at 60 minutes, after which any emissions after 60 minutes are oxygen-constrained and generate less CO. The monitors with longer transport delays sample more of these lower post-failure emissions, and hence lower peaks are recorded. (Monitors 3-5 are estimated based on the patterns of the spatial distributions and the known distance-attenuation gradient)

4.3.3 Temperature and Heat Distribution

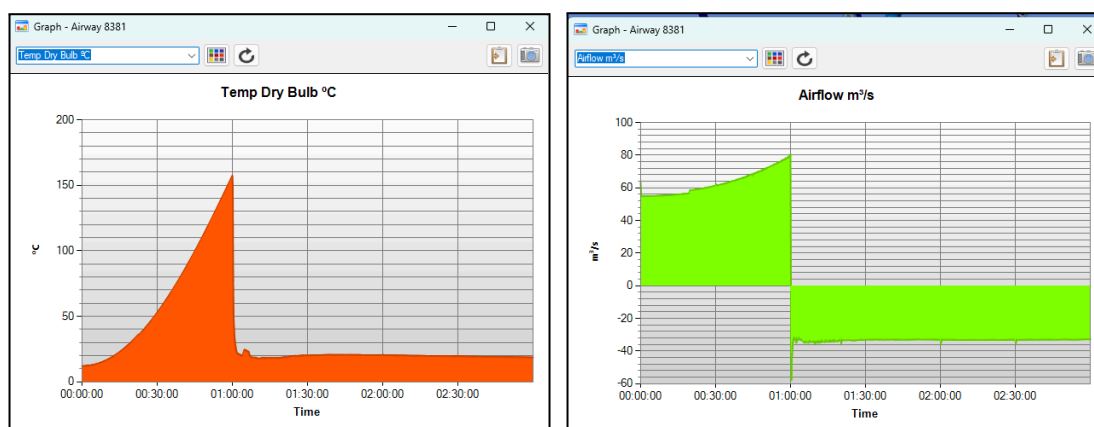


Figure 40–41. Monitor 1 temperature (left) and airflow (right), Scenario 3.

The temperature profile of the Monitor 1 (Figure 40) demonstrates a lower and shorter thermal peak than Scenario 2 (Figure 29), which is expected with less heat released following fan failure. Figure 41 of the velocity of airflow indicates a clear decrease in velocity at 60 minutes when the fan is switched off.



Figure 42. Heat distribution after fire simulation with fan failure (Scenario 3).

Figure 42 (Scenario 3 heat distribution) indicates a more localized thermal footprint, compared to the one in Scenario 2 (Figure 31). The decreased post-failure heat release restricts the spatial scale and the severity of the thermal anomaly, and the rock mass is more effective at capturing the decreased heat release.

4.4 Scenario 4: LHD Fire with Fan Failure at 30 Minutes

Scenario 4 is the same 163 GJ LHD fire as Scenarios 2 and 3 but with the main VOD-30 fan shut down at $t = 30$ min, that is, in the growth phase rather than in the fully developed flaming phase. The time before the fan failure (0-30 min) is the same as in the other two scenarios. The post-failure atmosphere, monitor traces and airflow field in the production section are very different to those for Scenarios 2 and 3.

4.4.1 Spatial CO Propagation

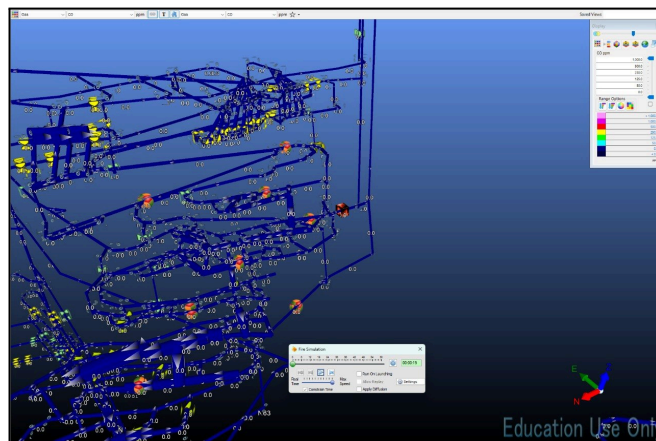


Figure 47. CO distribution at $t = 0$ (Scenario 4) - start of simulation, no contamination.

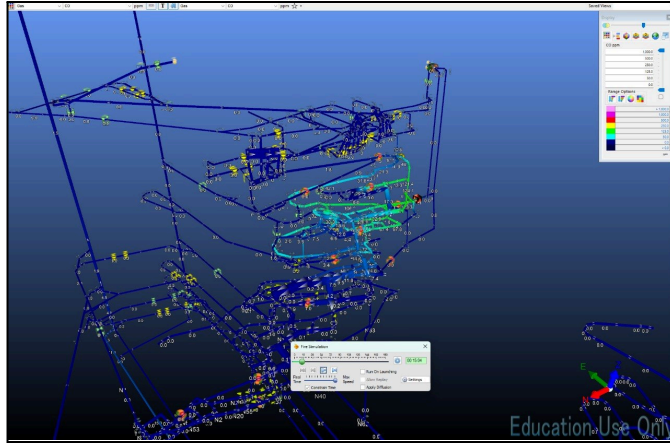


Figure 48. CO distribution at 15 minutes (growth phase, before failure), Scenario 4.

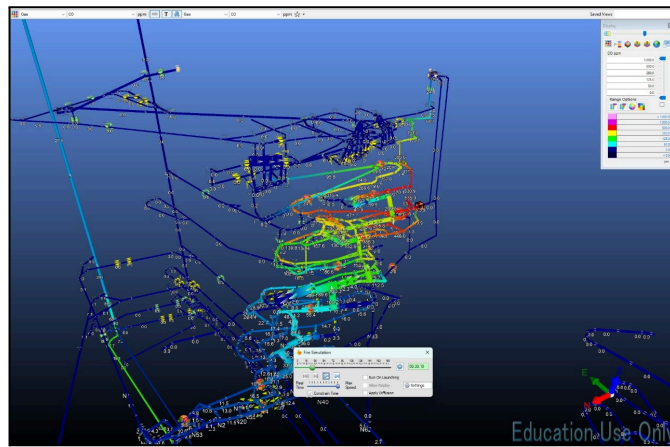


Figure 49. CO concentration at fan failure (t = 30 min)

Figures 47-49 show that, prior to fan failure, Scenario 4 is equivalent to the other two. At the beginning of the simulation (Figure 47) all monitors are at zero. At 15 minutes (Figure 48) the contamination is still confined to the fire region with concentrations lower than 250 ppm and a plume starting to form in the airways just downstream of the LHD. At the time of the fan event ($t = 30$ min, Figure 49) the nearest airways to the fire exhibit the highest concentrations of the Scenario 4 simulation with localised peaks in the 1,500-2,000 ppm range and visible fire plume extending several hundred metres downstream. This is the same time at which the "fan event" occurs and therefore the following evolution of the fire is different to Scenarios 2 and 3.

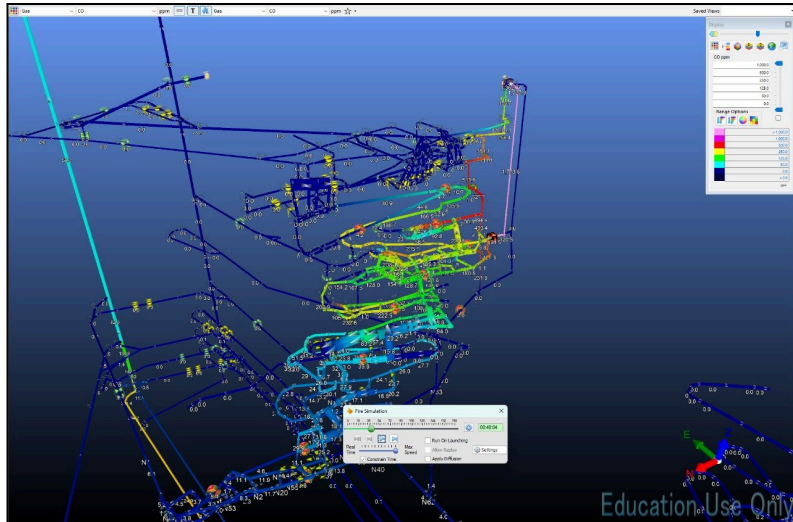


Figure 50. CO distribution 10 minutes after fan failure ($t = 40$ min)

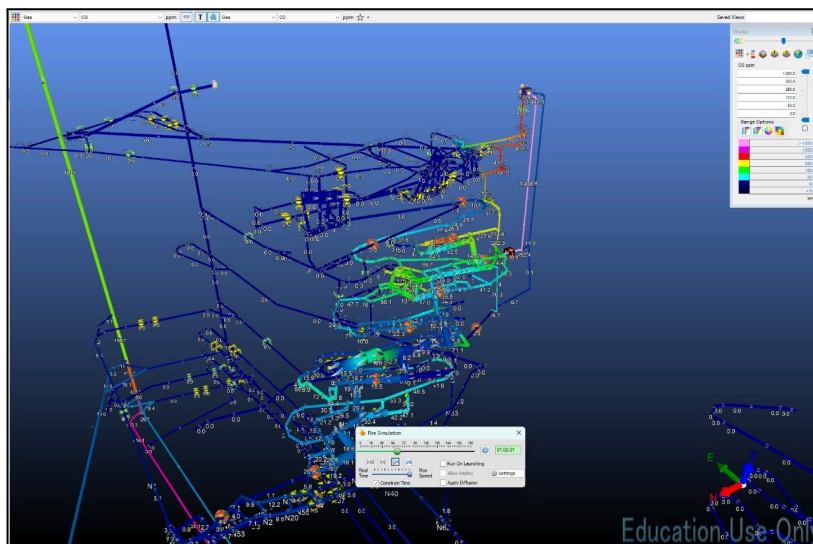


Figure 51. CO distribution 30 minutes after fan failure ($t = 60$ min)

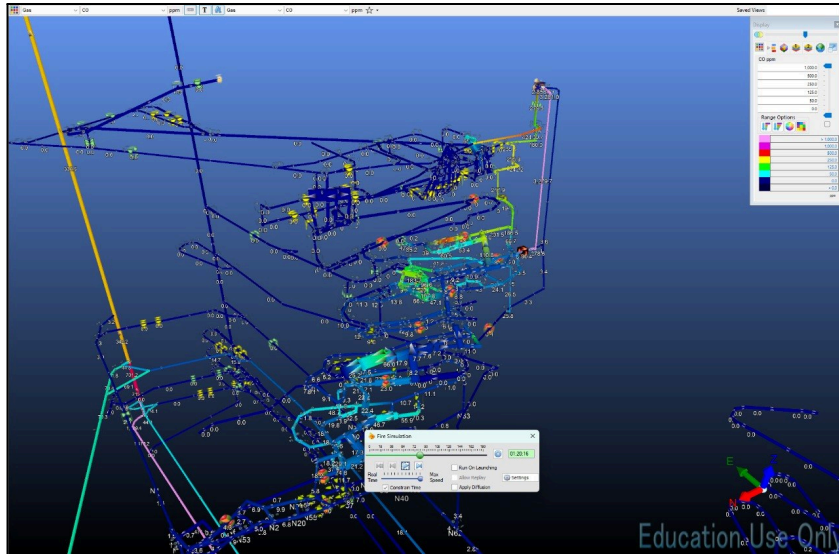


Figure 52. CO distribution 80 minutes (50 min after failure)

After the fan failure the system is in a new mode. At 40 minutes (Figure 50, 10 minutes after failure) the CO front has temporarily spread out as the pre-existing gas is no longer being cleared away by the full airflow; intermediate airways are at 250-500 ppm and several short branches are at 1,000+ ppm. By 60 minutes (Figure 51, 30 min after failure) the pattern has reversed: the production section is almost empty and only a few small "islands" are still coloured. At 80 minutes (Figure 52, 50 min after failure) the section is almost completely blue, with most airways less than 100 ppm.

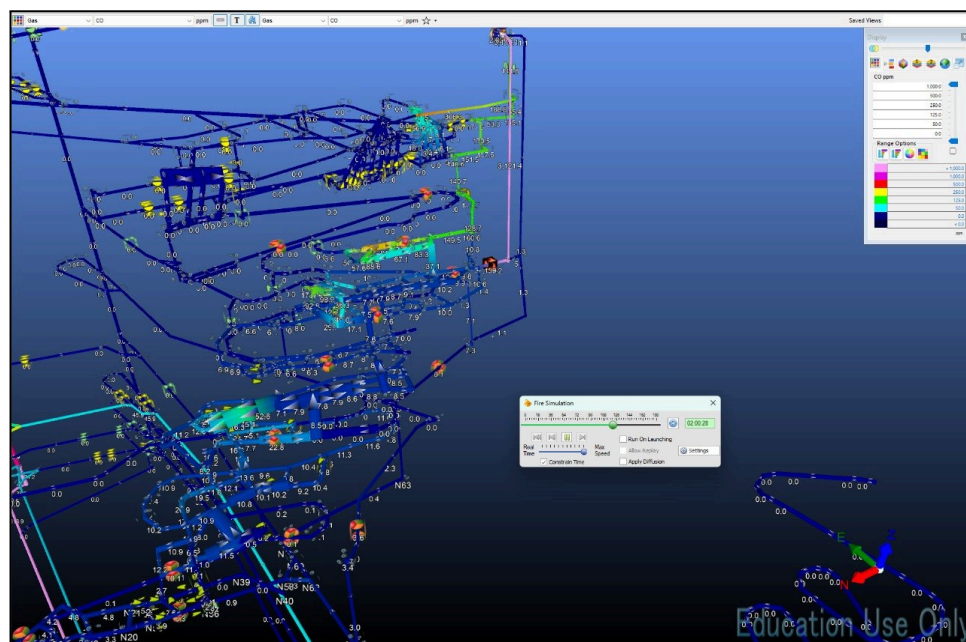


Figure 53. CO distribution at 120 minutes (90 min after failure)

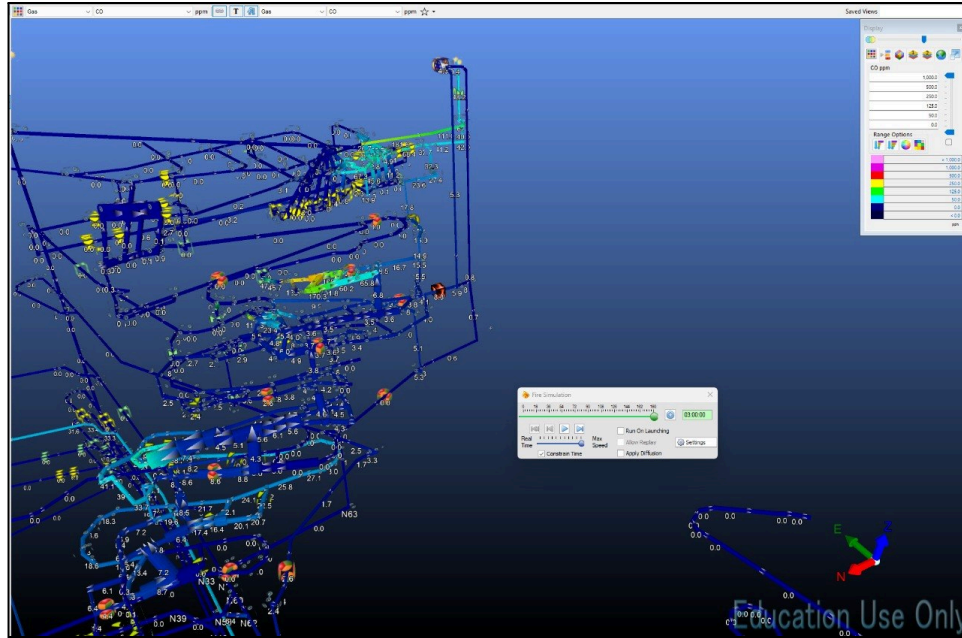


Figure 54. CO distribution at 180 minutes (final state), Scenario 4 - almost complete recovery.

