



Simulating underground mine fires for emergency planning

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ABSTRACT

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The mining industry plays a vital role in the economy of South Africa, and continued growth depends on maintaining safe working conditions. Fires in underground mines are considered one of the most serious hazards as they pose a risk to lives and disrupt operations. The complexity of underground ventilation systems complicates fire management. Contaminants such as carbon monoxide can spread rapidly throughout the ventilation network, reaching distant areas and endangering worker safety. Effective planning and fire mitigation strategies are essential for maintaining safe working conditions and minimising incident impacts.

The existing literature mainly focuses on the localised effects of fires in mine ventilation systems but offers limited insight into the spread of fire-related contaminants throughout the ventilation network. There is also a lack of detailed assessments of indirect ventilation control strategies, such as pressure control and airflow partitioning, which can mitigate the effects of fires across interconnected mine areas.

This study developed a method to identify and evaluate ventilation control strategies to mitigate the effects of fire in underground mines. A risk assessment revealed that conveyor belts pose the greatest risk to the ventilation system. To address this issue, a simulation model was developed to represent the ventilation network of a twin-shaft gold mine located in South Africa. The model was calibrated using actual mine data and achieved a mean absolute error of less than 5%. Standardised design fire scenarios were applied to investigate the spread of temperature and carbon monoxide. The study analysed the impact of airflow reversal, which can worsen the spread of contaminants and increase the risk to the health and safety of mineworkers.

The findings indicated that indirect ventilation control strategies, including pressure control, airflow partitioning, and smoke extraction, are crucial for mitigating the spread of contaminants. The study validated the effectiveness of the developed simulation model, highlighting its value as a proactive tool for fire mitigation and emergency response planning in underground mines.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
DXF	Drawing Exchange Format
FDS	Fire Dynamics Simulator
KPI	Key Performance Indicator
HRR	Heat Release Rate
IAW	Intake Airway
MAE	Mean Absolute Error
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational Exposure Limit
PTB	Process Toolbox
RAW	Return Airway
TMRT	Taipei Mass Rapid Transient
VUMA	Ventilation of Underground Mine Atmospheres

NOMENCLATURE

Symbol	Description	Units
E_{fuel}	Total heat emitted by the fuel	MJ
$\dot{G}$	Gas flow rate	kg/s
H_c	Effective heat of combustion	MJ/kg
$\dot{m}_a$	Air mass flow rate	kg/s
m_{fuel}	Mass of fuel source	kg
t	Time	s
$\dot{Q}$	Heat release rate	kW

Greek symbol

$\alpha_{D,q}$	Exponential decay rate	s^{-1}
α_{ggr}	Gas flow growth rate	kg/s^3
$\alpha_{g,L}$	Linear growth rate	kW/s
$\alpha_{g,q}$	Quadratic growth rate	kW/s^2

Chemical symbol

CO	Carbon monoxide
CO ₂	Carbon dioxide
NO	Nitric oxide
NO ₂	Nitrogen dioxide
SO ₂	Sulphur dioxide

CHAPTER 1: INTRODUCTION AND LITERATURE STUDY

1.1 Preamble

Chapter 1 of this study delves into the literature and research concerning the ventilation networks of underground mines and their direct connection to fire hazards. The aim of Chapter 1 is to identify a method that utilises a calibrated ventilation simulation model to simulate fire hazard incidents and develop proactive remediation strategies to minimise or eliminate the associated risk.

1.2 Background: Underground mining operations

Underground mining is a critical sector for global mineral resources that provides essential materials for various industries. Over the years, the South African mining industry has made a significant contribution to the total turnover in the formal business sector, which continues to increase. Figure 1-1 illustrates the overall financial contribution of mining to the total formal business turnover from 2005 to 2022 [1].

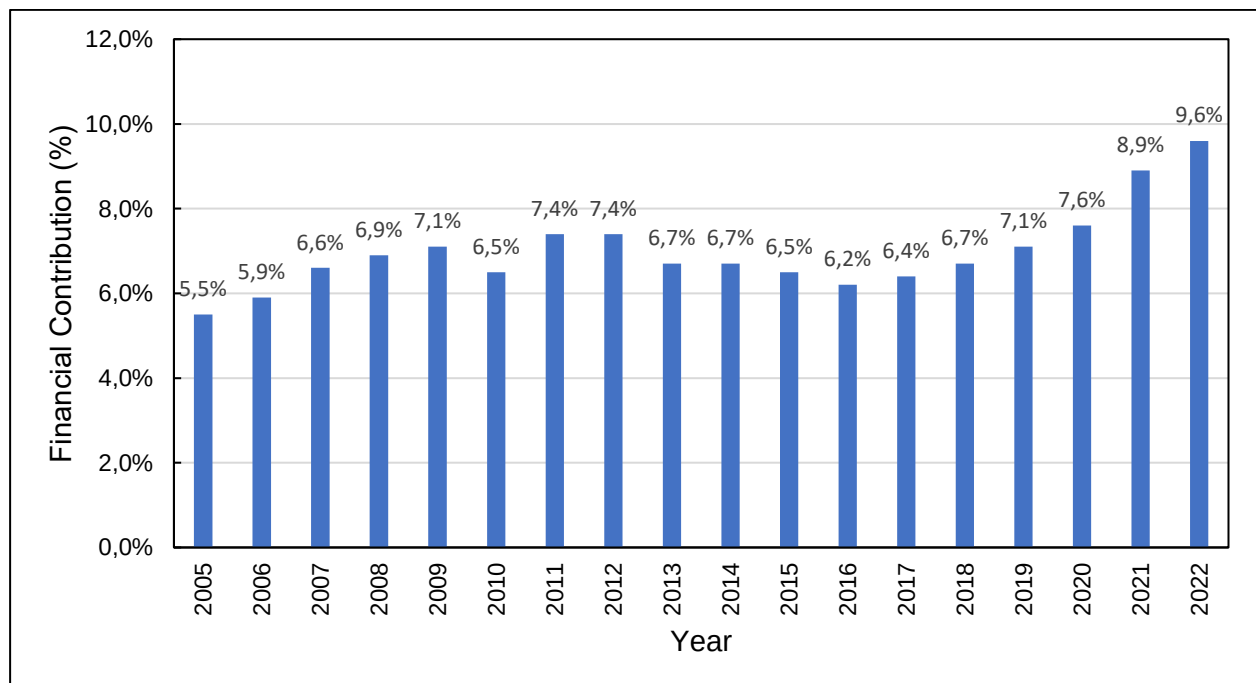


Figure 1-1: Financial contributions of the mining sector to the South African formal business economy [1]

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According to the latest approved mining statistics report from Statistics South Africa, the total income for the South African mining industry in 2019 was R552.1 billion [2]. Coal, platinum, and gold mining were among the primary contributors, with underground mining operations accounting for 68% of the total income. This clearly demonstrates that the underground mining sector is a major contributor to the economic growth of South Africa.

It is important to note that a key factor in any organisation's success is the dedication of its employees to meeting targets [3]. To achieve the financial growth illustrated in Figure 1-1, the underground mining industry must prioritise and maintain safe working conditions. Considering that employees are the backbone of any organisation, it is crucial to concentrate on the occupational health and safety of every individual [3]. Underground mining presents a formidable challenge in ensuring the health and safety of employees due to various hazards [4].

Figure 1-2 illustrates the number of injuries per category, as reported in the most recent available occupational health and safety report provided by the Department of Mineral Resources of the Republic of South Africa [5].

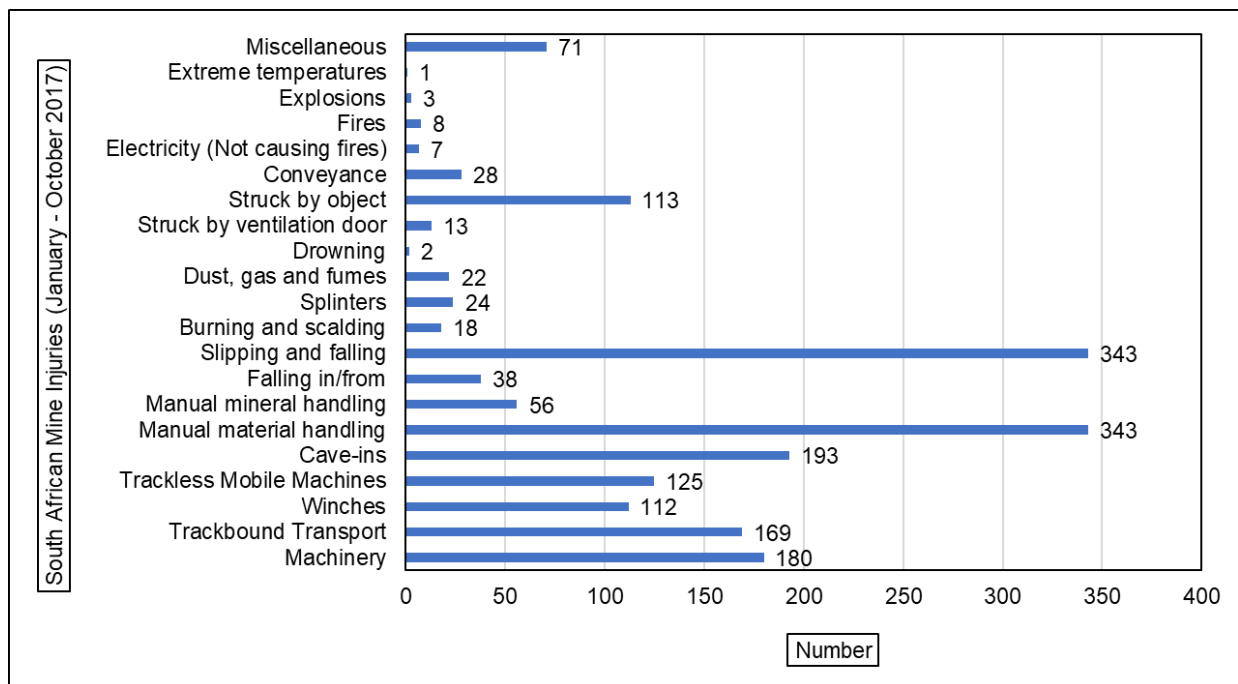


Figure 1-2: South African mine injuries (January–October 2017) [5]

Among these hazards, several can be directly linked to ventilation-related issues, such as dust, gas, and fumes, which accounted for 22 injuries, and extreme temperatures, which, although less frequent, can pose significant challenges in certain mining operations [4]. Effective ventilation

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control practices can help avoid some of these hazards by maintaining appropriate working temperatures, preventing dust pick-up, and eliminating gas build-up [6].

1.3 Ventilating an underground mine

The mine ventilation system is responsible for providing fresh air and removing harmful contaminants [7]. Underground mine ventilation networks consist of interconnected sections and applications that form part of the ventilation process of supplying fresh air and returning contaminated hot air [8]. Figure 1-3 is a basic representation of a ventilation network in an underground mine.

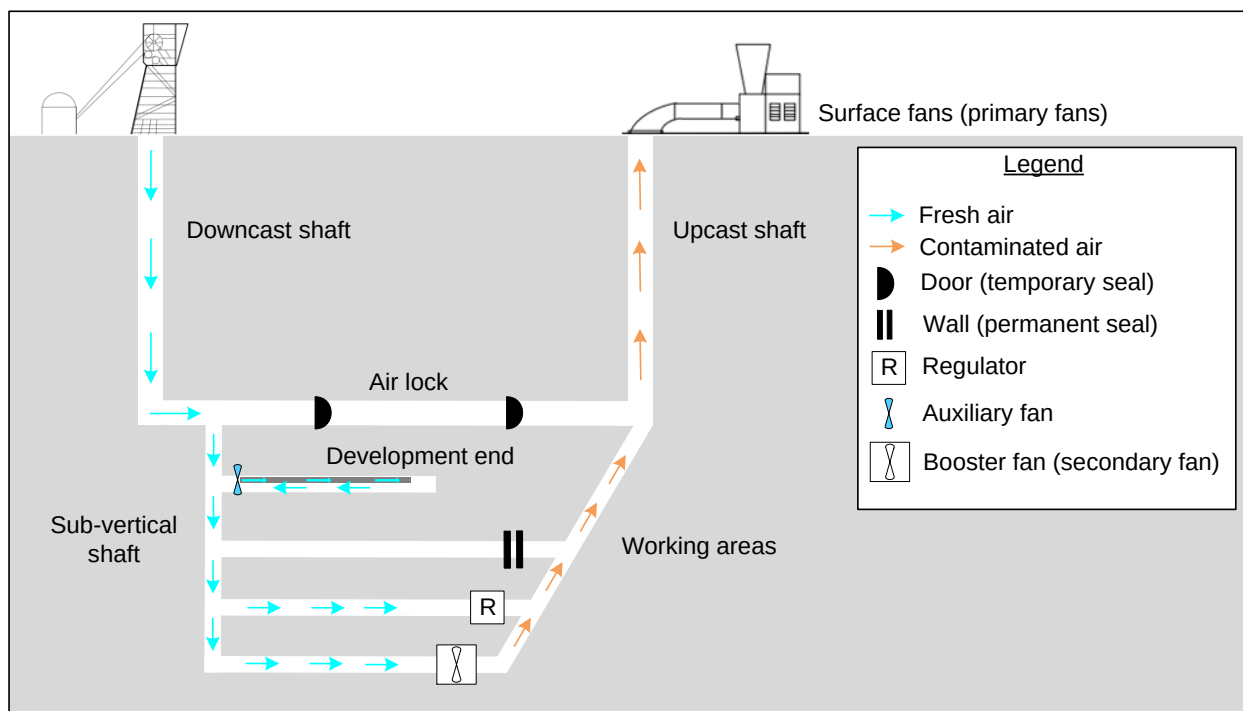


Figure 1-3: Common set-up of an underground mine ventilation network [9]

Figure 1-3 illustrates the components contributing to effective ventilation in a typical underground mine, highlighting the two main types of airways: intake airways and return airways. Fresh air descends through the downcast and sub-vertical shafts, flowing into the intake airways that lead to the active working areas and level stations. The working areas usually contain and contribute to the hazardous pollutants mentioned earlier. The contaminated air then flows through the return airway towards the upcast shaft [9].

To ensure that air flows adequately and efficiently, fans are introduced to the system. In a typical underground mine ventilation network, fans are divided in three groups, namely primary,

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secondary, and auxiliary fans. Primary fans, also referred to as surface fans, extract the return air through the upcast shaft and expel it to the surface of the mine. These fans are the primary source of air throughout the mine. Secondary fans are introduced to the ventilation network to manage and mitigate system resistance challenges. These fans provide targeted ventilation to underground areas where system resistance cannot be overcome and, in turn, they assist the primary ventilation fans. Auxiliary fans are used in development areas of the mine where there is no flow-through ventilation [9].

In conjunction with fans, ventilation control is an important discipline that contributes to the effective ventilation of any underground mine. The amount of airflow is primarily regulated through fan speed and its control strategy, while physical barriers such as seals are strategically used to direct and maintain airflow. Seals are primarily divided into two categories, namely permanent and temporary. As their name suggests, permanent seals are used to direct airflow permanently to the desired area. Temporary seals are used to isolate specific areas and are not designed to withstand long-term conditions [9].

The ventilation network of an underground mine is a complex, integrated, and dynamic system, with numerous components that require effective planning to ensure the health and safety of employees. Beyond maintaining air quality and temperature control, ventilation systems play a crucial role in managing hazardous conditions. This foundation underscores their importance in addressing an even greater challenge – the threat of fires in underground mines, where effective ventilation can be the difference between containment and disaster [10].

1.4 Underground fires

1.4.1 Threat of fires in underground mines

Fires that occur in underground mines pose a significant threat to the health and safety of employees, as well as to the underground infrastructure and overall productivity of mining operations [10]. Several critical factors, which are connected to mine fires, can result in the loss of both lives and revenue for any mining enterprise. They include the following:

- Human safety
- Rapid spread
- Structural and equipment damage
- Loss of production

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The main factors contributing to the increased risk of underground fires are the confined nature of excavations, the substantial production of smoke and noxious fumes relative to the limited availability of fresh air, and the limited ability to promptly evacuate the mine [10]. Fires can ignite any combustible material underground, resulting in a complex mixture of different ingredients that form smoke. The composition of smoke can vary depending on the fuel source. The resultant smoke poses a serious risk for employees, who may experience asphyxia and smoke inhalation injuries [11]. From 2004 to 2017, the South African mining industry has reported 19 fatalities, 149 fire-related injuries, and 71 documented dangerous fire-related occurrences due to underground fires [10].

Fires in underground mines spread rapidly through interconnected shafts, tunnels, and working areas, with their confined nature escalating the situation and making it difficult for miners to escape and for response teams to respond effectively [12]. Hence, it is crucial to implement ventilation strategies in conjunction with fire and rescue strategies to prevent the spread of fire and smoke in underground mines.

The intense heat generated by fire can deteriorate the structural integrity of shafts, tunnels, and support systems, increasing the risk of ground collapses. These failures not only endanger the health and safety of employees but also impede rescue efforts. Additionally, the damage to equipment and machinery disrupts mining operations, leading to significant financial losses for the enterprise[13].

Each of these three factors contributes to the loss of production for the mining enterprise involved. Areas rendered inaccessible due to fire, injuries, or fatalities often lead to temporary or permanent cessation of mining operations. This affects production schedules, resulting in financial losses for the mining enterprise [13].

It is evident that fires in underground mines can affect the broader economy, especially if the mining enterprise is a major contributor to regional or national resources. However, the main responsibility of any mining enterprise is the occupational health and safety of their employees. Ensuring a safe working environment requires strict adherence to occupational health regulations, particularly in controlling environmental hazards that miners are exposed to daily.

The Mine Health and Safety Act, no. 29 of 1996, mandates employers to implement and uphold an occupational hygiene measurement system for all work areas [14]. The environmental hazard limits are detailed in Table 1-1.

Table 1-1: Environmental hazard limits underground [14]

Criteria	Occupational Exposure Limit
Thermal stresses	• Wet bulb (WB): 32.5 °C • Dry bulb (DB): 37.0 °C
Occupational exposure limit of airborne pollutants	• Carbon monoxide (CO): 30 ppm • Carbon dioxide (CO₂): 5 000 ppm • Nitric oxide (NO): 25 ppm • Nitrogen dioxide (NO₂): 3 ppm • Sulphur dioxide (SO₂): 2 ppm

Table 1-1 lists the exposure limits of the relevant environmental hazards applicable to this study. These airborne pollutants are the most commonly monitored gases in underground metal/non-metal mines [15].

1.4.2 Effect of fires on the underground ventilation network

In the event of a fire, large amounts of gas with a very high temperature and very low density are produced. They result in the four main effects on the ventilation network of an underground mine, namely throttling or choking, natural ventilation, flow reversal, and rollback [16].

The throttling or choking effect

Throttling or choking is the result of an increase in the volume of air passing through the area affected by fire. As temperature rises during a fire incident, the gas expands, increasing the air volume. As the air volume increases, the velocity in the network also increases, causing higher frictional pressure losses. The throttling or choking effect restricts the airflow in the ventilation network. This restriction leads to an insufficient fresh air supply to working areas, which limits the extraction of hazardous gases and contaminants [17].

The natural ventilation effect

Natural ventilation, also referred to as the chimney or natural draft effect, is caused by an increase in the buoyancy of air downwind from a fire incident. This leads to a significant rise in natural ventilation pressures in different parts of the ventilation network. Typically, the natural ventilation pressure increase is unstable, causing unpredictable shifts in air density and the distribution of airflow. This effect is more pronounced in fire incidents that occur in a shaft or sloping airway. Upward airflow is usually encouraged, while downward airflow is limited [17].

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The flow reversal effect

The flow reversal effect results from a combination of factors that create a pressure imbalance in the system. Due to the complex interaction between a mine fire and the ventilation network, the pressure balance is difficult to predict. The pressure imbalance, which can lead to flow reversal or recirculation, may occur due to convection currents (buoyancy effects) and constrictions (throttling effects) caused by the fire incident. It is important to note that the effects of a fire incident depend on the slope angle and flow direction (dip or raise) of the area where it occurs [17].

The rollback effect

The rollback effect occurs when hot gases and vaporised burning fuel from a fire incident rise and reach the hanging wall of an underground tunnel. The increase in natural ventilation pressure is caused by the high temperature of the burning fire. If there is not velocity in the forward ventilation direction, the combustion product is forced along the hanging wall both upstream and downstream of the fire incident [18]. Figure 1-4 illustrates an example of a computational fluid dynamics (CFD) model that demonstrates the effect of rollback in a ventilation tunnel.

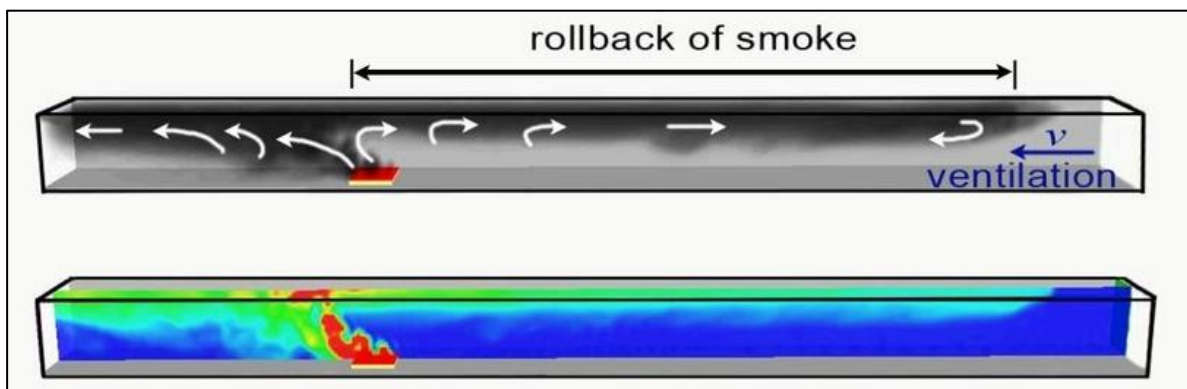


Figure 1-4: Example of a CFD model illustrating the rollback effect [19]

From investigating the above-mentioned effects, it seems that these impacts are primarily studied in the localised area surrounding the origin of the fire incident. However, these effects influence the entire ventilation network of an underground mine. Rising temperatures and gas concentrations follow the ventilation network throughout the mine until the gases are eventually extracted. It is crucial to evaluate the spread of contaminated air and identify appropriate control methods based on these evaluations when developing comprehensive occupational safety plans.

1.4.3 Methods for controlling fire incidents

Mine fires are classified into two main states, namely oxygen-rich fires and fuel-rich fires. Oxygen-rich fires thrive on the high oxygen content of downwind air, which is typical for most mine fires. Fuel-rich fires occur when a fire reaches high temperatures and heats the air volume, which spreads the fire to a level that induces pyrolysis in the fuel source. The state of the fire results in effectively zero oxygen content downwind of its origin because the fire consumes all available oxygen [20].

The two methods for controlling fires can be classified as follows [21]:

- **Direct method:** Immediate and explicit actions targeted at the fire itself or its immediate effects.
- **Indirect method:** Ventilation control techniques targeting factors surrounding the fire and its affects.

Direct methods

Direct methods that aim to combat open fires and their effects primarily refer to fire suppression systems. Examples of such systems include water deluge and sprinkler systems, high-expansion foam, high-pressure high stability nitrogen foam, and water misting technology [22-25]:

In this study, direct methods are excluded. The investigation focuses on worst-case scenarios in an underground mine's ventilation network.

Indirect methods

Indirect methods refer to ventilation control techniques. These techniques affect the combustion process, the distribution of combustion byproducts, the direction and rate of fire propagation, and airflow distribution in other parts of the mine [21]. Ventilation control techniques tend to control the airflow rate, which may shift the fire's dynamic from oxygen-rich to fuel-rich by reducing convective heat dissipation [21]. It is therefore important to recognise the sensitivity of an open fire to air velocity.

Managing underground fire incidents using ventilation control techniques is a complex topic because each mine has a unique ventilation network. The following examples offer a comprehensive overview of the strategies employed in the mining industry [26-29]:

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- **Pressure control:** Maintaining higher pressures in areas surrounding the fire incident by means of effective sealing strategies. The pressurised zone prevents fire gas infiltration.
- **Airflow regulation:** Adjusting the air supply to reduce the airflow to the fire zone limits the oxygen supply and slows down the combustion process.
- **Airflow partitioning:** Dividing the mine into separate ventilation zones and redirecting airflow to isolate the fire-affected region. This prevents temperature variation and smoke distribution to other parts of the mine.
- **Smoke extraction:** Using smoke extraction systems, such as exhaust fans, to remove contaminated air from the mine's ventilation network.

The effects outlined in Section 1.4.2 will be used to assess the applicability of the ventilation control techniques discussed above.

1.5 Developing a realistic simulation model

A realistic representation refers to a simulated depiction of a real-world system, object, or process [30]. Its purpose is to generate a dynamic, realistic portrayal of a physical system that reflects its characteristics, behaviour, and status [30]. This technology aligns with the objectives of Industry 4.0, which represents the Fourth Industrial Revolution where simulation modelling transitions into cyber-physical systems [31, 32]. The simulation aspect of a realistic representation is used for development planning and exploratory modelling to not only assist mine personnel in optimising their decision-making strategies but also designing and managing a complex, dynamic, and integrated system [33, 34]. Figure 1-5 explains the dynamics of a realistic simulation model.

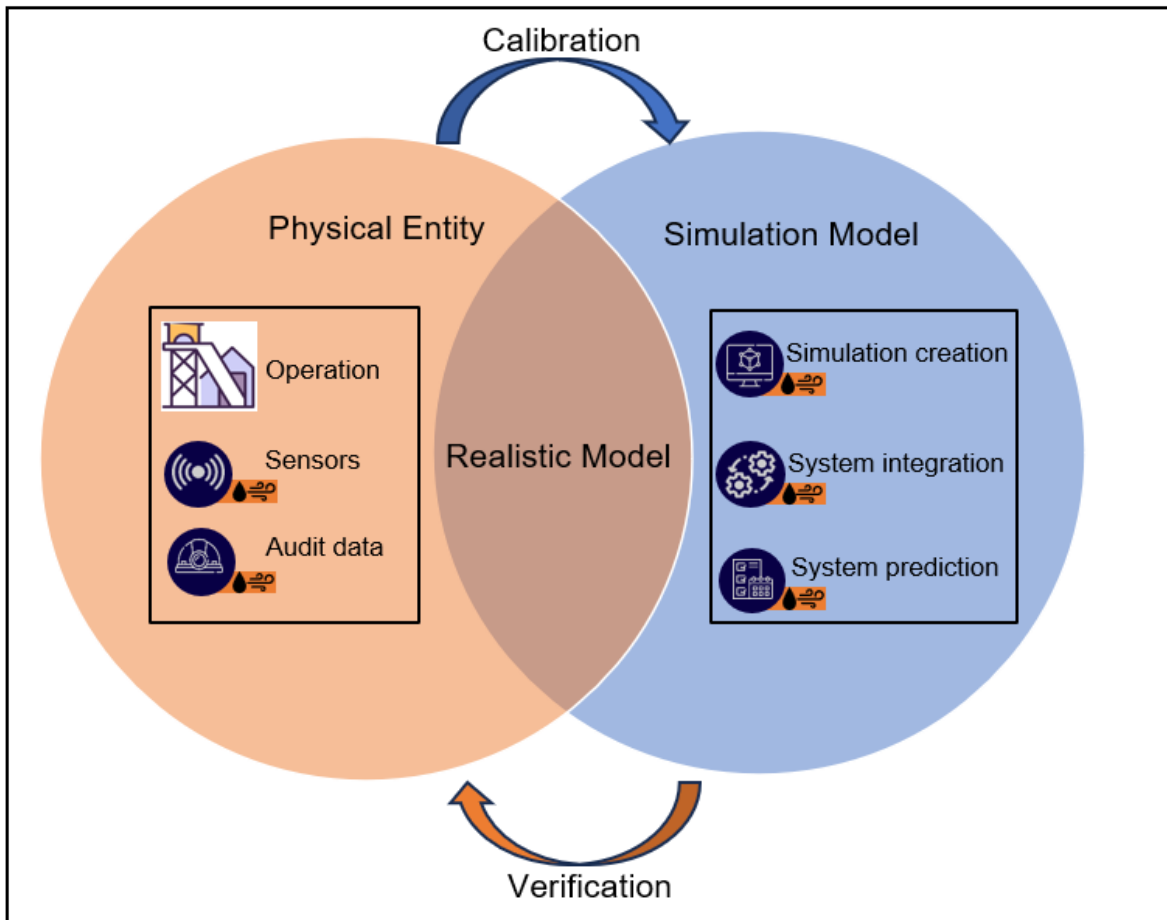


Figure 1-5: Illustration of the realistic simulation model process [33, 34]

Figure 1-5 illustrates the process of accurately modelling a physical entity, resulting in a realistic representation. By using actual data of the physical entity, the virtual model is calibrated to form an integrated, dynamic system that predicts the effect of specific changes to the entity without the need for actual implementation. A baseline simulation is used to verify the accuracy of the virtual model [35].

Studies have shown that a simulation model can be utilised to develop a scalable method that optimises and evaluates a mine's ventilation network through predictive simulation modelling [34]. It is evident that a virtual simulation model can be utilised to predict the outcome of a fire-related incident and help develop remediation strategies without implementation. The most common simulation software packages used in mining include Ventsim, Ventilation of Underground Mine Atmospheres (VUMA)–network 5.0, and Process Toolbox (PTB) [35].

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Ventsim

Ventsim offers a fully integrated software package for designing and testing ventilation circuits in mines and tunnels. It covers a wide range of ventilation aspects, such as airflow, fire, gases, heat, power, pressure, radon, and other pertinent ventilation data [36]. The drawing exchange format (DXF) layouts provided by mines can be imported into simulation software. This layout serves as an outline for constructing the model, therefore ensuring that the simulation model is built using accurate dimensions [37].

Ventsim offers a fire modelling module called VentFIRE™, which simulates the dynamic nature of fire by considering factors such as changes in air density caused by added heat, oxygen consumption, and the generation of combustion products [16].

VUMA–network 5.0

VUMA–network 5.0 is an interactive software program designed for Windows. It enables mine ventilation engineers and practitioners to plan, design, and operate mine ventilation systems [38]. The DXF layouts provided by mines can be used as an outline to ensure the simulation model is developed with accurate dimensions.

VUMA–network 5.0 incorporates fire modelling capabilities by using the latest version of MFIRE, which is a trusted system developed and maintained by the National Institute for Occupational Safety and Health (NIOSH) in collaboration with the Centers for Disease Control and Prevention [39]. The fire module evaluates how fire affects the ventilation network, including flow turnaround, and simulates both potential firefighting scenarios and the adequacy of existing fire control measures [39].

PTB

PTB is a one-dimensional CFD simulation software that solves intricate thermo-hydraulic networks. PTB can simulate incompressible (water), compressible (air), and two-phase fluids (steam). The scalability of PTB enables the simulation of transient, integrated cooling, and ventilation networks in an underground mining operation [40].

PTB allows the user to import the DXF layout provided by the mine into a three-dimensional graphical user interface to create an outline for accurate dimensions. A library containing a wide variety of components is available for dragging and dropping onto the DXF layout [40]. The

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component library contains all the necessary components required for constructing an accurate representation of a mine's ventilation and refrigeration system.

PTB allows the user to adjust the time steps and time periods during simulation, facilitating the creation of an accurate representation of a predefined time frame. Users are able to input values for heat, gas, and airflow for each time period, which enables the simulation of transient fire dynamic behaviour over a realistic time span.

1.6 Design fires

1.6.1 Preamble

Design fires are crucial to this study as they illustrate the performance of hypothetical fire scenarios used for planning and evaluating fire safety measures in underground mining. Fitzgerald and Meacham [41] describe design fires as the load against which the resultant risk to exposed employees and the effectiveness of the active fire remediation strategy are evaluated. More specifically, a design fire outlines assumed fire characteristics, such as the heat released, air mass flow conditions, and smoke generated over time. This section aims to discuss the idealised stages of a design fire and the methods devised in literature for creating a realistic theoretical fire scenario.

1.6.2 The idealised design fire curve

The idealised design fire curve describes the full specification of the temporal evolution of a design fire. This curve can be adapted to illustrate the evolution of the heat release rate (HRR), air mass flow, and gas generated during the stages of combustion. The idealised stages of a design fire in the ventilation network of an underground mine are illustrated in Figure 1-6 [42].

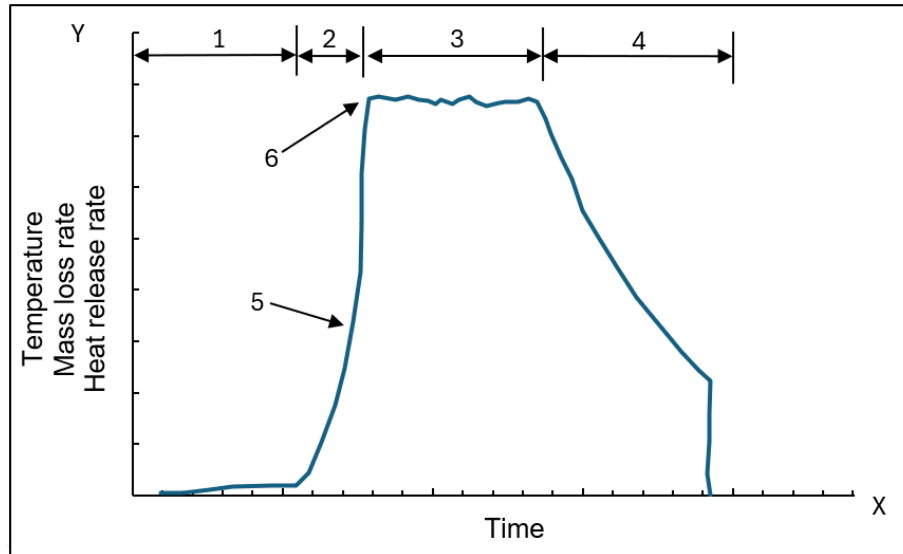


Figure 1-6: Idealised design fire stages in an underground mine ventilation network [42]

Figure 1-6 represent the following stages [42]:

1. Incipient: The initial stage of fire development that is characterised by the ignition of the fuel source and the beginning of combustion.
2. Growth: At this stage of the fire propagation, the rate of the heat released rapidly increases along with significant smoke production resulting in an overall increase in fire intensity.
3. Fully developed: The peak stage of the fire, where it has reached its maximum intensity.
4. Decay: During this stage, the fire starts to diminish in intensity as the fuel is consumed.
5. Flashover: This point refers to the critical transition in the growth stage where all combustible materials ignite almost simultaneously.
6. Ventilation controlled: This stage refers to a condition in which the fire growth and the heat released are restricted by the airflow rather than by the amount of fuel.

1.6.3 Method for determining fire characteristics

A method for determining fire characteristics is necessary to establish the study's design fire curve. It provides the foundational data required to accurately model the worst-case fire incident scenario in the ventilation network of an underground mine. The stages of a design fire as illustrated in Figure 1-6 are characterised by determining the HRR, gas flow rate, and the air mass flow rate over time [43]. The primary methods for determining a fire's characteristics during combustion relevant to this study are the cone calorimeter test and tunnel fire test.

Cone calorimeter test

Figure 1-7 illustrates the cone calorimeter test, which is a method for determining the characteristics of a test sample [44].