At 120 minutes (Figure 53) and 180 minutes (Figure 54) the section is virtually free of contamination, with CO concentrations below the OSHA TWA of 50 ppm in nearly all airways. This is achieved well before the end of the 180-minute simulation in Scenario 3 where the section was still contaminated above 200 ppm, and much earlier than in Scenario 2 where the section is still above 200 ppm at the end of the 180-minute simulation.

4.4.2 Monitor 1 Analysis

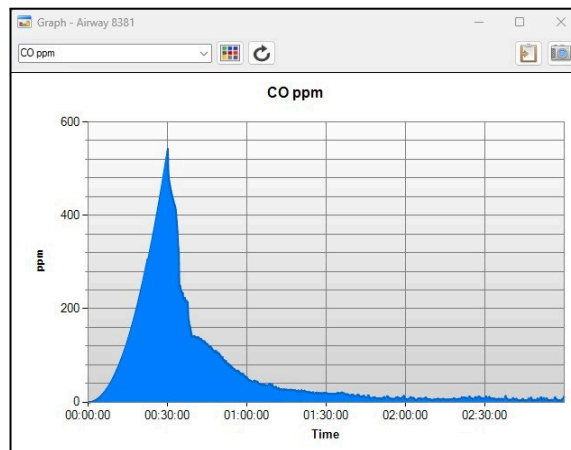


Figure 55. Monitor 1 (Airway 8381) - CO vs time

The most interesting quantitative result of Scenario 4 is the CO concentration at Monitor 1 (Figure 55), which is nearest the fire. The concentration begins to increase at about 15 minutes (as in Scenarios 2 and 3) and spikes at about 550 ppm at 30 minutes, which is the time of fan failure. It

then decreases quickly: reaching less than 200 ppm after approximately 20 minutes, less than 50 ppm (the OSHA TWA) after approximately 60 minutes, and almost zero after 150 minutes. This peak of 550 ppm is about 4.2 times smaller than the peak concentration (2,300 ppm) at the same monitor in Scenarios 2 and 3, and Monitor 1 never reaches the IDLH of 1,200 ppm during the simulation. The concentration-time integral (cumulative exposure) at Monitor 1 in Scenario 4 is on the order of 25,000-30,000 ppm·min, which is about 87-88 % lower than the 230,000 ppm·min in Scenario 2, and 75-79 % lower than the 120,000 ppm·min in Scenario 3.

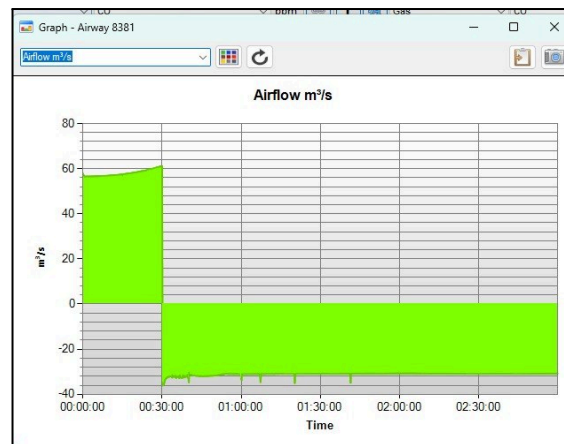


Figure 56. Monitor 1 (Airway 8381) - airflow velocity vs time

The airflow record at Monitor 1 (Figure 56) shows what is happening. Up to the time of failure the airflow at this location is about +60 m³/s in the design (downstream of fire) direction. At $t = 30$ min the airflow abruptly reverses direction (within a single time step) to approximately -30 to -35 m³/s for the rest of the simulation. The reversed airflow is approximately half the magnitude of the original airflow and it is not oscillatory, suggesting that the buoyancy of the LHD plume (which is still burning) and NVP, together with the residual pressure of the remaining (auxiliary) fans, creates stable but reversed airflow through Monitor 1. The reversed flow is then recirculating air from a different location in the network back over the sensor, hence the abrupt drop in the proximal CO.

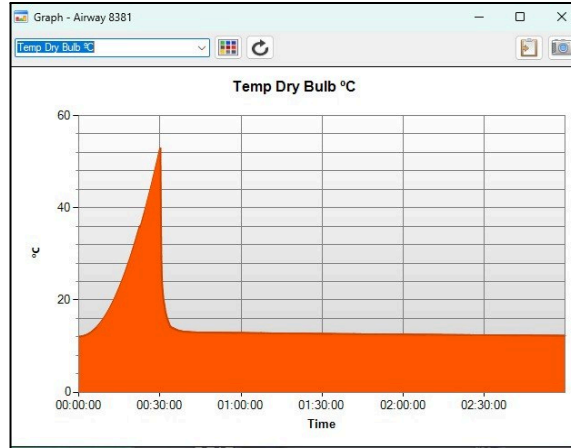


Figure 57. Monitor 1 (Airway 8381) - dry-bulb temperature vs time.

The dry-bulb temperature at Monitor 1 (Figure 57) is consistent with this. It rises from ambient (~12 °C) to a peak of ~53 °C at 30 minutes (coincident with the CO peak and fan failure), and falls back to ambient within 5 minutes as the reversed flow sweeps out the hot plume. The 53 °C peak is below the Purser tenability limit of 60 °C dry bulb, and the duration of the hot period is so brief (less than 5 minutes above 30 °C) that even the unprotected personnel would not have been incapacitated by heat at Monitor 1.

4.4.3 Comparison with Scenarios 2 and 3

Scenario 4 shows that when to fail the fan is as important as whether or not to fail the fan. In Scenario 3, the fan failure at 60 minutes occurred after the fire had already reached the fully developed phase and produced its peak emissions for 30 minutes; the Monitor 1 CO profile was a triangular wave with peak 2,300 ppm and IDLH-exceedance of 25-30 minutes. In Scenario 4, fan failure at 30 minutes catches the fire in the growth phase: it never reaches fully developed conditions, the Monitor 1 CO peak is capped at about 550 ppm (much less than IDLH), and the duration of IDLH-exceedance is zero minutes at all monitors in the production section. Table 4b summarises the comparison.

Table 4b. Monitor 1 metric comparison across the four fire scenarios.

Metric (Monitor 1)	Scenario 2	Scenario 3	Scenario 4	Scenario 4 vs Scenario 2	Scenario 5
Peak CO (ppm)	~2,300	~2,300	~550	-76 %	~ 0 (no transport)
Time of peak (min)	60–120 (plateau)	~60	~30	Earlier	N/A
Time above IDLH (1,200 ppm)	~60 min	~25–30 min	0 min	Eliminated	0 min

Time above STEL (200 ppm)	~110 min	~50–60 min	~25–30 min	–73 %	0 min
Cumulative CO (ppm·min)	~230,000	~120,000	~25,000–30,000	–87 %	~ 0
Peak temperature (°C)	>60 sustained	~50 brief	~53 (5-min spike)	Brief spike only	Ambient
Airflow at Monitor 1	+60 m ³ /s sustained	Drops, mild reversal	+60 → –30 m ³ /s reversal	Buoyancy-driven	Unaffected (~+60 m ³ /s)
Time to <50 ppm at Monitor 1	>180 min	~150 min	~90 min	≈ 1/2 of Sc. 2	N/A (always <50 ppm)

4.4.4 Implications for the Fan-Shutdown Dilemma

For emergency response, Scenario 4 reinforces the finding of Scenarios 2 and 3: the earliest possible (deliberate) fan loss during the growth phase of an LHD fire is the single most effective ventilation intervention, as long as the section evacuation dynamics are such that people can reach refuge in time for the short, intense peak around the failure moment. However, the 5-minute thermal spike (53 °C) and the 30-minute airflow reversal at Monitor 1 are the operational consequences of this intervention: if anyone is still located in the immediate fire downstream at the time of the fan stop, they will experience a brief period of unsteady buoyancy-driven flow that can carry fire gases in the opposite direction. Thus, Scenario 4 is not evidence that all earlier fan failures are safer - it is evidence that, after a critical evacuation time, controlled fan stop can turn a 3-hour event into a 60-90-minute event with sub-IDLH conditions essentially everywhere in the affected production section.

4.5 Scenario 5: LHD Fire with Fan Failure at 0 Minutes

Scenario 5: This scenario simulates the same 163 GJ LHD fire as the previous scenarios but with the main VOD-30 fan having been shut down at the time of ignition ($t = 0$ min). The rest of the auxiliary fans will be running throughout the simulation which lasts 180 minutes. In order to capture the local response around the fire source in this regime, an extra seventh monitor was fitted in Airway 4934, which is near the fire location. In addition to the six monitors used in Scenarios 2-4. The position of this monitor in the Ventsim model is indicated in Figure 58.

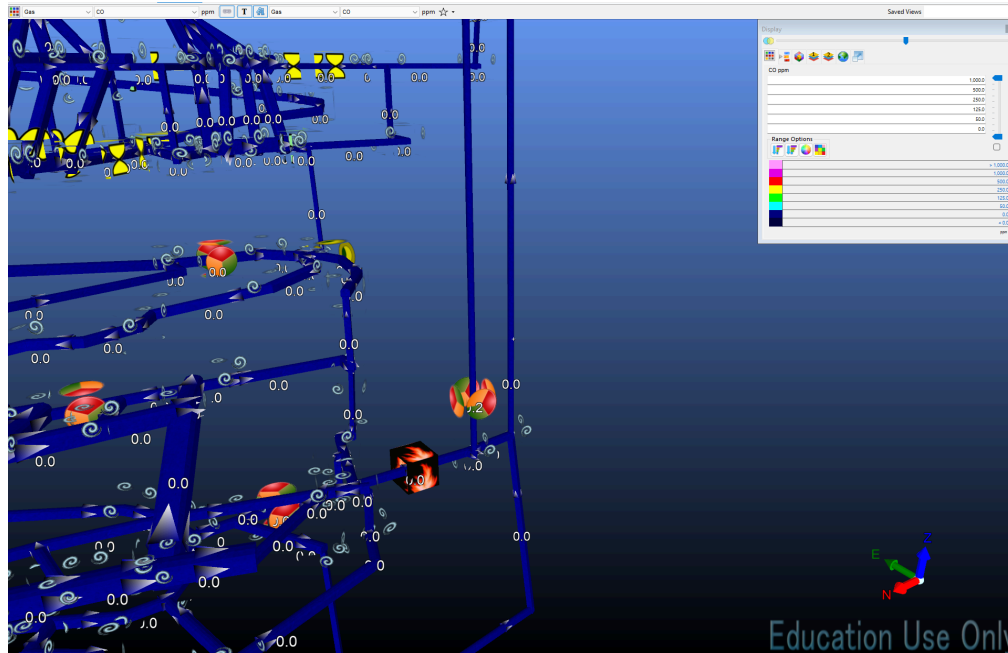


Figure 58. Installation of the seventh monitor in Airway 4934, approximately over the fire source in the LHD (Scenario 5).

4.5.1 Spatial CO Propagation

Figures 59-65 show a series of CO distribution snapshots across the entire 180 minute simulation in 30 minute intervals (with one more snapshot at 20 min covering the early growth phase). Since ignition unavailability of the main fan, the airflow field is fundamentally different to Scenarios 2–4: forced ventilation does not occur, and transport of the gas is driven by buoyancy (the hot fire plume) and residual pressure of auxiliary fans. Consequently, the CO plume is highly concentrated in the airway with the LHD and in the vertical airway immediately above the LHD, but its lateral dispersion through the remainder of the production section is significantly less than in Scenarios 2 and 3.

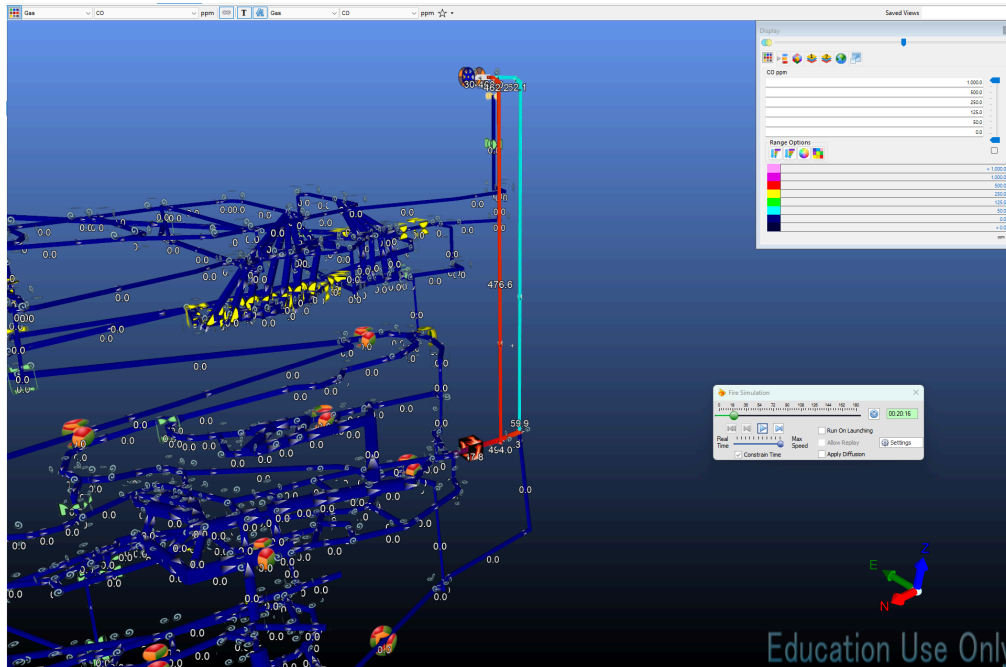


Figure 59. CO distribution at 20 minutes (Scenario 5 - fan failure at $t = 0$).

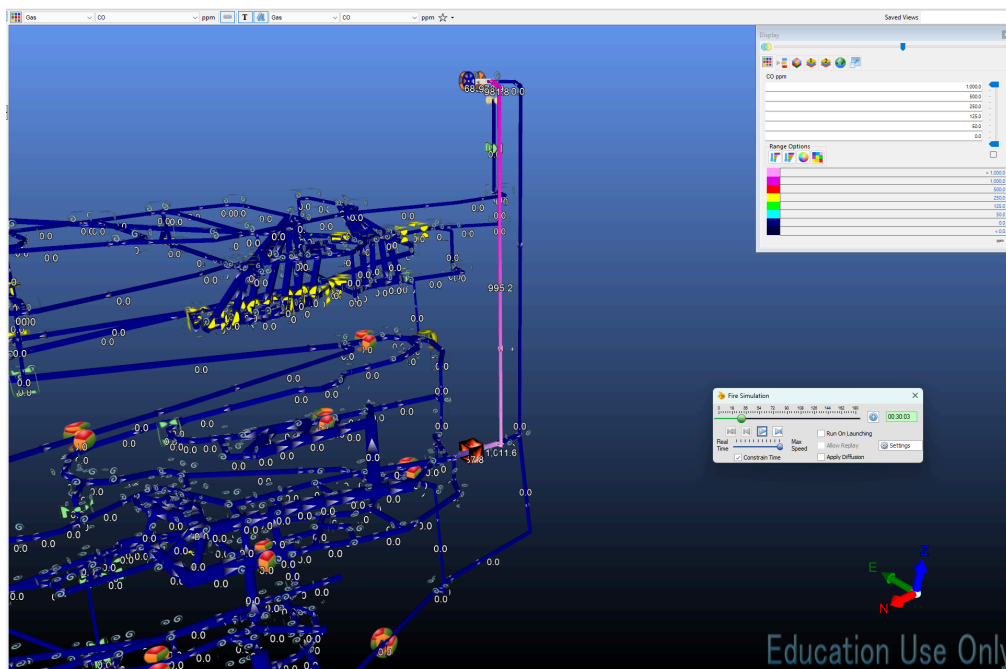
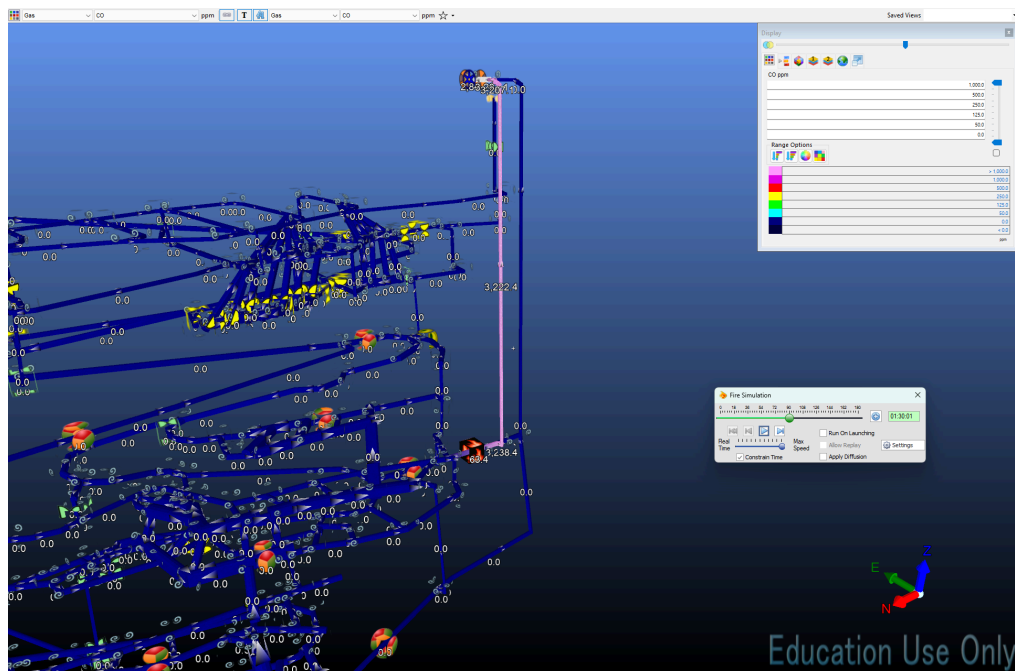
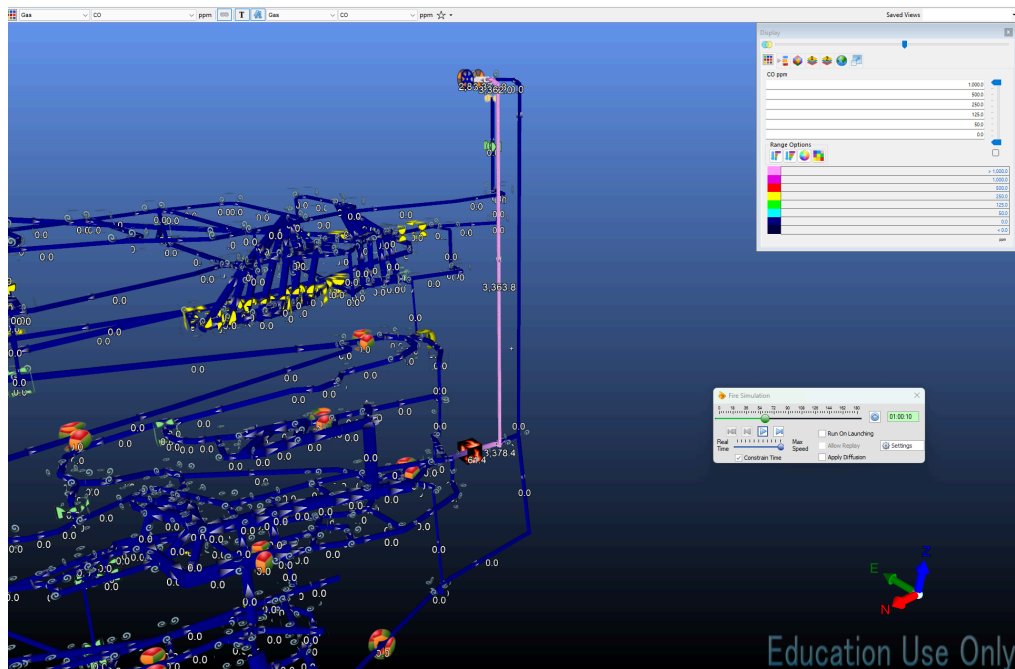


Figure 60. CO distribution at 30 minutes (Scenario 5).



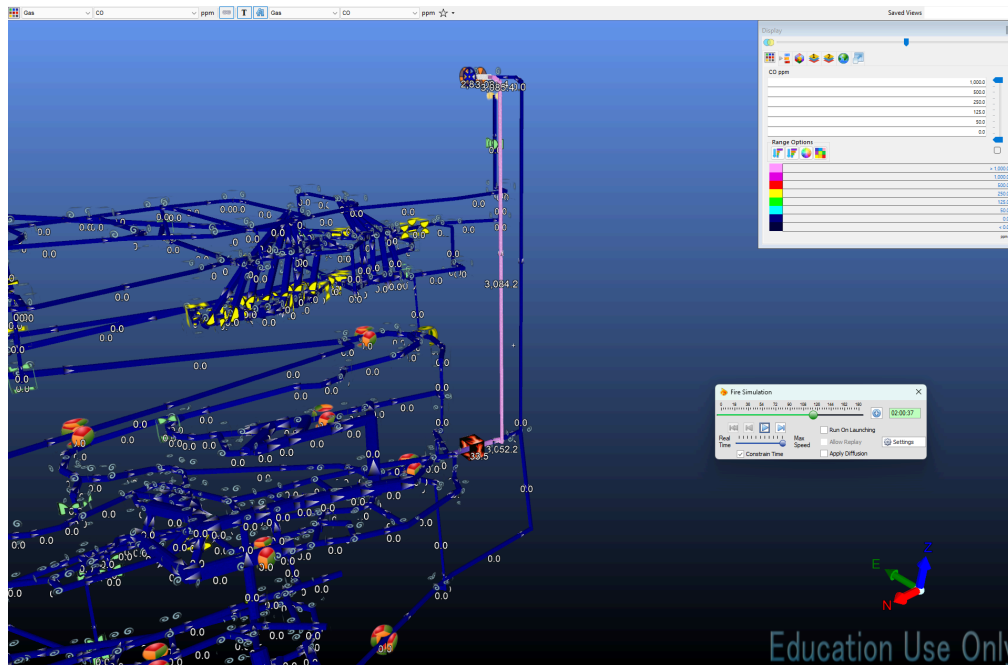


Figure 63. CO distribution at 120 minutes (Scenario 5).

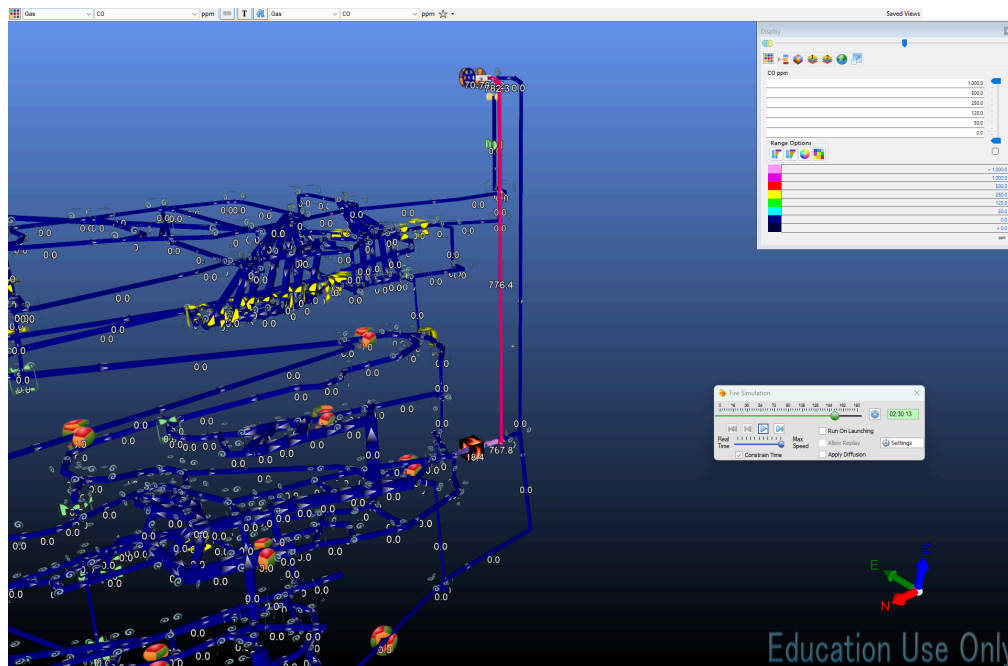


Figure 64. CO distribution at 150 minutes (Scenario 5).

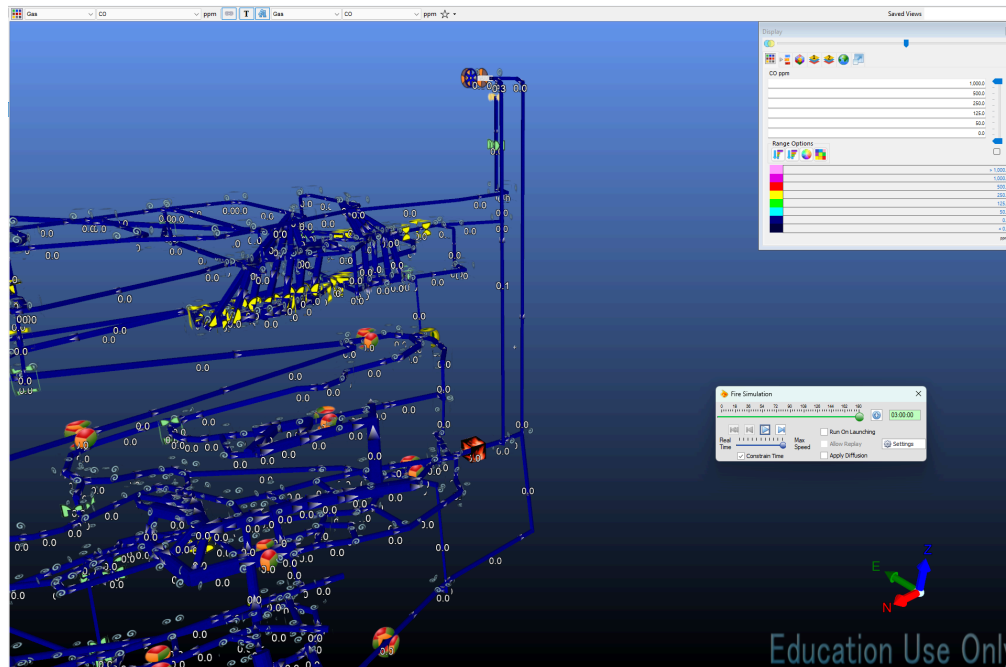


Figure 65. CO distribution at 180 minutes (Scenario 5 - final state).