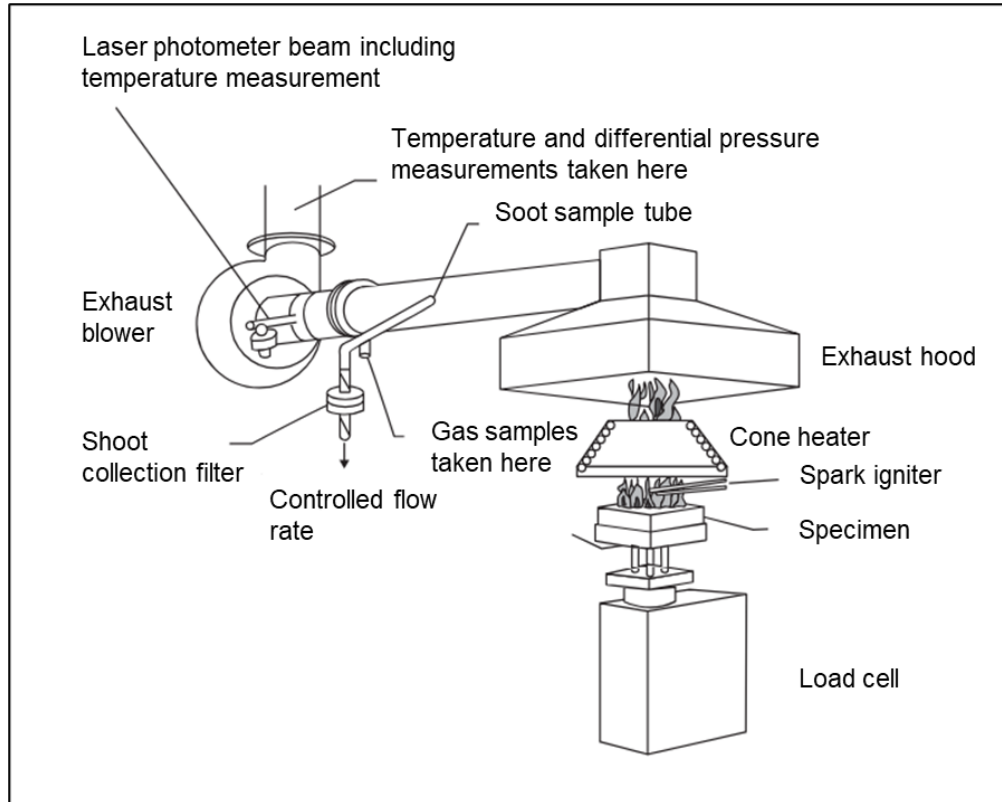


Figure 1-7: Cone calorimeter test set-up [44]

The cone calorimeter test operates on the principle of oxygen consumption calorimetry, which is based on the correlation between the amount of oxygen consumed during combustion and the heat released. The test sample is placed on a load cell to monitor mass loss throughout the combustion process. A conical radiant electrical heater provides uniform irradiation from above, while an electric spark ignites the sample. The combustion gases pass through the heating cone and are captured by the exhaust duct system. This system measures smoke density and gas emission rates, including concentrations of oxygen, CO, and CO₂. The gas flow and oxygen concentration data are used to calculate the HRR, expressed in kW/m², indicating the amount of heat released per unit time and surface area [44].

The cone calorimeter test is an essential tool in fire safety engineering that is primarily used to determine the HRR of materials. By measuring oxygen consumption during combustion, the cone calorimeter accurately calculates the HRR, which forms the basis of the HRR curve. This curve

not only indicates the HRR per unit time and surface area but also allows for the derivation of gas emission rates and air mass flow, as these parameters are intrinsically linked to the HRR. Consequently, the HRR curve effectively forms the design fire curve, representing the stages discussed in Figure 1-6 [45].

Tunnel fire test

Tunnel fire tests are conducted on either a full-scale or model-scale basis, with both approaches aiming to evaluate fire combustion characteristics under varying ventilation conditions. The primary goal is to investigate how different ventilation velocities affect smoke and temperature distribution, fire growth, flame spread along the fuel source, and the maximum HRR throughout the fire's duration [46, 47].

1.6.4 Review of standard HRR curves in literature

Apart from the idealised design fire behaviour illustrated in Figure 1-6, there are many simplifications in literature to configure design fire curves for the HRR. These methods are illustrated and described in Figure 1-8 to Figure 1-11. The most simplistic method is referred to as the traditional method. This method uses a steady-state approach in which a constant HRR is assumed [48]. Figure 1-8 illustrates the traditional HRR model.

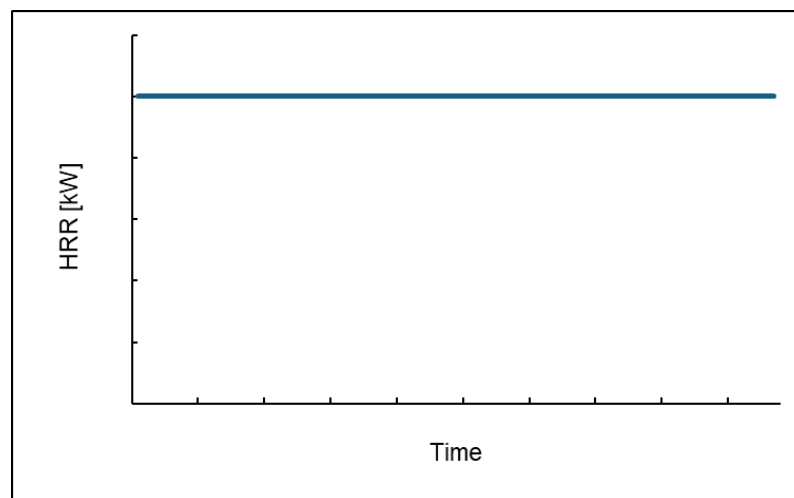


Figure 1-8: Traditional HRR model [48]

This approach calculates the average HRR of a fire incident. The average is based on the sum of the calorific values of each combustible present in the combustion process and is dependent on the duration of the fire.

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Duggan proposed a method for predicting the HRR of a fire with multiple fuel sources [48]. Figure 1-9 illustrates the HRR model referred to as the Duggan method.

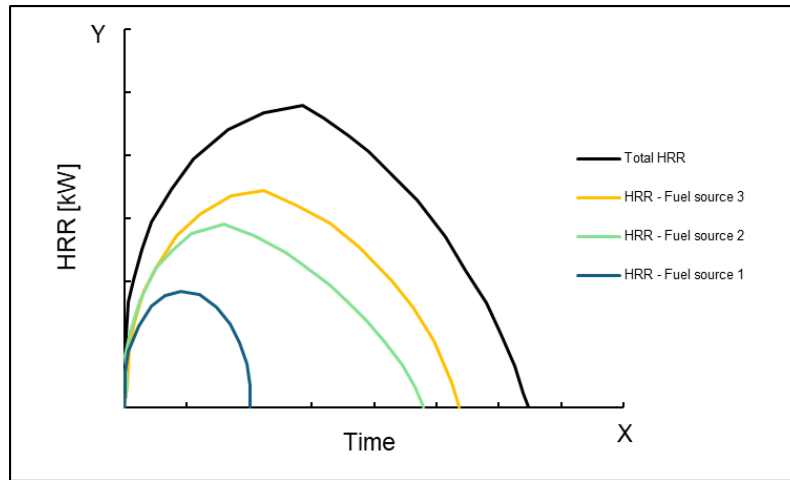


Figure 1-9: Duggan HRR method [48]

Duggan's method for determining the total HRR is based on cone calorimeter experiments. In these experiments, the HRR per unit area for each burning fuel source is derived. The HRR generated by each fuel source is determined by multiplying the exposed surface area of the fuel source by the HRR per unit area obtained from the cone calorimeter test. The total HRR is obtained by summing the HRR of each individual fuel source [49].

Ingason [50] identified three main types of design fire curves: linear, quadratic, and exponential. These curves describe both the growth and decay phases of a fire and can be combined in various ways to create a hypothetical design fire scenario [50]. Lacroix [51] assumed a design fire in which both the growth and decay periods are linear functions of time as illustrated in Figure 1-10.

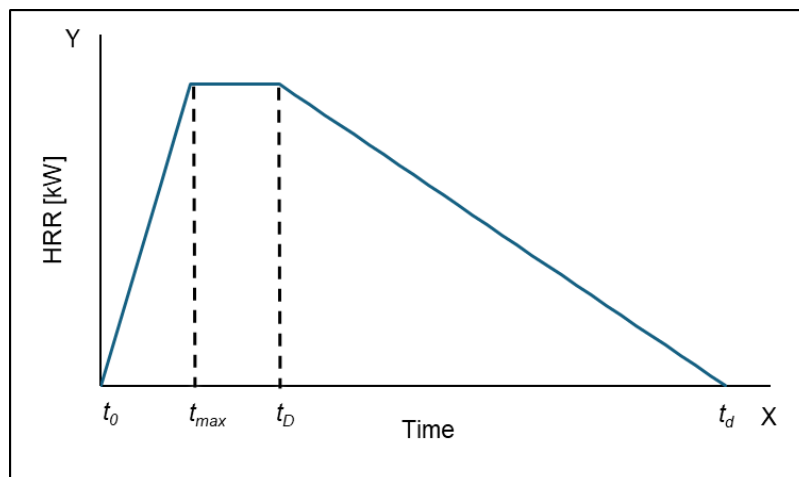


Figure 1-10: Linear growth and decay HRR model [51]

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The HRR model in Figure 1-10 is described by the following equations:

- Linear growth curve: $\dot{Q}(t) = \alpha_{g,L}t$ (1)

- Maximum HRR: $\dot{Q}_{max} = \alpha_{g,L}t_{max}$ (2)

- Linear decay curve: $\dot{Q}(t) = \dot{Q}_{max} - \alpha_{D,L}(t - t_D)$ (3)

In the HRR model illustrated in Figure 1-10, the growth period is a linear function of time dependent on the linear growth rate $\alpha_{g,L}$ from time t_0 to time t_{max} . A constant maximum HRR occurs from time t_{max} to time t_D . The decay period is a linear function of time dependent on the linear decay rate $\alpha_{D,L}$ from time t_D to time t_d .

Ingason [52] proposed an HRR model where the growth period is represented by a quadratic function of time and the decay period by an exponential function of time, as illustrated in Figure 1-11.

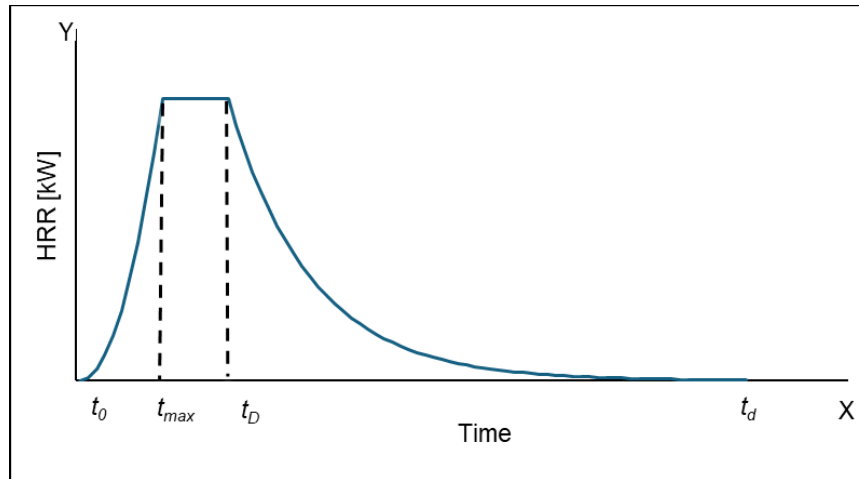


Figure 1-11: Quadratic growth and exponential decay HRR model [52]

The HRR model in Figure 1-11 is described by the following equations:

- Quadratic growth curve: $\dot{Q}(t) = \alpha_{g,q}t^2$ (4)

- Maximum HRR: $\dot{Q}_{max} = \alpha_{g,q}t_{max}^2$ (5)

- Exponential decay curve: $\dot{Q}(t) = \dot{Q}_{max}e^{-\alpha_{D,q}(t-t_D)}$ (6)

In the HRR model illustrated in Figure 1-11, the growth period is a quadratic function of time dependent on the quadratic growth rate $\alpha_{g,q}$ from time t_0 to time t_{max} . A constant maximum HRR occurs from time t_{max} to time t_D . The decay period is an exponential function of time dependent on the exponential decay rate $\alpha_{D,q}$ from time t_D to time t_d .

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The various methods discussed above provide insights into the key derivations used to define a theoretical fire scenario. Investigating and understanding different design fire methods is crucial for formulating a method tailored to worst-case scenarios and emergency planning. The design fire derived for this study will form the input values for the simulation model that represents the ventilation network of an underground mine.

1.7 Literature review and state-of-the-art criteria

1.7.1 Preamble

This section of the study aims to present a detailed review and critical examination of prior studies related to the literature scope (Section 1.7.2). Each study's focal point, the obtained results, relevance, and shortcomings are identified to determine clear research gaps that need to be addressed.

1.7.2 Literature scope

Fires in underground mines are unpredictable, and the resulting changes in environmental factors pose a significant threat to the health and safety of employees. Research on the effects of fires in underground ventilation networks, as previously mentioned, has primarily focused on localised impacts. This raises curiosity about how these localised effects spread throughout the entire ventilation network. This emphasises the importance of developing remediation strategies, which are based on the results of ventilation simulation, in order to combat the spread of contaminated air and ensure effective emergency planning. Emergency planning is only truly effective when worst-case scenarios are considered [5].

1.7.3 Summary of previous studies

Conducting research on simulating fires in underground mines for emergency planning involved a comprehensive investigation of 28 studies. These studies were identified by systematically searching for the following key phrases: "simulation", "underground mining", "design fire", "heat release rate", "gas flow rate", "temperature distribution", "emergency planning", and "ventilation control". This approach enabled the gathering of a robust collection of literature relevant to the core themes of this thesis. The search process involved utilising search engines and academic databases such as Google Scholar, Science Direct, and Research Gate to identify peer-reviewed articles, conference papers, and technical reports that address the critical aspects of fire dynamics and safety in underground mining environments.

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The 28 studies that were identified provided a diverse range of insights and empirical data, which helped to identify the following criteria for evaluating and determining a clear gap in the literature:

- **Fire risk assessment:** Did the study identify potential fire hazards and quantify their associated risks?
- **Simulation based:** Did the study utilise simulation software packages to obtain results and, if so, was the study performed partially or on the entire ventilation network of the underground mine?
- **Design fire scenarios:** Did the study use a design fire curve to replicate a hypothetical fire scenario and, if so, was the method standardised to apply to any hypothetical scenario to determine worst-case outcomes?
- **Environmental factors:** Did the study investigate the effect of temperature, pollutants and/or airflow conditions?
- **Ventilation control practices:** Did the study use ventilation control practices to reduce or eliminate the risk of fire incidents and, if so, were these practices simulated to assess their effectiveness?

Of the original 28 studies, 12 were found to be most applicable to the topic of this thesis. These studies will be summarised and discussed with the following points of interest:

- **Overview:** Provide insight on the content of the study.
- **Results:** Discuss the results obtained in the study.
- **Relevance:** Discuss the relevance of the study, considering the predetermined criteria and the essential information required to successfully complete this study.
- **Shortcomings:** Discuss the shortcomings identified in the study that will contribute to identifying a gap in the literature.

Study 1 [16]

Title: Fire modelling in underground mines using Ventsim Visual VentFIRE software.

Author: D.J. Brake.

Relevant criteria: Design fire scenarios; simulation based; environmental factors; ventilation control practices.

Overview

This study examined the modelling of three significant fire incidents in an underground hard rock mine. It involved simulating fire scenarios in a diesel refuelling facility, explosives magazine, and

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ore transport conveyor. Utilising Ventsim's VentFIRE fire simulation module, the study outlined the design basis, key assumptions, and methodology employed to generate outputs, conclusions, and recommendations concerning the effects of these fires. The study also proposed general principles for enhancing ventilation network design based on the simulations.

Results

Fire in diesel refuelling facility: The simulation result showed that closing fire doors at the fuel bay entry decreased the HRR by limiting oxygen but resulted in adverse effects due to inadequate sealing. This included higher CO levels and prolonged fire duration, causing longer entrapment times and delayed firefighting. It is recommended that fire doors be primarily used to isolate points of combustion.

Fire in explosives magazine: The simulation result indicated that the configuration of two short access entries and a fixed orifice regulator in the magazine caused points of combustion to circulate back into the travel way and other mine sections. Solutions included closing one fire door or adjusting the regulator to ensure airflow, especially for intense fires.

Fire in conveyor: The simulation results revealed that the primary issue with conveyor belt fires is the open connections to the adjacent service drive. This, combined with the downward ventilation system, leads to fluctuating airflow conditions caused by natural ventilation pressure generated by the fire. The simulation emphasises the importance of setting up conveyors in their own self-contained ventilation area, which can be isolated during a major fire.

The author stipulated that it is evident that the results are not applicable to all fire-related incidents, but it is important to realise that they are contra-intuitive in some respects. Therefore, fire simulation modelling should form part of ventilation planning in the future.

Relevance

The study conducted by Brake aligns with the research scope of this study as it used simulation software to assess the effectiveness of ventilation control practices in mitigating fire incidents in underground mines. The study provided insight into simulating dynamic fire scenarios and assessing the influence of pollutants and airflow variation in the ventilation network of an underground mine. The study discussed the stages of combustion, which in effect represent a design fire curve.

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Shortcomings

The study identified three fire hazards that formed part of the overall case study but lacked in evaluating their potential in becoming an incident. This study seemed to focus solely on the area surrounding the point of combustion, resulting in the effect on work area intakes being discarded. Therefore, there is a necessity to investigate changes in environmental factors, such as temperature, pollutants, and airflow, throughout the entire ventilation network of an underground mine. Although the study simulated a hypothetical design fire, the resulting design fire curve is based on assumptions and does not represent a standardised curve for worst-case scenarios.

Study 2 [53]

Title: Understanding mine fires by determining the characteristics of deep-seated fires.

Author: M.A. Trivets, L. Yuan, K. Teacoach, M. Valoski, and J. Urosek.

Relevant criteria: Simulation based; environmental factors.

Overview

This study was conducted by NIOSH along with the Mine Safety and Health Administration. It focused on understanding mine fire characteristics and dynamics. Two deep-seated fire experiments were conducted, one with coal and one with coal and wooden cribbing blocks. While the fires were set to burn to completion, combustion products were analysed and flame spread rates were determined. A CFD model was created using Fire Dynamics Simulator (FDS). Data from the coal fire test was used as input values. The simulation results were compared with the test results for accuracy assessment.

Results

The study depicted that the maximum surface temperature predicted by the CFD modelling closely matched those measured in the coal fire test, with a percentage error of 1.40%.

Relevance

One of the key criteria of this study was simulation modelling. Although this study was based on experimental procedures related to a coal mine's ventilation network, the effectiveness of the simulation technology was proven to be very accurate. This study facilitated an understanding of the characteristics of mine fire combustion products and flame spread through deep-seated fires. The use of FDS modelling provided an understanding on how flame spread rates along with fire mechanics can be studied through computer modelling.

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Shortcomings

This study focused exclusively on analysing results derived from fire experiments conducted in a fire suppression facility. Utilising CFD simulations, the study aimed to quantify these experimental outcomes. Consequently, neither did it investigate fire-related incidents occurring in the ventilation network of an underground mine nor did it address proactive planning strategies aimed at mitigating such risks. Although the results provided valuable information for designing an accurate fire curve, the study did not focus on creating a standardised worst-case scenario design fire curve. Instead, the simulation model was used to quantify actual experimental results.

Study 3 [54]

Title: Simulation of ventilation and fire in the underground facilities.

Author: L.H. Cheng, T.H. Ueng, and C.W. Liu.

Relevant criteria: Simulation based; environmental factors; ventilation control practices.

Overview

This study discussed the utilisation of a revised fire outbreak and evacuation simulation model aimed at improving emergency ventilation strategies, damage mitigation, and safety protocols in underground ventilation networks. The numerical model, MFIRE, was utilised to simulate the interaction between ventilation systems and its relevant fans and structures, illustrating the change in environmental factors resulting from the presence of a heat source. Laboratory-based fire experiments validated MFIRE's accuracy in simulating airflow rates, while highlighting disparities in temperature distribution due to scale differences. Application of MFIRE in simulating a hypothetical fire outbreak in the Taipei Mass Rapid Transient System (TMRT) confirmed the effectiveness of a push-pull ventilation model in efficiently exhausting high temperature and smoke.

Results

The numerical simulation results confirmed those of the physical experiments, indicating that without induced ventilation, heat from the fire incident could not dissipate, which led to high temperatures. Promptly introducing a fan into the ventilation network rapidly discharged the hot gases, gradually bringing the tunnel temperature to equilibrium.

The hypothetical fire incident simulated in the TMRT system used a push-pull ventilation control strategy in an attempt to mitigate the risk. The simulation results confirmed adequate flow rates

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in evacuation tunnels, ensuring safe evacuation. Temperature simulations indicated an immediate rise near the fire, which in turn caused a gradual decrease downstream due to the push-pull method. This method efficiently extracted high-temperature air and smoke, maintaining normal temperatures in other tunnels.

Relevance

Insights into transient-state simulations were gained, emphasising the importance of accurate thermal properties and fan characteristic curves in simulation models. The study also assessed the effectiveness of the push-pull method and discussed the use of simulation models to analyse variation in tunnel air velocity, hot air temperature, required air velocity for smoke risk mitigation, and predicted air behaviour.

This study therefore investigated the simulation of a fire incident on a ventilation network and the identification and implementation of a mitigation strategy. The evaluation of the impact on environmental factors determined the effectiveness of the identified mitigation strategy.

Shortcomings

The study focused on a single hypothetical fire incident and did not explore potential fire hazards or quantify their associated risks. Although this study discussed the impact of fire incidents in the mining industry during its literature survey, the focus was on the simulation of ventilation and fire in the underground railway facilities of Taipei, a city in Taiwan. The study did not define a standard method for developing a design fire curve tailored for worst-case scenario planning.

Study 4 [55]

Title: Fire behavior analysis of a mine future plan.

Author: A. Haghighat and S. Gillies.

Relevant criteria: Simulation based; environmental factors; ventilation control practices.

Overview

This study aimed to gain a deeper understanding of fire behaviour during unpredictable incidents. It investigated the fire behaviour in the airways of the Missouri University of Science and Technology's experimental limestone underground mine using Ventsim Visual software modelling. The objective of this study was to highlight the importance of developing emergency protocols through simulation predictions before a fire incident occurs. Two scenarios, located in the eastern and western part of the mine, were evaluated in this study, both involving the ignition

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of a bobcat vehicle. Parameters such as CO, CO₂, psychrometric behaviour, visibility, and airflow direction were analysed. Furthermore, fire control procedures aimed at mitigating the effects in two main sections of the mine, transitioning from external to excavation areas, were proposed.

Results

This study thoroughly examined different ventilation control practices aimed at mitigating the impact of fire incidents. Mitigation procedures were recommended for both the eastern and western scenarios based on the results obtained from evaluating airflow and O₂ behaviour, CO and CO₂ behaviour, psychrometric behaviour, and visibility at the respective locations.

Relevance

This study successfully identified mitigation strategies based on ventilation control practices by evaluating environmental factors such as temperature variations, exposure to pollutants, and airflow behaviour. It provided insights into the precise specification of scenarios, ensuring accurate input values for the simulation model. Insights to develop a methodology for accurately simulating fires in underground mines and predicting the outcome of identified mitigation strategies were therefore acquired.

Shortcomings

The findings of this study indicated that the distribution of CO and CO₂, as well as temperature variations, were notably influenced by both distance and airflow direction. The fire outcome was difficult to predict before the event due to the estimated location of the fire incident. Therefore, the study suggested the necessity of employing risk assessment techniques to identify potential combustible sources accurately, thus facilitating a more precise prediction through simulation. This study also lacked an investigation into the effect a fire incident on the entire ventilation network of an underground mine. This study specified the assumptions that were made to define the burn rate of the fire scenario but did not determine a standardised method for developing a design fire curve that represents a worst-case scenario.

Study 5 [48]

Title: Modeling and simulation of multiple underground mine fire scenarios at Freeport Indonesia.

Author: R. Brake, A. Hatt, and R. Sani.

Relevant criteria: Design fire scenarios; simulation based; environmental factors.

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Overview

This study investigated the potential impact of fires occurring at the Freeport-McMoRan underground mining facility in Indonesia. A comprehensive risk assessment was conducted during which 17 critical fire scenarios were examined, including fires involving magazines, mine mobile equipment, fuel bays, a compressor, light vehicles, an electrical substation, a conveyor, buses transporting personnel, spontaneous combustion, and naturally ventilated tunnels.

The study examined available technical data from civil and mining sources relating to peak HRR and HRR-time growth/decay curves. Literature was compiled regarding human survivability limits, which set the boundaries of this study. Each scenario was modelled using Ventsim Visual.

Results

The scope of this study was determined by human survivability limits. Consequently, the assessment of simulation results for the scenarios relied on the 30-minute exposure limit prescribed by the oxygen-generating self-contained self-rescuer manufactured by SavOx. The findings revealed safe conditions where exposure limits exceeded 30 minutes.

Relevance

This study investigated the impact of fire incidents, which were identified by conducting a risk assessment on mine personnel and considering environmental pollutants and temperature variations in surrounding areas. It used simulation software to model fire incidents in the ventilation network of an underground mine. Addressing common fire risk scenarios, the study elaborated on fire parameters relevant to the research context and discussed variations in HRR curves, which were integral to the methodology employed in this study.

Shortcomings

The results illustrated safe working conditions, implying that the results did not exceed the established limits. Therefore, this study did not report on developing mitigation strategies based on ventilation control practices. Although the study discussed and developed design fire curves, the method was not developed to represent worst-case scenarios for emergency planning.

Study 6 [56]

Title: Mine fire behavior under different ventilation conditions: Real-scale tests and CFD modeling.

Author: F. Fernández-Alaiz, A.M. Castañón, F. Gómez-Fernández, and M. Bascompta.

Relevant criteria: Simulation based; environmental factors.

Overview

This study explored various experimental fire scenarios in an underground drift at the Bierzo School Mine. The mine is located in La Ribera de Folgosos, León (Spain), and is under the jurisdiction of the Santa Barbara Foundation. The study examined the dynamics of key environmental factors, including airflow, temperature, oxygen, and pollutants, before and after the introduction of fire load. The progression of the fire was analysed to establish a trend based on the airflow and fuel load ratio. The study employed FDS to simulate the five most relevant experimental scenarios and established correlations between simulated and experimental outcomes.

Results

A comparison of the experimental and simulated results revealed a strong correlation, with an average maximum deviation of 24%. The study found the smallest deviations, around 10%, near the fire's origin in the upper part of the drift. This study suggested that simulation modelling is valuable for analysing and defining effective emergency measures and understanding the impact of fire incidents in critical mine areas.

Relevance

This study effectively assessed the impact of a fire incident in an underground mine drift. Examining the progression of the fire incident over time revealed the fluctuations in environmental factors in the ventilation network, which was crucial for this study's comprehensive analysis and success. The study results revealed that a sudden decrease in air supply had a more significant impact on gas concentration variation than an increase in fuel load. The assessment of the experimental findings offered significant insight into evaluating this study's experimental results.

Shortcomings

The study focused on the simulation of fire incidents at different heat loads, therefore lacking in the identification of specific fire hazards. This study concentrated on analysing the impact of fire

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incidents in a single underground mine drift, thus overlooking the broader context of a full-scale ventilation network in an underground mine. Its sole focus on the effects of fire incidents neglected the consideration of mitigating these effects once they occur. Various fire scenarios were simulated to verify the accuracy of the modelling against actual measurements. Consequently, this study did not develop a standardised method for determining worst-case scenario design fire curves.

Study 7 [21]

Title: Dealing with open fire in an underground coal mine by ventilation control techniques.

Author: N. Sahay, A. Sinha, B. Haribabu, and P.K. Roychoudhary.

Relevant criteria: Simulation based; environmental factors; ventilation control practices.

Overview

This study devised a methodology to address advanced stage underground fires using a modified ventilation-controlled approach. It offered insights into the behaviour of open fires, identification of problems, and the application of ventilation control techniques. The developed methodology effectively managed an open fire in Surakachhar 3 and 4 incline mine in central India.

Results

The methodology involved sealing the area upstream of the fire, short-circuiting airflow at the nearest point to the fire origin, and reducing the impact of fan and barometric pressure on the fire. The observed results from monitoring the fire's status suggest that this methodology is effective.

Relevance

This study investigated the distribution of pollutants in the ventilation network of an underground mine. A methodology was devised to mitigate the effect of a fire incident based on ventilation control practices. This study discussed techniques for managing open fires, the influence of ventilation, and the impact of air pressure on fire intensity. Such insights are vital for properly assessing the results of this study.

Shortcomings

This study concentrated solely on analysing pollutant distribution in the ventilation network, thus neglecting to report on temperature and airflow variations resulting from the implemented

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methodology. The study focused on simulating a specific fire scenario and, therefore, did not focus on developing a standard method for determining a worst-case scenario design fire curve.

Study 8 [57]

Title: Conducting a fire modeling study.

Author: B. Prosser and R. Ruckman.

Relevant criteria: Design fire scenarios; simulation based; environmental factors; ventilation control practices.

Overview

The authors conducted a comprehensive investigation into simulating several potential fire incidents in large underground mining operations. They derived a methodology for conducting fire modelling studies based on the obtained results. The study delved into the benefits and usefulness of fire modelling studies and addressed the limitations of such research. Moreover, it offered a method for performing risk analysis, and identifying and implementing strategies to minimise potential risks.

Results

The study presented the findings of an oxygen-rich fire burning at a refuelling facility in an underground haulage of a metal mine. The simulation model without intervention showed that the entire intake ventilation network would be engulfed in about 45 minutes. To mitigate this, the recommended action was to switch off the fans in the network after the fire has burned for approximately 10 minutes. As a result, the fire fumes moved towards the beginning of the haulage levels, and after approximately 20 minutes, they started to upcast in the fresh air raise due to the buoyancy of the hot fire fumes.

Relevance

This study assessed the effectiveness of simulation software in predicting fire incident outcomes in underground mine ventilation networks, which is relevant to the development of a solution for this study. Insight was gained into conducting hazard analysis and fire control procedures. Additionally, the study outlined the process of developing a fire model and identified essential factors for consideration.

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Shortcomings

The simulated scenario lacked evaluation of temperature and airflow fluctuations. Although the study examined the simulation of fire growth and fume spread throughout the ventilation network, it did not address a standardised method for defining a design fire curve for worst-case scenarios.

Study 9 [18]

Title: Underground fire rollback simulation in large scale ventilation models.

Author: C.M. Steward, S.M. Aminossadati, and M.S. Kazil.

Relevant criteria: Simulation based; Environmental factors.

Overview

The study explored the potential for developing a single network model that replicates both the ventilation system of a mining operation and the rollback behaviour on a smaller scale. It aimed to construct a detailed three-dimensional mesh of pathways around a fire to simulate its rollback behaviour. This localised simulation integrated into a simpler network representing the larger ventilation system. The study analysed this method, compared it with empirical approaches, and discussed its potential for fully simulating a mine's ventilation network without the need for complex computer analysis or empirical equations.

Results

The simulation results indicated that fume rollback happened roughly 40 metres upstream of the fire source. The complexity of these simulation outcomes implied that unforeseen conditions might arise during such a fire incident, potentially endangering mining personnel further. Consequently, the study recommended that the findings of this investigation be considered during the planning phase of any rescue or evacuation scenario.

Relevance

This study investigated the effect of a fire incident in the ventilation network of an underground mine. The study used simulation software to obtain the predicted results regarding the distribution of pollutants in an underground drift. This study offered insights into the impact of fume rollback on the ventilation network of an underground mine. The use of a simulation model provided valuable information that will contribute to the investigation conducted in this study.

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Shortcomings

The study focused on a single predetermined fire incident and lacked the evaluation of multiple fire hazards becoming an incident. The purpose of this study was to examine the impact of fume rollback; thus, it did not explore the effects of temperature and airflow variations on the entire ventilation network. Additionally, the study did not include any mitigation strategies based on ventilation control protocols to minimise or eliminate the effects of the fire incident. Due to the evaluation of the nature of the fire, no method was derived for defining a worst-case scenario fire design curve.

Study 10 [58]

Title: Numerical simulation and application study on a remote emergency rescue system during a belt fire in coal mines.

Author: K. Wang, S. Jiang, X. Ma, Z. Wu, H. Shao, W. Zhang, and C. Cui.

Relevant criteria: Simulation based; environmental factors; ventilation control practices.

Overview

The objective of this study was to evaluate the effectiveness of a fire smoke plume control system. The authors investigated the flow of fire smoke in the west-wing mining area of the Long-Dong coal mine, prompted by a conveyor belt fire incident. A mathematical model of the ventilation network was created to analyse the distribution of smoke parameters and airflow temperatures in the underground facility before and after implementing smoke flow control measures. These measures were simulated using Fluent software.

Results

The study results illustrated that approximately 37 minutes after the fire initiated, a smoke plume invaded the entire ventilation network of the west-wing area. The average temperature in the roadway was 58.85 °C, the O₂ concentration 5.1%, the CO₂ concentration 5.1%, and the CO concentration 0.98%. These results illustrate an unsafe working environment.

After the implementation of the smoke plume control system, the average temperature in the roadway was 28.85 °C, the oxygen concentration 19.1%, the CO₂ concentration 0.08%, and the CO concentration 0%. The simulation results illustrated that a smoke plume control system can alter the state of the ventilation system, avoid smoke plume from entering working areas, and extract the smoke plume into the return airway.

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Relevance

The spoke plume control system mainly consisted of a local automated air-door that regulated flow through the area. The study therefore used ventilation control practices to mitigate the effect of a fire incident. Alternatively, the study used simulation software to evaluate the effect of a fire incident in an underground facility.

Shortcomings

The study focused primarily on simulating a conveyor belt fire incident and did not evaluate multiple fire hazards. The focus point was localised on the west-wing mining area of the Long-Dong coal mine. A need therefore exists for investigating the effects of a fire incident on the entire ventilation network of an underground mine. The simulation did not characterise a design fire curve.

Study 11 [42]

Title: Design fires in underground hard rock mines.

Author: R. Hansen.

Relevant criteria: Design fire scenarios.

Overview

This thesis investigated design fire curves applicable to underground hard rock mines and presents results from scale fire experiments. Methodologies to determine the total HRR of multiple fuel objects under both uniform and non-uniform conditions were outlined. The study performed experimental tests in a 1:15 model-scale tunnel by using wooden pallets as fuel source. Parameters, such as the spacing between piles of wooden pallets and the longitudinal ventilation rate, were evaluated to examine the fluctuation in HRRs. Furthermore, the study explored several potential methods for determining the total HRR using model-scale fire experiments to validate the results.

Results

It was found that increasing the ventilation rates resulted in higher peak HRRs. Varying distances between ignited pallet piles affected ignition times of adjacent piles, with longer distances delaying ignition, resulting in staggered peak HRRs. A method based on critical heat flux as an ignition criterion showed good agreement with fire experiments for both uniform and non-uniform conditions.

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Relevance

The study addressed important safety considerations in underground hard rock mines regarding fire behaviour and HRRs. Understanding how ventilation affects fire dynamics can inform safety protocols and design considerations, which forms part of this study's outcomes.

Shortcomings

While the study provided valuable insights, it may have limitations in its scalability to real-world mining environments. Model-scale experiments may not fully capture the complexity and variability present in actual underground mines. The study reported on the importance and need for further investigation by using ventilation network simulation programs. The study discussed various types of design fire curves but did not establish a method for developing a standardised curve that could be applied to any worst-case scenario fire incident.

Study 12 [59]

Title: Simulation and optimization of evacuation routes in case of fire in underground mines.

Author: V. Adjiski, D. Mirakovski, Z. Despodov, and S. Mijalkovski.

Relevant criteria: Design fire scenarios; simulation based; environmental factors.

Overview

This study focused on identifying the most effective evacuation routes in underground mines in the event of a fire. Through computer simulation, the study created detailed evacuation plans by incorporating the analysis of various fire scenarios in the underground ventilation network. The proposed methodology aimed to enhance the effectiveness of evacuation and rescue efforts during a fire, ultimately saving lives and protecting the mine's financial investments.

Results

Through the evaluation of the rise in temperature and CO gases in the ventilation network, this study identified routes filled with smoke and fire gases, routes that are safe for travel, and the optimal route for evacuation.