At 20 minutes (Figure 59) the contamination is already established in the fire and immediate vertical airway with localised concentrations of approximately 460 ppm and a distinct plume forming above the LHD. Without forced ventilation the plume cannot be diluted and pushed downstream as in Scenarios 2 and 3; instead it builds up vertically through buoyancy. At 30 minutes (Figure 60) the same vertical airway has approximately 1,000 ppm and the LHD source is approximately 1,000 ppm. After 60 minutes (Figure 61) the local CO at the fire airway has peaked at about 3,400 ppm at the fire source and 3,378 ppm just above the fire. The colour of the plume is deep magenta on a single vertical column, but the surrounding production headings are dark blue (< 50 ppm), which confirms that the lateral dispersion is severely limited.

Between 90 and 120 minutes (Figures 62 and 63) the local concentration is maintained at about 3,200-2,240 ppm indicating a saturation regime in which the pyrolysis of the fuels is in approximate equilibrium with the limited oxygen reaching the source through residual auxiliary-fan flow. After 150 minutes or later (Figure 64) the concentrations start to decrease, as the available oxygen in the immediate fire region is depleted, and the fire transitions to smouldering. After 180 minutes (Figure 65) the production section is essentially clear: most of the section is reading below 1 ppm, the previously magenta vertical column has fallen below 1 ppm, and even the LHD airway

itself is reading 0.0-0.3 ppm. The entire network has been successfully able to self-heal without forced ventilation.

4.5.2 Monitor 7 (Airway 4934) Analysis

Monitor 7 in Airway 4934 right next to the source of fire recorded the highest local CO, temperature and reversed-airflow values of any monitor in any situation. Figure 66 68 depicts the time series of CO concentration, dry-bulb temperature and airflow at this monitor during the entire 180 minute simulation.

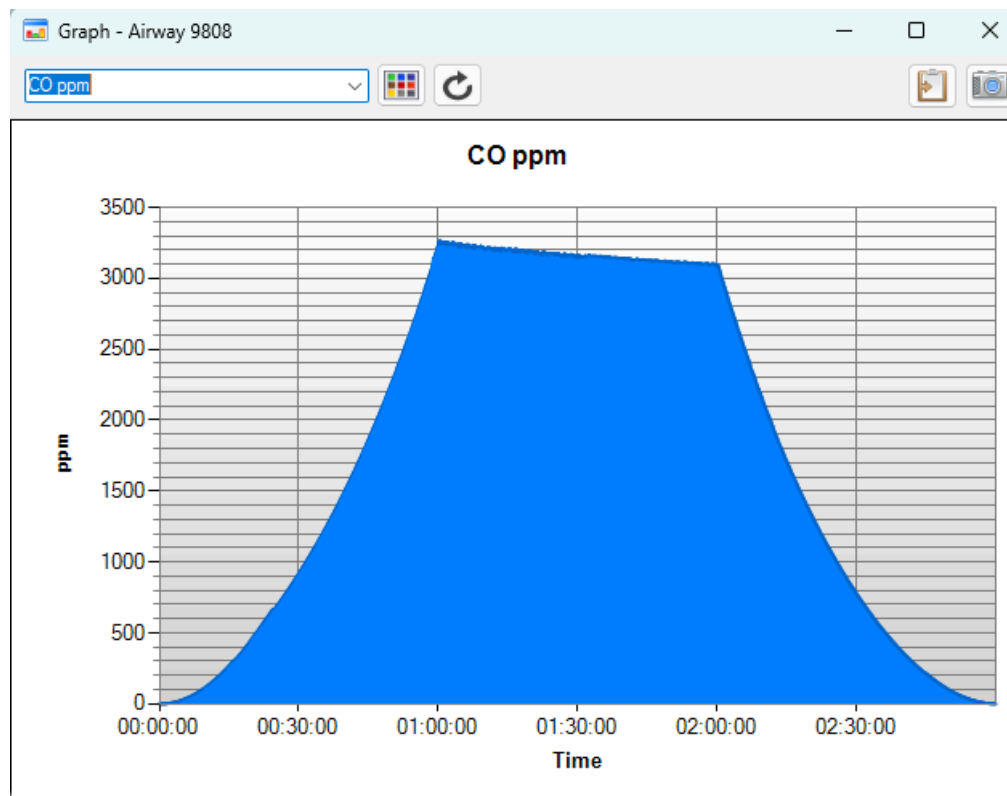


Figure 66. Monitor 7 (Airway 4934) - CO concentration vs time, Scenario 5.

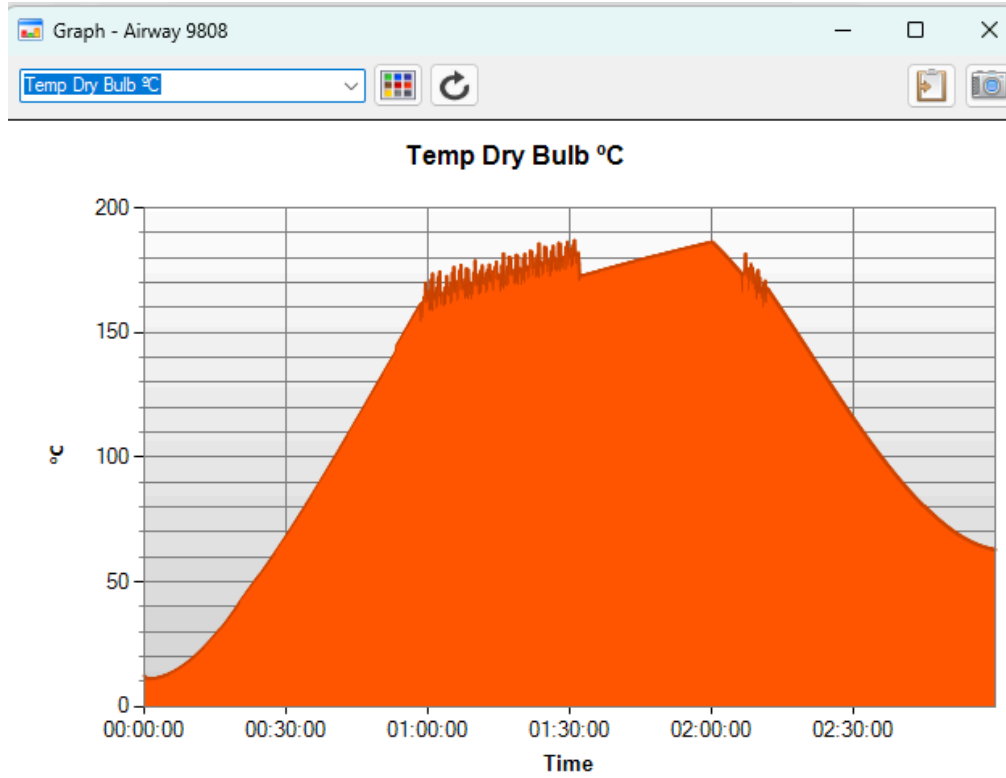


Figure 67. Monitor 7 (Airway 4934) - dry-bulb temperature vs time, Scenario 5.

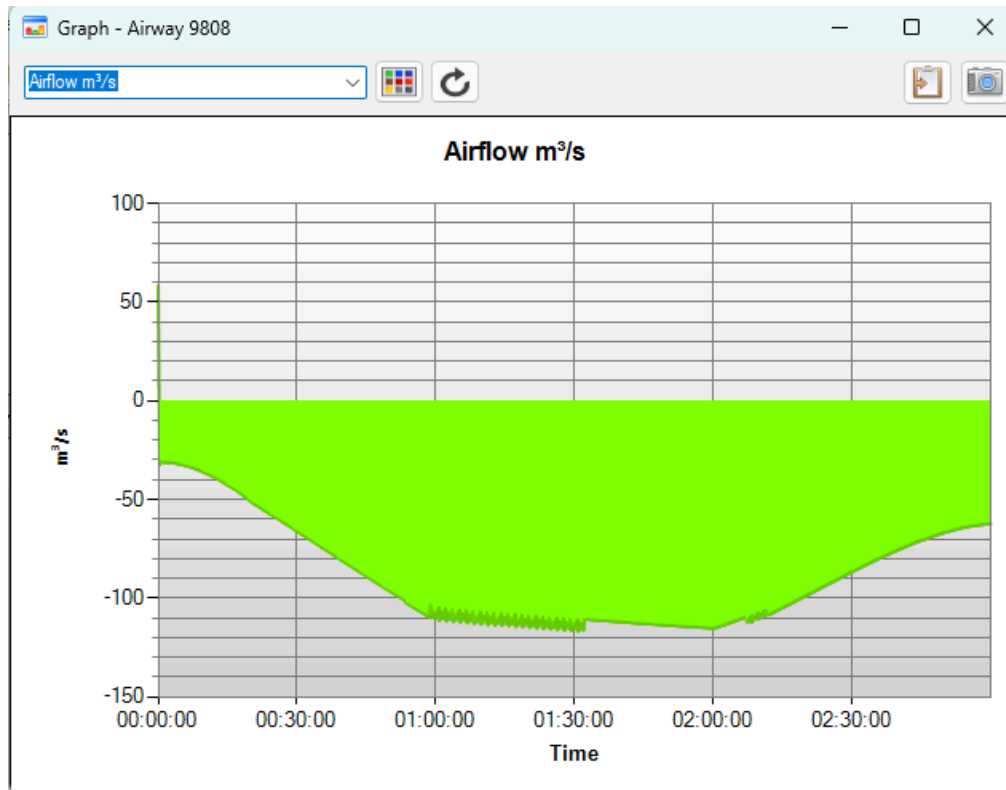


Figure 68. Monitor 7 (Airway 4934) - airflow vs time, Scenario 5.

The CO record at Monitor 7 (Figure 66) indicates a smooth growth of 0 ppm at ignition to a maximum of about 3,300 ppm at 60 minutes, which is followed by a quasi-plateau of 3,000 to 3,300 ppm between 60 and 120 minutes, followed by a steep decay to near zero by 180 minutes. The peak concentration is approximately 1.4 times the corresponding Scenario 2/3 peak (approximately 2,300 ppm at Monitor 1) but the period above IDLH is similar to Scenario 2 (approximately 90/100 minutes). Its shape is that of a stretched trapezoid: a 60-minute growth phase, a 60-minute plateau, and a 60-minute decay phase, all of which are being driven by the local rate of oxygen-supply, rather than by a downstream advective transport.

The dry-bulb temperature (Figure 67) follows the same envelope, but increases to a peak of about 185/190 °C between 60 and 120 minutes, then decays to about 60 °C at the end of the simulation. The maximum temperature is far beyond the Purser 60 °C tenability limit and above 100 °C during more than 90 minutes, which means that the airway with LHD in it is non-tenable throughout the entire growth and plateau phases of the fire. The airflow record (Figure 68) is always negative throughout the plateau phase, and stabilizes at approximately -100 -120 m³/s. This is an indication of steady fully reversed flow at the Monitor 7 due to buoyancy of the LHD plume and remaining pressure of the auxiliary fans, as opposed to the main fan. As opposed to Scenarios 3 and 4, there is no positive to negative flow transition as the main fan was never operating; the airflow is reversed since $t = 0$ onwards.

4.5.3 Comparison with Scenarios 2, 3 and 4

The spatial pattern generated in Scenario 5 is a very distinct pattern compared to the preceding three. The peak local CO is the highest of any scenario (approximately 3,300 ppm in the fire airway versus approximately 2,300 ppm in Scenario 2 and 3 and about 550 ppm in Scenario 4) but the spatial distribution of the gas throughout the rest of the production section is the least. At Monitors 2-6 (the same locations as in Scenarios 2-4) the recorded CO peaks are significantly below the IDLH and in most cases below the OSHA STEL, simply because without the main fan the CO is not advected out of the network. The fire practically seals its own products of combustion in the immediate vicinity of the LHD and the vertical airway located above the LHD. This is the most direct evidence of the oxygen-limitation/transport-limitation mechanism: when the main fan is turned off at $t = 0$, the fire is simultaneously starved of oxygen (limiting its global emission rate)

and starved of advective transport (limiting the spread of what it does emit). The combination of these two effects gives rise to a hazard footprint which is intense locally but limited.

In the case of emergency planning the implication is twofold. First, the airway in which the LHD itself lies has become virtually inhabitable during the entire 180-minute window, with peak temperatures of nearly 190 C and CO over 3,000 ppm (any personnel who happens to be in the airway at ignition would have had very little time to escape (estimated ASET of less than 35 minutes using the data in Figures 66 and 67). Second, the tenable conditions experienced by the personnel located more than two or three airways away at the fire can be explained by the fact that the gas does not propagate as it does in the case of sustained ventilation. Scenario 5 thus represents an upper-bound scenario of pre-ignition fan-loss events (e.g. a power outage that coincides with an LHD fire) and shows that, even in this worst case of the fire-airway personnel, the network-wide tenability is better than in Scenarios 2 and 3.

4.5.4 Escape Routes - Scenario 5

Scenario 5 was run using the Ventsim Emergency Escape Route module with the same starting airway as in the previous three scenarios to allow a direct comparison of the results with the previous three scenarios. Figure 69 indicates the colour-coded route map and the spreadsheet of tenability parameters of all 14 destinations.

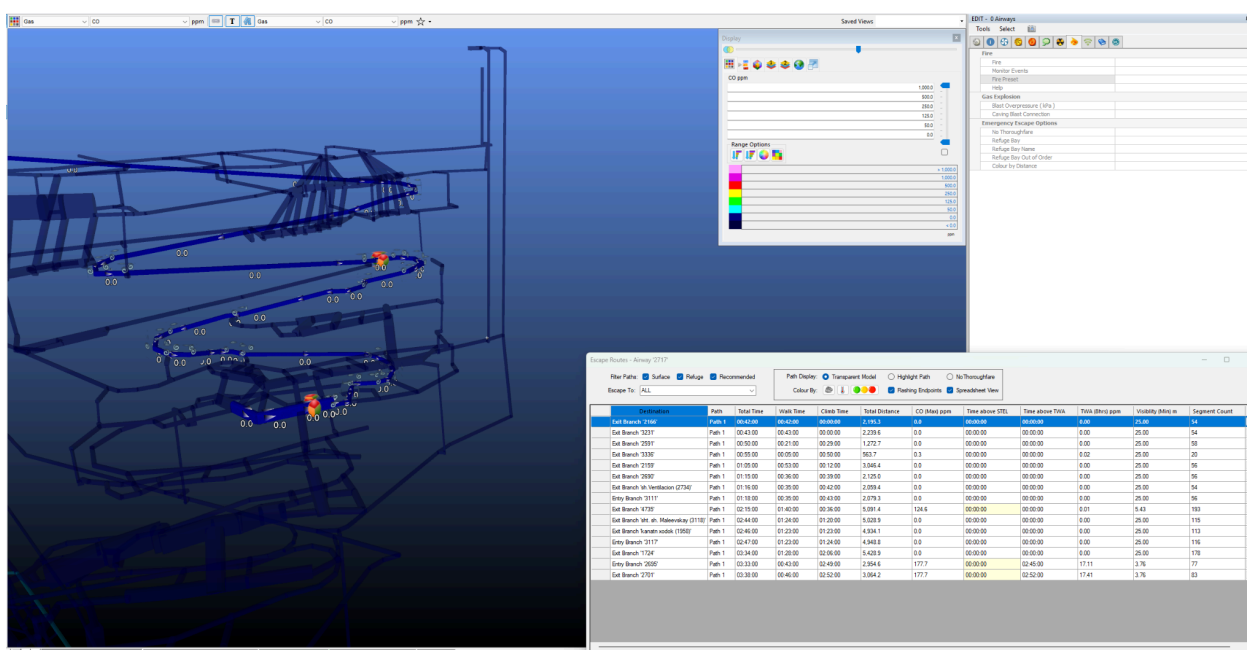


Figure 69. Results of Ventsim Escape Routes module Scenario 5 - 14 destinations starting with the production starting airway, route map (left) and spreadsheet of tenability parameters (right).

The findings are in line with the spatial CO findings of Section 4.5.1. Out of the 14 destinations, 12 record a route-maximum CO of 0.0 ppm and a minimum visibility of 25 m throughout the entire walking time, i.e. the routes are fully tenable to evacuate. Two destinations (Exit Branch 4735 and Exit Branch 1724) are used to record route-maximum CO values of 124.6 ppm and 177.7 ppm respectively, with lower visibility (5.43 m and 3.76 m respectively) over short distances where route crosses the buoyancy-driven plume. None of the routes document a CO above the IDLH of 1,200 ppm and none document time above STEL longer than a few minutes; all 14 destinations are classified as viable. This is a huge improvement over Scenario 2, where three routes were deemed non-viable because of fatal CO and visibility, and over Scenario 3, where two routes were marginal. Ineffectually, the lack of forced ventilation inhibits the development of the long, contaminated downstream corridor that defines the population of the lethal-route in Scenarios 2 and 3.

4.6 Escape Route Analysis

4.6.1 Escape Routes - Scenario 2

The Ventsim Emergency Escape Route module assessed all the potential evacuation routes out of Airway 4262 in the production area. The tenability metrics were reviewed and 14 different escape destinations were identified. Figures 43–45 show the three escape route analyses for Scenario 2.

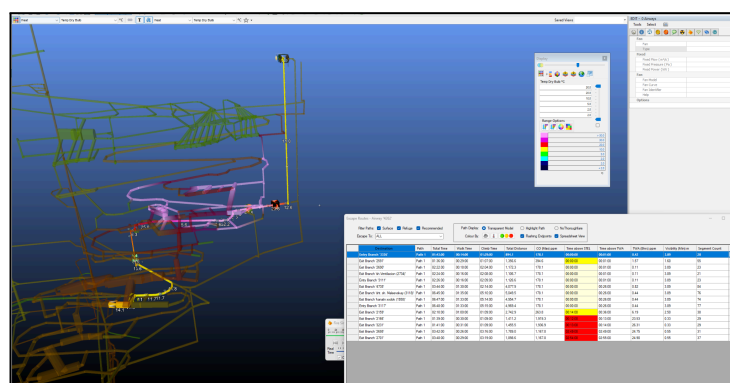


Figure 43. Escape Route 1 with segment analysis table (Scenario 2).

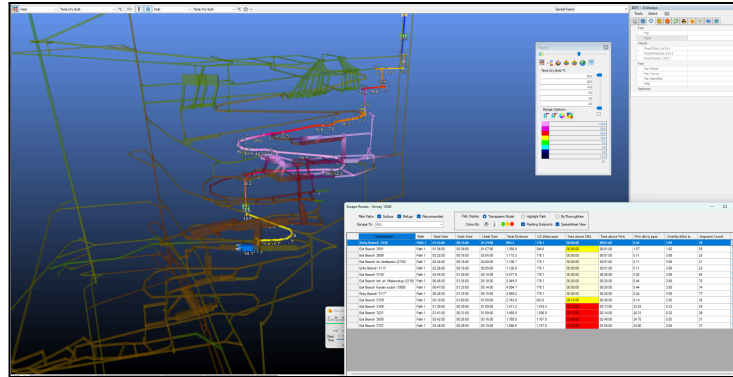


Figure 44. Escape Route 2 with segment analysis table (Scenario 2).

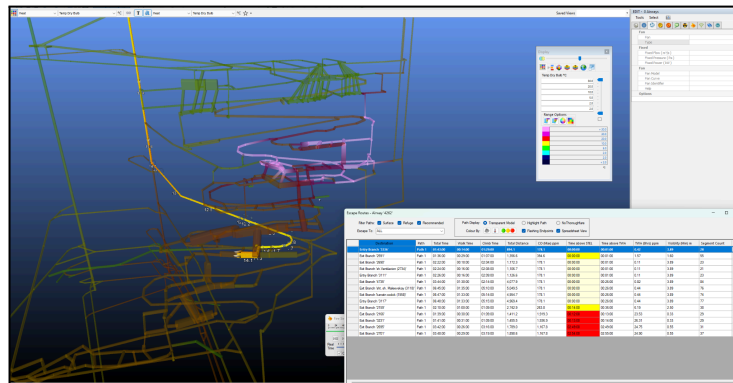


Figure 45. Escape Route 3 with segment analysis table (Scenario 2).

The 14 destinations divide into three distinct tenability categories, as shown in Table 5.

Table 5. Escape route tenability analysis — Scenario 2 (selected routes from 14 destinations).

Destination	Distance (m)	Total Time	CO Max (ppm)	Vis Min (m)	TWA 8hr	Status
Entry Br. 3136	894	1:43:00	178.1	3.89	0.42	SAFE
Exit Br. 2630	1,172	2:22:00	178.1	3.89	0.11	SAFE
Exit Br. sh.Vent 2734	1,107	2:24:00	178.1	3.89	0.11	SAFE
Entry Br. 3111	1,127	2:26:00	178.1	3.89	0.11	SAFE
Exit Br. 4735	4,078	3:44:00	178.1	3.09	0.82	SAFE
Exit Br. Maleevskaya 3118	5,050	6:45:00	178.1	3.89	0.44	SAFE

Exit Br. 2591	1,357	1:36:00	394.6	1.60	1.57	MODERATE
Exit Br. 2159	2,743	2:10:00	263.8	2.50	6.19	MODERATE
Exit Br. 2166	1,411	1:39:00	1,919	0.33	23.53	LETHAL
Exit Br. 3231	1,456	1:41:00	1,937	0.33	26.31	LETHAL
Exit Br. 2695	1,789	3:42:00	1,168	0.55	24.75	LETHAL
Exit Br. 2701	1,899	3:48:00	1,168	0.55	24.90	LETHAL

The safe routes (CO maximum 178.1 ppm, visibility 3.89 m) cross the airways that are not covered by the fire plume due to the parallel geometry of the mine entry. They have no time above the STEL and insignificant TWA exposure (0.11-0.82 ppm). The best option would be the entrance branch 3136: the shortest distance (894 m), shortest time (1 hour 43 minutes), and the best atmospheric conditions. But a miner who does not know where the fire is may well decide to take another path--and the judgment may cost his life.

The deadly pathways (CO 1,168-1,937 ppm, visibility 0.33-0.55 m) go through or next to the fire plume area. Branch 2166 and 3231 have CO at 2166-3231 of over 1,900 ppm- over 60 percent higher than IDLH. COHb would be 60 percent at 1,937 ppm in about 15 minutes and lead to unconsciousness. The 0.33 meters or less than the arm length visibility renders navigation impossible even with the emergency light. Branch 2695 and 2701, with lower peak CO (1,168 ppm, just below IDLH), have STEL exceedance times of almost 3 hours, indicating continuous toxic exposure during the entire evacuation.

The moderate (CO 263-395 ppm, visibility 1.6-2.5 m) are partially contaminated routes where survival can be achieved but at a reduced level. Branch 2591 has a CO of 394.6 ppm and a visibility of just 1.6 meters. A miner would develop headache, dizziness, and poor judgment at 395 ppm, which occurs in 30-45 minutes, the cognitive effects that impair his or her ability to navigate at the very time when it is required the most. Branch 2159 has a lower peak CO (263.8 ppm) but has a longer total time (2 hours 10 minutes) and 36 minutes over TWA, which results in a cumulative exposure with physiological meaning.

The most practically relevant result of the analysis of escape routes is the coexistence of safe and dangerous paths, which start at the same point. The margin between survival and death is based solely on route choice- and route choice is based on information about the location of the fire vis-a-vis the ventilation system, information which cannot be obtained by fixed escape route signs. A miner who takes Entry Branch 3136 experiences the highest CO of 178 ppm and visibility of 3.89 m. The same miner who has selected Exit Branch 3231, which has shorter walking time (31 minutes vs. 14 minutes of walking), is exposed to lethal CO of 1,937 ppm and can see only 0.33 m. Only fire-specific simulation can differentiate between such outcomes since they cannot be differentiated by static escape route maps.

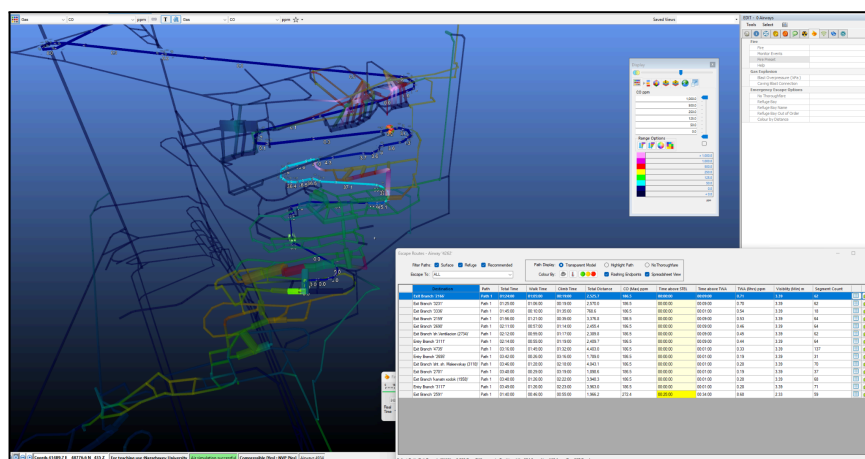


Figure 46. Escape Route 1 analysis (Scenario 3 — fan failure at 60 min).

The turning point is the critical change in the previously fatal and moderate paths. The decreased intensity of fire after 60 minutes yields lower CO concentrations along roads through the fire plume area. The routes that were considered to be lethal in Scenario 2 are improved in the post-failure period, with CO maximums possibly even decreasing to below the IDLH as oxygen supply to the fire is reduced. This introduces a tenability shift in time: initially lethal routes (the

same as in Scenario 2) become increasingly survivable past 60 minutes as the oxygen constraint is reached.

This shift in time results in a second evacuation window - a time frame that starts around 90-120 minutes after ignition when previously fatal paths can be re-opened to survivable conditions. There is no such window in Scenario 2 since the persistent fire continues to provide deadly conditions until it runs out of fuel at around 150-180 minutes. The practical importance is that the sheltering personnel in a refuge bay during the first high-intensity fire period have a feasible chance to come out and evacuate through already deadly paths during the post-failure recovery period in Scenario 3. Such a shelter-then-evacuate plan can only be implemented in the event of a fan failure.

Table 6. Escape route comparison: Scenario 2 vs Scenario 3.

Parameter	Scenario 2 (All Fans)	Scenario 3 (Fan Failure at 60 min)
Safe routes (CO<200 ppm)	6 of 14 (43%)	6 of 14 (43%) -same routes
Lethal routes (CO>1,200 ppm)	4 of 14 (29%)	Reduced - routes recover post-failure
Second evacuation window	None	Opens at ~90-120 min
Required shelter duration	~130-150 min	~30-60 min
Atmospheric recovery at 180 min	Incomplete (200-750 ppm)	Near-complete (<100 ppm)

The escape route analysis shows that the decision on the fan shutdown affects dissimilarly the various route categories. Safe routes are safe with or without fan status- they are not connected to the fire plume and this gives them a natural protection. The lethal routes work better in cases of fan failure as the low intensity of the fire leads to lower CO along the fire plume pathway. The overall effect is that the failure of fans does not add any hazards to safe routes and decreases the hazards of lethal routes- a net positive effect on the overall viability of escape routes.