Relevance

Although the study did not carry out a comprehensive fire risk assessment in the ventilation network of a specific underground mine, case studies were identified through risk assessments

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based on available statistics. This study used simulation software to evaluate the fluctuation in environmental factors throughout the entire ventilation network of an underground mine.

Shortcomings

The study primarily focused on developing effective evacuation routes but overlooked strategies related to ventilation control practices, which are crucial for mitigating the spread of environmental factors during a fire in underground mines. Although the study discussed factors relevant to design fires, such as HRR, gas flow rates, and material burning rates, it did not provide a method for determining standardised design fire curves for worst-case scenarios.

1.7.4 Evaluation of previous studies

The assessment of the studies provided clarity on the existing research and highlighted areas where contributions can be made in this field. Table 1-2 evaluates each study based on the criteria outlined in Section 1.7.3. Green indicates studies that focused on the identified criteria, while orange indicates those that did not consider them.

Table 1-2: Summary of the state-of-the-art criteria for underground fire simulation and emergency planning

Study number	Fire risk assessment	Design fire scenarios			Scale of simulation		Environmental factors			Remediation strategies
		Design fire	Standardised	Worst case	Partial	Full scale	Temperature	Pollutants	Airflow	
[1]										
[2]										
[3]										
[4]										
[5]										
[6]										
[7]										
[8]										
[9]										
[10]										
[11]										
[12]										

	Study considered criteria
	Study did not consider criteria

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Table 1-2 shows that adequate research has been undertaken to obtain the relevant knowledge in order to identify a clear gap in the field of simulating fires in underground mines.

The literature review has uncovered a significant gap in research as only a few studies have conducted comprehensive risk assessments to identify the hazards that pose the greatest risk for fire incidents. Furthermore, none of the existing studies have established a method for defining a design fire curve that accurately reflects the combustion process of a worst-case scenario fire incident. While there has been extensive research on determining design fire curves, there has been limited exploration of their application in ventilation simulation software. It is essential to address this gap in order to evaluate environmental fluctuations in a full-scale underground mine ventilation network and to develop effective ventilation control practices to mitigate their impacts.

1.8 Problem statement and objectives

Underground mine fires are very dangerous, yet most research focuses on the impact of a small subsection rather than examining the full impact throughout the entire ventilation network. While understanding design fires is essential for emergency planning, existing studies have often overlooked the integration of worst-case scenarios into ventilation simulation software. This oversight creates a substantial need for the development and utilisation of a simulation model that can accurately forecast the consequences of standardised design fires in the ventilation network of underground mines. Such a capability is crucial for formulating proactive planning strategies that effectively address fire incidents and ensure the safety of mineworkers.

To address this need, the aim of this study is to develop a calibrated simulation model that can accurately forecast the consequences of underground fire hazards. This will facilitate the formulation of effective remediation strategies, which will focus on ventilation control practices and will be specifically customised for scenarios where a fire has already been initiated. The study will pursue the following objectives:

1. Define a methodological approach to evaluate identified fire hazards and quantify the associated risks.
2. Construct, calibrate, and verify a simulation model for the entire ventilation system of an underground mine.
3. Develop a standardised method that can:
 - a. Define a worst-case design fire curve and simulate its impact on the ventilation network.

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- b. Identify remediation strategies based on ventilation control practices to combat fire incidents and implement these strategies in the ventilation simulation model to quantify their effectiveness.
4. Validate results through comparison with existing literature.

1.9 Study overview

1.9.1 Research methodology

The research objectives outlined in Section 1.8 define the standards that will determine the success of this study. To ensure that these objectives are met, a clear research methodology is needed to provide a systematic framework for conducting the research.

Section 1.2 to Section 1.7 of this study provided a contextual understanding of fires in the ventilation network of an underground mine. Furthermore, this study needs to comprehensively analyse specific case sites and design a holistic approach to remediate fires once they occur. This study will employ a research methodology that is based on a case study methodological approach [60]. To ensure that a case study methodology is sufficient to effectively support the research findings and recommendations of this study, it is essential to delineate how this study aligns with the principles of a case study methodology. Table 1-3 depicts how this study aligns with case study principles.

Table 1-3: Alignment of study with case study principles [60]

Case study principles	Study alignment	Applicable? (Yes/No)
Help to define the problem	Defining the problem accurately is crucial for guiding the research objectives and formulating effective solutions.	Yes
Facilitate contextual data collection	Collecting data within the context of a mine's layout, ventilation system, and geological conditions is essential for developing an accurate simulation model.	Yes
Adaptable to both quantitative and qualitative studies	Combining quantitative data, such as sensor readings and numerical simulations, with qualitative data from case studies to provide a comprehensive understanding of the problem.	Yes
Support data analysis and interpretation	Employing data analysis techniques to process data generated by the simulation model and extract adequate information that can identify proactive planning strategies.	Yes
Provide means for validation	Using validation mechanisms to confirm the effectiveness of the simulation model in accurately forecasting underground fires in underground mines, thus increasing confidence in the proposed proactive planning strategies.	Yes

Table 1-3 demonstrates that the case study methodology is well-suited for this study. Figure 1-12 illustrates the standard case study methodology that will be used to successfully address the objectives of this study.

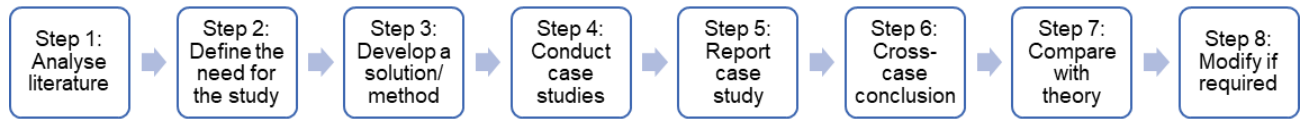


Figure 1-12: Flow diagram of a typical case study methodology [60]

Section 1.1 to Section 1.7 set the foundation of the literature review, which is required to achieve a comprehensive understanding of what this study entails. This section addressed the need for the study, which completes the first two steps of the research methodology.

1.9.2 Chapter outline

The case study methodology illustrated in Figure 1-12 sets the framework of the study. The steps depicted in Figure 1-12 are addressed in the chapters of this study, as shown in Figure 1-13.

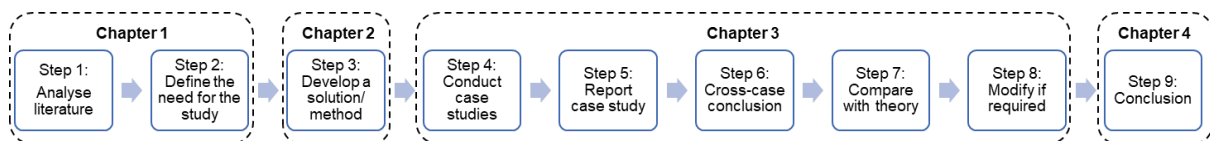


Figure 1-13: Study chapter overview and alignment with the research methodology

Below is a brief overview of each chapter that this study encompasses:

Chapter 1

Chapter 1 offered a detailed literature review, which was aimed at thoroughly understanding fire behaviour in the ventilation network of an underground mine. This review equipped the study with essential information for accurately approaching fire simulation modelling. Analysing essential groundwork helped to identify the problem and formulate the study objectives required to address. By identifying gaps and clearly illustrating the need for the study, this chapter completed the first step of the case study methodology as depicted in Figure 1-13.

Chapter 2

Chapter 2 outlines the development of the solution that was designed to address the research objectives identified in Section 1.8. Each required step to address the study's problem statement

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is discussed thoroughly, offering guidance on how these steps integrate the literature from Chapter 1 and how to implement them. This addresses the third step of the case study methodology.

Chapter 3

Chapter 3 presents the implementation of the solution from Chapter 2 in the ventilation network of an underground mine. It identifies and reports on various case studies, detailing the steps involved in the solution's development. This chapter specifically addresses Steps 4 and 5 of the case study methodology. This chapter concludes by examining the results from the case studies. The findings are compared with theoretical frameworks to assess whether any modifications are needed for the solution outlined in Chapter 2, covering Steps 6, 7, and 8 of the methodology.

Chapter 4

Chapter 4 presents a study overview, confirming the achievement of the research objectives and the resolution of the problem statement. It offers recommendations for future research in this field. This chapter addresses Step 9 of the case study methodology, thus concluding this study.

CHAPTER 2: DEVELOPMENT OF SOLUTION

2.1 Introduction

The aim of this chapter is to devise a solution for identifying and evaluating effective fire remediation strategies. This will be achieved by using a ventilation simulation model capable of simulating the effects of fire hazards after quantifying the associated risks. The development of the solution will include using existing literature, historical data, system information, and simulation software. Figure 2-1 illustrates the simplified solution developed in this chapter.

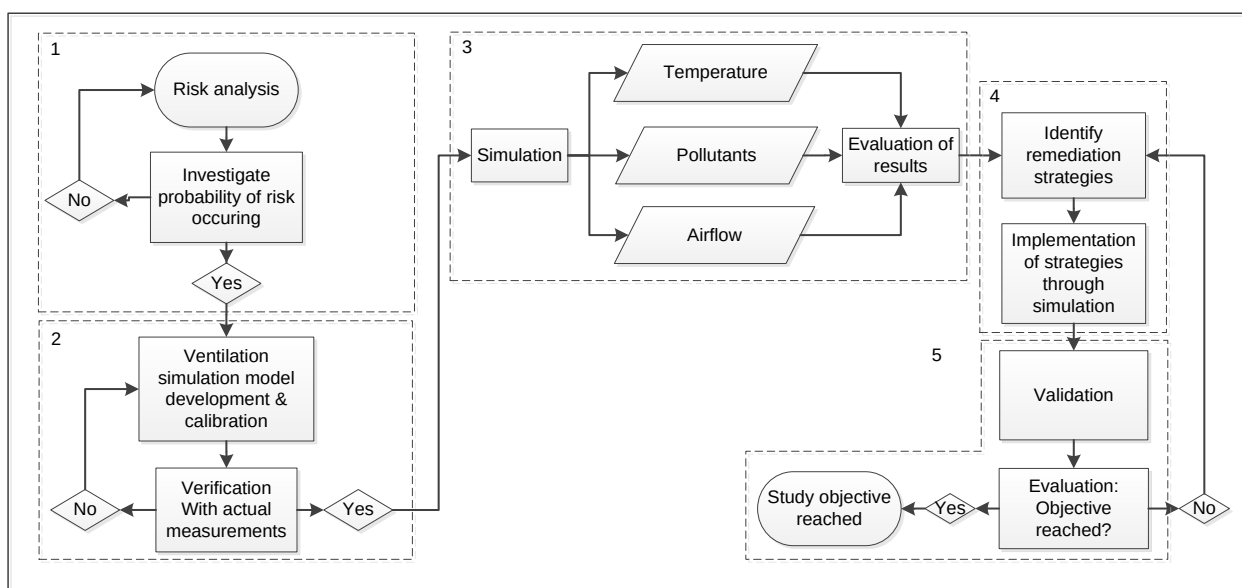


Figure 2-1: Basic proposed solution for simulating fires in underground mines for emergency planning

2.2 Risk analysis

2.2.1 Preamble

This section aims to utilise the industry-standard risk assessment procedure as a method for selecting the most suitable case study in the chosen underground mine. This method will identify fire hazards in the mine's ventilation network and assess the risk rating of each hazard. The hazard with the highest risk rating will be used for the case study.

2.2.2 Hazard assessment

The hazard assessment used in this study is a standard assessment developed by the mining enterprise that operates the mine on which this study's results are based. This assessment is

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developed to assess each fire hazard with the objective of complying with the requirements of Section 11 of the Mine Health and Safety Act, no. 29 of 1996 as amended.

For each hazard identified, the probability of the hazard becoming an incident is assessed along with the consequence the hazard poses once it becomes an incident. Table 2-1 illustrates the criteria for evaluating the consequence of a fire hazard.

Table 2-1: Evaluation of hazard consequence [57]

		H (Health)	S (Severity)	E (Environmental)	D (Damage)	L&R (Legal & regulatory)	R (Reputation)	C (Social/ Community)
Consequence/Severity	C5 (Catastrophic)	Impact on health is ultimately fatal	Multiple fatalities	Extreme environmental harm – incident irreversible	Substantial or total loss of operation/ more than R5m damages	Significant breach of law	International impact – international public attention	Major widespread social impact
	C4 (Major)	Irreversible impact on health, loss of quality of life/ permanent disability	Single fatality	Major environmental harm – incident remediable post life of mine	Partial loss of operation/ R1m to R5m damage	Breach of law may attract criminal prosecution	National impact – national public concern	Significant social impact
	C3 (Moderate)	Potential irreversible impact on health	Serious injury	Serious environmental harm – incident remedial in life of mine	Partial shutdown/ R100k to R1m damage	Minor breach of law	Considerable impact – regional public concern	Ongoing social issues
	C2 (Minor)	Require medical intervention and reversible impact on health	Lost time injury	Material environmental harm – incident remediable short term	Brief disruption to operations/ R10k to R100k damage	Breach of regulatory requirements	Limited impact – local public concern	Some impacts on local population
	C1 (Insignificant)	Exposure to minor health risk	First aid case	Minimal environmental harm	No disruption to operations/ below R10k damage	Technical non-compliance	Slight impact – awareness may exist	Minor disturbance of culture

The consequence of each identified hazard is assessed according to the columns in Table 2-1. Each of these categories evaluates the consequences of the hazard as follows:

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1. **H (Health):** Assesses the potential health impact resulting from a fire incident, ranging from minor health risks to irreversible health effects.
2. **S (Severity):** Assesses the severity of a fire incident, ranging from minor injuries to multiple fatalities.
3. **E (Environmental):** Evaluates the potential environmental damage due to a fire incident, categorised by different levels of environmental harm.
4. **D (Damage):** Reflects the financial impact on operations, ranging from minimal disruptions to substantial losses.
5. **L & R (Legal and regulatory breach):** Indicates the likelihood of breaching laws or regulations, from technical non-compliance to significant breaches.
6. **R (Reputation):** Considers the national or international impact on the organisation's reputation.
7. **C (Cultural/social impact):** Addresses the social or cultural disturbances that might arise from the fire incident.

Each fire hazard is assigned a consequence rating, ranging from C1 to C5, based on these categories. This rating is used together with the probability rating of each fire hazard to ascertain the risk rating. The probability rating is evaluated by referring to the categories assigned to the consequence rating. Table 2-2 lists the criteria for determining the probability of the fire hazard becoming an incident.

Table 2-2: Evaluation of hazard probability [57]

	Likelihood/Frequency/Probability				
	P1 (Rare)	P2 (Unlikely)	P3 (Possible)	P4 (Likely)	P5 (Almost certain)
Unwanted event (E, D, L&R, R, C)	Event may occur in next 20 years	Event may occur once every 5–10 years	Event may occur once every 2–5 years	Event may occur once every 1–2 years	Once a year
Safety incident (S)	< One per year	One (annually)	Few (monthly)	Many (weekly)	Full shift (daily)
Exposure (H)	1 person	2–10 persons	11–50 persons	51–100 persons	> 100 person

Table 2-2 considers the frequency of unwanted events, safety incidents, and number of people exposed when assigning a consequence rating to each identified fire hazard. These consequence ratings range from rare (P1) to almost certain (P5).

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The following key performance indicators (KPIs) are considered when determining the consequence and probability ratings of each identified fire hazard:

- Quantity (total number of hazard sources per type underground).
- Fuel type.
- Number of fuel sources.
- Ignition source (heat, electrical, mechanical, chemical).
- Location (intake airway/return airway).
- Proximity to other sources.

Once the probability and consequence ratings are known, the risk rating of each fire hazard can be determined using the risk matrix.

2.2.3 Risk matrix

The risk matrix acts as an extensive tool for managing risks, facilitating the identification and assessment of potential hazards. It plays a crucial role in selecting the case study, which will validate the effectiveness of fire risk management by utilising a ventilation simulation model. Table 2-3 displays the risk matrix used to assess each fire hazard.

Table 2-3: Risk matrix to be used in this study [57]

5 × 5 Risk Matrix						
Consequence/Severity	C5 (Catastrophic)	High risk – Stop fix – A – H15	High risk – Stop fix – A – H19	High risk – Stop fix – A – H22	High risk – Stop fix – A – H24	High risk – Stop fix – A – H25
	C4 (Major)	Medium risk – Immediate action plan – B – M12	High risk – Stop fix – A – H14	High risk – Stop fix – A – H18	High risk – Stop fix – A – H21	High risk – Stop fix – A – H23
	C3 (Moderate)	Medium risk – Immediate action plan – B – M9	Medium risk – Immediate action plan – B – M11	Medium risk – Immediate action plan – B – M13	High risk – Immediate action plan – B – M17	High risk – Stop fix – A – H20
	C2 (Minor)	Low risk – Action later – C – L3	Low risk – Action later – C – L5	Medium risk – Immediate action plan – B – M8	Medium risk – Immediate action plan – B – M10	High Risk – Stop fix – A – H16
	C1 (Insignificant)	Low risk – Action later – C – L1	Low risk – Action later – C – L2	Low risk – Action later – C – L4	Low risk – Action later – C – L6	Medium risk – Immediate action plan – B – M7
		P1 (Rare)	P2 (Unlikely)	P3 (Possible)	P4 (Likely)	P5 (Almost certain)
		Likelihood/Frequency/Probability				

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The risk matrix depicted in Table 2-3 features a numerical scale ranging from 1 to 25, where 1 represents the least significant risk and 25 represents the most catastrophic risk. In addition to these numerical values, the risks are categorised as shown in the Table 2-4.

Table 2-4: Risk matrix categories [57]

Risk level	Guideline for risk matrix	Risk category
H – high	Implement specific action plans	A
M – medium	Proactively manage	B
L – low	Monitor and manage as appropriate	C

Factors that pose a high risk are classified as Category A risks, which require specific action plans to mitigate their consequences. Medium-risk factors are classified as Category B risks, which require the implementation of appropriate systems to proactively manage their consequences. Low-risk factors are classified as Category C risks, which require that their consequences are monitored and managed accordingly.

For the sake of simplicity, this study only considers hazards that are permanently situated at specific locations and do not change position.

2.3 Development and verification of a simulation model

2.3.1 Preamble

To accurately simulate and predict the outcome of a fire in an underground mine, a well-calibrated ventilation model is essential. In a study carried out by Jacobs [61], a step-by-step method was derived for developing a ventilation simulation model. This methodology will form a crucial part of this study as it describes each element of the process of building a ventilation simulation model. The basic method for developing a ventilation simulation model is categorised in four main steps, namely obtain system information, construct the model, calibrate the model, and verify the model [61].

2.3.2 Obtain system information

To obtain the required system information, a combination of the methods followed by Jacobs [61] and Nel, Vosloo, and Mathews [62] has been utilised. Combining these methods ensures that all relevant aspects of this study are accounted for. Figure 2-2 illustrates the necessary information for constructing a ventilation simulation model of a mine ventilation network.

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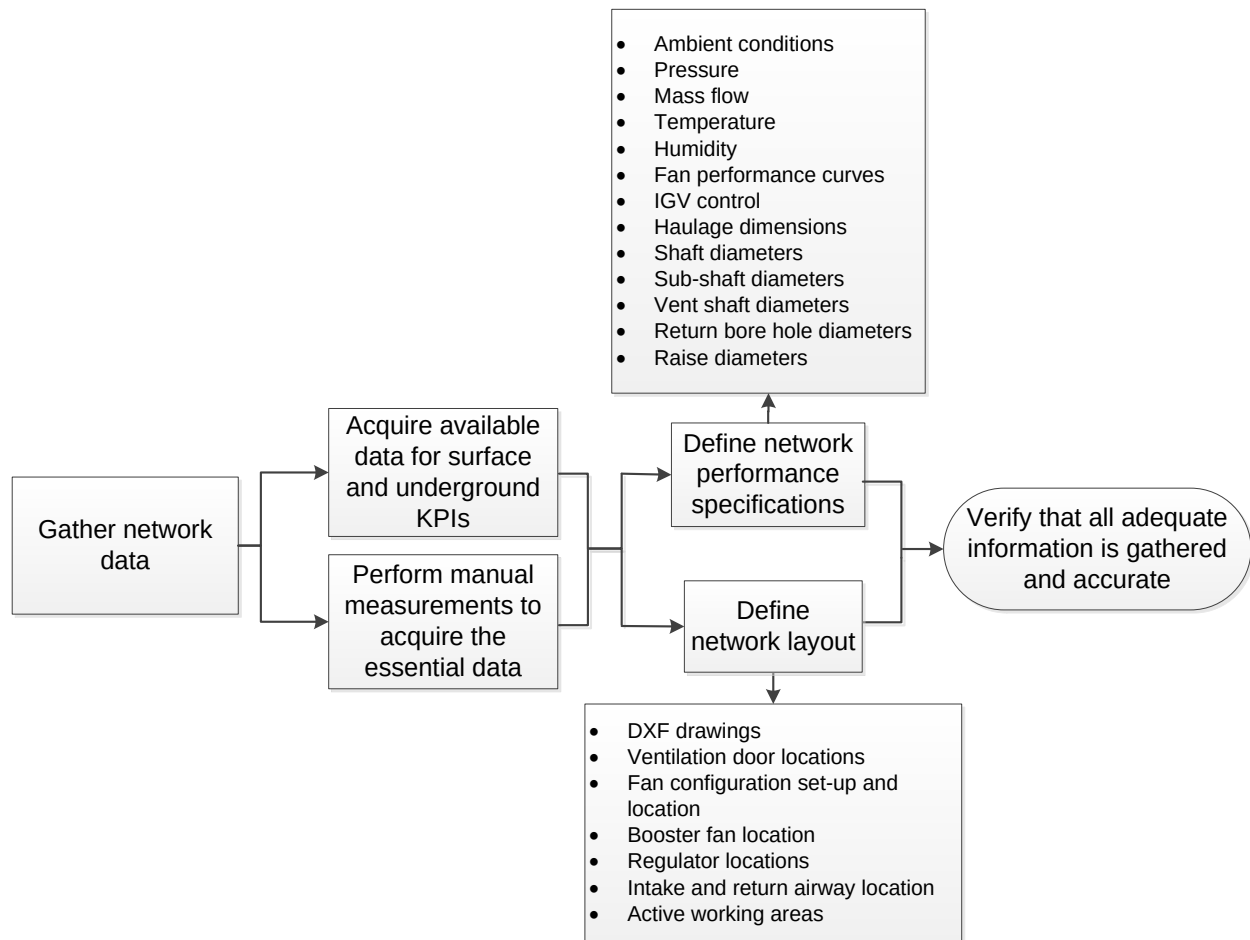


Figure 2-2: Method for obtaining a mine's ventilation network data [61, 62]

Figure 2-2 illustrates the recommended method for obtaining all the relevant network data. The first step in obtaining the necessary data is identifying the data that is readily available. According to the Mine Health and Safety Act, no. 29 of 1996, it is the responsibility of the employer to implement measures to ensure that the relevant survey records and plans, resulting from the conditions described in regulations 17(5)(a) to 17(5)(e), are regularly updated by the competent person referred to in regulation 17(2) at intervals not exceeding three months [14]. These survey records and plans form part of the gathering of available data for surface and underground KPIs.

The following ventilation network parameters are crucial when considering up-to-date information:

- Air mass flow [kg/s].
- Barometric pressure [kPa].
- Dry-bulb temperature [°C].
- Wet-bulb temperature [°C].

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These parameters form part of the calibration process and, if no data is available, manual underground ventilation audits are necessary to acquire the essential information. The process of conducting underground ventilation audits is fully described in the study conducted by Fair [63].

2.3.3 Construct model

To construct a comprehensive, dynamic, and integrated representation of the physical ventilation network of the mine under study, it is necessary to identify the simulation software package best suited for simulating fires in an underground mine. When selecting a simulation software package, several key aspects should be considered [35]:

- **Accuracy and realism:** The software should accurately depict the behaviour of fire in specific conditions of an underground mining environment. Factors resulting from fire such as airflow patterns, temperature variations, and pollutants should be accurately modelled.
- **Scalability:** The software should be capable of simulating the complexity of an integrated ventilation network that incorporates large-scale systems such as cooling and refrigeration processes.
- **Transient modelling:** The software should support transient simulation capabilities to account for the evolving nature of fires and their interactions with the ventilation network over time.
- **Time-step modelling:** The software should be able to simulate real-life time steps to ensure an accurate representation of the evolution of fire dynamics over time.

Each of these key aspects was utilised to assess which simulation software package, discussed in Section 1.5, would be the most appropriate for simulating the impact of fires in underground mines. The evaluation of the software packages is shown in Table 2-5.

Table 2-5: Ventilation simulation software package evaluation

Simulation software package	Accuracy and realism	Scalability	Transient modelling	Time-step modelling
Ventsim	✓		✓	
VUMA–network 5.0	✓		✓	
PTB	✓	✓	✓	✓

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Table 2-5 illustrates that PTB can accurately depict the evolving nature of a fire in an integrated ventilation network of an underground mine over a predetermined period. Therefore, this study will use PTB as the simulation software to conduct the identified case study. It should be noted, however, that the other software packages considered could also be suitable under different scenarios and investigations.

The process of constructing a ventilation simulation model involves creating the basic layout of the system using PTB. This entails accurately dividing the model into discrete components, placing equipment in their designated locations, adding cooling elements and appliances, and ensuring that the network is complete. It is important to realise that while the constructed model represents the overall structure of the system, it does not capture its performance [61].

While gathering the network layout data, as discussed in Section 2.3.2, a DXF file is obtained to construct the ventilation simulation model. Each line on the DXF file represents the coordinates and depth of the mine. These lines accurately depict the X, Y and Z coordinates of each underground location, properly configuring the system's elements in relation to one another [64]. Figure 2-3 illustrates the DXF file of level A of Mine A imported in PTB.

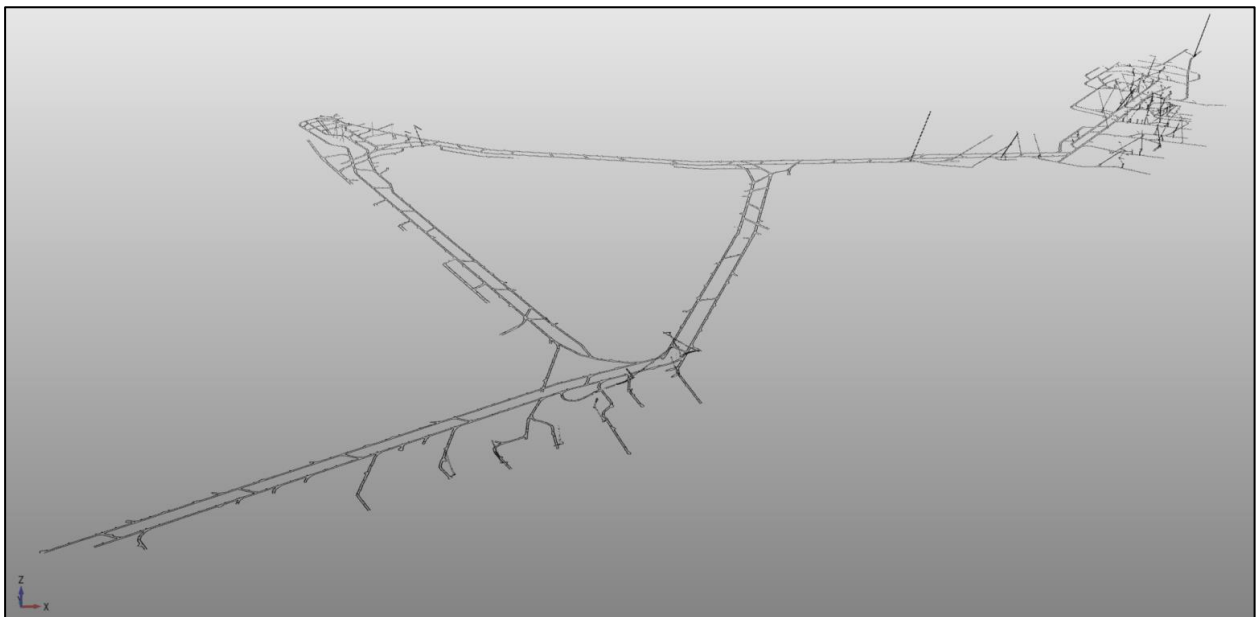


Figure 2-3: Example of a DXF file imported into PTB

PTB has a drag-and-drop function that allows users to conveniently place each component on imported DXF lines. This automatically adjusts the component's location according to the system layout [64]. The components dragged onto the PTB layout contains an auto-length function that operates in conjunction with the coordinates of the component it is linked with. This simplifies the

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construction of the ventilation simulation model by eliminating the need for a constant distance between two components. Figure 2-4 presents components that are dragged and dropped onto the DXF lines in PTB.

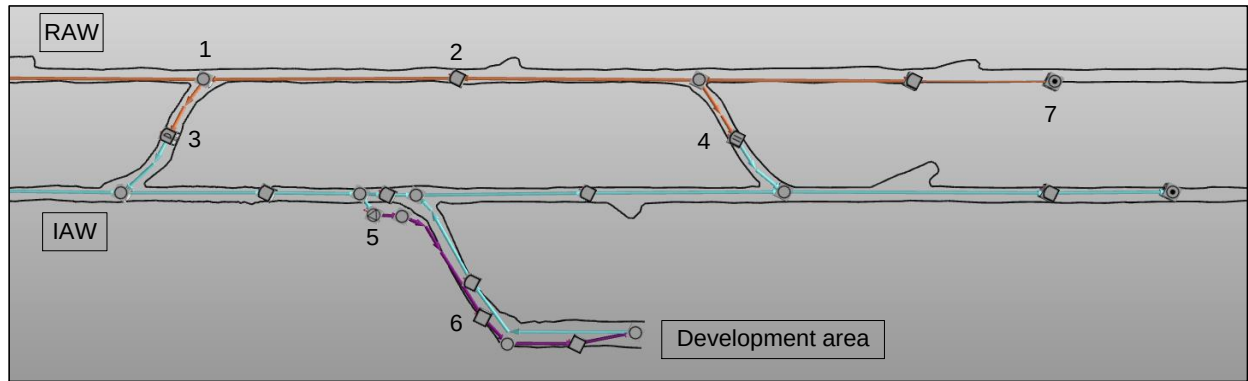


Figure 2-4: Example of components on DXF line in PTB

Figure 2-4 contains the most relevant components used in a ventilation simulation model. These components are as follows:

- | | |
|---------------------|--------------------------|
| 1. Air node | 5. Auxiliary fan |
| 2. Air tunnel | 6. Fan duct |
| 3. Ventilation door | 7. Air pressure boundary |
| 4. Wall | |

All the components mentioned above should be included in the skeleton model to create a true representation of the ventilation network. Characterising haulage involves defining the parameters such as haulage sizes, friction factors, and virgin rock temperature. To accurately represent the haulage areas in the ventilation simulation model, these variables must be entered into PTB as input values. This ensures that each haulage of each level can be defined precisely by its size, friction coefficient, door fraction, and virgin rock temperature [61].

The lines connecting the components are coloured with uniform colours to make it easier to distinguish between the various parts of the system. Intake airways are represented by light blue, return airways by orange, active mining areas by green, developing areas by purple, and areas without airflow by black [61].

Jacobs discussed the development of a ventilation simulation model in great detail [61]. Once the ventilation simulation model has been constructed, the calibration procedure can begin to create an accurate depiction of the system's performance.

2.3.4 Calibrate model

A calibrated ventilation model is necessary to accurately predict the outcome of an underground mine fire. At this stage of the development of the ventilation simulation model, the model should represent the actual layout of the mine. To ensure that the ventilation simulation model behaves in the same manner as the actual mine ventilation network, the methodological approach follows the method developed by Jacobs [61], as presented in Figure 2-5.

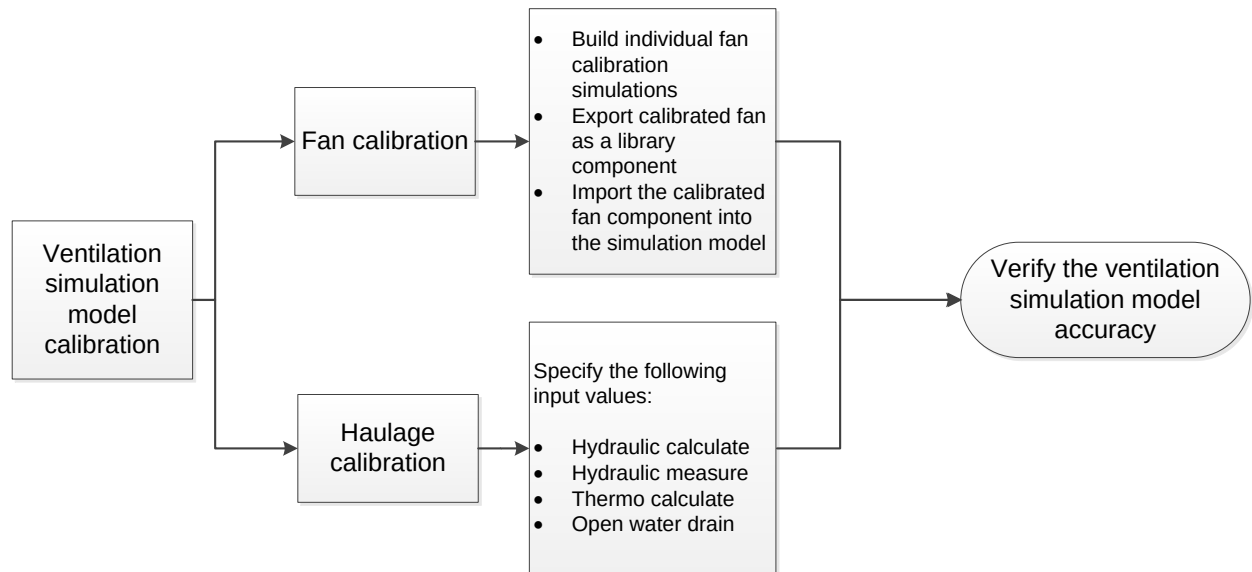


Figure 2-5: Method for calibrating a ventilation simulation model [61]

Fan calibration

Calibrating ventilation fans is a critical part of the calibration process because they significantly influence airflow within the ventilation network and play a key role in ensuring that adequate ventilation strategies are in place. The calibration process requires the specific fan performance curve of each fan that needs calibration, as obtained in Section 2.3.2. The first step is to build an individual simulation model in PTB that acts as a calibration tool. Figure 2-6 illustrates the simulation model developed in PTB.

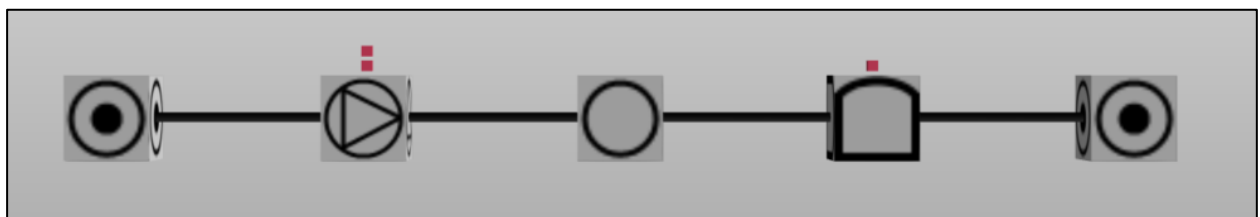


Figure 2-6: Fan calibration model simulated in PTB [61]

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This calibration model includes two pressure boundaries that ensure a pressure difference across the fan. The properties of the inlet pressure boundary are determined based on the inlet conditions used to plot the performance curve of the fan. The outlet air pressure boundary requires the barometric pressure needed to establish the appropriate pressure difference over the fan.

The properties used for the input values of the fan are obtained from the performance curve of the fan. These performance curves mostly illustrate pressure versus flow and power versus flow. The efficiency of the fan can be determined from the known properties. For the input values of the fan, three points are used on the pressure versus flow performance curve and the efficiency of each point is determined. The air density obtained from the performance curve is also required as an input value. Thereafter, the calibration model is simulated, and the fan performance curve is compared with the actual fan performance curve to determine if they correlate. Figure 2-7 illustrates the fan performance curve of a fan calibrated in PTB.

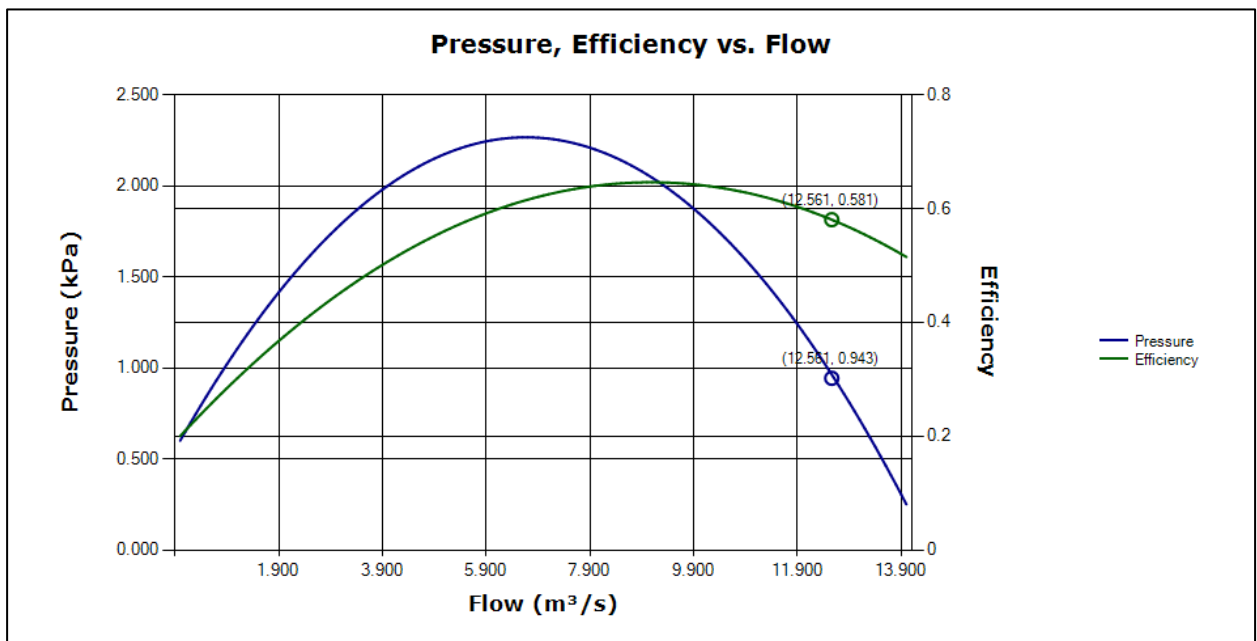


Figure 2-7: Extract of a fan's performance curve calibrated in PTB

Figure 2-7 illustrates the performance curve of the fan in relation to the pressure difference depicted by the air pressure boundaries. Once the fan operates on its performance curve for any pressure within its range, the fan can be considered calibrated [61]. The calibrated fan is exported as a library component, which can then be imported into the main ventilation simulation model.

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Haulage calibration

Underground haulage areas are represented as air tunnels in PTB. The system information gathered in Section 2.3.2 is used as input values to calibrate the air tunnels. Table 2-6 contains a description of each input value used to calibrate an air tunnel accurately.

Table 2-6: Required ventilation air tunnel input values

Category	Input	Purpose
Hydraulic calculate	Flow area [m ²]	Provides the tunnel flow area.
	Flow perimeter [m]	Provides the tunnel flow perimeter.
	Tunnel length [m]	PTB contains a built-in auto-length calculator that automatically determines the length between two air tunnel components.
	Friction coefficient	The Atkinson friction factor for the tunnel characterises the resistance of the airflow in the tunnel.
	Door fraction	Suggests the ventilation door opening between 0 and 1, where 0 means totally closed and 1 means 100% open.
Hydraulic measure	Hydraulic measure active	For an entered value of: - 0 = Option is inactive - 1 = Option is active
	Flow [kg/s]	Provides the tunnel mass flow rate.
	Inlet pressure [kPa]	Provides the total inlet air pressure.
	Outlet pressure [kPa]	Provides the total outlet air pressure.
	Inlet temperature [°C]	Provides the tunnel inlet air temperature.
Thermo calculate	Thermo calculate active	For an entered value of: - 0 = Option is inactive - 1 = Option is active
	Surface virgin rock temperature [°C]	Provides the temperature of the undisturbed rock material on the mine's surface area.
	Virgin rock temperature gradient [°C/m]	Provides the rate of change in temperature with respect to the depth of the mine.
	Days exposed	Provides the duration of time that the specified area has been exposed to certain conditions.
	Rock thermal conductivity [kW/m]	Provides the intrinsic property of rock to determine the efficiency of heat transmission.
	Rock density [kg/m ³]	Provides the mass per volume of the rock.
	Rock specific heat [kJ/kg/°C]	Provides the underground rock property, specific heat, which depicts the rock's capability to store and release heat.
	Wet area fraction	Refers to the fraction of the tunnel inside surface area that is covered by water.
	Heat [kW/m]	Provides the internal head load per tunnel length.
	Latent heat [kW/m]	Provides the heat transfer associated with the phase change of moisture in the air.
	Transient rock active	For an entered value of: - 0 = Option is inactive - 1 = Option is active
Open water drain	Open drain active	For an entered value of: - 0 = Option is inactive - 1 = Option is active
	Inlet water temperature [°C]	Provides the temperature of the water flowing in the open water drain.
	Water flow rate [kg/s]	Provides the rate at which the water flows.
	Drain width [m]	Provides the width of the open water drain.

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Table 2-6 provides all the relevant input values that are required to simulate the actual conditions of an underground tunnel. These input values form part of the gathering of system information as discussed in Section 2.3.2. The air tunnel component is considered calibrated once all these input values have been entered. The air tunnel component can be exported as a library component and used in the main ventilation simulation. However, it is crucial to note that certain input values are depth-dependent and therefore require updating based on the specific depth being considered.

2.3.5 Verify model

A ventilation simulation model is verified by comparing the outputs of the calibrated simulation model with the actual audit data. The simulation model is considered calibrated when the outputs of the simulation model deviate by less than 5% from the actual audit data, which is considered to be accurate in the mining industry [61]. Due to the unique ventilation layout of each underground mine, it is necessary to specify the locations that are required to be at least 95% accurate.

Section 2.3.2 outlined the process of identifying all active working areas in an underground mine. These areas are of primary focus due to their significant fire risk impact on employee health and safety. Ensuring that environmental variables are verified in high-risk areas helps to ensure that the simulation model accurately reflects real-world conditions. Since these areas are crucial to mining operations, validating them with actual measurements provides a strong basis for assuming the overall accuracy of the model.

The environmental variables applicable to all underground mine fire risk regions are as follows:

- Level intake air mass flow [kg/s], dry-bulb temperature [°C], wet-bulb temperature [°C], and barometric pressure [kPa].
- Active stoping cross-cut intake air mass flow [kg/s], dry-bulb temperature [°C], wet-bulb temperature [°C], and barometric pressure [kPa].
- Active development cross-cut intake air mass flow [kg/s], dry-bulb temperature [°C], wet-bulb temperature [°C], and barometric pressure [kPa].

2.4 Simulation of impact

2.4.1 Preamble

This section aims to develop a method for simulating the effects of a fire incident in the ventilation network of an underground mine. In Chapter 1 of this study, the relevant aspects of a fire incident

were thoroughly investigated to create a robust method that can predict the worst-case outcome for any identified fire risk. This is accomplished by determining the fire design curve, simulating the set-up in PTB, and evaluating the results.

2.4.2 Determination of the fire design curve

It is necessary to determine an accurate method for simulating a worst-case scenario for any identified fire hazard. Section 1.6 discussed the relevant design fire methods found in literature. These methods are used as reference [42, 44-47, 50-52] for the methodology devised in this section, as illustrated in Figure 2-8.

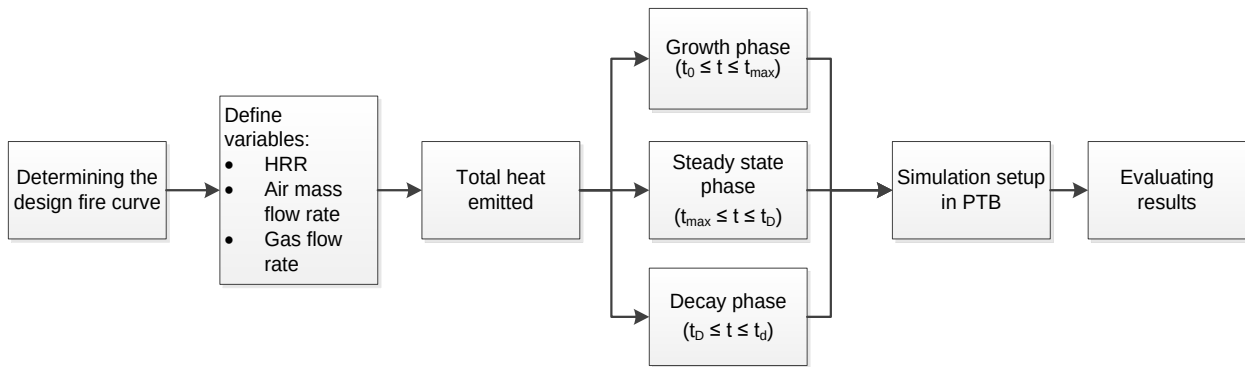


Figure 2-8: Method for determining the fire design curve [42, 44-47, 50-52]

The variables used to characterise the design fire in this study are the input values required by PTB to replicate the effects of a fire on the ventilation network of an underground mine. These variables include $HRR = \dot{Q}$ [kW], air mass flow rate = $\dot{m}_a$ [kg/s], and gas flow rate = $\dot{G}$ [kg/s].

HRR

To predict a realistic HRR model of a hypothetical fire scenario, it is necessary to determine the total heat that can be emitted by the material. Section 1.6.3 described the cone calorimeter test. This method provides a measure known as the effective heat of combustion, which represents the heat release per unit mass consumed. This measure can be used to estimate the total heat released by a material with a known mass [65]. The total heat emitted by the material that acts as the fuel source in the hypothetical fire incident is determined as follows:

$$E_{fuel} = H_c \times m_{fuel} \quad (7)$$

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Where:

$$\begin{aligned} E_{fuel} &= \text{Total heat emitted by the fuel [MJ]} \\ H_c &= \text{Effective heat of combustion [MJ/kg]} \\ m_{fuel} &= \text{Mass of the fuel source [kg]} \end{aligned}$$

In order to determine the HRR curve for a fire incident with a known total heat emitted value, it is necessary to identify the profile and duration of each stage of the fire incident. This study focuses on a three-step modelling approach, which includes a growth, steady-state, and decay phase to represent the hypothetical fire incident.

1. Growth phase

Section 1.6.4 discussed the standard HRR models found in literature. Based on these methods, it has been found that a quadratic function of time is the best way to realistically capture the rapid increase in fire intensity during the growth phase. The growth phase occurs between time t_0 and time t_{max} and is expressed as follows:

$$\dot{Q}_g(t) = \alpha_{g,q} t^2 \quad (8)$$

Where:

$$\begin{aligned} \dot{Q}_g(t) &= \text{HRR at time } t \text{ for } t < t_{max} \text{ [kW]} \\ \alpha_{g,q} &= \text{Quadratic fire growth rate [kW/s}^2\text{]} \\ t &= \text{Time [s]} \end{aligned}$$

The duration of this phase is determined by the time it takes for the fire incident to reach steady state. Steady state is reached once the fire incident reaches a constant maximum HRR. The time it takes to reach steady state is therefore referred to as t_{max} , and is expressed as follows:

$$t_{max} = \sqrt{\frac{\dot{Q}_{max}}{\alpha_{g,q}}} \quad (9)$$

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Where:

t_{max} = Time the fire incident takes to reach steady state [s]

$\dot{Q}_{max}$ = Maximum HRR [kW]

The maximum HRR and quadratic fire growth rate are typically determined by investigating the material's combustion capabilities under different ventilation conditions, as described in Section 1.6.3. With these known values, a curve representing the heat released during the growth phase can be compiled. The total heat released during this stage is determined as follows:

$$E_g = \int_0^{t_{max}} \alpha_{g,q} t^2 dt \quad (10)$$

2. Steady-state phase

As mentioned previously, the steady-state phase occurs once the fire incident reaches its peak HRR. For the worst-case scenario, it is assumed that the fire incident will remain in a steady-state phase until the decay phase begins at time t_D . According to ISO/TC 92 [66], the decay phase tends to occur once 80% of the available fuel has been consumed. The steady-state phase is therefore expressed as follows:

$$\dot{Q}_{ss}(t) = \dot{Q}_{max}, (t_{max} \leq t \leq t_D) \quad (11)$$

If 80% of the fuel is consumed during the growth and steady-state phases, the duration of the steady-state phase is determined by calculating the total heat emitted during this period:

$$E_{ss} = 0.8E_{fuel} - E_g \quad (12)$$

The duration of steady-state phase from time t_{max} to time t_D is then derived as follows:

$$t_{ss} = \frac{E_{ss}}{\dot{Q}_{max}} \quad (13)$$

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3. Decay phase

To represent the worst-case scenario, it is assumed that the remaining 20% of the fuel is consumed during the decay phase. The HRR curve for this study is taken to be a linear function of time, which is expressed as follows:

$$\dot{Q}_d(t) = \dot{Q}_{max}(1 - \frac{t}{t_d}) \quad (14)$$

Where:

$\dot{Q}_d(t)$ = HRR at time t for $t_D < t < t_d$ [kW]

t_d = Time until complete fuel consumption occurs [s]

The total heat emitted during the decay phase is expressed as the area under the linear decay HRR curve:

$$E_d = \int_0^{t_{decay}} \dot{Q}_d(t) dt = 0.2E_{fuel} \quad (15)$$

Through the integration of the HRR curve, the time t_d is determined and denoted as follows:

$$t_d = \frac{0.4E_{fuel}}{\dot{Q}_{max}} \quad (16)$$

By combining Equations 8, 11, and 14, the design fire curve can be configured, which will be used to define this study's hypothetical fire scenario. Figure 2-9 illustrates the configured design fire curve for this study.

Simulating underground mine fires for emergency planning

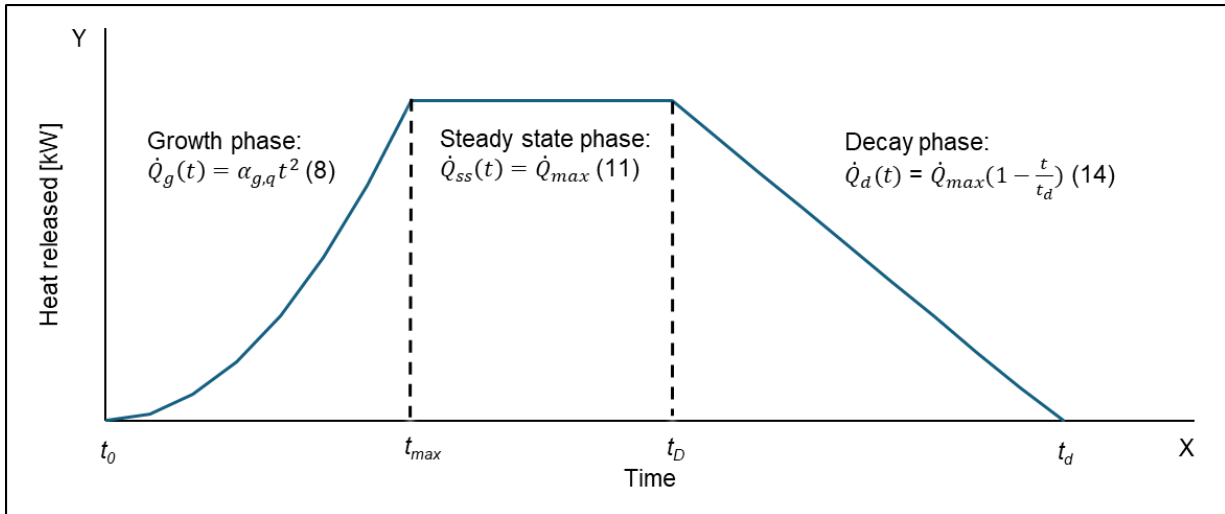


Figure 2-9: Devised design fire curve for this study

Air mass flow rate

To accurately simulate the design fire curve derived above, PTB requires a constant air mass flow rate in kg/s as input. This value represents the maximum amount of air required for the fire to sustain steady-state combustion. The air mass flow rate indicates how much air and, therefore, oxygen is being supplied to the fire. To sustain the maximum HRR during the steady-state phase, the air mass flow rate should also be at its peak to meet the demand for oxygen [43]. Figure 2-10 illustrates the assumption derived from literature for the air mass flow rate at peak HRR.

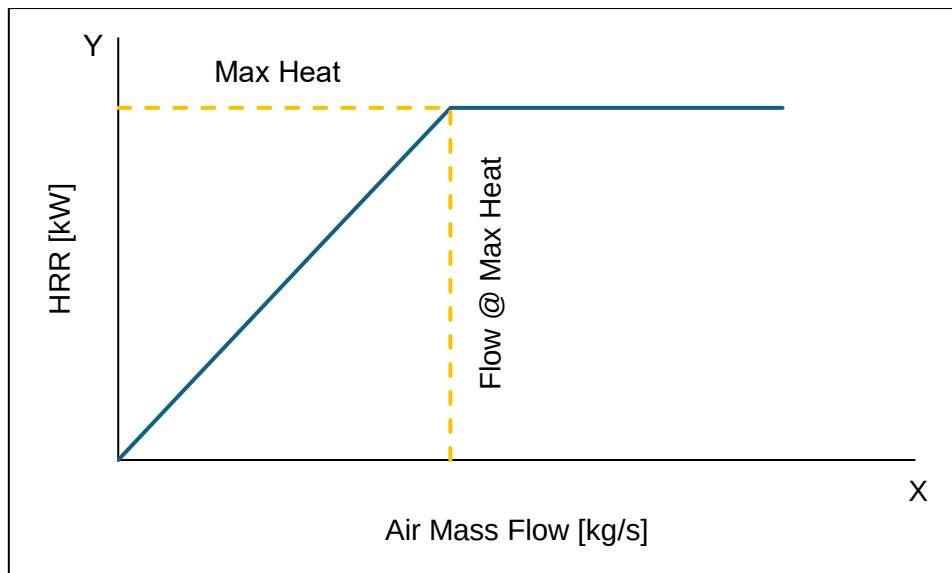


Figure 2-10: Correlation between the HRR and air mass flow rate [43]

Simulating underground mine fires for emergency planning

Figure 2-10 illustrates the relationship between the HRR and the air mass flow rate during the combustion process. If the air mass flow rate exceeds what is necessary for the maximum HRR to sustain a steady-state phase, the HRR will not increase further as it is limited by the amount of fuel available as well as the combustion conditions. The value required by PTB for the air mass flow rate is therefore the air mass flow rate required to reach the maximum HRR.

Gas flow rate

The gas flow rate is a crucial aspect of this study because the gas emitted poses a serious threat to the health and safety of employees. For the worst-case scenario, it is necessary to determine the gas that poses the most significant threat. Table 1-1 in Section 1.4.1 lists the occupational exposure limits (OELs) for the airborne pollutants most commonly found in underground mine ventilation networks. Therefore, it is necessary to devise a method for determining the toxicity of a material based on these OELs.

During a cone calorimeter test, the gases produced during combustion are measured. The concentration of these gases and the OELs provided in Table 1-1 are used to determine a normalised value for each gas present. These normalised values are determined as follows:

$$NV = \frac{\text{Measured Concentration [ppm]}}{OEL \text{ [ppm]}} \quad (17)$$

The gas with the highest normalised value is used to investigate the gas distribution in the ventilation network of the underground mine.

The combustion process that dictates the HRR also dictates gas production. A higher HRR indicates a more intense combustion, which consumes more fuel and thus produces more gases [43]. Therefore, it can be assumed that as the fire grows, reaches a peak, and decays over time, both the HRR and gas flow rate will follow the design curve illustrated in Figure 2-9. For this study, the production of combustion gases is assumed to be directly proportional to the HRR.

Since the maximum gas release rate is assumed to be the gas release rate at $\dot{Q}_{max}$, the following variables are assumed to be the same as for the HRR design fire curve illustrated in Figure 2-9:

- t_0
- t_{max}
- t_D
- t_d

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The only unknown variable is the gas flow growth rate, which is obtained as follows:

$$\alpha_{ggr} = \frac{\dot{G}_{max}}{t_{max}^2} \quad (18)$$

Where:

$$\begin{aligned} \alpha_{ggr} &= \text{Gas flow growth rate [kg/s}^3\text{]} \\ \dot{G}_{max} &= \text{Maximum gas flow rate [kg/s]} \end{aligned}$$

Each stage of the gas flow rate during the fire combustion process is expressed as follows:

$$\text{Growth phase:} \quad \dot{G}(t) = \dot{G}_g(t) = \alpha_{ggr} t^2 \quad t_0 \leq t \leq t_{max} \quad (19)$$

$$\text{Steady-state phase:} \quad \dot{G}(t) = \dot{G}_{max} \quad t_{max} \leq t \leq t_D \quad (20)$$

$$\text{Decay phase:} \quad \dot{G}_d(t) = \dot{G}_{max} \left(1 - \frac{t}{t_d}\right) \quad t_D \leq t \leq t_d \quad (21)$$

The simulation of the HRR, air mass flow rate, and gas flow rate provides an accurate representation of the worst-case scenario fire incident. The representation is evaluated to develop the most effective emergency planning strategies using ventilation simulation procedures.

2.4.3 Simulation set-up in PTB

The combustion process of a fire incident is a dynamic process with variables that change continuously over time [43]. Performing a transient simulation is essential to accurately predict the nature of the fire caused by the hazard with the highest risk factor. The simulation set-up requires the input values specified in Section 2.4.2. The input values and process of transient simulation modelling apply to any simulation set-up, regardless of software package chosen.

As mentioned previously, other software packages can also be used to investigate the effects of a dynamic fire model in underground mine ventilation networks. The simulation set-up in PTB, however, differs. Appendix F describes the procedure that has to be followed to perform a transient fire simulation in PTB effectively [67]. This procedure provides the step-by-step method for accurately simulating the effects of a hypothetical fire scenario in the ventilation network of an underground mine. Based on the results obtained, the effects can be evaluated to determine the most effective remediation strategies.

2.4.4 Evaluation of results

To evaluate the results obtained by following the procedures discussed in Table F-1, a specific set of KPIs must be used within a predetermined boundary condition in the ventilation network of the underground mine.

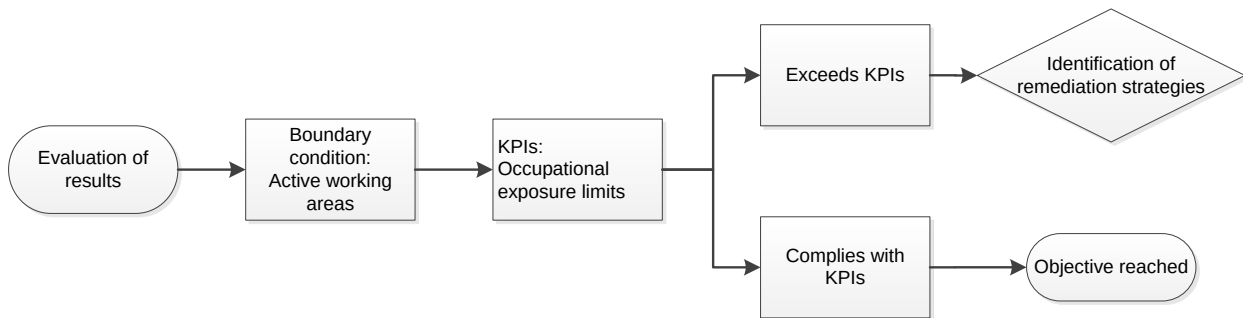


Figure 2-11: Method for evaluating the results of the fire incident [14]

Figure 2-11 illustrates the process for evaluating the results obtained from simulating a hypothetical fire scenario in the underground mine's ventilation network. Section 2.3.2 discussed how the relevant system information is gathered, which includes the active working areas requiring adequate ventilation. These areas define the boundary condition required to sustain a ventilation demand that complies with the KPIs, which are the OELs defined in Table 1-1. Whenever these KPIs are exceeded, adequate remediation strategies are required to reduce the effect of the fire incident.

To illustrate all the areas at risk within the defined boundary conditions, a temperature gradient colour map and a gas concentration colour map are generated in PTB after simulating the fire scenario. Figure 2-12 is a typical example of a colour map that indicates the distribution of temperature due to a simulated fire incident.

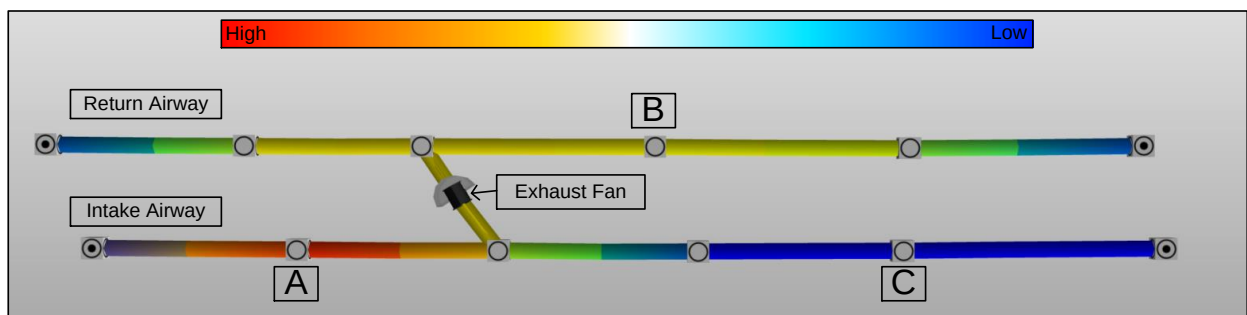


Figure 2-12: Colourmap illustration of a simulated fire incident in PTB

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Figure 2-12 depicts the temperature distribution resulting from a standard fire incident in the intake airway. The colour scale visually represents the temperature distribution, with blue indicating areas with low temperature and red indicating areas with high temperatures. Point A, where the fire originated, is considered an area of high temperature followed by Point B where temperatures are moderate. Point C is considered an area of low temperature, which does not pose a risk to the health and safety of employees. A colour map depicting the distribution of gas concentrations in the air can also be generated to ensure that all possible high-risk work areas are identified within the defined boundary conditions.

The results obtained from simulating the impact serve as the baseline for identifying and implementing the remediation strategies.

2.5 Identification and implementation of remediation strategies

2.5.1 Preamble

The identification and implementation of remediation strategies aim to reduce or eliminate the effects of a hypothetical fire scenario. This section devises a method for completing the third objective of this study by identifying and implementing remediation strategies.

2.5.2 Identification of remediation strategies

Chapter 1 discussed the effects of fires on the underground ventilation networks of mines, along with the methods for controlling fire incidents. These effects refer to the localised effect that must be eliminated in order to reduce its impact on the ventilation network area, as evaluated in Section 2.4.4. The effects are addressed by the indirect methods for controlling fire incidents. Figure 2-13 illustrates the proposed method for identifying remediation strategies based on literature.

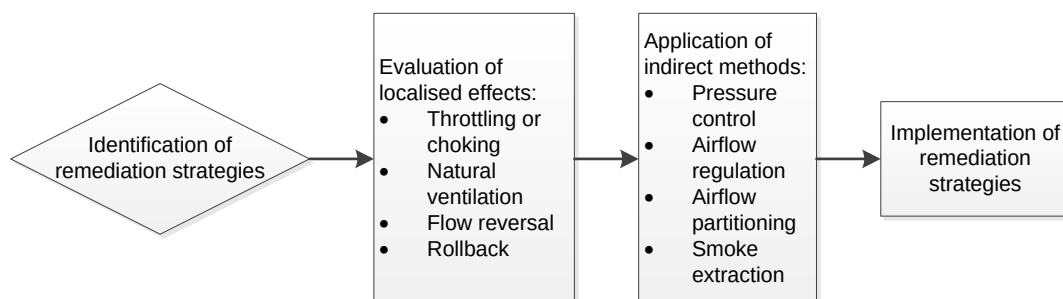


Figure 2-13: Proposed method for identifying remediation strategies for underground fires [17-19, 26-29]

The method for identifying remediation strategies, illustrated in Figure 2-13, is an iterative process. Each indirect method can be applied to address the localised effects of a fire incident based on the layout of the ventilation network where it originates. Remediating the localised effect will, in turn, alleviate the impact on the area within the identified boundary condition.

2.5.3 Implementation of remediation strategies

The implementation of the identified remediation strategies completes the second part of Objective 3 of this study. Figure 2-14 illustrates the method for implementing the identified remediation strategy.

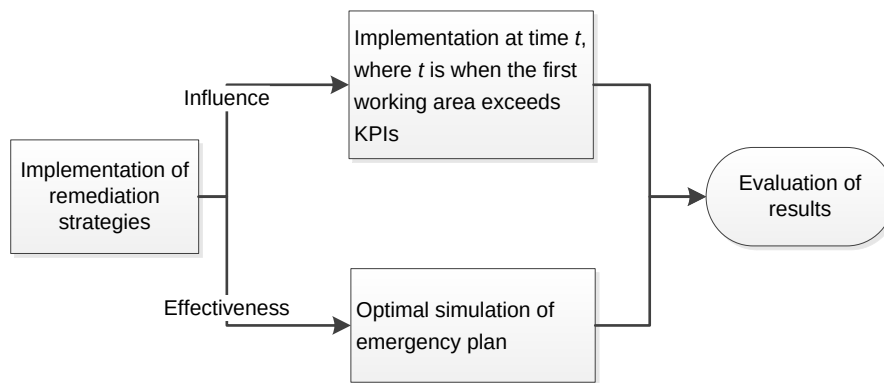


Figure 2-14: Proposed method for implementing remediation strategies

The purpose of the method illustrated in Figure 2-14 is to demonstrate the influence and effectiveness of the devised remediation strategy. The influence of the remediation strategy is evaluated by determining the maximum time required to implement it and demonstrating its impact. The remediation strategy is introduced to the ventilation network at time t , which denotes the point when the first working area exceeds the identified KPIs.

The effectiveness of the remediation strategies is determined by implementing them as intended and ensuring they operate as designed. This evaluation confirms whether any active working area remains unaffected, thus verifying the success of the applied strategies.

For simulations of both influence and effectiveness, the fire scenario is assumed to extend from time t_0 to time t_d in order to account for a worst-case scenario where direct methods of combating the fire are not accounted for.

2.6 Verification of the developed solution

To verify the devised solution of this study, the state-of-the art criteria identified in Section 1.7.4 have to be met. Table 2-7 illustrates the sections of the solution development devised in this chapter that meet the identified criteria.

Table 2-7: Verification of the proposed solution

State-of-the art criteria		Section	Solution considered criteria (Yes/No)
Risk assessment		2.2	Yes
Design fire scenarios	Design fire	2.4.2	Yes
	Standardised	2.4.2	Yes
	Worst-case	2.4.2	Yes
Full-scale simulation		2.3	Yes
Environmental factors	Temperature	2.4.4	Yes
	Pollutants	2.4.4	Yes
	Airflow	2.4.4	Yes
Remediation strategies		2.5	Yes

Table 2-7 shows that each criterion of the state-of-the art matrix is met when the devised solution is implemented on an actual case study.

2.7 Conclusion

The solution developed for this study comprises a combination of various methodologies that provide a comprehensive approach to simulate a fire in the ventilation network of an underground mine for emergency planning. Each method includes a visual representation of the necessary processes. Figure 2-15 illustrates how these visual representations combine to form the complete solution developed for this study.

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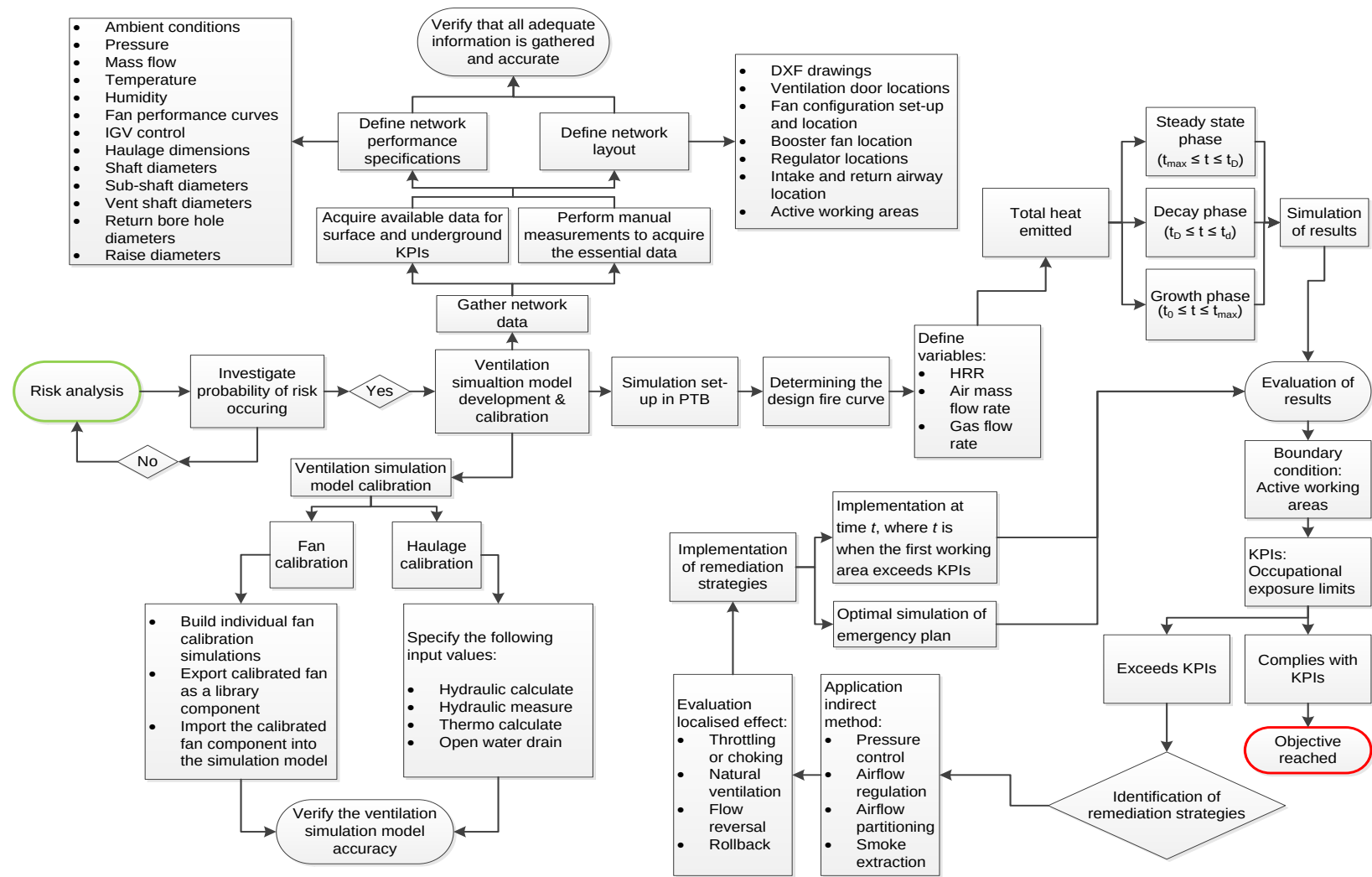


Figure 2-15: Complete proposed solution for simulating fires in underground mines for emergency planning

CHAPTER 3: CASE STUDY

3.1 Introduction and case study background

This chapter investigates the implementation of the solution that was developed in Chapter 2 based on the identified case study. To provide the necessary information relevant to the study's outcomes, an overview of the mine used for the case study is included. The case study mine is referred to as Mine A going forward to maintain confidentiality.