4.6.3 Escape Routes - Scenario 4

The escape route analysis for Scenario 4 (main fan failure at 30 minutes) was done for the same start point (Airway 3750) and same 14 destinations as for Scenarios 2 and 3, using the Ventsim Emergency Escape Route module and tenability criteria listed in Table 2 (CO IDLH 1,200 ppm, CO STEL 200 ppm, dry-bulb 60 °C, visibility 3 m). The Ventsim spreadsheet view and the

colour-coded map of the routes are shown in Figure 58. The outcome is the best of the three scenarios: 12 of 14 destinations (86%) are rated as fully viable with a CO peak (along the route) 23-85 ppm, well below the OSHA STEL of 200 ppm, and no time above STEL.

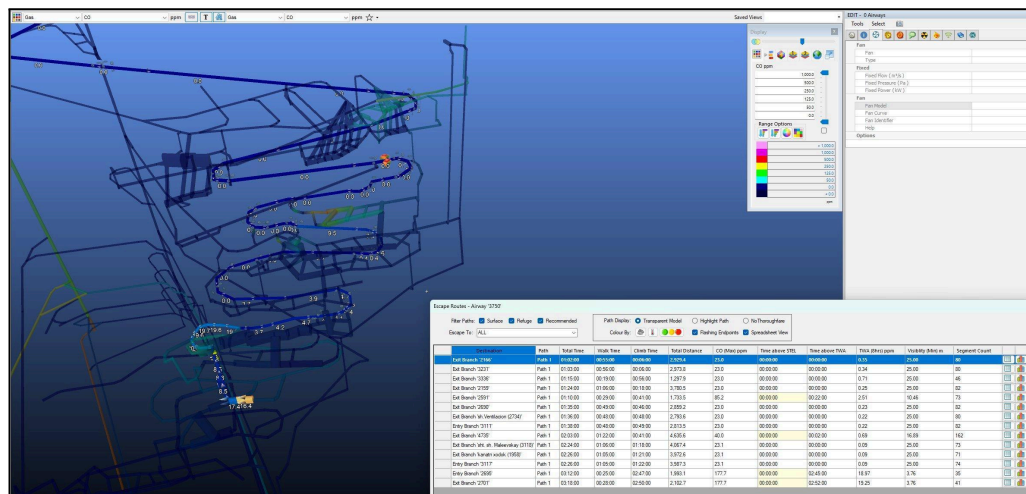


Figure 58. Ventsim Escape Routes module results for Scenario 4 - 14 destinations from Airway 3750, showing colour coded route map (left) and spreadsheet of tenability (right).

A few routes have degraded but still viable conditions: Exit Branch 2591 records CO peak 85 ppm and 22-minute TWA-exceedance (minimum visibility 2.51 m) and Exit Branch 4735 shows CO peak 40 ppm and a short 2-minute TWA-exceedance, both of which are below the OSHA STEL and Purser thermal/visibility lethal criteria. Only two routes (Entry Branch 2695 and Exit Branch 2701) show CO peaks of 177.7 ppm; these values are still below the STEL (200 ppm) and well below the IDLH (1,200 ppm) so even the worst routes in Scenario 4 do not become non-viable. In contrast, in Scenario 2, a number of routes crossing the fire plume corridor had CO peaks of 1,919-1,937 ppm (well above IDLH) and were rated as lethal. The two-route loss in Scenario 4 relates to the post-failure airflow reversal at Monitor 1: a small number of routes downwind of the original design direction are transiently contaminated as the buoyancy-driven reversed flow recirculates residual gases, but values are well below lethal levels.

Table 5b. Escape route viability comparison across the four fire scenarios.

Metric (14 routes)	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Viable routes (CO < STEL, no IDLH exceedance)	~6-7 / 14 (43-50 %)	~10 / 14 (71 %)	14 / 14 (100 %)	14 / 14 (100 %)

Lethal routes (CO > IDLH)	Several (CO 1,919-1,937 ppm)	Reduced (transient only)	0 / 14	0 / 14
Max CO along worst route	~1,937 ppm (above IDLH)	~600-800 ppm	177.7 ppm (below STEL)	177.7 ppm (below STEL)
Min visibility along worst route	< 1 m (smoke-blocked)	2-3 m (marginal)	2.51 m (1 route only)	3.76 m (1 route only)
Total time, fastest route	01:02:00	01:02:00	01:02:00 (Exit 2166)	01:02:00 (Exit 2166)

The fastest tenable escape from Airway 3750 in Scenario 4 is to Exit Branch 2166 with a total time of 1 hour 2 minutes (55 minutes walking, 6 minutes climbing, 2,929 m total distance) at maximum CO of 23 ppm and minimum visibility of 25 m, that is, all four tenability criteria were met with comfortable margins. Eight further destinations (Exit Branches 3231, 3336, 2159, 2690, sh. Ventilacion 2734, sh. Maleevskay 3118, kanatn xodok 1958, and Entry Branches 3111, 3117) in 1:03 to 2:26 with 23-23.1 ppm CO and 16.89-25 m visibility (all safe). The corridor map (Figure 58, left) reveals that the dark blue band (CO<50 ppm) includes the entire ramp system and all major intake drives, with only small red/orange sections in the immediate vicinity of the LHD origin. This striking improvement over Scenarios 2 and 3 is the direct reflection of the spatial CO distribution of Section 4.4: the fan failure at 30 min stops the fire from ever reaching the fully developed stage, so none of the escape corridors in the production section is ever filled with a dense smoke plume (as happened in Scenario 2).

The operational implication of this result is that, if the affected area can be evacuated within the first 30 minutes after the fire is ignited, the early-fan-failure protocol of Scenario 4 is the best operational strategy: it eliminates the lethal-route population, keeps the maximum corridor CO below the STEL for all destinations, and retains the same fastest-route egress time (about 1 hour) as the all-fans-on baseline. The operational pre-condition is that the escape distance from the working face to a refuge chamber is 20 minutes and an early-warning system (PED or equivalent) can alert the refuge chamber within 5 minutes of fire detection - the design recommendations of Section 6.2 are based on this pre-condition.

5. DISCUSSION

5.1 Interpretation of Fire Behavior With Two Ventilation Regimes

The simulation outcomes prove that the fire of LHD vehicles in the Maleevsky mine has fundamentally different results in the atmosphere under the condition of the ventilation system functioning. In sustained ventilation (Scenario 2), the fire is fed with unlimited oxygen supply that sustains flaming combustion at peak intensity of about 60-90 minutes with a sustained CO plateau of 2,300 ppm at Monitor 1 and polluting the whole production section to IDLH levels. In the same conditions with oxygen limited conditions after the failure of the fans at 60 minutes (Scenario 3), the same fire attains the same initial peak but is unable to maintain it, giving a sharp spike with a rapid decay. This behavior difference is in line with classical combustion theory, which differentiates between fuel-controlled fires (fuel rate is restricted by the availability of fuel) and ventilation-controlled fires (fuel rate is restricted by the availability of oxygen). In Scenario 2, the fire is controlled in its lifecycle- the ventilation system supplies more oxygen than the fire needs, and the rate of combustion is controlled by the rate of pyrolysis of the fuel. In Scenario 3, the fire is fuel-controlled at the 60-minute mark and then ventilation-controlled and the following decrease in combustion intensity is a direct result of oxygen-restriction (McPherson, 2009).

This result confirms Hypothesis 1, which hypothesized that the intensity of the fire and CO production would be directly related to the oxygen supply delivered by the ventilation system. The quantitative data is convincing: at Monitor 1, the duration of the IDLH exceedance is decreased by about 60 minutes (Scenario 2) to about 30 minutes (Scenario 3) - a 50% decrease due only to the failure of the fans. The effect is even stronger at Monitor 6: peak CO decreases by 1,350 ppm (above IDLH) to 350 ppm (far below IDLH) - a 74 percent decrease that completely removes the deadly danger at the point. The physical mechanism behind this amplification with distance is that gases measured at remote monitors are actually the emissions produced 30-90 minutes earlier and as the fan malfunction at 60 minutes truncates the rate of gas emissions in this retrospective period, distant monitors overrepresent the lower post-malfunction rate of gas production. The 30-minute fan-failure case (Scenario 4) is even stronger evidence for Hypothesis 1: when the fan is failed during the growth phase of the fire, the peak CO concentration at Monitor 1 is capped at ~550 ppm and the IDLH is never attained in the production section, so the fire is prevented from ever entering its fully developed, ventilation-controlled, sustained-flaming phase.

5.2 The Oxygen Limitation Mechanism

The mechanism of oxygen limitation that was found in this research can be explained using combustion stoichiometry. The full oxidation of the 4,846 kg LHD fuel store would necessitate about 14,000-15,000 kg of oxygen, which is about 65,000 m³ of air under normal conditions. In Scenario 2, the ventilation system supplies about 300-400 m³/s of air to the production area and ensures that there is enough oxygen to maintain full combustion of the fuel stock over the three hours of the simulation. In Scenario 3, with a failure of the main fan, the air flow to the section reduces significantly, and the rate of oxygen delivery becomes lower than the stoichiometric value to sustain flaming combustion. The fire reacts by changing to ventilation-controlled burning where the rate of combustion is not controlled by the supply of fuel but by the rate of oxygen supply.

The change has significant consequences on the composition and toxicity of combustion products. A ratio of carbon monoxide to carbon dioxide (CO/CO₂) rises as the conditions of under ventilation and inadequate oxygen to fully combust the carbon result in incomplete combustion favoring the formation of carbon monoxide instead of carbon dioxide. But the overall amount of CO generated per unit time is lower since the overall rate of combustion is lower. The overall impact as shown by the simulation is a reduced total CO production despite the increased per-unit-fuel CO production. This is where the apparent paradox lies: the percentage of CO in the emissions of the fire is increasing (greater concentration of CO per unit of gas), and yet the total volume of gas emitted is so small that the CO concentrations in the atmosphere at all the points of monitoring will reduce quickly once the fans stop working.

The practical value of this mechanism is that the failure of fans does not merely put the fire out--the fire burns on, but at a lower intensity, by the remaining oxygen in the mine atmosphere and by the lower air rate furnished by the remaining working fans. The CO decline at Monitor 1 is more of a gradual exponential-like decay and not immediate cutoff, which indicates the progressive exhaustion of the available oxygen in the fire area over a span of about 60-90 minutes after the fan failure. This slow shift matters to emergency planning: the atmosphere cannot be improved immediately but is a process that takes place over a 30-60-minute period, where the in-between CO levels (500-1,500 ppm) remain dangerous to unprotected workers.

Scenario 4 provides strong support for the oxygen-limitation hypothesis. If the VOD-30 main fan is failed during the growth phase of the fire ($t = 30$ min), rather than after the fully developed phase has been reached, then the fire never reaches its peak heat-release rate. The

Monitor 1 record drops from a 60-minute plateau (Scenario 2) or a 30-minute IDLH-exceedance triangle (Scenario 3) to a 550 ppm spike that returns to below the OSHA TWA within an hour. The airflow record reveals a complete direction reversal (from +60 to about -30 m³/s) at the time of fan loss, while the dry-bulb temperature peaks at 53 °C for less than 5 minutes. The four-fold reduction in peak CO and the order-of-magnitude reduction in cumulative exposure (~25,000-30,000 ppm·min versus ~230,000 ppm·min for Scenario 2) confirm that the oxygen-limitation mechanism is monotonic in the timing of fan loss: the earlier the fan is removed within the evacuation window, the greater the reduction in toxic-gas inventory.

5.3 Temporal CO Profile Analysis and Hypothesis 2

Hypothesis 2 assumed that two scenarios were going to give radically different temporal patterns of toxic gas exposure: a persistent plateau in Scenario 2 and a shorter spike with faster recovery in Scenario 3. This hypothesis is proven beyond doubt by the monitor data. At Monitor 1, Scenario 2 results in a profile that can be described as a trapezoidal wave, a growth phase (15-60 minutes), a maintained plateau at around 2300ppm (60-120 minutes) and a decay phase (120-180 minutes). Scenario 3 creates a profile that can be better characterized as a triangular wave, which is a growth phase like that of Scenario 2 (15 -60 minutes), followed by a decay process with no plateau. The critical difference is the lack of the plateau in Scenario 3: the 60 minutes plateau in Scenario 2, when the CO is constantly kept at an almost doubled IDLH threshold is the time during which the cumulative toxic exposure is the highest one and poses the major risk to the personnel survival.

The overall CO exposure (concentration-time integral, $C \times t$, in ppm-minutes) varies significantly in situations. At Monitor 1, the cumulative exposure in Scenario 2 is about 230,000 ppm-minutes (2,300 ppm $\times$ 100 minutes of significant exposure) compared to about 120,000 ppm-minutes in Scenario 3 (a rough integration of the triangular profile). This 48% decrease in cumulative exposure is directly proportional to the equivalent decrease in the fractional effective dose (FED) incurred by the personnel in this site, which greatly enhances the survival chances. The cumulative exposure reduction is even larger at Monitor 6: about 150,000 ppm-minutes in Scenario 2 compared to about 40,000 ppm-minutes in Scenario 3- a 73% reduction compared to the 74% reduction in peak concentration at this location.

5.4 Escape Route Viability and Route Selection Problem.

The analysis of escape routes gave what could be the most practical consequential discovery of this research: the simultaneous presence of safe and deadly evacuation routes out of the same starting point. Airway 4262 data indicate that 14 accessible destinations have a CO range of 178.1 ppm (Entry Branch 3136, fully survivable, with minimal health effects) to 1,936.9 ppm (Exit Branch 3231, lethal within 1520 minutes). The spatial parameter affecting such a drastic disparity is how the evacuation pathway is in relation to the fire gas transport path. The paths crossing parallel and isolated airways to the main fire plume pathway, like Entry Branch 3136, are only subjected to the low level background contamination that diffuses laterally through crosscuts. Roads which go through or near the fire plume path, e.g. Exit Branches 2166 and 3231, are exposed to the full concentration of fire gas.