This chapter evaluates the effectiveness of developing a calibrated and verified ventilation simulation model that can predict the outcome of a fire incident on the entire ventilation network of Mine A. Additionally, it assesses the effectiveness of the identified remediation strategy to validate the necessity of this study.

3.1.1 General information

Mine A is a twin-shaft gold mining operation that utilises a scattered mining approach on the Beatrix Reef. It focuses on selective areas at an average depth of 1 300 m below surface while leaving complex mining areas unmined. The mine is located in the Free State region of South Africa and is situated at the south-western edge of the Witwatersrand Basin.

The latest available public statistics from Mine A's gold mining and exploration enterprise indicate that in the 2010 financial year, 27 254 shifts were lost due to occupational injury or illness. These lost shifts resulted in decreased production and subsequently lower revenue. Figure 3-1 illustrates the revenue losses incurred by the mining enterprise that owns Mine A from the 2006 to the 2010 financial year as a result of fatalities.

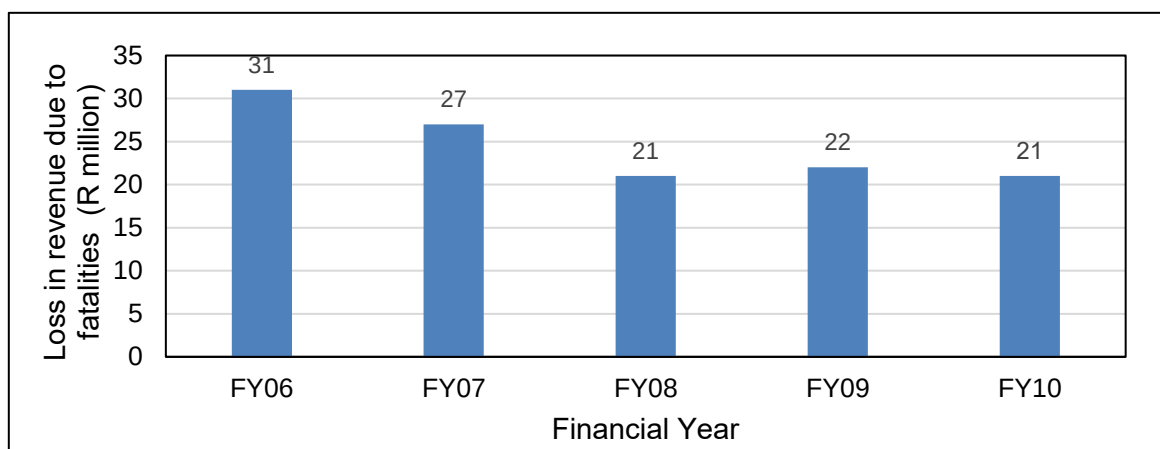


Figure 3-1: Mine A's loss in revenue due to fatalities

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Figure 3-1 illustrates the importance of occupational safety in the continuous exploration of gold deposits. The aim is to utilise a ventilation simulation model of Mine A to achieve the objectives of this study and contribute to the proactive planning for optimal occupational safety, with a focus on fire-related incidents.

3.1.2 Mine A's ventilation network

The ventilation network of Mine A consists of two downcast shafts and one upcast shaft. Mine A relies solely on ambient conditions and does not use any surface refrigeration. The mine has four active working levels with depths ranging from 1 170 m to 1 418 m. There are nine active stoping areas and two development ends situated on these levels. A simplified schematic representation of Mine A's ventilation network is provided in Figure 3-2.

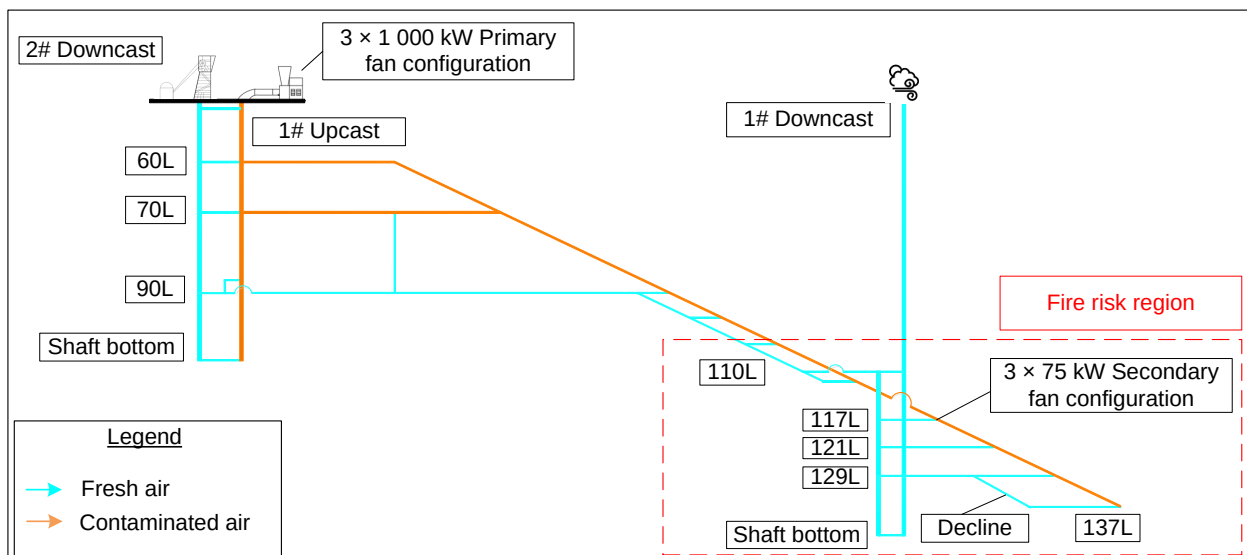


Figure 3-2: Schematic representation of Mine A's ventilation network

Active stoping and development areas are located between 117 level and 137 level, with Downcast Shaft 1 being the main source of air. This case study focuses on the area surrounding the active work zones, which is referred to as the fire risk region. The first step of the developed solution, discussed in Section 2.2, is to identify the location and source of ignition in the region shown in Figure 3-2.

3.2 Risk analysis

This section identifies both the location and source of ignition of the fire incident that was investigated in this case study. As discussed earlier, the selection of the case study depends on

Simulating underground mine fires for emergency planning

the identification and quantification of risks that are assumed to be stationary. Table 3-1 lists all the fire hazards that were found in the fire risk region of Mine A.

Table 3-1: Mine A's risk assessment

Workplace	Consequence rating	Probability rating	Risk rating
Conveyor belts	C5	P4	H24
Cross-cut	C4	P2	H19
Decline	C5	P2	H19
Haulage	C5	P2	H19
Shaft	C5	P2	H19
Shaft bottom	C5	P2	H19
Drill rig	C4	P2	H14
Station	C4	P2	H14
Oil/paint store	C3	P3	M13
Battery bay	C4	P3	M12
Development end	C4	P1	M12
Diamond drilling/geological drilling/lib drilling	C4	P1	M12
Hoist room	C4	P1	M12
Hot work	C4	P1	M12
Mini substation	C4	P1	M12
Mining store	C4	P1	M12
Pump chambers	C4	P1	M12
Stopes panel	C4	P1	M12
Substation	C4	P1	M12
Tips, filters, and foggers	C4	P1	M12
Waiting area	C4	P1	M12
Workshop	C4	P1	M12
Refuge bay	C3	P2	M11
Toilet	C3	P2	M11
Worked-out areas	C3	P1	M9
Booster fan	C2	P3	M8
Dams	C1	P1	L1

Table 3-1 illustrates the results obtained after evaluating the consequence and probability of each identified hazard. Appendix A contains the detailed assessment of each identified hazard. It has been found that conveyor belts pose the most significant risk for a fire incident on Mine A.

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Mine A has four conveyor belts located in the main intake decline that supplies air to 129 level and 137 level. This case study simulated and evaluated the results to determine remediation strategies for the fire risk associated with each of the four conveyor belts. Each conveyor belt was treated as an individual case study, which collectively addressed a major issue identified in the overarching study. This approach enabled a detailed examination of multiple scenarios, leading to a comprehensive analysis and deeper understanding of the broader problem. Figure 3-3 illustrates the layout of the four conveyor belts in the decline.

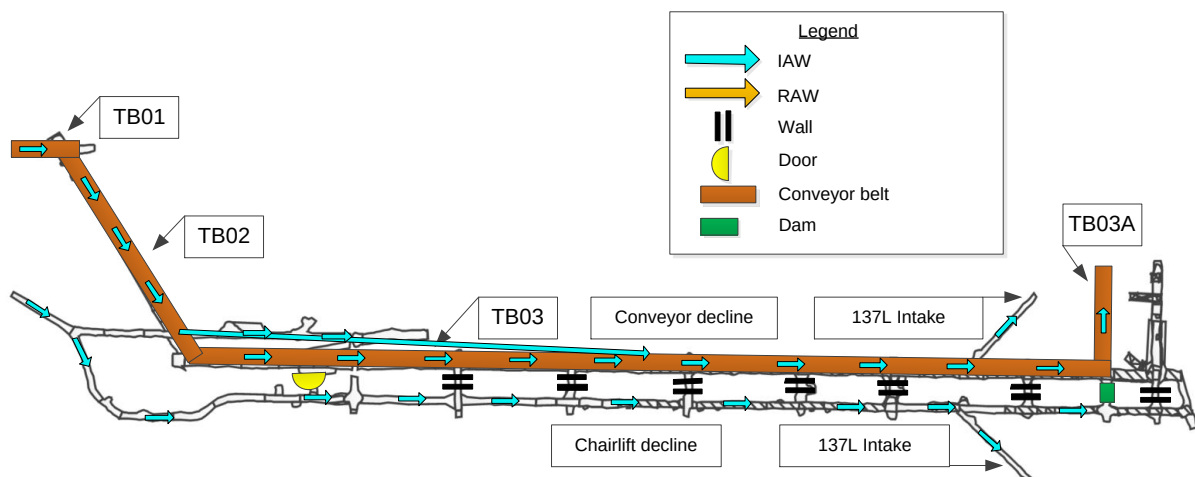


Figure 3-3: Mine A's decline conveyor belt configuration

The primary concern with the configuration in Figure 3-3 is that although direct methods to prevent fires from spreading are installed on the conveyor belts, there are no indirect ventilation control techniques in place to mitigate the spread in case the direct methods fail. Using the method explained in Chapter 2, the specifications of the conveyor belt given in Table 3-2 were employed to identify the ventilation control strategies to combat fire spread in Mine A.

Table 3-2: Conveyor belt specifications

Conveyor belt	Length [m]	Width [mm]	Thickness [mm]	Surface area [m ²]	Volume [m ³]	Weight factor [kg/m]	Weight [kg]
TB01	32	1 050	11	33.60	0.37	22.60	723.20
TB02	160	1 050	11	168.00	1.85	22.60	3 616.00
TB03	708	1 050	11	743.40	8.18	22.60	16 000.80
TB03A	72	1 050	11	75.60	0.83	22.60	1 627.20

3.3 Development and verification of Mine A's simulation model

This section describes the process of developing a calibrated ventilation simulation model of Mine A, which can accurately predict the hypothetical fire outcome of conveyor belt fires. The following sections, which include obtaining system information, constructing a model, calibrating the model, and verifying the model, are thoroughly described.

3.3.1 Obtain system information

The system information was gathered using available data for both surface and underground KPIs provided by mine personnel, supplemented by manual measurements for essential data that were previously unknown. The network layout of Mine A was obtained from the DXF drawing illustrated in Figure 3-4.

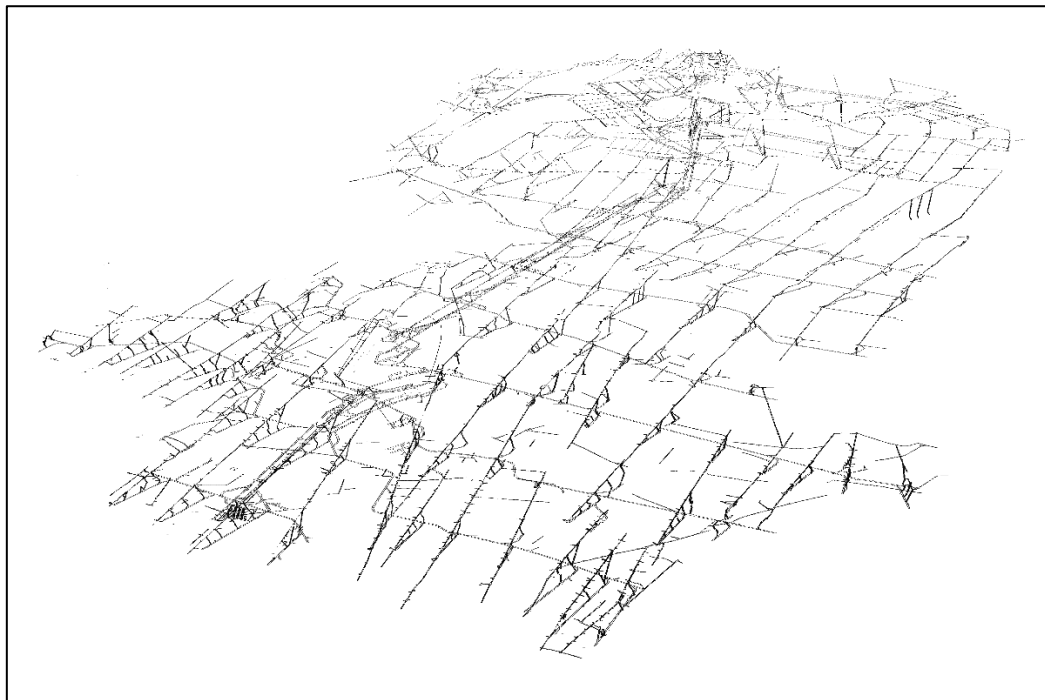


Figure 3-4: Mine A's DXF layout

Figure 3-4 provides the overall ventilation layout of Mine A, which was essential in the construction of the ventilation skeleton model. The DXF files were separated to illustrate the layout of each level contributing to the overall layout of Mine A. These files acted as an audit sheet, which was used to navigate each level and denote all relevant ventilation network data mentioned in Figure 2-2. The audit data sheets, which can be found in Appendix B, were integral to the model construction and input data for calibrating the skeleton model and verifying the virtual ventilation simulation model.

Simulating underground mine fires for emergency planning

Due to the relative shallow nature of Mine A, there is no additional cooling and the ventilation network is highly dependent on ambient temperature conditions. The ventilation network relies on both the surface and underground fan configurations. Table 3-3 shows all the available fan configurations from surface up to 137 level.

Table 3-3: Mine A's fan configuration set-up

Fan configuration	Location	Type	Quantity	Power rating [kW]
Primary fans	Surface (Upcast Shaft #1)	Centrifugal	3	1 000.0
Secondary fans	117L	Axial	1	75.0
	121L	Axial	2	75.0
Auxiliary fans	117L	Axial	3	45.0
			1	22.0
			1	15.0
	121L	Axial	3	45.0
			1	22.0
	129L	Axial	6	45.0
			1	22.0
			1	15.0
	137L	Axial	4	45.0
			1	15.0
			1	7.5

The fan configurations listed in Table 3-3 are crucial in ensuring the accuracy of the ventilation simulation as they have a direct impact on the air distribution. This, in turn, affects the accurate representation of the variations in temperature and air pollutants during fire incidents. The fan curves are provided in Appendix C.

3.3.2 Construct model

Mine A's ventilation skeleton model was constructed in PTB following the method devised in Section 2.3.3. The skeleton model contained 2 653 components, which formed the basic layout of the ventilation network. This emphasises the complexity and scale of the ventilation network. Figure 3-5 illustrates the ventilation skeleton model of Mine A along with the location of the conveyor belt.

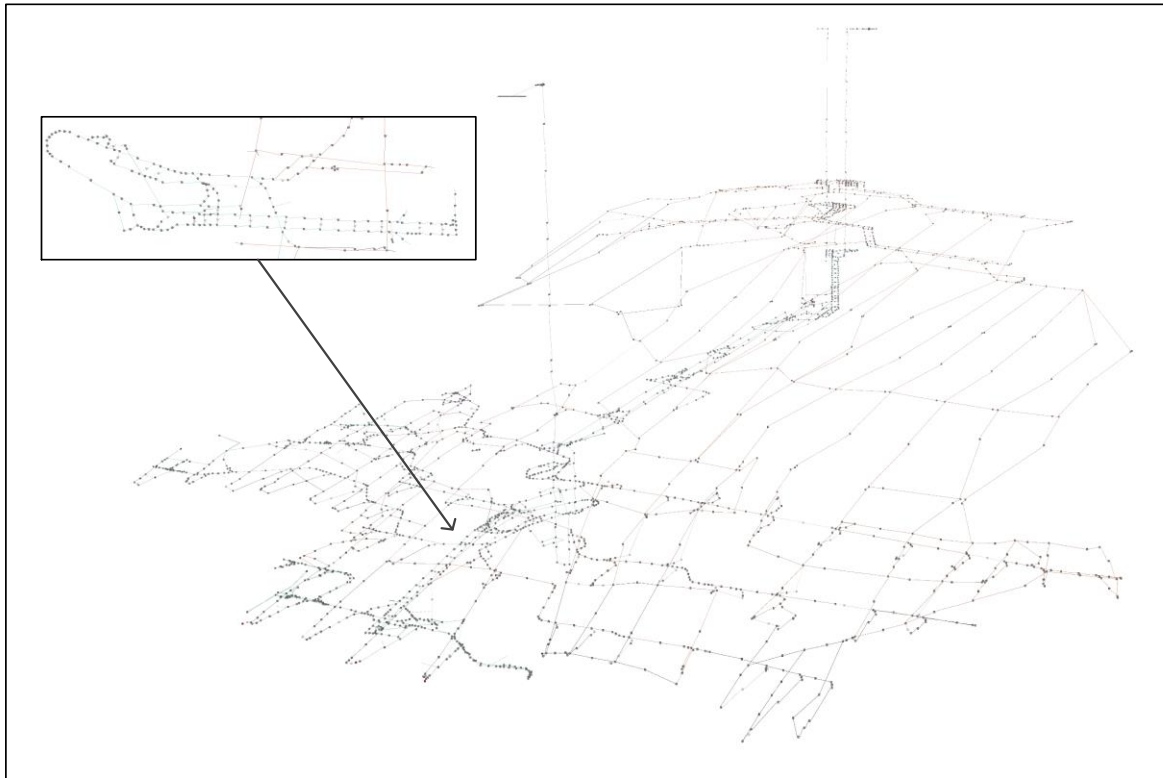


Figure 3-5: Mine A's ventilation skeleton model

The ventilation skeleton model in Figure 3-5 included all the necessary components to represent the actual underground ventilation network of Mine A. To configure the skeleton model into a virtual model that represents an accurate representation of the actual ventilation network, it was necessary to calibrate the relevant components as discussed in Section 2.3.4.

3.3.3 Calibrate model

By following the process described in Figure 2-5, the skeleton model was converted into a virtual model that represented the underground ventilation network of Mine A. The first step of the calibration process involved calibrating each fan component. The fan performance curves presented in Appendix C were used to calibrate the fan configurations listed in Table 3-3.

The second part of the calibration process involved calibrating the cooling components. Since Mine A lacks cooling infrastructure, it was essential to input accurate ambient conditions into the ventilation model. These conditions were obtained from surface temperature and humidity sensors at Mine A. Since this study simulated fire incidents in a transient state, the variations in surface temperature and relative humidity during the underground audit were recorded and used as input values for the model. Figure 3-6 illustrates the dry-bulb temperature and relative humidity profile of the day the underground audit was conducted.

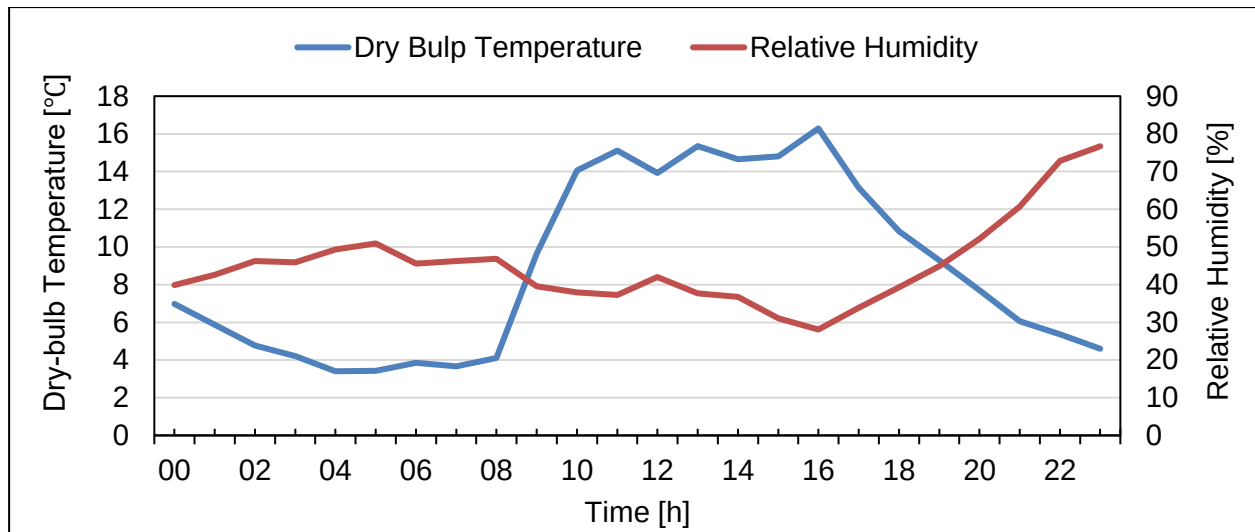


Figure 3-6: Mine A's daily ambient temperature profile

The results presented in Figure 3-6 served as input values for the ventilation skeleton model constructed in PTB. The wet-bulb temperature was calculated automatically by PTB using the dry-bulb temperature, relative humidity values, and the measured barometric pressure of 87 kPa.

To calibrate the haulage areas, the input values illustrated in Table 2-6 were required. These input values were obtained from historical data provided by the mine personnel. The complete list of input values for the tunnel components representing the haulage areas of Mine A can be found in Appendix D.

Once the fan components, surface temperature conditions, and air tunnel components had been calibrated, the ventilation skeleton model was deemed a calibrated virtual representation of Mine A's actual underground ventilation network, as long as it met the verification criteria discussed in the Section 2.3.5.

3.3.4 Verify model

The calibrated simulation model was verified using the methodology outlined in Section 2.3.5. Underground ventilation audits were conducted on the same day as represented by the temperature profile in Figure 3-6. During these audits, the wet-bulb temperature, dry-bulb temperature, air mass flow, and air pressure were measured at the intake of each level, spanning from 117 level to 137 level. Additionally, the measurements were recorded at the active stoping cross-cuts and active development ends. The specific time was recorded and the corresponding simulated time period's results were compared to evaluate the simulation model's accuracy.

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The results depicted in Figure 3-7 illustrate that the simulated wet-bulb temperatures at all locations deviated by 5% or less from the actual measurements taken underground. The mean absolute error (MAE) of 4% was within the limit specified in Section 2.3.5.

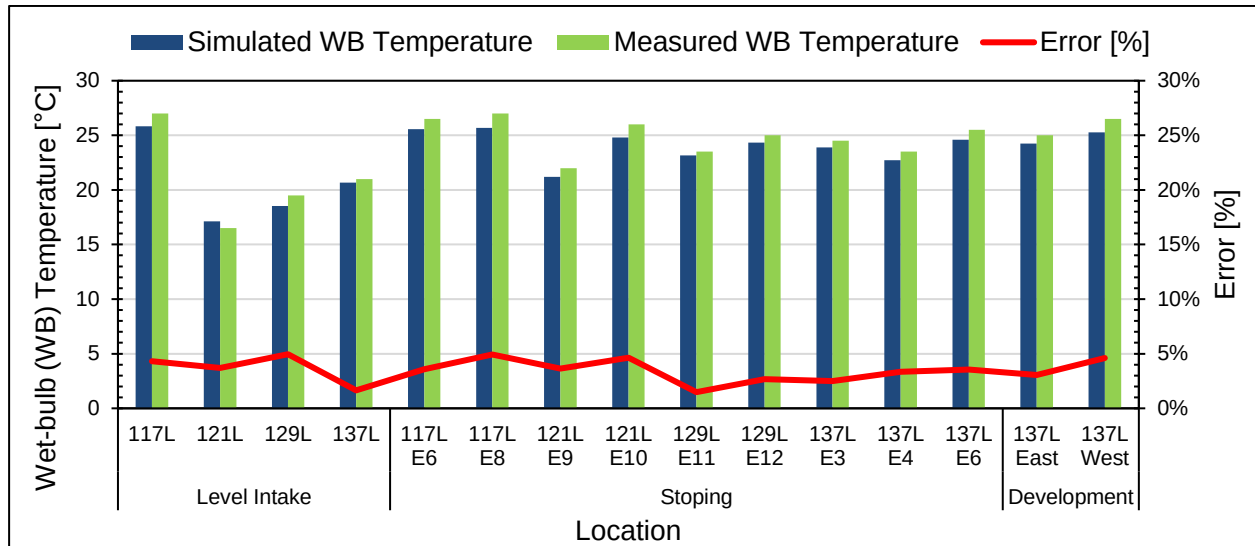


Figure 3-7: Mine A's simulated vs measured wet-bulb temperatures

Figure 3-8 illustrates that the simulated dry-bulb temperatures at all the identified locations deviated by 4% or less from the actual underground measurements. The MAE of 3% was within the limit specified in Section 2.3.5.

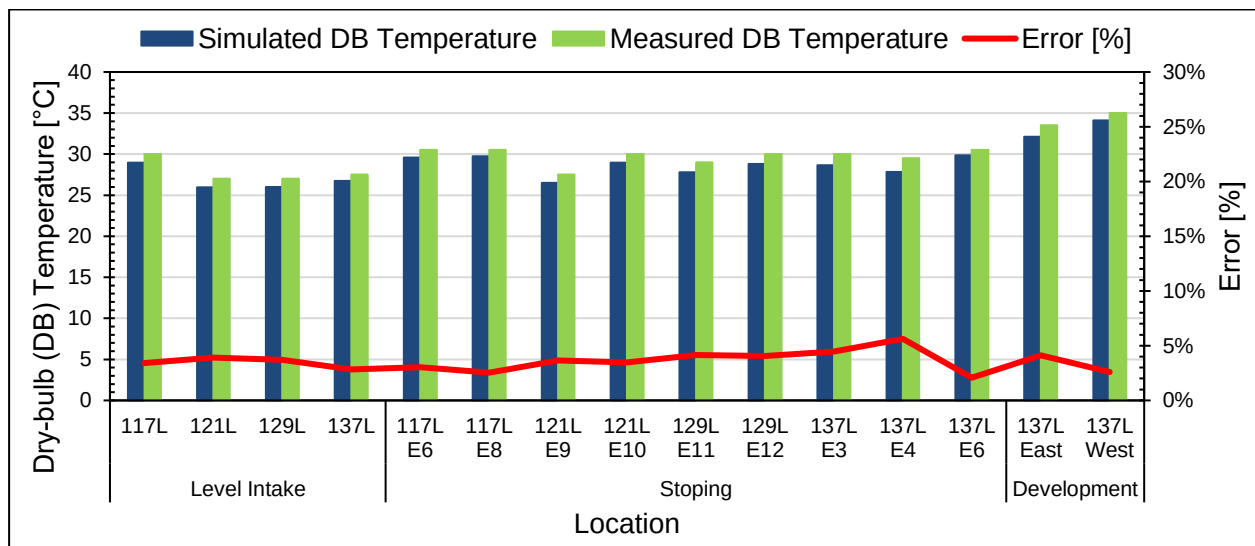


Figure 3-8: Mine A's simulated vs measured dry-bulb temperatures

Figure 3-9 compares the simulated air mass flow in identified areas with actual measurements. Some areas showed margin errors that exceeded 5%, primarily because of their low flow values,

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where even small differences can result in significant errors. The total delta mass flow for areas with an MAE over 5% was 5.2 kg/s, which represented only 1.9% of the total intake mass flow of 268 kg/s descending from the two intake shafts. Given that the airflow direction in the simulation model aligned with the actual ventilation network of Mine A and the overall MAE was 4%, the simulation model was considered an accurate representation of Mine A's ventilation network.

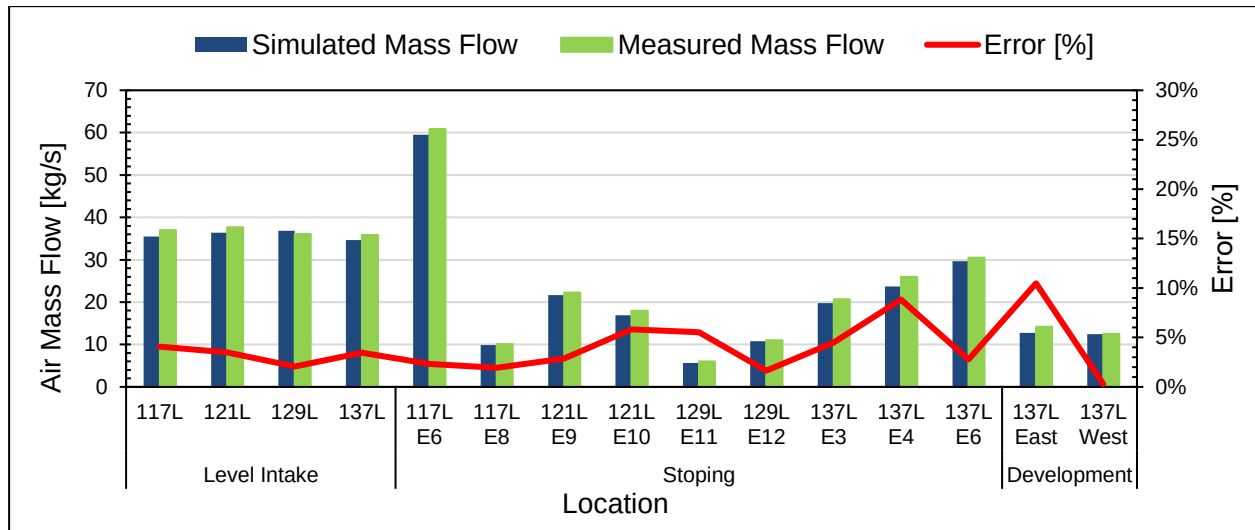


Figure 3-9: Mine A's simulated vs measured air mass flow

Figure 3-10 compares the air pressure measured at each location with the simulation results. The simulated air pressure at all locations deviated by less than 2%, staying well within the limit specified in Section 2.3.5. The MAE was 1%, highlighting the accuracy of Mine A's ventilation simulation model.

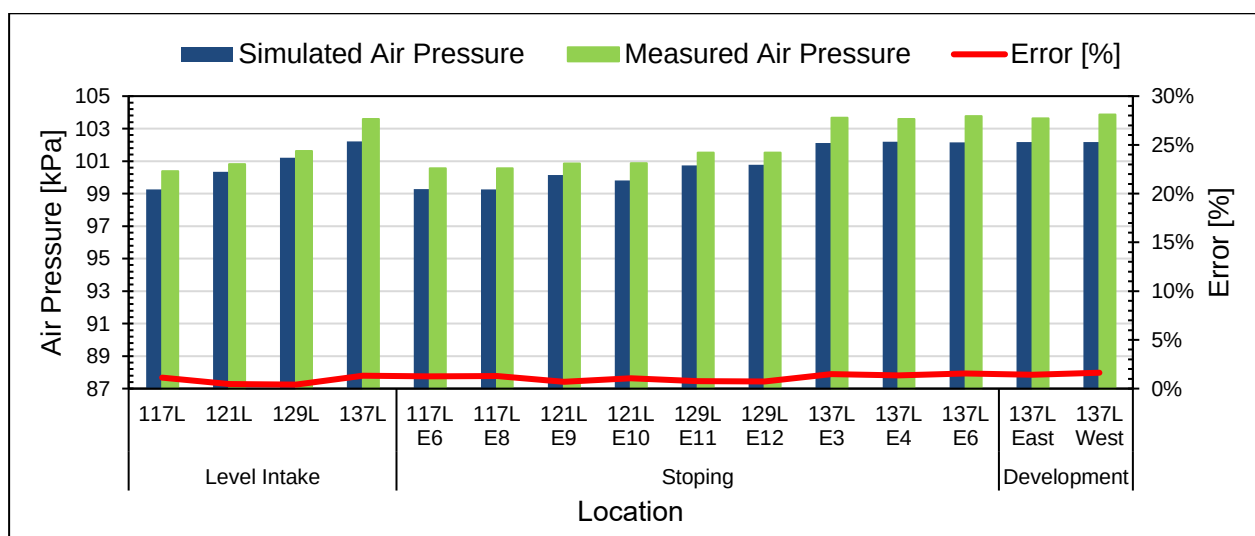


Figure 3-10: Mine A's simulated vs measured air pressure

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The actual measurements of the variables mentioned above were recorded manually. The ventilation audit sheets are provided in Appendix B. All simulated variables had an MAE of less than 5%, verifying and classifying Mine A's ventilation simulation model as calibrated. This model could now serve as a virtual representation of Mine A's underground ventilation network and could be used to simulate fire scenarios for identifying remediation strategies.

3.4 Simulation of impact

This section describes the simulation of various conveyor belt fire incidents in the ventilation network of Mine A. The purpose of this section is to identify the distribution of pollutants and evaluate the change in temperature at the identified locations. The results of the following sections contribute to the method for determining the appropriate remediation strategies: fire design specification, simulation set-up in PTB, discussion of results, and results summary.

3.4.1 Fire design specification

It was not feasible to conduct fire tests on conveyor belts in the mine due to the inherent safety risks and operational constraints. As mentioned in Chapter 1, underground mine fires, such as those that occur on conveyor belts, pose significant hazards, including potential harm to personnel, damage to infrastructure, and disruption of critical operations. Furthermore, a lack of access to specialised fire test galleries, which offer controlled environments for such experiments, necessitated an alternative approach. Consequently, this study relied on literature data derived from standardised tests performed under controlled conditions. The study used established data to effectively simulate fire scenarios and develop remediation strategies, while also following safety protocols and considering the practical limitations of working in an active mining environment.

The data used in this study was based on the results of studies performed by Wachowicz [68] and Wachowicz and Janoszek [69]. In the two reference studies, the flammability of testing samples were determined using a cone calorimeter test. Test samples of the same material were burned in a fire test gallery under controlled ventilation conditions. Table 3-4 contains the results of the two experiments that are relevant to this study's outcome.

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Table 3-4: Literature data on design fire specification [68, 69]

	Data set	Value	Units
Cone calorimeter test	Average effective heat of combustion	17.89	MJ/kg
Fire test gallery	Length	100	m
	Width	2	m
	Semi-spherical roof radius	1	m
	Airflow velocity	1.2	m/s
	Air density	1.225	kg/m ³
Conveyor belt	Length	42	m
	Width	0.5	m
	Thickness	0.01	m

In order to simulate the conveyor belts applicable to this study, it was crucial to obtain the maximum HRR and maximum gas flow rate. To determine the maximum gas flow rate, it was necessary to identify which gas released during the combustion of the burning conveyor belt posed the highest threat to the health and safety of employees. This was done by determining the normalised values of the gas present as discussed in Section 2.4.2.

Firelab [70] conducted an experiment to evaluate the toxicity of a type F cover compound Dunlop conveyor belt. For this purpose, 1 g of the compound was burned in 1 m³ of air, following the DEFSTAN (NES 713) test protocol. The concentrations of various specified gases were measured using calorimeter tubes, and these values were scaled to estimate the amount of gases that would be released if 100 g of the material was burned. The results of this test were used solely to determine the normalised values of each toxic gas produced during the combustion of a conveyor belt. The obtained results are presented in Table 3-5.

Table 3-5: Toxicity index of combustion gases [70]

	Formula	Concentration [ppm]	OEL [ppm]	Normalised value
Carbon dioxide	CO ₂	120 000	5 000	24
Carbon monoxide	CO	3 000	30	100
Phenol	C ₆ H ₅ OH	250	5	50
Hydrogen chloride	HCL	Traces	–	–
Nitrous oxide	N ₂ O	200	50	4
Hydrogen cyanine	HCN	Traces	–	–

Based on the results presented in Table 3.5, CO exhibited the highest normalised value. The studies conducted by Wachowicz [68] and Wachowicz and Janoszek [69] evaluated the concentration of CO during a conveyor belt fire incident in a fire test gallery, which represented an underground drift. Therefore, these studies focused on investigating the distribution of CO to assess the distribution of gas particles.

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The fire test gallery experiment showed a maximum heat release of 3 258 kW, peak gas flow rate of 0.0424 kg/s, and air mass flow rate of 5.25 kg/s [69]. Since an entire conveyor belt does not burn all at once, these values were adjusted for this study using a scaling factor based on the width ratio between the experimental set-up and the conveyor belt configurations listed in Table 3-2. The adjusted values for the design fire scenario used in this study are listed in Table 3-6.

Table 3-6: Scaling of experimental results

	Experimental set-up (fire test gallery)	Scaling factor	Design fire
Maximum heat released [kW]	3 258	$\frac{1\ 050\ \text{mm}}{500\ \text{mm}} = 2.1$	6 842
Maximum CO flow rate [kg/s]	0.0426	$\frac{1\ 050\ \text{mm}}{500\ \text{mm}} = 2.1$	0.0895
Maximum air mass flow [kg/s]	5.25	$\frac{1\ 050\ \text{mm}}{500\ \text{mm}} = 2.1$	11.01

The maximum heat release, CO flow rate, and air mass flow rate at which these values peaked for the four conveyor belt fire incidents are presented in Table 3-6. To account for the worst-case scenario, the fire growth rate selected was based on the National Fire Protection Association's fast-growing fire classification, set at 0.056 kW/s² [71]. Using this growth rate, along with the data in Table 3-2, Table 3-4, and Table 3-6, the key specifications for each fire incident were determined as summarised in Table 3-7.

Table 3-7: Design fire properties of the respective conveyor belt configurations

Conveyor belt	Fire growth rate [kW/s²]	CO growth rate [kg/s³]	Maximum heat released [kW]	Maximum CO release rate [kg/s]	Total heat emitted [MJ]	Fire duration [min]
TB01	0.056	7.3×10^{-7}	6 843	0.089	12 938	42
TB02					64 690	193
TB03					286 254	841
TB03A					29 111	89

Table 3-7 outlines the key variables that were necessary in order to define the design fire for each conveyor belt configuration. As explained in Section 2.4.2, the HRR and gas flow rate follow a similar pattern during combustion, which made it possible to calculate the CO growth rate. The design fire curve for each conveyor configuration is provided in Appendix E.

3.4.2 Simulation set-up in PTB

The simulation set-up in PTB used the design fire properties in Table 3-7 to establish a baseline for evaluating changes in work area temperatures and CO particle concentrations. These environmental changes provided the foundation for configuring effective remediation strategies to mitigate their impact. The areas to be assessed were the same as those included in the underground ventilation audit illustrated in Figure 3-7 to Figure 3-10. Figure 3-11 presents a front view of Mine A's ventilation network, indicating the location of each work area under evaluation.

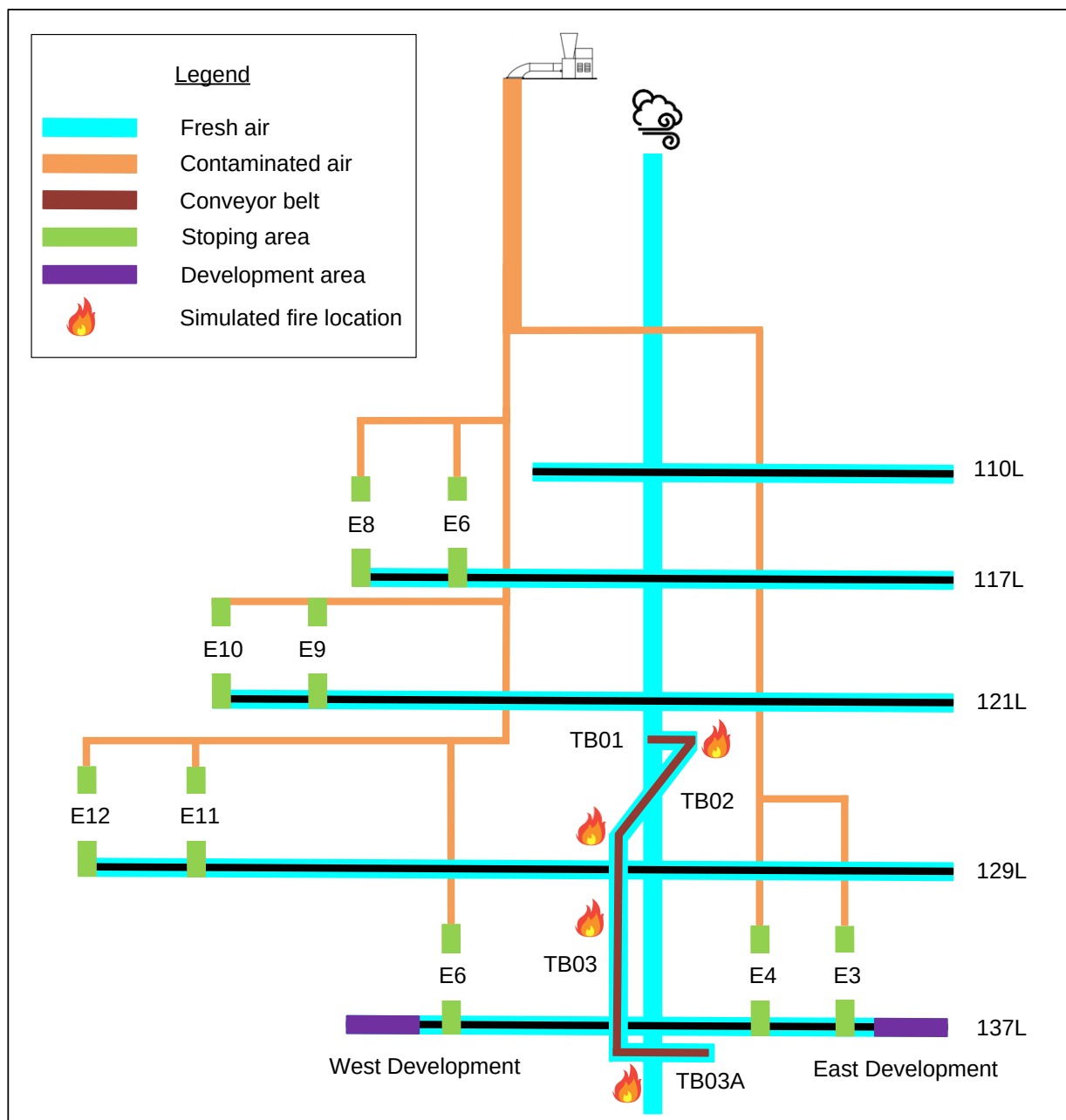


Figure 3-11: Front view of Mine A's work area annotation

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Figure 3-11 shows the ventilation network layout, focusing on work areas between the 117 and 137 levels. It also illustrates the conveyor belt configurations along the decline, descending from 121 level to 129 level and extending below 137 level, where the tips are located. Simulations were conducted to assess how the design fire scenarios affected the level intakes and active work areas. Additionally, Figure 3-12 presents a front view of Mine A, as represented by PTB, before any fire incidents were simulated.

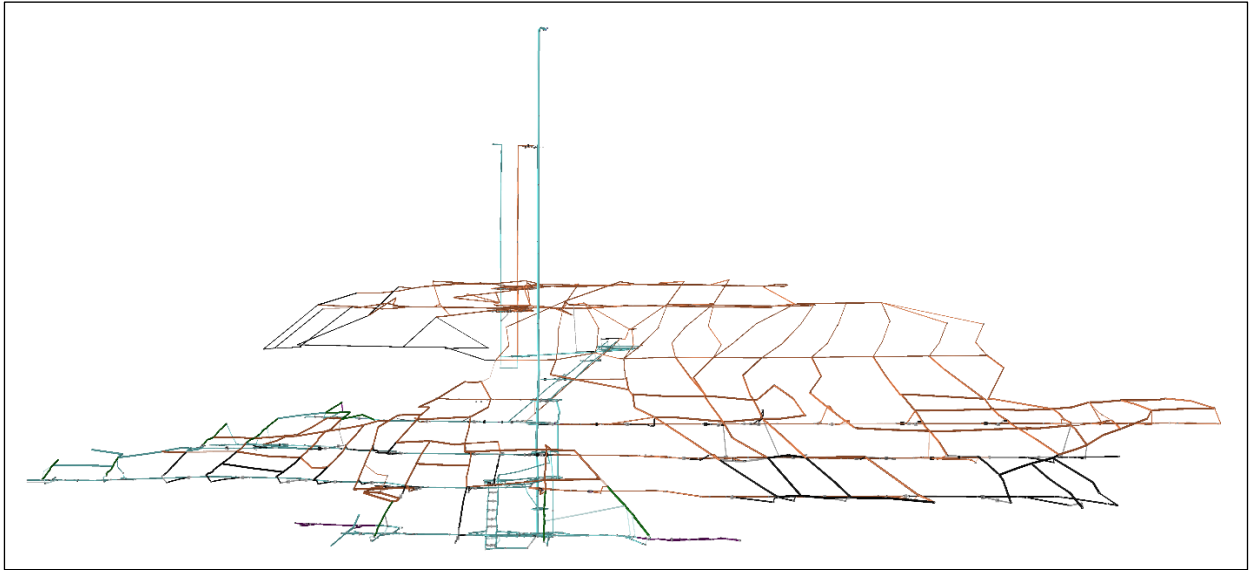


Figure 3-12: Front view of Mine A's PTB illustration

The method outlined in Section 2.4.3 was used to set up the simulations for each conveyor belt's design fire configuration in the simulation model of Mine A, as illustrated in Figure 3-12. The locations of these fire design configurations are shown in Figure 3-11. These simulations were used to evaluate the impact of the design fire scenarios at the respective identified locations.

3.4.3 Discussion of results

The results obtained from simulating the four conveyor belt fire scenarios are discussed in order to thoroughly assess the outcomes using the approach outlined in Section 2.4.4. Each active work area was examined for temperature and CO concentration, and these values were identified once they exceeded the specified OELs. This evaluation was conducted for each design fire scenario, including those for conveyor belts TB01, TB02, TB03, and TB03A.

The results presented in this chapter are those from Design Fire Scenario 3, which includes conveyor belt TB03, the largest conveyor belt configuration. The results of the remaining three conveyor belt configurations are presented in Appendix G.

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As detailed in Table 1-1, the OEL for CO is 30 ppm and the maximum dry-bulb temperature is 37 °C. These standards were used to evaluate each work area. The discussion focuses on reporting the changes in the ventilation network resulting from the fire scenario and summarising the outcomes for each active work area where the criteria were exceeded.

Design Fire Scenario 3: TB03

The TB03 conveyor belt configuration is the longest out of all four conveyor belt set-ups. It operates in the main fresh air intake, which distributes air from TB02 and 129 level to the working areas on 137 level. TB03 extends below the 137 level intake and connects with the TB03A conveyor configuration. A total of 45 kg/s of air flows over TB03A at a velocity of 1.78 m/s. TB03 operates in an area of 22 m². Figure 3-13 shows the temperature profile of Mine A during a fire incident involving TB03.

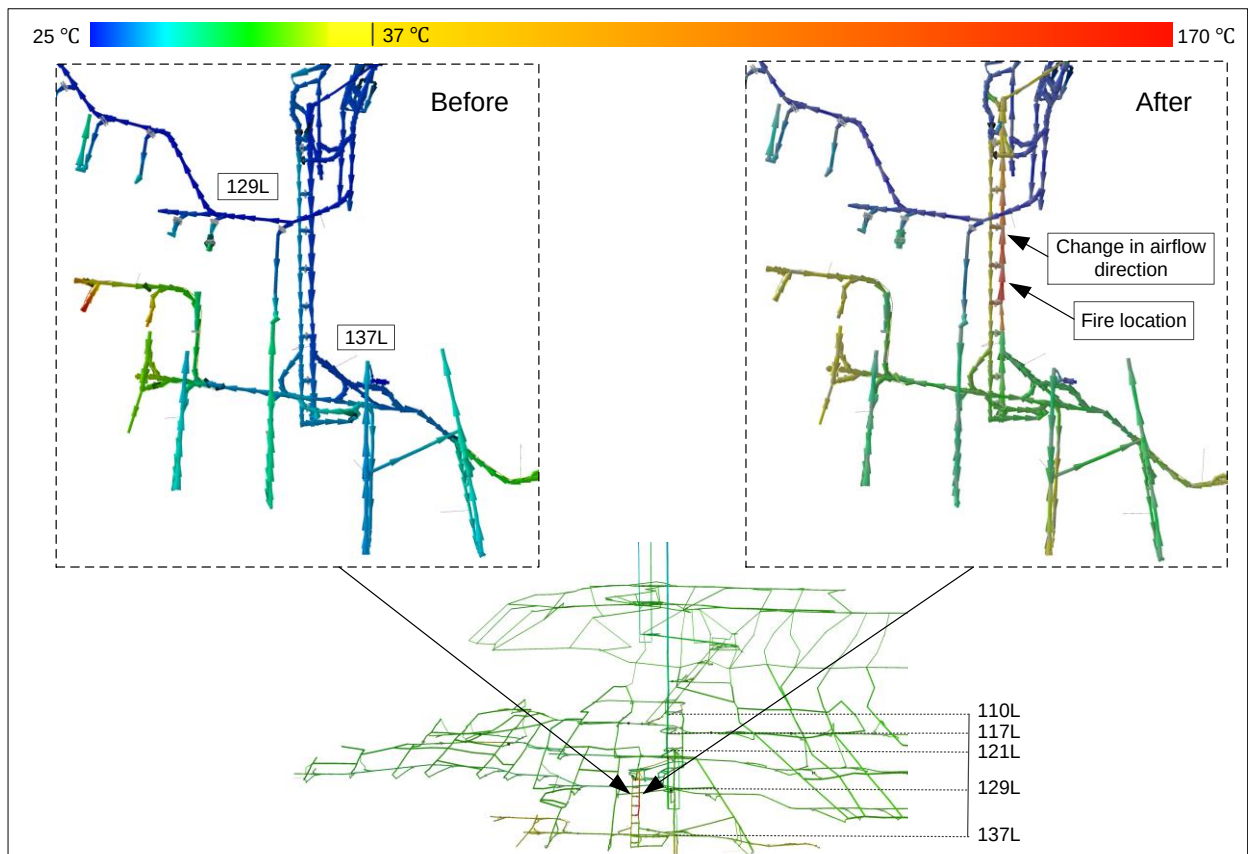


Figure 3-13: Temperature simulation results – TB03

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In the event of a fire involving the TB03 conveyor belt, the airflow in the conveyor decline changed direction as illustrated in Figure 3-13. This change was the result of the throttling or choking effect, which caused a flow reversal. Temperatures reached a maximum of 234 °C, leading to gas expansion and an increase in air volume. Figure 3-14 illustrates the increase in air volume and the change in the flow direction.

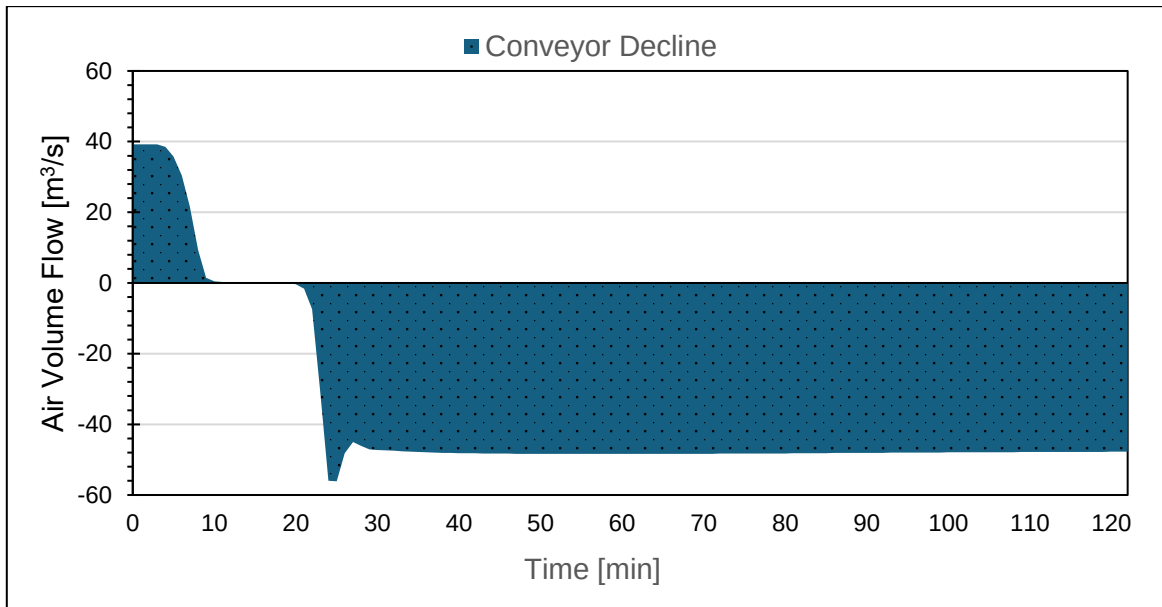


Figure 3-14: Change in air volume flow direction – TB03

As a result of the air volume increase and changing direction, contaminated air made its way up the conveyor decline towards the chairlift decline intake. Since 137 level still set the demand for airflow, contaminated air was directed down the chairlift decline, continuing to affect the work areas on 137 level. Some of the contaminated air moved upwards through the raise bore hole towards the intake of 121 level and the rest of the ventilation network of Mine A. Although the temperature reached extreme levels, the primary concern was the spread of CO throughout the ventilation network in Mine A. Figure 3-15 illustrates the CO distribution resulting from the fire incident involving TB03.

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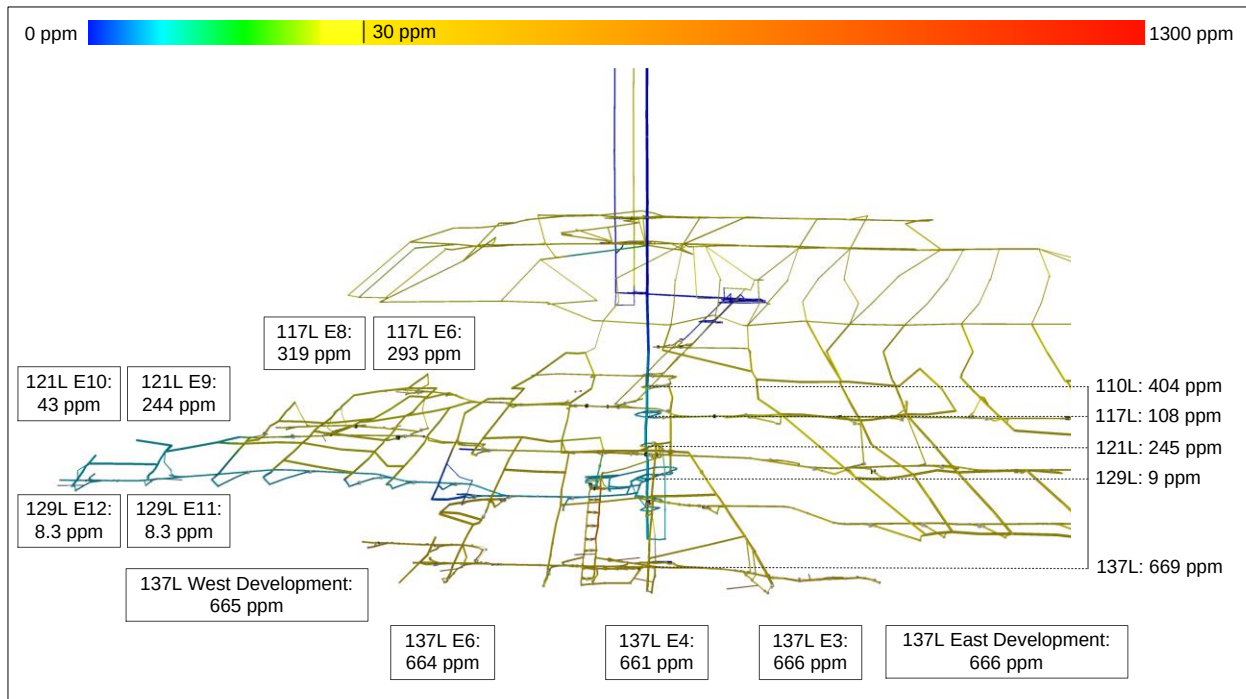


Figure 3-15: CO simulation results – TB03

Figure 3-15 shows that most active working areas exceeded the OEL of 30 ppm, with the exception of 129 level. This is because 129 level receives fresh air directly from the main shaft, while on 121 level, contaminated air is prevented from reaching 129 level as no recirculation takes place. Given the high concentration of CO in the ventilation network of Mine A, it is evident that remediation strategies are necessary to mitigate the impact.

3.4.4 Results summary

The first step of Objective 3, as detailed in Section 1.8, was completed by simulating the conveyor belt fire scenarios. Through these simulations, the design fire curves were applied, allowing for a detailed evaluation of the level intake and active working areas. The time it took to exceed the OELs and reach the maximum values was recorded. Table 3-8 lists the simulated temperature results for each identified working area that exceeded the OEL during the fire incident involving conveyor belt TB03.

Table 3-8: Simulated design fire temperature results – TB03

Location	Time to exceed OEL [h:mm]	Time to reach maximum	
		Time [h:mm]	Temperature [°C]
137L Intake	00:06	00:06	41.11
137L E4	01:52	04:11	42.28

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Although Table 3-8 highlights the areas where temperatures exceeded the OEL, the rise in temperature during a fire incident was not the primary concern, as discussed in the results section. The simulated CO concentration results are presented in Table 3-9.

Table 3-9: Simulated design fire CO results

Location	Time to exceed OEL [h:mm]	Time to reach maximum	
		Time [h:mm]	Maximum CO concentration [ppm]
117L Intake	01:13	07:28	99.34
121L Intake	00:29	01:20	245.27
137L Intake	00:04	02:28	668.51
117L E6	01:11	07:27	99.43
117L E8A	01:08	07:22	91.64
121L E9	00:35	01:27	243.74
121L E10	01:21	02:18	42.96
137L E3	00:11	02:46	665.61
137L E4	01:30	06:18	661.02
137L E6	00:27	02:56	663.93
137L E Dev	00:13	02:42	666.17
137L W Dev	00:29	02:33	665.13

The results presented in Table 3-9 provide key insights, detailing the time it takes for each identified area to exceed the OEL and the time required for each working area to reach maximum CO concentrations. These findings clearly demonstrate the significant impact that a fire incident on a conveyor belt can have on the ventilation network of Mine A. The simulation was based on worst-case scenarios and provides a baseline for assessing the potential risks associated with such incidents.

This section established an understanding of how fire events affect mine ventilation and air quality. The results are a crucial starting point for developing targeted remediation strategies to ensure the health and safety of workers in Mine A. These strategies would address CO concentrations and compromised airflow in the ventilation network.

3.5 Identification and implementation of remediation strategies

This section aims to identify remediations strategies based on ventilation control practices to combat the effects of the fire incidents as discussed in Section 3.4. The aim is to implement the identified strategies and quantify their effectiveness on the ventilation network of Mine A. This section follows the method discussed in Section 2.5 for defining an effective emergency plan: identification of remediation strategies, implementation of remediation strategies and results discussion, and results summary.

3.5.1 Identification of remediation strategies

The goal is to develop an emergency plan that can be applied to all conveyor belt scenarios, thereby ensuring that the risk of contaminated air reaching active working areas is mitigated in the event of a fire in any conveyor belt configuration. Section 1.4.3 focused on indirect methods for controlling fire incidents, which formed the basis for identifying remediation strategies based on ventilation control techniques. From the results discussed in Section 3.4, it is clear that all four strategies must be included in the emergency plan for any conveyor belt fire scenario in Mine A due to the following reasons:

- **Pressure control:** Figure 3-3 shows the decline descending from below 121 level down to 137 level. Fresh air moved through both the conveyor and chairlift declines. If a higher pressure is not maintained in the chairlift decline, contaminated air from a fire in the conveyor decline will descend through the chairlift decline.
- **Airflow regulation:** The design fire curves indicated that the fire reached its peak intensity at an airflow of 11 kg/s. The air mass flow over all conveyor configurations was higher than 11 kg/s, as measured during the underground audit. Controlling the air mass flow will reduce the oxygen supply and slow down the combustion process.
- **Airflow partitioning:** The western side of Mine A contains all the active working areas, except for those on 137 level, while the eastern side has mined-out areas. Therefore, in the event of a fire, the contaminated air should be directed through the eastern side of Mine A.
- **Smoke extraction:** The fire scenario involving conveyor belt TB03A demonstrated that extracting and partitioning contaminated air through cross-cut E4 led to minimal contamination in other areas. This highlights the necessity of smoke extraction to ensure that contaminated air is efficiently removed from the ventilation network of Mine A.

Pressure control

The first step in defining the emergency plan was to maintain a higher pressure in the chairlift decline as it descended to 137 level. As there was still a high demand for ventilation on 137 level, the amount of air descending through the chairlift decline increased. This increased air quantity would help achieve the necessary higher pressure, provided that efficient sealing between the conveyor decline and the chairlift decline is maintained. Mine A has walls between the chairlift decline and the conveyor decline, and the locations where additional sealing is required are illustrated in Figure 3-16.

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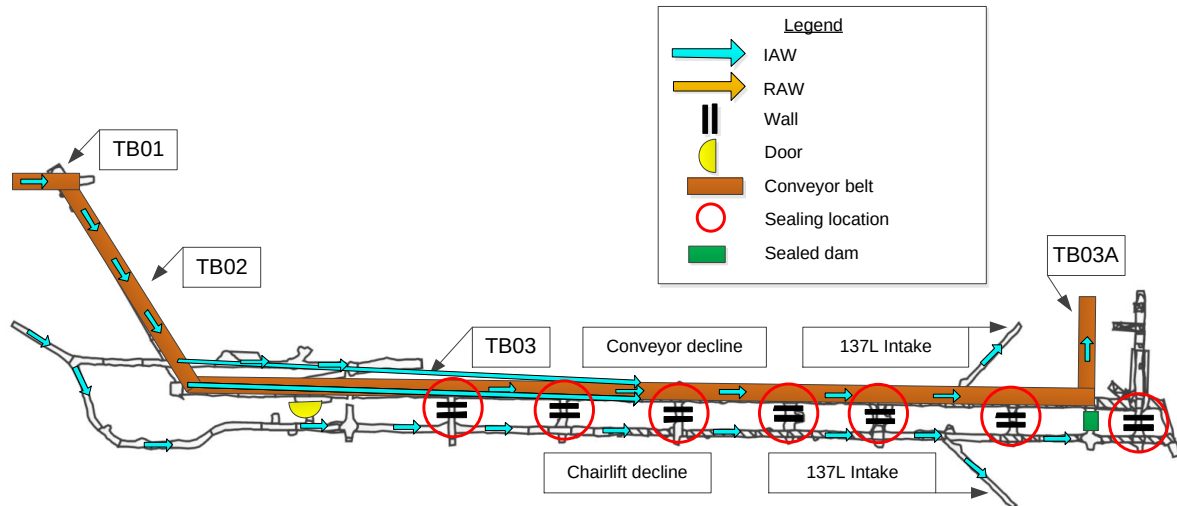


Figure 3-16: Sealing locations in decline

Figure 3-16 illustrates the location of each connection between the chairlift decline and the conveyor decline that had to be sealed properly.

Airflow partitioning and regulation

The second step in defining the emergency plan involved establishing airflow partitioning and regulation in the fire risk region. As previously noted, the eastern side of Mine A has mined-out areas, making it ideal for returning contaminated air. Since Mine A has already been divided into separate ventilation zones, in the event of a fire, the strategy would be to direct contaminated air towards the eastern side while isolating the western side from the incident. Figure 3-17 illustrates the ventilation zones identified for airflow partitioning in the event of a fire.

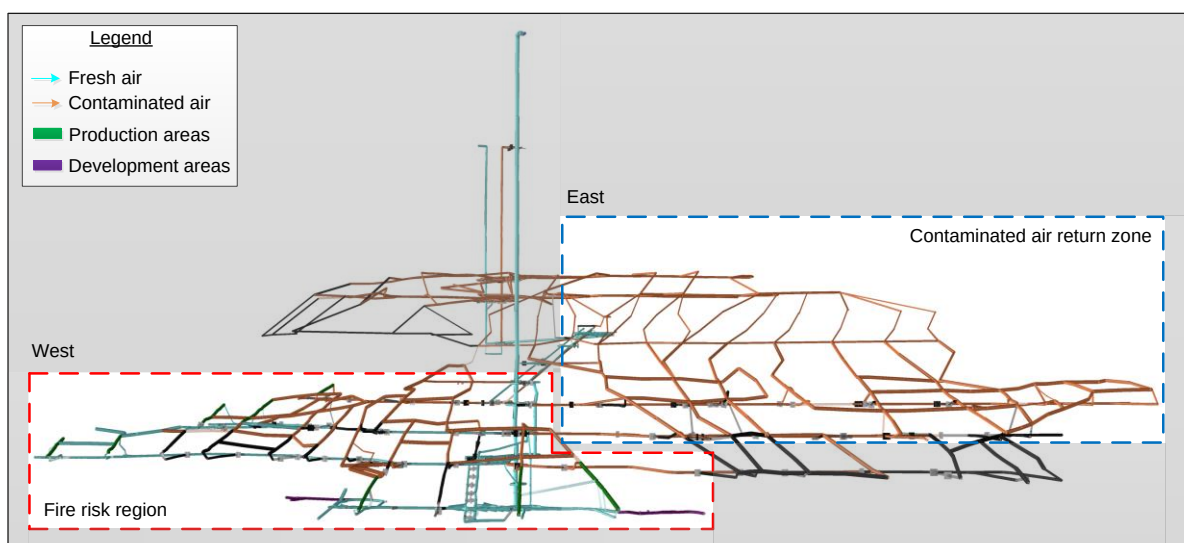


Figure 3-17: Zones identified for airflow partitioning in Mine A

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The evaluation of the results in Section 3.4 revealed that in the event of a fire involving conveyor belts TB01, TB02, or TB03, the airflow changed direction and upcast into the intakes of 110 level, 117 level, and 121 level, with air recirculating back into the intake of 129 level. To prevent this, it was crucial to isolate the entire conveyor decline from the intakes of these levels, thereby protecting the western area of Mine A from potential contamination. This was achieved by installing automatic fire doors at the locations shown in Figure 3-18.

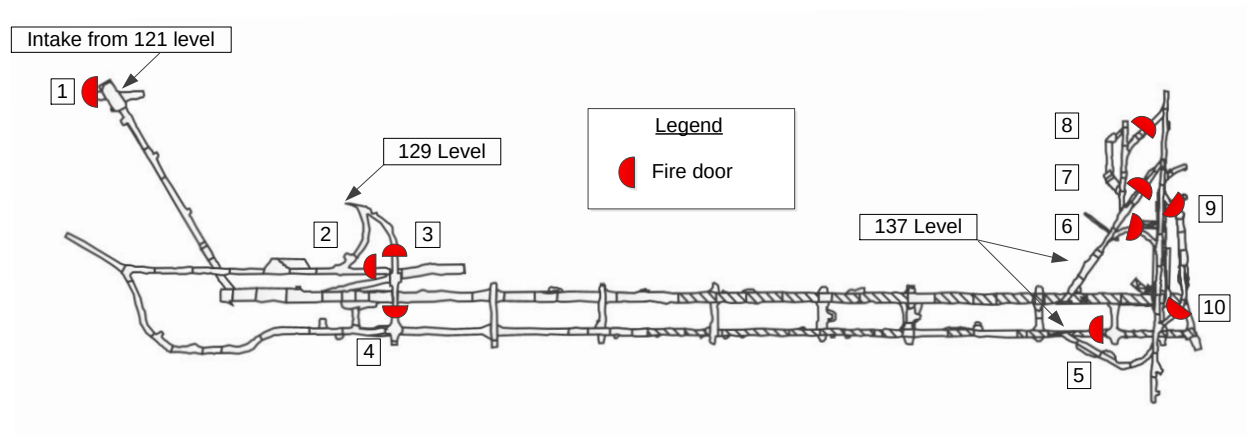


Figure 3-18: Location of automatic closing fire doors

The installation of automatic fire doors supported airflow partitioning and acted as a ventilation regulator, reducing the airflow over the conveyor belt to limit the combustion process. These doors automatically close when CO levels reach 25 ppm. This set point was selected to ensure closure before the OEL of 30 ppm would be exceeded.

The following fire doors were implemented in PTB:

- Fire Door 1, located at the top of the decline intake, restricted airflow from 121 level over TB01 and the remainder of the conveyor belt configurations. Its purpose was to prevent contaminated air from upcasting into the western working areas once the direction of the airflow changed.
- Fire Doors 2 and 3 were installed at the connections between 129 level and the conveyor decline, preventing contaminated air from entering 129 level. Fresh air from the main shaft continued to supply 129 level, though at a reduced quantity.
- Fire Door 4 was installed between the conveyor and chairlift declines. Normally, this connection would remain open to balance airflow between the two declines. However, in

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the event of a fire, this door closed, increasing airflow through the chairlift decline, which raised the pressure and supplied fresh air to the working areas on 137 level.

- Fire Door 5 was installed in the chairlift decline below the intake to 137 level. Its purpose was to prevent contaminated air from moving up the chairlift decline into 137 level as both declines were connected at the bottom.
- Fire Doors 6 to 8 were located at the three connections between the conveyor decline and 137 level. These doors ensured that the chairlift decline would remain the only intake to 137 level.
- Fire Doors 9 and 10 were located on 137 level in the tram loop designated for the ore tips, which transfer material onto conveyor belt TB03A. As the tips are connected to conveyor belt TB03, these fire doors were crucial in preventing contaminated air from rising and affecting the working areas on 137 level. The conveyor infrastructure prevented the installation of a single fire door to block the raise bore. As a result, fire doors nine and ten were required to stop contaminated air from moving up into 137 level.

The aim of the fire door configuration was to reduce the combustion process until the fire incident could be extinguished. Thereafter, smoke extraction could commence to clear the conveyor decline from contaminated air.

Smoke extraction

In the event of a fire, it is crucial to extract the contaminated air redirected from the working areas and remove it from Mine A's ventilation network. Extracting contaminated air was the final step of the emergency plan configured for a conveyor belt fire incident in Mine A.

As demonstrated by the simulation of Design Fire Scenario 4, presented in Appendix G, it is crucial that the contaminated air must be directed to the eastern side of Mine A. Cross-cut E4 on 137 level connects to cross-cut E4 on 129 level, a mined-out area designated for returning air from the development and production areas on 137 level. The development of a raise bore from 137 level to cross-cut E4 on 129 level was identified as the most effective method for extracting contaminated air in any of the four conveyor belt fire scenarios. The configuration of this set-up is shown in Figure 3-19.