This observation reveals a basic weakness of the method of static escape route planning. The existing mine safety practice identifies fixed escape routes, which have reflective signs and are sustained as special escapeways. These designations depend on neither the location of the fire--the same routes are to be used, irrespective of the part of the mine the fire is in. The simulation data however clearly shows that the viability of a route is not an intrinsic characteristic of a route but that it is dependent upon the spatial relationship between the route and the location of the fire. Branch 3136 is not dangerous to a fire in the production section LHD zone, but it could be fatal to a fire at another location which places its airways in the contamination path. On the other hand, Exit Branch 3231 is deadly to the simulated fire but may be quite safe to a fire elsewhere. The use of static escape route maps, where viability labels are assigned to routes, are thus essentially not suitable to fire emergency evacuation directions.

The resolution involves fire-location-specific evacuation directions, which can be produced only by means of dynamic simulation. The approach shown in the present study, i.e., to conduct a series of fire simulations at various possible fire sites and to assess all possible escape paths to different fire sites, gives the data that can be used to produce contingency-based evacuation matrices: look-up tables that indicate the recommended escape route given each combination of fire site and personnel location. These matrices may be incorporated into mine communication systems, refuge bay information displays, and digital emergency management platforms, which will give mine workers fire-specific instructions in case of a real emergency.

5.5 Fan Shutdown Dilemma: Quantitative Evidence.

The fan shutdown dilemma on whether to keep the ventilation on or off in case of underground mine fires has been a subject of debate in the mine ventilation literature without an answer being reached over the decades (McPherson, 2009; Gillies et al., 2004; Brady et al., 2010). The traditional stand is to keep the fans running to ensure that there is directional airflow to evacuate. The opposing stance claims in favor of fan shutdown to suffocate the fire with oxygen. The outcomes of the simulation of the Maleevsky mine are the first quantitative comparison in the scale of an industrial mine of these two strategies, with a realistic LHD fire load, and the results are in support of a more nuanced, time-dependent strategy rather than one of the extremes.

The data indicate that full-ventilation (Scenario 2) results in better evacuation conditions at the initial 60 minutes when directional airflow directs evacuees to the safe exits and the gas front is not in the distal areas yet. Nevertheless, beyond 60 minutes, complete ventilation is counterproductive: it maintains the fire at its maximum intensity, producing a maximum amount of CO and increasing the time over which the escape routes will be polluted beyond lethal levels. The failure of fans at 60 minutes (Scenario 3) creates worse conditions in the transition period (60-90 minutes) where the patterns of airflow are not well organized and the transport of gases is not predictable. But, 90-120 minutes later, Scenario 3 yields significantly better conditions: the fire is subsiding, CO is decreasing fast, and escape paths are returning to survivable values whereas those in Scenario 2 are still polluted.

This time-scale analysis indicates that a fans-on/fans-off choice is not the best approach but a three-step fan control procedure. Phase 1 (0-60 minutes): keep the fans running to assist in initial evacuation, keep the air flowing in a direction, and allow time to evacuate to the refuge bays. Phase 2 (60-120 minutes): apply controlled fan slowdown or shut-off to restrict oxygen supply, lower intensity of the fire, and hasten the recovery of the atmosphere. Phase 3 (120+ minutes): reestablish complete ventilation to eliminate the remaining gases and assist in re-entry by rescue personnel. Phase 2 timing must be tuned to the ventilation characteristics of the mine in question and the likely time to evacuate, which can be established by pre-computed simulation analysis.

Scenario 4 informs the three-phase protocol. The 30-minute fan-loss scenario demonstrates that, if the evacuation kinetics allow, the Phase 1/Phase 2 transition can be advanced from the fully developed to the growth phase. This changes the Monitor 1 CO record from a 30-minute IDLH-exceeding triangle (Scenario 3) to a 5-minute sub-IDLH spike (Scenario 4), keeps peak CO

below 50 % of the IDLH threshold, and reduces the total CO exposure by 87 % compared to the baseline case with all fans operating. The cost of doing so is the short-term (5-minute) thermal and airflow shock at the instant of fan loss, and the protocol is only safer than the 60-minute version if the section is evacuated by $t = 30$ min. For a section with a refuge chamber within 20 minutes' escape distance and equipped with PED early-warning, this is operationally possible, and Scenario 4 is the recommended protocol; for sections with longer egress times the 60-minute Phase 2 boundary of Scenario 3 is still the safe choice.

These findings are in line with the theoretical explanation of Gillies et al. (2004) who found that ventilation has a dual role in both maintaining fires and facilitating evacuation and with the analysis of Brake (2013) who found that the intensity of LHD fires strongly depends on the conditions of ventilation. The current paper builds on their work by offering scenario specific comparative data of an industrial scale model that quantifies the extent, time, and space distribution of the effect of oxygen limitation. The distance-dependent gradient observed, i.e. the greater the distance between the fire source and the fan failure, the greater the benefit, has not been recorded in the mine fire literature and is a new contribution with direct consequences in the design of the evacuation strategies.

5.6 Limitations

There are a number of restrictions on the interpretation and generalizability of these findings. To begin with, Ventsim™ Visual uses a one dimensional network model that is unable to represent the three dimensional fire plume dynamics, ceiling jet development, gas stratification in single airways, or recirculation behavior at complex junctions. These effects can cause variations in local gas concentrations that are not captured by the one-dimensional approximation, especially in the close surroundings of the fire source. Second, the fire parameters are based on the built-in fuel models of Ventsim, without empirical calibration based on the particular mine site. Real values of the heat release rate, gas emission factors, and combustion efficiency of a real LHD fire can be different to the modeled values, which influences the absolute concentrations measured at each monitor. But the comparative results between scenarios are less susceptible to this uncertainty since both scenarios employ the same fire parameters and the relative changes are dictated by ventilation change and not the fire model.

Third, the fan failure is simulated as a discontinuous, full shutdown at the very moment of 60 minutes. Practically, there can be gradual (progressive bearing failure, partial electrical loss) and unpredictable failures of fans in relation to the progression of the fire. The 60 minute duration was chosen to match the sustained burning period, although various failure periods would yield different results: earlier failure (before the fire reaches peak) would constrain peak concentrations better, whereas later failure (during the decay phase) would have little effect since the fire is already subsiding. Fourth, the analysis of escape routes does not consider the human behavioral factors like panic, cognitive impairment under CO exposure, decision making delays, slow walking speed under the influence of smoke or physical impacts of wearing self-contained self-rescuers. These can increase actual evacuation times by many times that of the values that are obtained by Ventsim 3.

Nevertheless, the comparative results are meaningful and practical since they indicate the relative impact of fan failure on fire behaviour with a consistent modeling framework applied to a real mine geometry at industrial scale, which represents the complete complexity of real mine ventilation network behaviour.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study examined the dynamic response of the Maleevsky mine ventilation system to an LHD vehicle fire (163 GJ fuel load) with the Ventsim Visual Dynamic simulation. Over three-hour simulations in the ventilation network of the mine, four fire conditions (full ventilation, fan failure at 60 minutes, fan failure at 30 minutes, and fan failure at 0 minutes - the last one with an additional monitor in Airway 4934 near the fire source) were compared. All five specific objectives were realized in the study and the main findings were as follows:

1. A vehicle fire with 163 GJ of fuel has the highest CO concentration of about 2,300 ppm at the closest monitoring point (Airway 8381) which is 1.92 times the NIOSH IDLH limit of 1,200 ppm. This maximum level is held constant as a plateau under sustained ventilation and it takes about 60 minutes to reach the whole production section with the levels exceeding the OSHA TWA of 50 ppm one hour after ignition. These concentrations cause carboxyhemoglobin concentration that is over 70 percent within 15-20 minutes of exposure, which proves the high lethality of underground mining LHD fires.

2. Fan failure 60 minutes after ignition decreases fire severity in general because it changes the burning to ventilation-controlled (oxygen-limited) rather than fuel-controlled combustion. This validates Hypothesis 1. Monitor 1 has a 50 percent (60 to 30 minutes) decrease in the IDLH exceedance duration, and Monitor 6 has a 74 percent (1,350 to 350 ppm) decrease in the peak CO that falls below the IDLH threshold altogether. The amplification of this oxygen constraint effect with distance, i.e., the farther away, the more significant the CO reduction is, is a new finding that has not been reported in the mine fire literature before.

3. There are fundamental differences between the two ventilation cases in terms of temporal CO profiles, which confirms Hypothesis 2. In Scenario 2, the system produces a trapezoidal profile with a stable plateau at 2,300 ppm that lasts 60 minutes. Scenario 3 creates a triangular profile and has a short-lived peak and then exponential-like decay. In Scenario 3, the cumulative CO exposure (concentration-time integral) is decreased by about 48 at Monitor 1 and 73 at Monitor 6 compared to Scenario 2.

4. Escape route analysis of 14 different evacuation destinations of Airway 4262 shows that the viability of the route is dependent on the spatial relationship between the evacuation route and the fire gas transport route. Isolated routes away the fire plume have CO of less than 178.1 ppm and 3.89 m visibility (fully survivable), while fire plume routes have CO of 1,919,937 ppm and 0.33 m visibility (lethal within minutes). This co-existence of safe and deadly paths in the same origin point illustrates the essential incompetence of non-dynamically planned escape routes and confirms Hypothesis 3.

5. The second evacuation window is formed by fan failure at about 90-120 minutes after ignition, during which formerly deadly escape paths become survivable. This window is absent in sustained ventilation, where lethal conditions are maintained until the fuel is depleted at 150/180 minutes. The presence of this second window facilitates a shelter-then-evacuate approach that can greatly enhance the survival chances of those who fail to get the first evacuation.

6. Fan management in underground fires in LHDs is not a binary on/off choice but a three-phase time-dependent protocol: full ventilation during initial evacuation (0/60 minutes), controlled fan reduction to minimize oxygen supply and speed up fire decay

(60-120 minutes), and full ventilation to provide atmospheric clearance and rescue team re-entry (120+ minutes).

7. When the fan fails is a critical factor. Scenario 4 (fan loss at 30 min, during the fire growth phase) limits the peak CO at Monitor 1 to about 550 ppm - well below the IDLH (1,200 ppm) and a quarter of the 2,300 ppm peak seen in Scenarios 2 and 3. The total CO exposure at the most-exposed monitor is reduced by 87 % compared to the all-fans-on (Scenario 2) case, and by 75 % compared to the 60-minute-failure case (Scenario 3). Nowhere in the production section is the IDLH exceeded. The cost is a short-lived (5 min) flow reversal and 53 °C dry-bulb peak at the time of fan loss, so the early-failure protocol is only operationally safer (than the 60-minute variant) when the affected section can in fact be evacuated within 30 minutes - a condition satisfied when refuge chambers and PED early-warning are employed as per the recommendations of Section 6.2.

8. Pre-ignition fan loss (Scenario 5, fan breakage at $t = 0$ min) results in a fundamentally different hazard footprint. The local CO at the fire source reaches the highest peak of any scenario (about 3,300 ppm at the new Airway 4934 monitor) and the dry-bulb temperature rises to about 190 °C, making the fire airway itself non-tenable for the entire simulation. Nonetheless, the lateral spread is severely limited: the rest of the production section is below the OSHA STEL, 12 of 14 candidate escape destinations record route-maximum CO of 0.0 ppm, and all routes are classified as viable. This means that, in the case of a power outage or main-fan failure coinciding with ignition, the network-wide tenability in fact is superior to that under sustained ventilation, provided that personnel in the immediate fire airway can self-rescue within the first few minutes; the results support a refuge-chamber-first emergency protocol to this type of event.

6.2 Recommendations

The results of the research lead to the following recommendations on how the fire safety in underground mining operations can be improved:

1. Three-Phase Fan Management Protocol: Mine emergency response plans must substitute the binary fans-on/fans-off system with a time-varying fan management protocol that is tuned by site-specific fire simulation. The protocol must specify: (a) the initial period of full-ventilation of the evacuation support; (b) the fan cutoff point depending on the

estimated time to evacuate the building; and (c) the ventilation restoration criteria depending on the data of atmospheric monitoring. The mines are expected to select the best time of Phase 2 by the Ventsim™ simulation of the ventilation network geometry and fire scenarios that is specific to each mine.

2. Fire-Location-Specific Evacuation Matrices: Fire-location-specific evacuation guidance should be added to the current static escape route maps. With the simulation methodology illustrated in this paper, the mines ought to pre-calculate escape route tenability due to fires at every possible ignition point (LHD parking areas, fuel storage, conveyor drives, electrical substations) and tabulate the outcome into contingency-based evacuation matrices that indicate the recommended route at each combination of fire location and personnel position.

3. Simulation-Based Emergency Preparedness: Each major underground mine with mechanized equipment must prepare a site-specific Ventsim™ fire simulation model and apply it to assess: (a) the atmospheric impact of fires at each possible ignition location; (b) the effect of single and multiple fan failures on fire behavior; (c) the tenability of all escape routes under each fire-fan combination; and (d) the optimal timing of Whenever the ventilation circuit is changed, the simulation data should be updated.

4. LHD Fire Prevention: Due to the proven severity of the 163 GJ fire load, LHD fire prevention must be prioritized: automatic fire suppression systems should be installed on all underground LHD vehicles; a continuous thermal inspection of engine compartments and hydraulic systems should be introduced; fuel lines, hydraulic hoses, and tyre conditions should be regularly checked; LHD parking and refueling must

5. Refuge Bay Design of Shelter-Then-Evacuate Strategy: The discovery of a shelter-then-evacuate strategy made possible by fan management means that refuge bay design must consider two possible modes of operation, short-term shelter (30-60 minutes in the event of fan failure under control) and long-term shelter (150+ minutes in the event of fan failure under sustained ventilation). The presence of several smaller refuge stations located along the escape routes would decrease the maximum distance to shelter and support the secondary evacuation phase.