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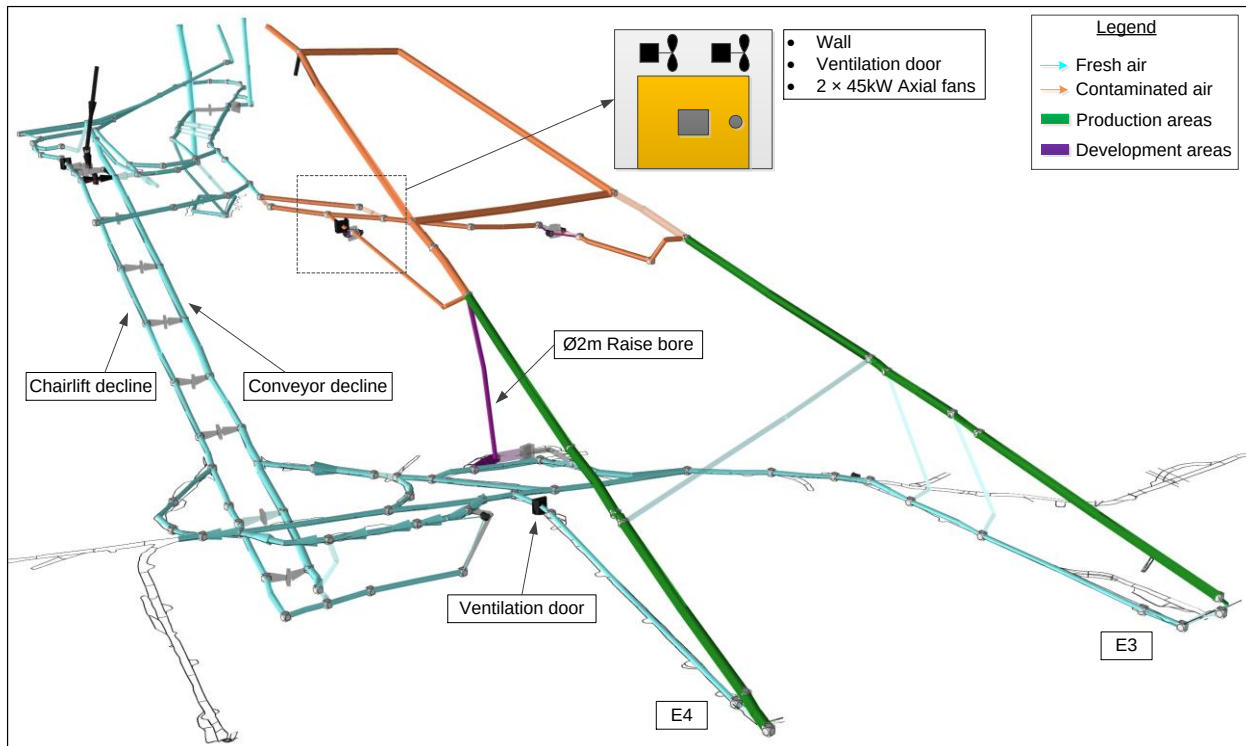


Figure 3-19: Smoke extraction configuration – dedicated chimney

Figure 3-19 shows the set-up for exhausting contaminated air from Mine A during a conveyor belt fire. The current ventilation system uses two 45 kW axial fans installed in a tight circuit in a wall, which also has a ventilation door for easy access to the E4 raise line. These fans support ventilation in cross-cut E4. The smoke extraction set-up includes a two-metre diameter raise bore, commonly used in drilling, which extends from the third connection at the intake of 137 level to the raise line connecting cross-cut E4 on 137 level and 129 level. The 100-metre long raise bore was the shortest and most effective location for developing a dedicated chimney.

Once the fire is extinguished, the ventilation door on 137 level cross-cut E4 must close and the raise bore has to open. This ensures that, along with the two 45 kW fans, the raise bore acts as an exhaust ventilation system to remove the contaminated air from the conveyor decline. Therefore, a dedicated chimney was created, resulting in no active work area being contaminated.

The four remediation strategies outlined in this section are the most common ventilation control techniques for mitigating the impact of underground mine fires. Each strategy's relevance to this case study was discussed, forming the basis of the final emergency plan. Section 3.5.2 provides further details regarding the effectiveness of this plan.

3.5.2 Implementation of remediation strategies and results discussion

The implementation of the identified remediation strategies followed the method outlined in Section 2.5.3. This method was used to evaluate the effectiveness of these strategies under worst-case conditions. This section aims to investigate the effectiveness of the emergency plan identified on each design fire scenario by simulating the following outcomes:

- Implementing strategy after time t (strategy impact shown after the first working area exceeds the OEL).
- Extinguishing the fire incident by implementing the defined set point.
- Extracting smoke after the fire burns out.

The implementation after time t , where time t represents the time when the first working area exceeded the OEL, was based on the results presented in Table 3-9. The time it took for each working area to exceed the OEL is presented, which formed the baseline for the evaluation of the first scenario.

To extinguish the fire incident, the defined 25 ppm set point was applied. This ensured that the fire doors would close automatically when the CO concentration exceeded this threshold in attempt to effectively mitigate the combustion process. After the fire had been extinguished, the smoke extraction configuration was applied in attempt to remove the contaminated air without affecting the active working areas of Mine A.

This section discusses the simulation results for the TB03 conveyor belt fire scenario. The results of the implementation of the emergency plan on the other three conveyor belt configurations are provided in Appendix H.

Design fire scenario 3: TB03

1. Implementation after time t

The simulation of a fire involving TB03 showed that the OEL of 37 °C was exceeded after just 6 minutes, while the OEL of 30 ppm was surpassed after 4 minutes at the intake on the 137 level. However, the primary focus was on cross-cut E3 on 137 level, where the OEL of 30 ppm was exceeded after 11 minutes, as illustrated in Table 3-9. Figure 3-20 illustrates the simulation results of the CO concentration following the implementation of the emergency plan after 11 minutes.

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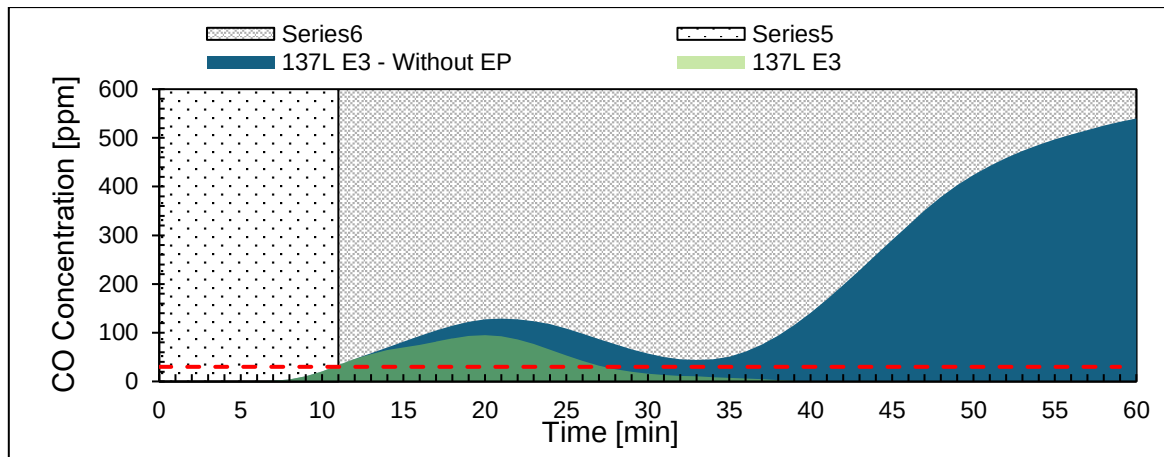


Figure 3-20: Effect of emergency plan on CO concentration after time t – TB03

The results presented in Figure 3-20 illustrate how CO concentration affected cross-cut E3 as the airflow changed. Initially, before the airflow changed direction, CO moved through the intake on 137 level and into cross-cut E3. As discussed in Section 3.4.3, the direction of the airflow changed and contaminated air made its way down the chairlift decline due to the air demand on 137 level. This resulted in a second phase in which the CO concentration increased in E3. The emergency plan reduced CO levels in E4 and prevented further contamination of the work area. These results emphasise the effectiveness of fire doors in regulating airflow and partitioning contaminated air along the conveyor belt. This helps to prevent contaminated air from infiltrating work areas.

As mentioned, the air mass flow in the chairlift increased once the emergency plan was implemented. This increase in air mass flow, combined with the effective sealing at the connections as illustrated in Figure 3-16, resulted in a higher pressure in the chairlift decline. These results are illustrated in Figure 3-21.

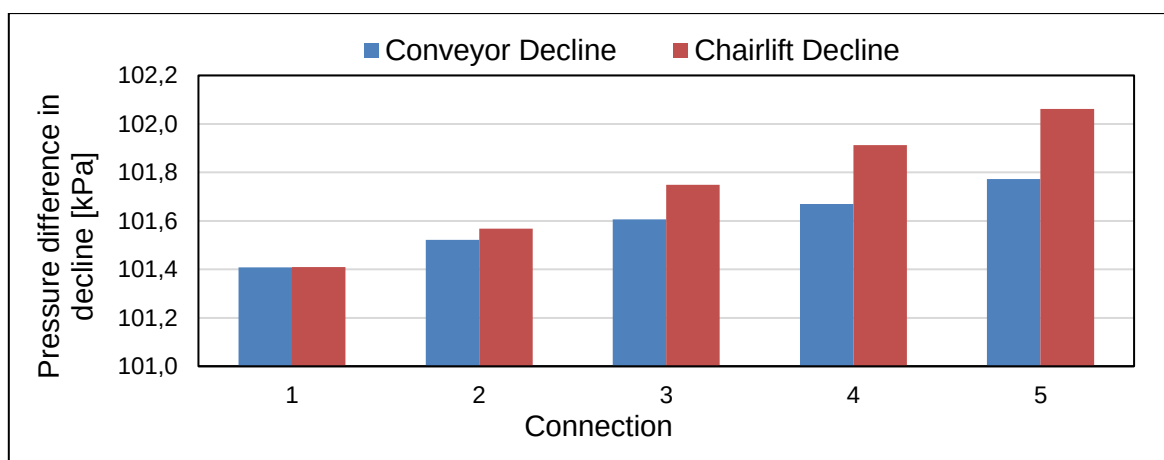


Figure 3-21: Pressure difference in decline – TB03

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Figure 3-21 shows the pressure difference between the chairlift and conveyor declines at each connection. The chairlift decline consistently maintained a higher pressure, causing any leakages to flow from the chairlift decline toward the conveyor decline. This prevented contaminated air from leaking into the intake and reaching the work areas.

2. Implementation of defined set point

The purpose of implementing the defined set point is to demonstrate the effectiveness of the defined emergency plan. This involved closing the fire doors once a CO concentration of 25 ppm was detected. After simulating the design fire curve for TB03 and implementing the remediation scenario, the results illustrated that no active work areas were affected by contaminated air. The results are shown in Figure 3-22.

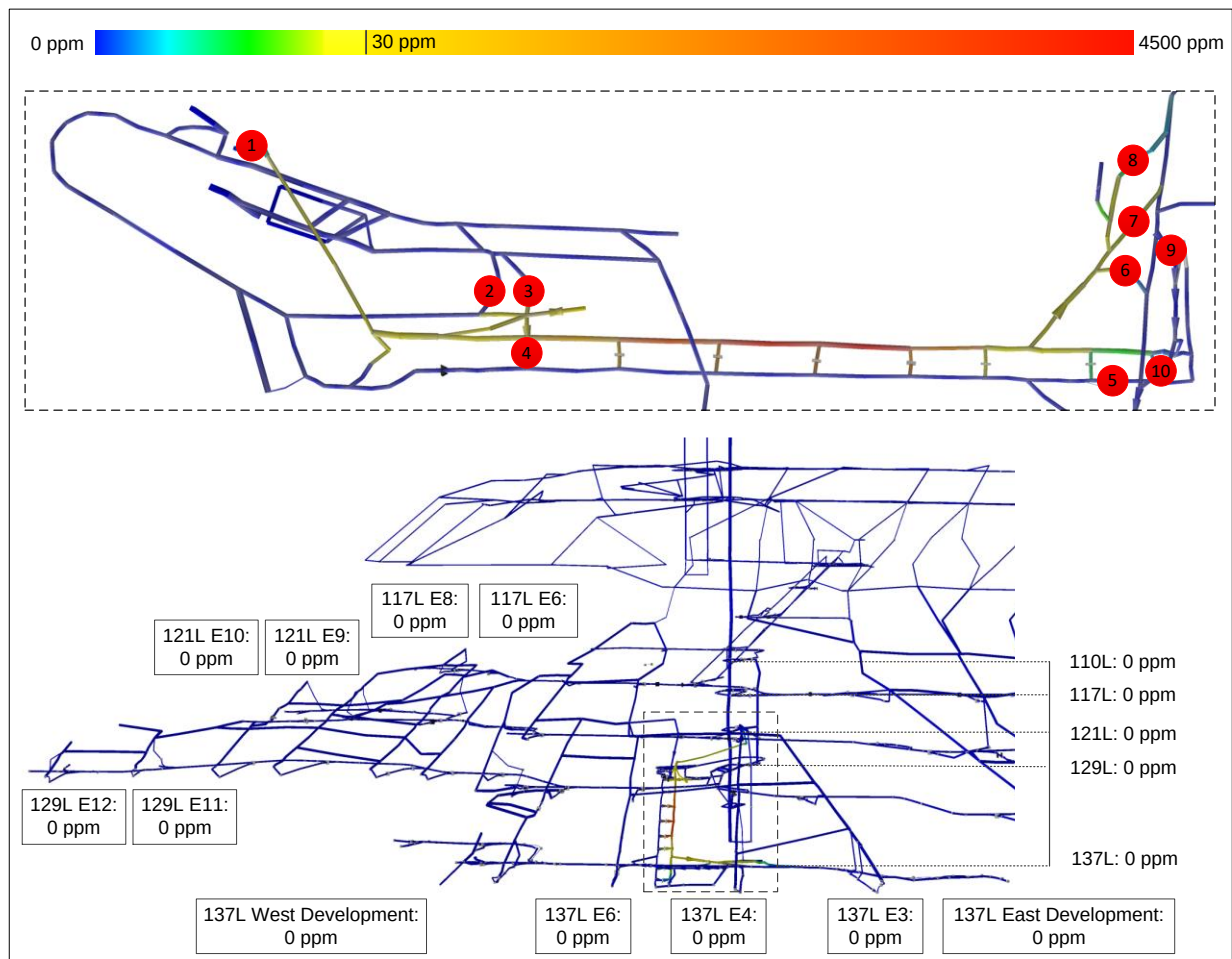


Figure 3-22: Effect of CO results after implementation of defined set point – TB03

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The effectiveness of the emergency plan is clear since no work area exceeded the OEL for either temperature or CO concentration. However, the entire conveyor decline was filled with CO-contaminated air at elevated temperatures. Figure 3-23 illustrates the distribution of the contaminated air along the conveyor belt decline after the implementation of the emergency plan.

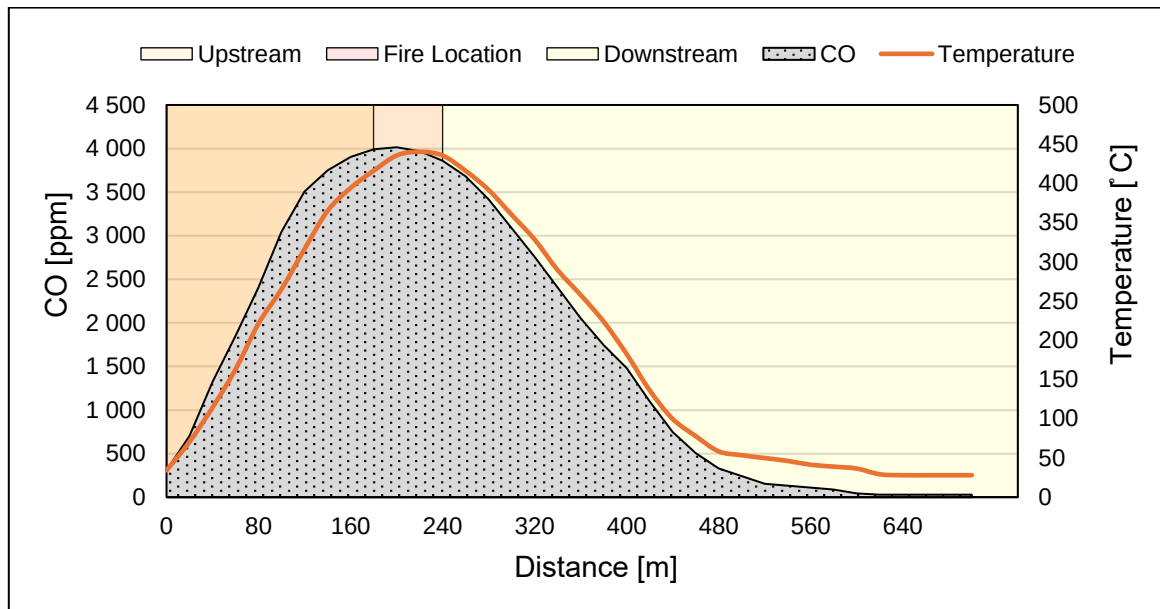


Figure 3-23: Contaminated air distribution along the conveyor decline – TB03

The impact of the flow reversal is evident in Figure 3-23. The highest CO concentrations and elevated temperatures are observed upstream of the fire location. However, contaminated air became trapped in the conveyor decline due to the closure of the fire doors. To prevent contaminated air from reaching active work areas, it was necessary to use the dedicated chimney, presented in Figure 3-19, as an exhaust system to remove the polluted air from the decline.

3. Smoke extraction

The contaminated air from the decline was extracted using the configuration presented in Figure 3-19. Through-flow ventilation was required to supply the 45 kW fans with sufficient airflow to extract smoke from the decline. To create a ventilation drift, Fire Door 1 at the intake of the conveyor decline had to be opened and the ventilation door in cross-cut E4 had to remain closed. This set-up established a closed circuit between the two 45 kW fans and the decline. The results of the smoke extraction are presented in Figure 3-24.

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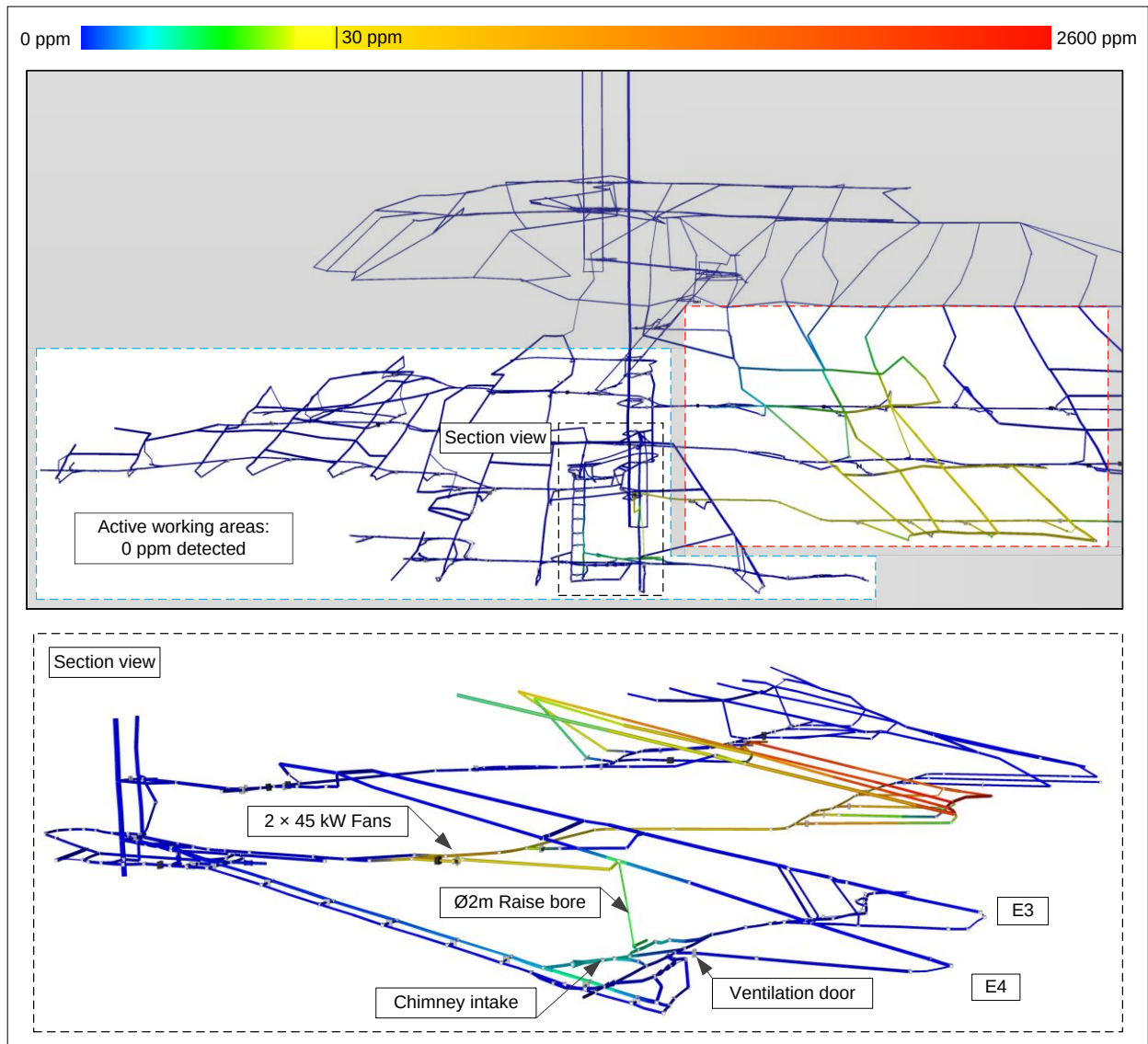


Figure 3-24: Smoke extraction simulation results – TB03

The dedicated chimney effectively extracted contaminated air from the conveyor decline and directed it towards the eastern side of the mine, ensuring that no active working areas would be affected. However, it is important to note that this configuration should only be implemented once the fire has been fully extinguished as increased air mass flow could reignite the fire.

The introduction of fresh air at the intake of the conveyor decline diluted the contaminated air and reduced its temperature. The maximum air temperature at the fan intake was 41 °C, which posed no risk of damage to the fan system. As shown in Figure 3-25, it took approximately 22 minutes for the contaminated air to be fully extracted from the conveyor decline and directed to the eastern part of Mine A.

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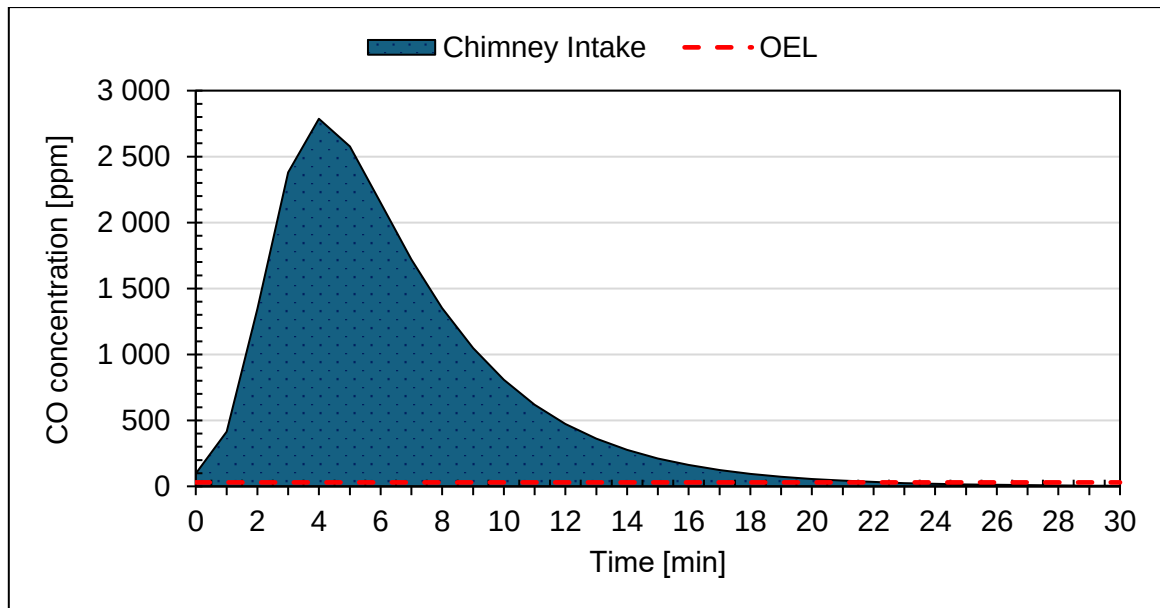


Figure 3-25: Time to extract contaminated air

Figure 3-25 shows the CO concentration at the chimney intake. After 22 minutes, the CO levels fell below the OEL, indicating that the conveyor decline had been cleared of contaminated air. Once the contaminated air has been removed from the conveyor belt decline, it could be concluded that the fire scenario had been resolved successfully. This allowed for the implementation of safety protocols for re-entry.

3.5.3 Results summary

The emergency plan for a conveyor belt fire at Mine A involved applying all four key ventilation control techniques, as discussed in Section 1.4.3, to reduce the fire's impact. To assess the plan's effectiveness, three simulation scenarios were carried out. Table 3-10 summarises each scenario, detailing the ventilation control technique that was applied and evaluated, and whether it achieved the expected outcomes.

Table 3-10: Evaluation of emergency plan

		Ventilation control technique			
		1. Pressure control	2. Airflow regulation	3. Airflow partitioning	4. Smoke extraction
Simulation scenario	1. Implementation after time t	✓ R	✓ R	✓ R	x
	2. Implementation of defined set point	✓	✓ R	✓ R	x
	3. Smoke extraction	✓	✓	✓	✓ R

✓	Applied	Effective	R	Reported
x	Not applied	Not effective		

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Table 3-10 demonstrates that each remediation strategy was implemented and evaluated. In each simulated scenario, at least one ventilation control technique was reported in order to finally reach a conclusion regarding the importance and effectiveness of each technique in contributing to the overall emergency plan. The strategies effectively contributed to the overall emergency plan for mitigating the impact of a conveyor belt fire incident in the ventilation network of Mine A.

3.6 Results and study validation

3.6.1 Validation of results

In accordance with the Mine Health and Safety Act, no. 29 of 1996, employers are responsible for ensuring that employees are not exposed to flames, fumes, or smoke resulting from a conveyor belt fire. This includes implementing measures to prevent, detect, and combat such fires [14]. To comply with this regulation, Mine A accepted the developed emergency plan as the most effective measure for mitigating the effect of a conveyor belt fire incident. Fire doors were installed at the respective locations along with effective sealing measures. A dedicated chimney is still being developed and the planned completion date is end of November 2024.

According to safety regulations, it is not feasible to initiate a conveyor belt fire in the ventilation network of Mine A. Consequently, it is necessary to validate the results by consulting relevant literature that has evaluated similar scenarios. The ventilation simulation model for Mine A was calibrated and verified, as shown in Figure 3-7 to Figure 3-10. The design fire curve specifications were determined based on validated literature. Therefore, it was only necessary to validate the factors that influenced changes in airflow direction.

The results of this study were validated using the findings presented in the work of Levin et al., titled *Experimental and Numerical Study of Air Flow Reversal Induced by Fire in an Inclined Mine Working* [72]. The study of Levin et al. explored airflow behaviour in an inclined mine working area during a fire and focused on the conditions that led to airflow reversal by using both experimental and numerical methods. A laboratory test bench was constructed to simulate an inclined mine working area with a heat source representing a fire. A mathematical model of heat and mass transfer was validated in this scenario. Levin et al. examined how factors such as pressure drop, ventilation settings, and HRR interact to either stabilise or reverse airflow. The geometric model used for the numerical simulation is shown in Figure 3-26.

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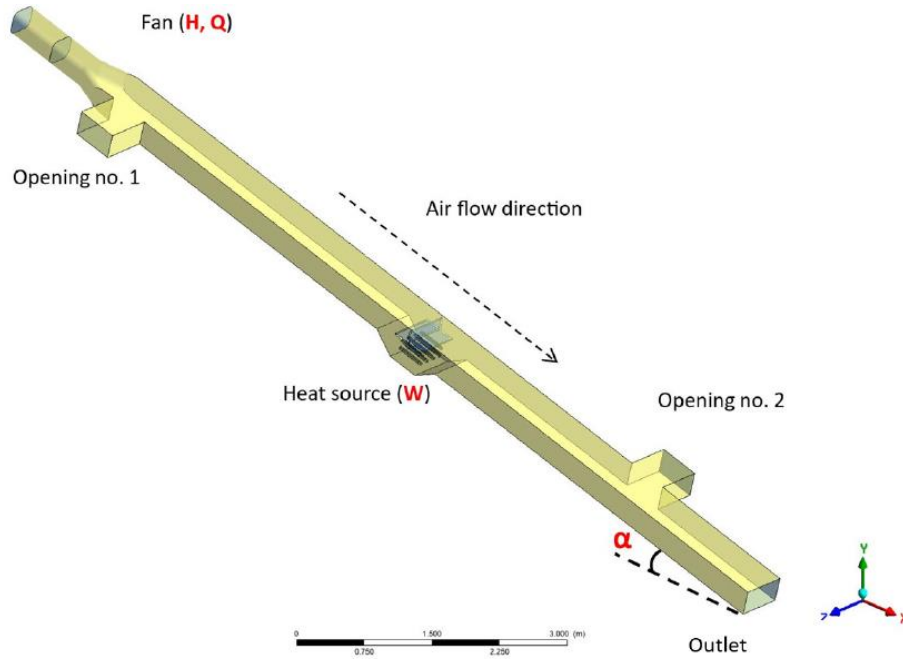


Figure 3-26: Geometric simulation model [72]

Figure 3-26 illustrates the experimental set-up described in the study by Levin et al., which was designed to simulate airflow in an inclined mine working. The experimental scenario that was used to verify the results of this study, consisted of the following [72]:

- **Inclined tunnel:** The set-up included a simplified, scaled-down model of an inclined mine working, represented by a long tunnel with two openings (Opening No. 1 and Opening No. 2).
- **Valve settings:** Opening No. 1 was kept open, while Opening No. 2 was intermittently opened to assess the effect of air resistance.
- **Fan (H, Q):** A fan near Opening No. 1 created airflow through the tunnel. The fan's parameters, such as pressure head (H) and flow rate (Q), controlled the air velocity.
- **Heat source (W):** The heat source, representing a simulated fire placed in the middle of the tunnel, produced 55 kW of heat, creating thermal gradients that influenced airflow dynamics.
- **Airflow direction:** Initially, airflow moved from Opening No. 1 towards the outlet at Opening No. 2.
- **Angle of inclination (α):** An inclination angle of -13° was implemented.

Figure 3-27 shows the dependencies of air mass flow at the outlet of the working area under different ventilation valve opening degrees when subjected to a 55 kW heat source. Positive mass flow values indicate reversed airflow in the inclined channel (from bottom to top), while negative values correspond to airflow in the same direction as at zero HRR (from top to bottom) [72].

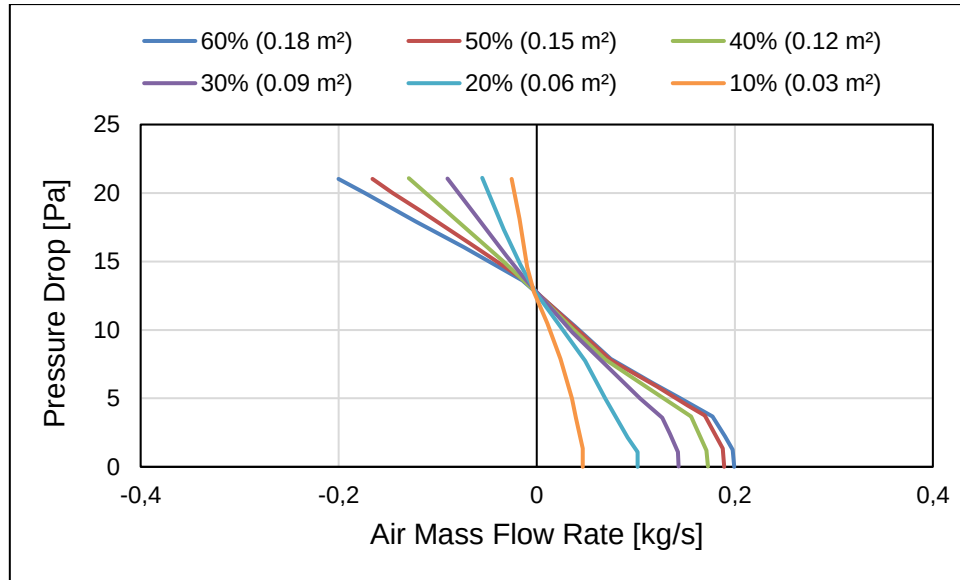


Figure 3-27: Air mass flow rate at outlet – literature results [72]

Figure 3-27 shows that the airflow was reversed in all scenarios where the valve was opened intermittently, with the intersection points of the curves nearly aligned. This observation indicates that the timing of airflow reversal is not significantly influenced by air resistance in the ventilation network. Instead, the reversal is primarily influenced by the fire's strength and the pressure drop in the inclined working area [72]. The same phenomenon was experienced in this study. Figure 3-28 shows the results of the air mass flow caused by the pressure drop in the conveyor decline, which led to a reversal of air volume flow direction as illustrated in Figure 3-14.

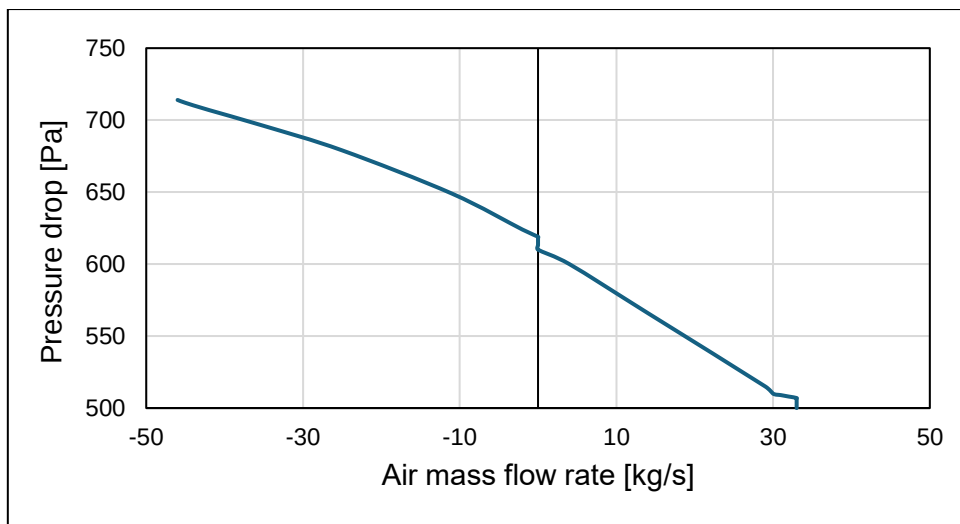


Figure 3-28: Air mass flow rate in the conveyor decline – TB03

Figure 3-28 shows the air mass flow rate in the conveyor belt decline as a result of the TB03 fire incident. The observed trend aligns with the findings of Levin et al. As the pressure in the conveyor

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belt decline decreased, the direction of airflow shifted, which was indicated by the positive mass flow values. Thus, it is reasonable to predict that a change in airflow direction would occur during a fire in the conveyor belt decline of Mine A. Therefore, the results presented in this study are based on validated data, leading to accurate conclusions and the formulation of an effective emergency plan.

3.6.2 Validation of study

This section extends the validation of the developed solution, as outlined in Section 2.6, by incorporating the results obtained in this chapter. The purpose is to evaluate whether the study's objectives, as detailed in Section 1.8, have been achieved successfully. The following key questions, along with their answers, determine the overall success of the study's outcomes.

Has a methodological approach been defined to evaluate the identified hazards, and have the associated risks been quantified?

Section 2.2 outlined a method for evaluating fire hazards and quantifying their associated risks. This method was applied in Section 3.2, where it was determined that conveyor belts presented the greatest risk for fire incidents in the ventilation network of Mine A. Consequently, the evaluation of conveyor belt fire incidents served as the foundation for the case study.