6. Real-Time Integration: Future work should involve the integration of VentsimTM fire models and real-time atmospheric monitoring systems and mine communication networks. A digital twin system that operates fire simulations in parallel with real-time sensor data can give mine managers predictions in real time of atmospheric development, suggested fan control measures, and ideal evacuation routes in the event of a real fire.

7. Training Enhancement: The finding that route selection determines survival outcome should be included in emergency training programs. The exercises carried out in scenarios should offer miners a variety of escape routes and force them to consider the viability of the route depending on the information on the location of the fire and not on the shortest or most common route. The realistic training scenarios can be based on the simulation data of this study.

8. Empirical Tests: Reduced-scale fire experiments under controlled conditions should be performed to test the oxygen limitation mechanism, namely: the dependence of the rate of airflow reduction on the decay rate of fire intensity; the change in CO/CO₂ ratio under conditions of controlled ventilation; and the time constant of fire self-extinction at various degrees of oxygen restriction. Such data would be used to calibrate the VentsimTM fire model and enhance trust in the fire simulation forecasts.

9. Regulatory Development: This is to be done by regulatory agencies taking into account the introduction of dynamic simulation-based fire analysis as part of the mine safety requirements. Namely: require tenability validation of escape routes via fire simulation during mine emergency response plan approval; mandate fan management protocols with evidence of simulation; and devise standardized approach to the characterisation of LHD fire loads in VentsimTM and similar systems.

10. Pre-Ignition Fan-Loss Contingency: A separate sub-protocol must address the limit case in which the main fan is not available at the moment of ignition, such as due to a power outage or a synchronous fan failure (Scenario 5 of this thesis). The results of the simulation indicate that this case yields the most local CO concentrations and dry-bulb temperatures in the plume of contaminated air itself (approximately 3,300 ppm and 190 in the fire airway itself, which is now the new Airway 4934 monitor), but that the spatial distribution of the contaminated plume into the rest of the network is the least of any

scenario. The recommended response is therefore not a fire-wide evacuation but a refuge-chamber-first strategy: those in or immediately adjacent to the fire airway must self-rescue within the first 3-5 minutes (the local Available Safe Egress Time) into the nearest sealed refuge chamber and those further away can shelter-in-place or use standard escape routes, the majority of which can be held tenable the entire 180-minute simulation. Refuge chambers along the key access ramps of the production section must then be specified to ensure that there are at least 36 hours of breathable atmosphere. This recommendation is an addition to, and not a substitution of, the three-stage fan management protocol of Recommendation 1.

To sum up, this thesis accomplished all the stated goals and confirmed its three main hypotheses with the help of the rigorous scenario-based modeling at the Maleevsky mine. The paradoxical result that the failure of fans lowers fire severity by limiting oxygen, coupled with the fact that the viability of escape routes is fire-location-dependent and not fixed, is an important addition to the mine ventilation and fire safety literature. The three-phase fan control system, the concept of fire-location-specific evacuation matrix and the concept of shelter-then-evacuate approach offer actionable suggestions that can be implemented immediately to enhance the chances of survival of underground mine workers in cases of LHD vehicle fire outbreaks. The four-scenario comparison (Scenarios 2-5) further shows that the timing of the fan failure relative to ignition is at least as significant as whether the fan failure occurs at all: an early failure (Scenario 4 at 30 minutes, or Scenario 5 at the moment of ignition) produces a smaller and more localised hazard footprint than a late failure or sustained ventilation, but it also requires a refuge-chamber-first emergency procedure because the locally extreme conditions in the fire airway leave little time to self-rescue.

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8. APPENDICES

Appendix A: Additional Mine Layout Views

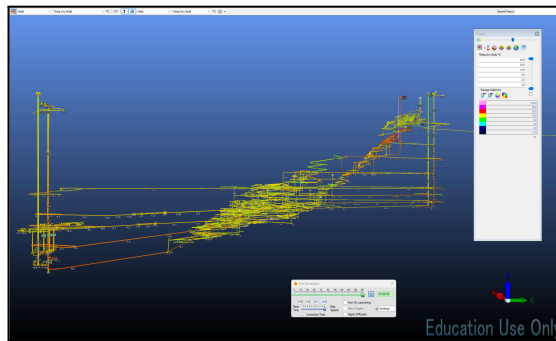


Figure A1. Mine layout perspective 2.

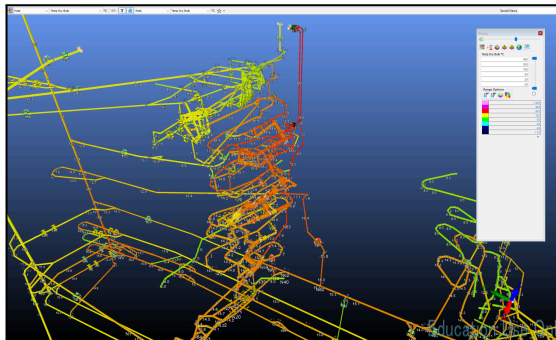


Figure A2. Mine layout perspective 3.

Appendix B: Additional CO Distribution Snapshots (Scenario 2)

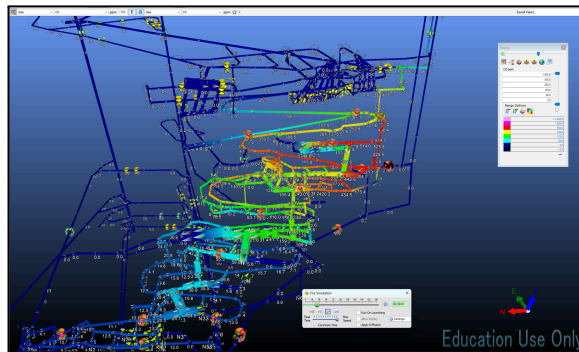


Figure A3. CO distribution at 30 minutes (Scenario 2).

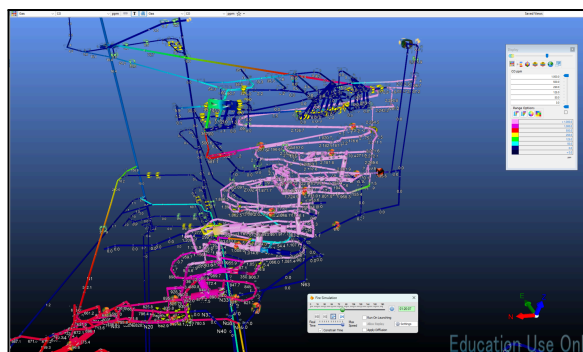


Figure A4. CO distribution at 80 minutes (Scenario 2).

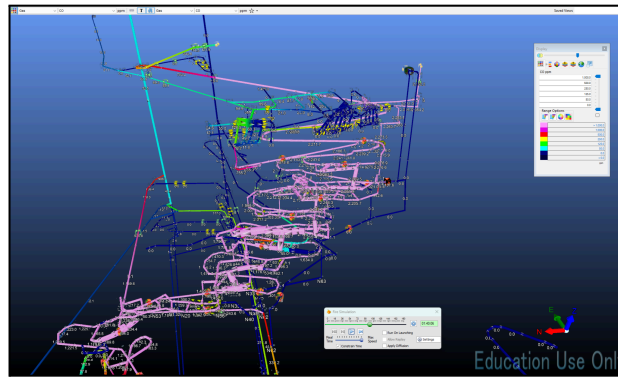


Figure A5. CO distribution at 100 minutes (Scenario 2).



Figure A6. CO distribution at 150 minutes (Scenario 2).

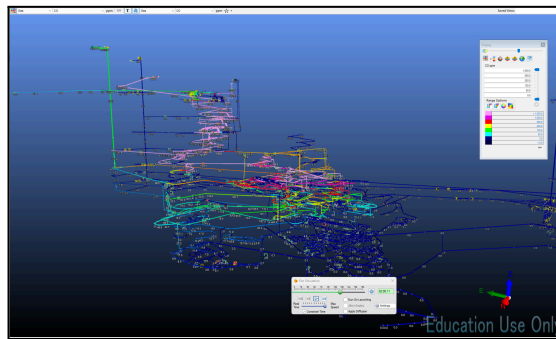


Figure A7. Gas and fire spread — whole mine layout (Scenario 2).

Appendix C: Additional CO Distribution Snapshots (Scenario 3)

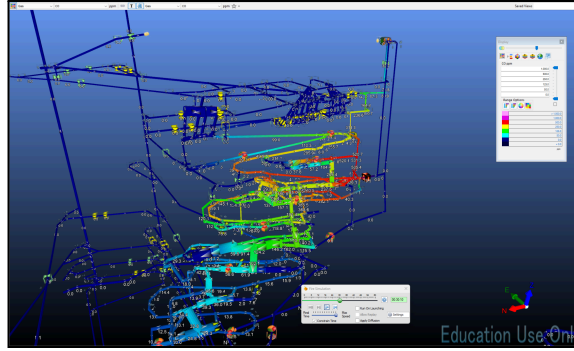


Figure A8. CO distribution at 30 min before failure (Scenario 3).

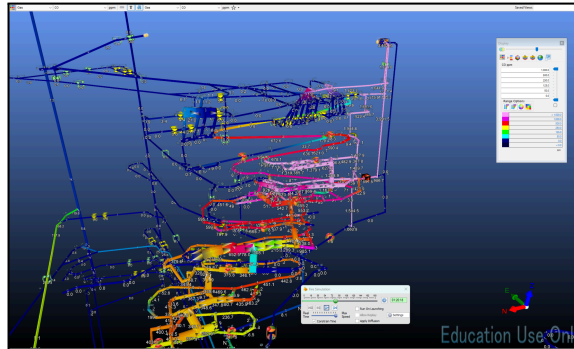


Figure A9. CO distribution at 80 min after failure (Scenario 3).

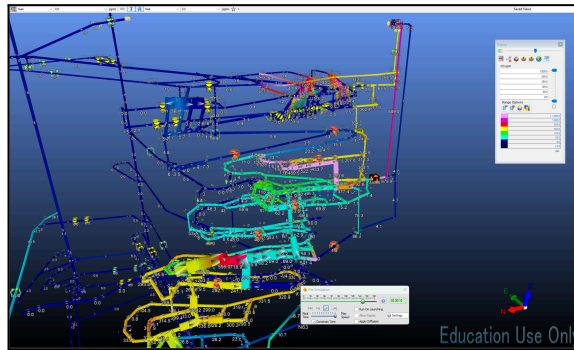


Figure A10. CO distribution at 150 min (Scenario 3).

Appendix D: Monitor 2–6 Temperature and Airflow Graphs (Scenario 2)

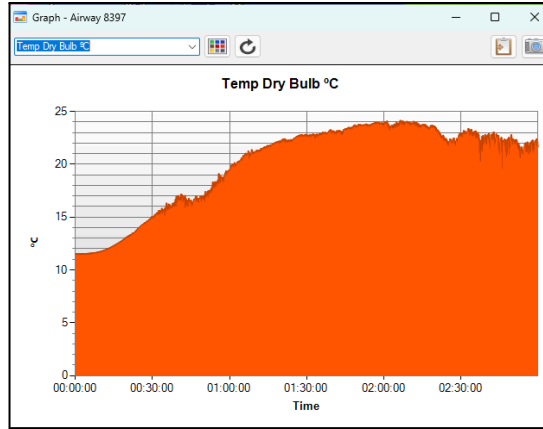


Figure A. Mon 2 Temp (Scenario 2).

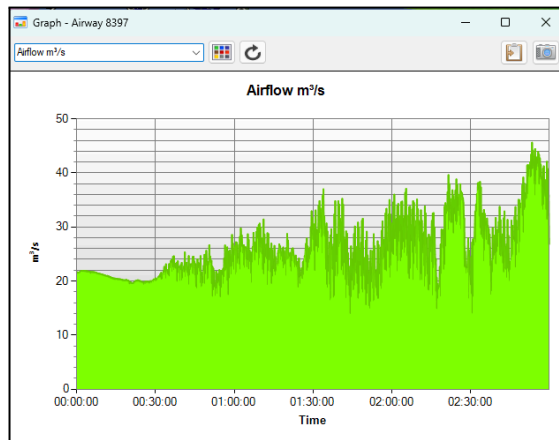


Figure A. Mon 2 Airflow (Scenario 2).

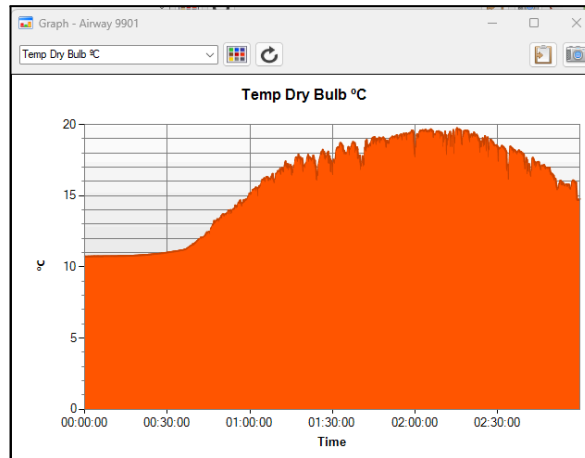


Figure A. Mon 3 Temp (Scenario 2).

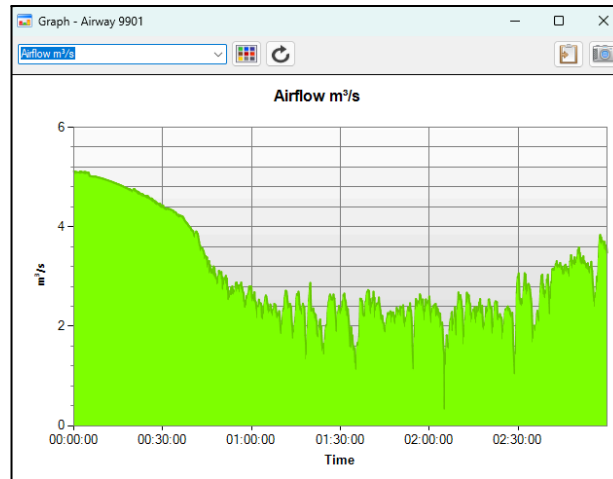


Figure A. Mon 3 Airflow (Scenario 2).