Was a simulation model of the entire ventilation network of the underground mine constructed, calibrated, and verified?

As outlined in Section 3.3, a skeleton model of Mine A's ventilation network was created and calibrated using the system information obtained. The results were compared with actual underground ventilation audits, with Figure 3-7 to Figure 3-10 demonstrating that the simulation model had an MAE of less than 5%. Thus, the ventilation simulation model was considered a reliable virtual representation of Mine A's ventilation network.

Has a standardised method been developed to define a design fire curve and simulate its impact on an underground mine's ventilation network?

In Section 2.4.2, a standardised method was established for determining design fire curves. Section 3.4.1 detailed the design fires for each conveyor belt configuration. The simulation and evaluation of the TB03 conveyor belt fire incident were presented in Section 3.4.3, while the fire incidents for the other conveyor belt configurations are discussed in Appendix G. The findings

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indicated that the distribution of CO had the most significant impact on the ventilation network of Mine A, highlighting the necessity for active remediation strategies.

Have remediation strategies based on ventilation control practices been identified, and have these strategies been implemented in the ventilation model to quantify their effectiveness?

In Section 3.5.1, four ventilation control techniques were identified and the necessity for implementation explained. Three simulation scenarios were established to evaluate their effectiveness. It was concluded that the implementation of these four identified remediation strategies formed the developed emergency plan. The emergency plan simulated in the event of TB03 catching fire resulted mitigated the fire incident effectively, as presented in Section 3.5.2. The defined emergency plan was implemented on the remaining three conveyor belt configurations to emphasise its effectiveness. These results are discussed in Appendix H.

Have the results been validated through a comparison with literature?

In Section 3.6.1, the study by Levin et al. [72] was evaluated thoroughly and a direct comparison was made between their results and those obtained in this study. Additionally, each design fire scenario was developed using data derived from validated literature sources.

By evaluating the answers to each of the questions above, it is evident that all the objectives of this study have been met successfully. Therefore, it can be concluded that this study is validated and successful.

3.7 Conclusion

This chapter focused on implementing the solution outlined in Section 2 through a hypothetical case study. An industry-standard fire risk assessment identified conveyor belt fires as the baseline for the case study. A skeleton model of the ventilation network for Mine A, a twin-shaft gold mining operation located in the Free State region of South Africa, was developed, as discussed in Section 3.3. This simulation model was calibrated and verified against actual underground ventilation audits, achieving an MAE of less than 5%. Based on the verification results, the model served as an accurate virtual representation of Mine A's underground ventilation network.

In Section 3.4.1, design fires for each conveyor configuration were determined using the method described in Section 2.4.2. The design fires were simulated, and their impact on the ventilation network of Mine A demonstrated that CO distribution posed the greatest risk to employee health and safety. Four main ventilation control techniques obtained from literature were identified as

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remediation strategies to form the emergency plan discussed in Section 3.5.1. Three simulation scenarios were carried out to evaluate the effectiveness of the plan.

The implementation of the solution successfully met the study objectives, and the emergency plan effectively isolated contaminated air from active working areas and extracted it from the ventilation network of Mine A. The verification results highlighted in Section 3.6 emphasise the accuracy and importance of simulation software in the mining industry, allowing personnel to optimise decision-making strategies. The outcomes confirm that all study objectives have been achieved successfully.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

4.1 Introduction

This chapter provides a comprehensive summary of the study and outlines the key findings and conclusions drawn from the research. Recommendations are also provided for future research in this field of study.

4.2 Summary

The mining industry makes a significant financial contribution to South Africa's formal business economy. The substantial growth in recent years is a testament to the dedication and success of mine employees in meeting production targets. To maintain this progress, it is essential to prioritise safe working conditions in the industry. One of the crucial factors in sustaining a healthy working environment underground is ensuring that the mine ventilation system supplies airflow in sufficient quality and quantity to reduce the concentration of contaminants. The mine ventilation system, however, is a complex and dynamic system that requires effective planning to ensure the health and safety of employees.

In Chapter 2, a comprehensive literature review was completed that focused on the formidable challenge regarding the threat of fires occurring in underground mines, which may contribute to the loss of both lives and revenue for any mining enterprise. Literature mainly focuses on the localised effects of fires in the underground ventilation networks of mines. This sparked curiosity on how these localised effects spread through the entire ventilation network of a mine and how these effects can be mitigated. To analyse this spread, it was evident that a realistic simulation model had to be created to represent the actual ventilation network of an underground mine. Given that the focus was on the impact on the rest of the ventilation network, design fires based on literature had to be implemented to form the baseline of this study.

A robust collection of literature relevant to the scope of this study was identified. The criteria for identifying the most relevant studies were defined based on the scope of this study. These criteria included whether studies utilised simulation software for evaluation, employed standardised design fire scenarios, investigated the variation of environmental factors, and assessed the effectiveness of ventilation control techniques for mitigation.

After thoroughly reviewing 12 studies, it became clear that there was a need for this study to be conducted. Specifically, there was a significant need to develop and use a simulation model

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capable of accurately forecasting the consequences of a standardised design fire in the ventilation network of an underground mine. This capability is crucial for formulating proactive planning strategies to effectively address fire incidents and ensure the safety of mineworkers.

To address this need, a solution was developed in Chapter 2, where a risk assessment determined the cases study to be investigated. The solution described the development and utilisation of a ventilation simulation that represents the ventilation network of an underground mine. A method was defined to specify the required design fire, whereafter the implementation and evaluation procedure was fully described. Finally, the solution described the process of developing, implementing, and evaluating proactive planning strategies based on ventilation control practices. To validate this study, the developed solution was implemented. The following study objectives were identified as a measure of validation:

1. Define a methodological approach to identify fire hazards and quantify the associated risks.
2. Construct, calibrate, and verify a simulation model for the entire ventilation system of an underground mine.
3. Develop a standardised method that can:
 - a. Define a design fire curve, then simulate and evaluate its impact on an underground mine's ventilation network.
 - b. Identify remediation strategies based on ventilation control practices to combat fire incidents and implement these strategies in the ventilation simulation model to quantify their effectiveness.
4. Validate results through comparison with existing literature.

The solution developed in this study was thoroughly tested and validated in Chapter 3 by applying it to the selected case study. Mine A is a twin-shaft gold mining operation located in the Free State region of South Africa. It was chosen to implement this solution in order to establish an effective emergency plan for fire incidents. An industry-standard risk assessment indicated that the four conveyor belt configurations in the decline, which serves as an intake to the 129 and 137 levels of Mine A, pose the greatest risk for fire incidents. This configuration formed the baseline for the case study.

A skeleton model of Mine A was constructed and calibrated using the obtained system information. This allowed the model to accurately represent the actual ventilation network of Mine A. Underground ventilation audits were conducted, and the findings verified the accuracy of the simulation model, which achieved an MAE of less than 5%.

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The method defined in Section 2.4.2 was used to establish the design fire for each conveyor belt configuration. These results were incorporated into the ventilation simulation model of Mine A, as described in Section 2.4.3. Upon evaluation, it was found that the distribution of CO posed a significant risk to employee health and safety. Upon analysing the distribution of contaminated air, the need for implementing indirect ventilation control techniques was recognised, as defined in Section 1.4.3.

The identified remediation strategies include pressure control, which requires effective sealing; airflow regulation and partitioning, which involves installing fire doors at strategic locations; and installing a dedicated chimney for extracting smoke from the partitioned area. The necessity of these strategies is discussed in Section 3.5.1. Together, these remediation strategies formed a comprehensive emergency plan that integrated various elements to enhance fire safety and effectiveness.

The implementation of the developed solution yielded positive results in evaluating the effects of a fire incident in the underground ventilation network of a mine. An effective emergency plan was developed using the results. Although the results presented in this study do not apply to all fire scenarios, the developed solution is certainly versatile, emphasising the need for simulation modelling in the planning process of fire mitigation.

In Section 2.6, the developed solution was validated, which was followed by the validation of the study in Section 3.6. Since all the objectives of the study have been met, it can be concluded that the outcome of this study is successful.

4.3 Recommendations for future research

This study effectively simulated the impact of a fire incident on the entire ventilation network of a mine. Based on the results, an effective emergency plan was developed and verified, which is currently being implemented in Mine A. While this study's outcomes are promising, potential for future research on related topics remains. The recommendations for future research are as follows:

- The implementation of a design fire in the mine's ventilation simulation aligns with this study's scope. However, to model the complex dynamic nature of a fire and its localised effects more accurately, three-dimensional CFD software, such as PyroSim developed by Thunderhead Engineering, is recommended. This software can simulate the specific characteristics of fire

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in the given environment, providing precise input values for the ventilation model of the mining operation.

- The design fires derived for this study, as outlined in Section 3.4.1, are based on verified literature, leading to accurate predictions. For future studies that aim to conduct a more detailed evaluation of the localised nature of a fire incident, it is recommended that all materials potentially contributing to the combustion process be included in the design fire, following Duggan's method outlined in Section 1.6.4. Additionally, where feasible, experimental procedures should be conducted in a fire test gallery to assess the behaviour of the fire involving all possible fuel sources.
- This study focused on stationary fire hazards. However, there is an opportunity to assess fire incidents involving fuel sources that are not stationary. Such scenarios could significantly influence airflow direction and the distribution of contaminated air, potentially altering the dynamics of fire behaviour and smoke propagation. Evaluating these mobile fuel sources would provide valuable insights into fire risk management and ventilation strategies in dynamic environments.
- The study highlighted the importance of implementing automated fire doors and ensuring effective sealing between connected areas. While standard methods for these procedures are available, there is potential for future research to evaluate the most effective configurations.
- The solution developed in this study was implemented successfully in the ventilation network of Mine A. Remediation strategies were formulated for a specific case study that poses a current risk. Moreover, there is significant potential for future planning. This approach not only supports immediate remediation efforts but also lays the groundwork for more effective long-term ventilation management, ensuring the safety and efficiency of mining operations.
- The developed solution was implemented in a relatively shallow mine where no additional refrigeration was required. It is recommended that the methods outlined in this study be applied to deep-level mines, where greater depth introduces more significant challenges. The integration of cooling systems and increased natural ventilation pressures may alter the outcome of a fire incident, potentially leading to the development of different ventilation control techniques.

4.4 Study insights on industry significance

This study makes a significant contribution to the mining industry by providing a comprehensive approach to mitigate fire risks in underground mines through the use of advanced simulation techniques. It addresses a crucial gap in understanding the spread of fire effects throughout the entire mine ventilation network, moving beyond the localised focus of previous studies. The development of a standardised method for simulating design fires and evaluating ventilation control strategies equips mining operations with proactive planning tools to enhance worker safety.

The solution, validated through a case study in a South African gold mine, provides a practical framework for emergency planning to prioritise the health and safety of mine workers. The importance of simulation modelling in fire mitigation strategies is emphasised, thereby contributing to safer mine operations and potentially reducing the loss of lives and revenue as a result of fire incidents.

This study's validated solution paves the way for widespread implementation across all underground mining sectors, further reinforcing its commitment to safety and operational continuity.

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APPENDIX A – RISK ASSESSMENT

Table A-1: Risk assessment

Workplace	No.	Fuel type	Fuel sources	Quantity of fuel	Ignition source type	Ignition sources	Intake/return	Proximity to other sources	Pre-control consequence	Pre-control likelihood	Pre-control risk rating
Conveyor belts	4	Belt	A	1 020 m ²	Drive pulley	C	Intake	Yes	C5	P4	H24
Cross-cut	14	Timber storage	A	40 m ³	[-]	[-]	Intake	Yes	C4	P2	H19
Decline	6	Timber	A	100 m ³	Friction	C	Intake	Yes	C5	P2	H19
Haulage	10	Waste	A	30 000 m	[-]	[-]	Intake	Yes	C5	P2	H19
Shaft	3	Plastic pipes	A	11 000 m	[-]	[-]	Intake	No	C5	P2	H19
Shaft bottom	3				[-]	[-]	Intake	No	C5	P2	H19
Drill rig	3	Grease and oil	B	20 kg	Contraband	B	Intake	No	C4	P2	H14
Station	12	Electrical switchgear	C	6 m ³	Electrical switchgear	B	Intake	No	C4	P2	H14
Oil/paint store	5	Oil	B	1 200 ℓ	[-]	[-]	Return	Yes	C3	P3	M13
Battery bay	7	Electric cable	C	160 m	Electric cable	B	Intake	No	C4	P3	M12
Development end	16	Electric cable	C	200 m	Electric cable	B	Intake	No	C4	P1	M12
Diamond drilling/ geological drilling/ lib drilling	4	Waste	A	1 m ³	[-]	[-]	Intake	No	C4	P1	M12
Hoist room	1	Electric cable	C	120 m	Electric cable	B	Intake	No	C4	P1	M12
Hot work	1	Cylinder	B	1 m ³	Sparks	[-]	Intake	No	C4	P1	M12
Mini substation	21	Electric cable	C	60 m	Electric cable	B	Intake	No	C4	P1	M12
Mining store	1	Electric cable	C	15 m	Electric cable	B	Intake	Yes	C4	P1	M12
Pump station/ chamber	4	Motor control centre	C	150 m ³	Motor control centre	B	Intake	No	C4	P1	M12

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Workplace	No.	Fuel type	Fuel sources	Quantity of fuel	Ignition source type	Ignition sources	Intake/return	Proximity to other sources	Pre-control consequence	Pre-control likelihood	Pre-control risk rating
Stopes panel	27	Electric cable	C	60 m	Electric cable	B	Intake	Yes	C4	P1	M12
Substation	7	Electric cable	C	180 m	Electric cable	B	Intake	No	C4	P1	M12
Tips, filters, and foggers	5	Filters	A	10 m ³	[-]	[-]	Intake	No	C4	P1	M12
Waiting area	18	Electric cable	C	10 m	Electric cable	B	Intake	No	C4	P1	M12
Workshop	10	Diesel	B	100 ℓ	[-]	[-]	Intake	No	C4	P1	M12
Refuge bay	14	Electric cable	C	20 m	Electric cable	B	Intake	No	C3	P2	M11
Toilet	25	Plastic	A	1 m ³	Contraband	[-]	Intake	No	C3	P2	M11
Worked-out areas	1	Expanded organic foam spray sealant	A	20 m ³	[-]	[-]	Return	No	C3	P1	M9
Booster fan	3	Electric cable	C	[-]	Electric cable	B	Return	No	C2	P3	M8
Dams	8	Electric cable	C	100 m	Electric cable	B	Intake	No	C1	P1	L1

Fuel/ignition sources	
A	Heat
B	Electrical
C	Mechanical
D	Chemical

APPENDIX B – UNDERGROUND VENTILATION AUDITS

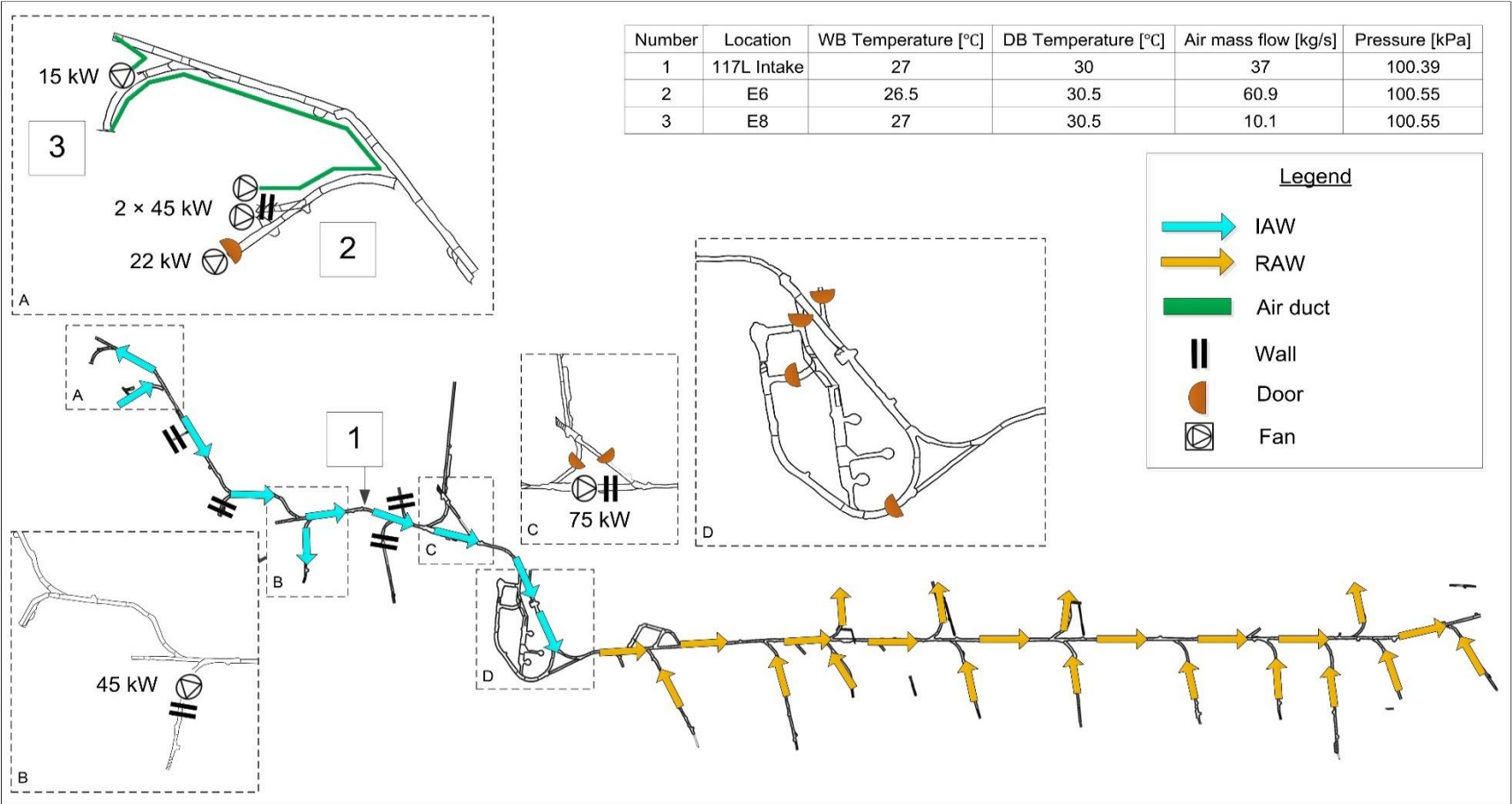


Figure B-1: Underground ventilation audit of 117 level

Simulating underground mine fires for emergency planning

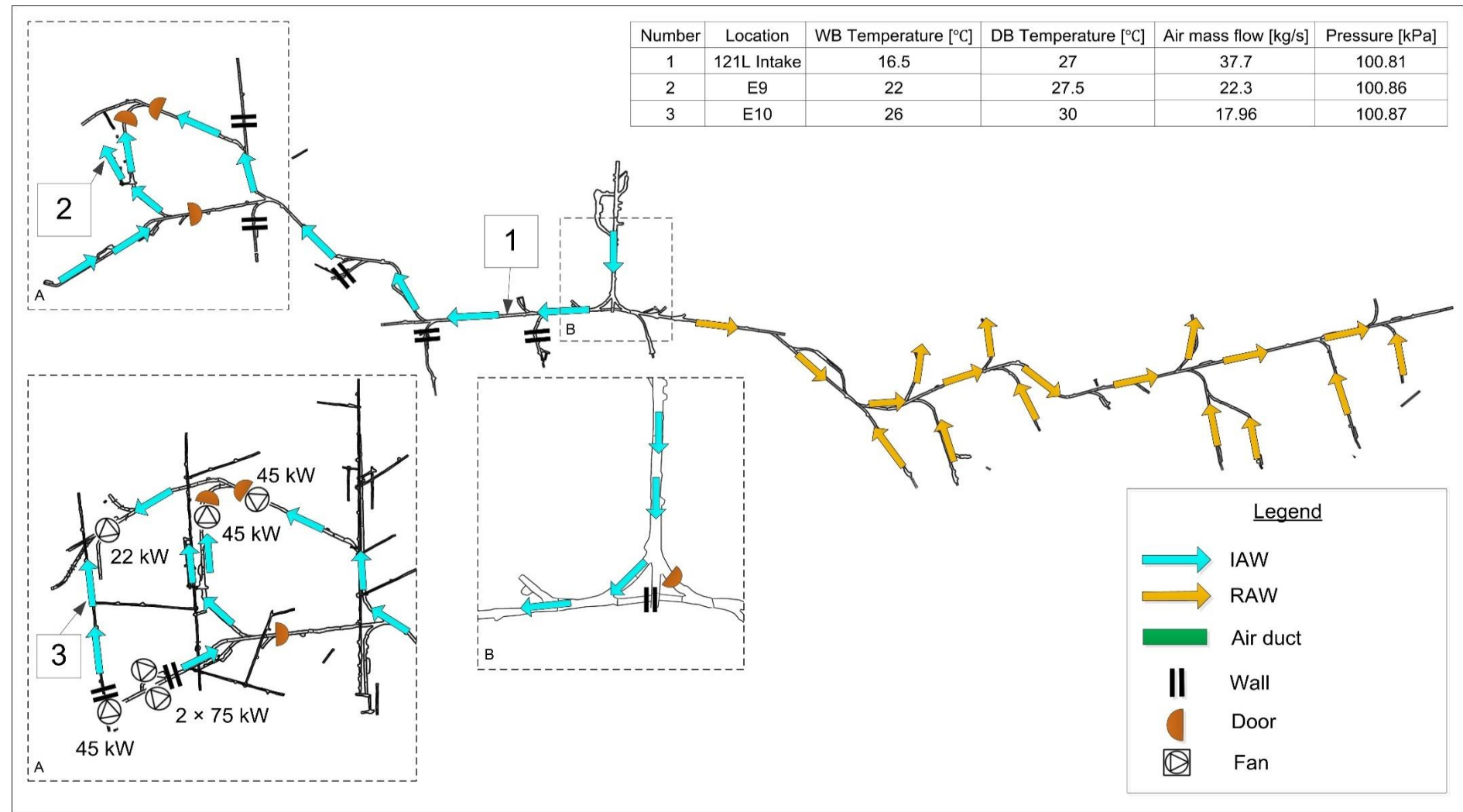


Figure B-2: Underground ventilation audit of 121 level

Simulating underground mine fires for emergency planning

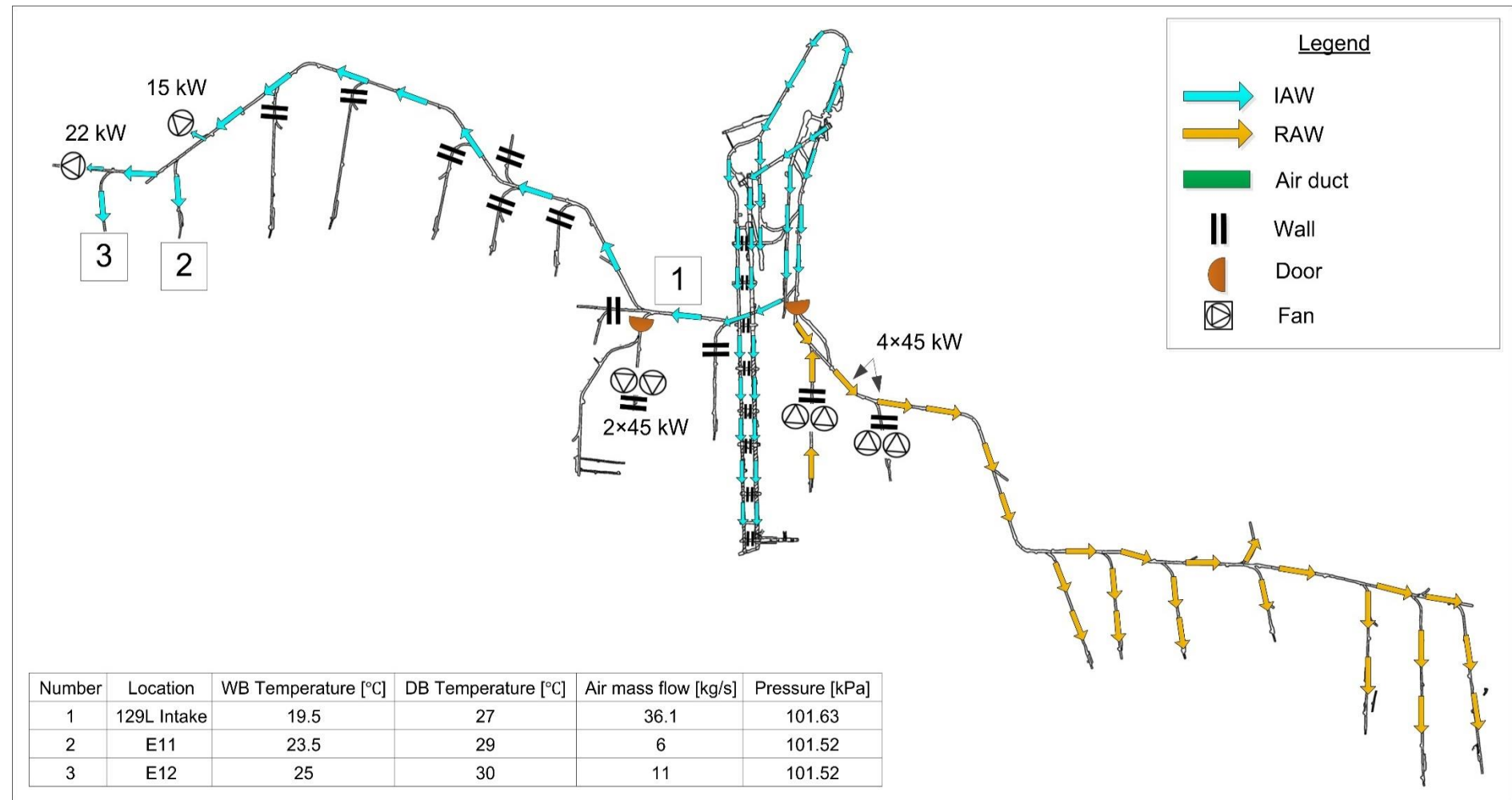


Figure B-3: Underground ventilation audit of 129 level

Simulating underground mine fires for emergency planning

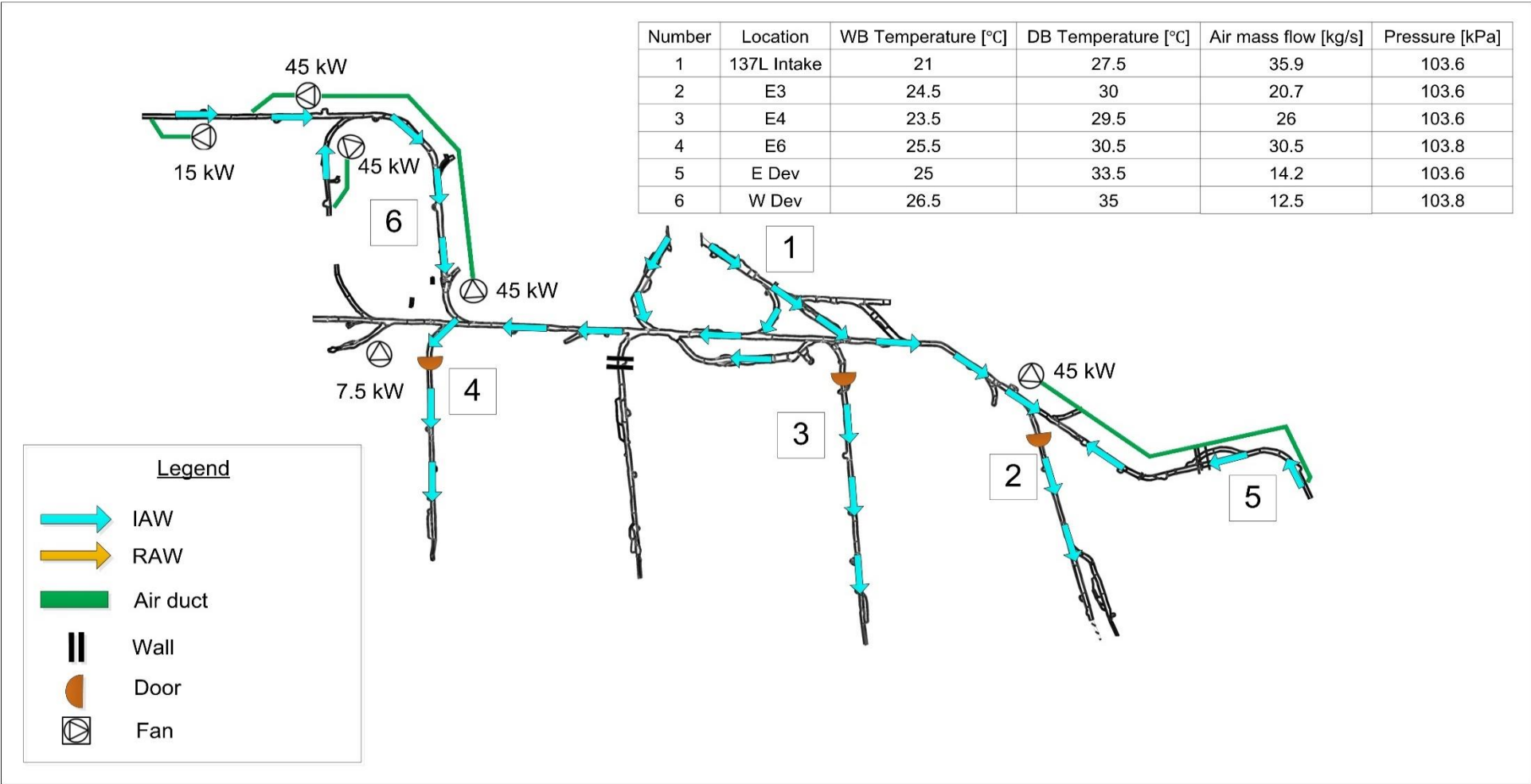


Figure B-4: Underground ventilation audit of 137 level

APPENDIX C – FAN CURVES

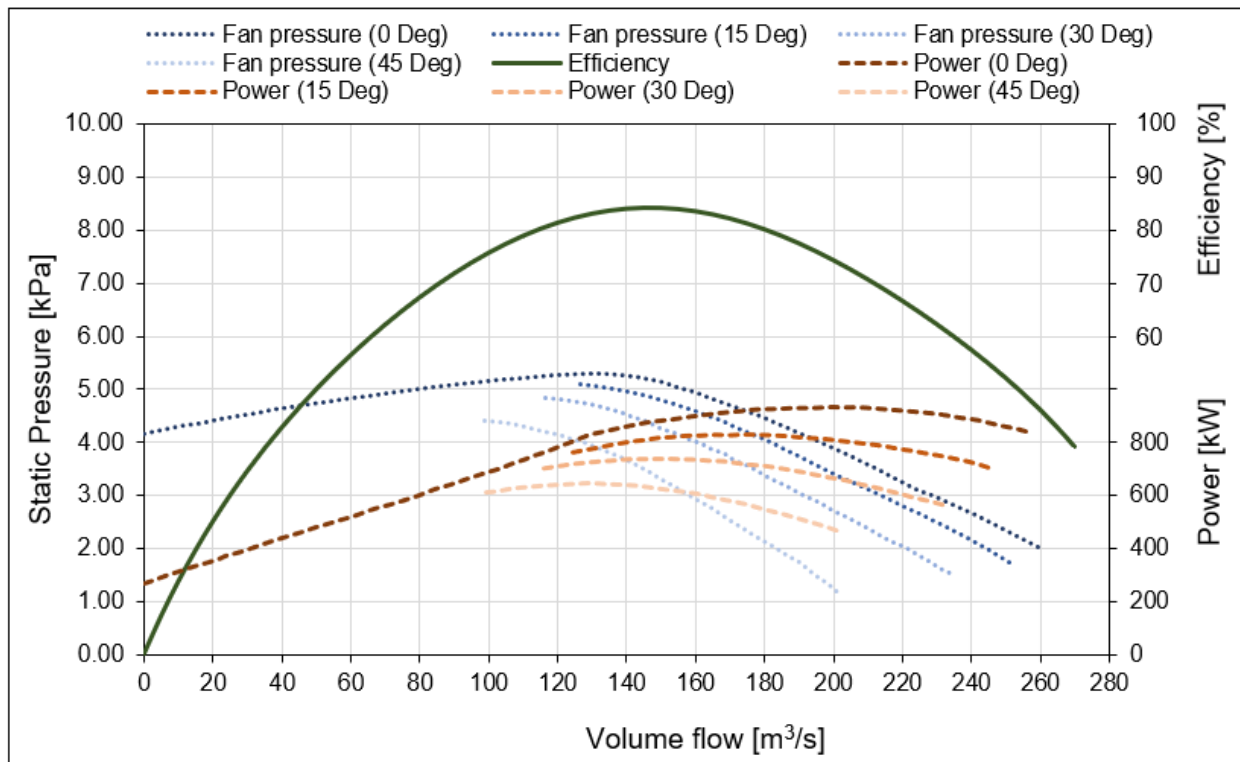


Figure C-1: 1 000 kW centrifugal fan performance curve

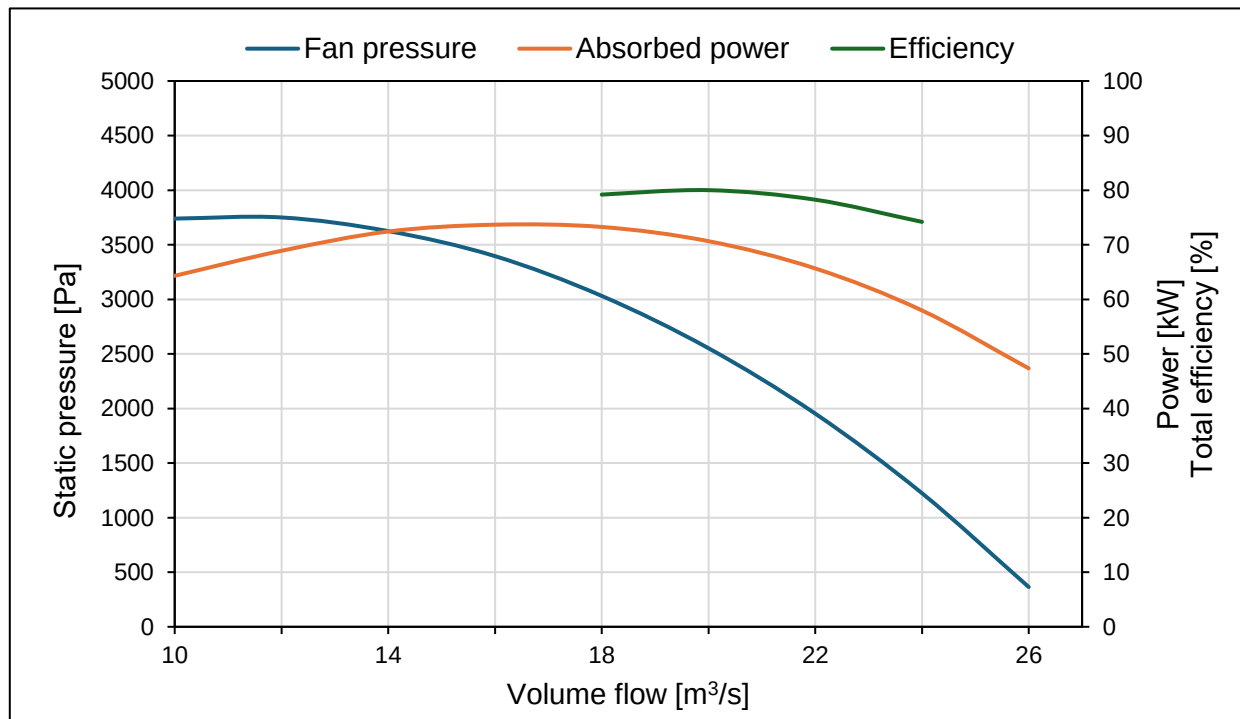


Figure C-2: 75 kW axial fan performance curve

Simulating underground mine fires for emergency planning

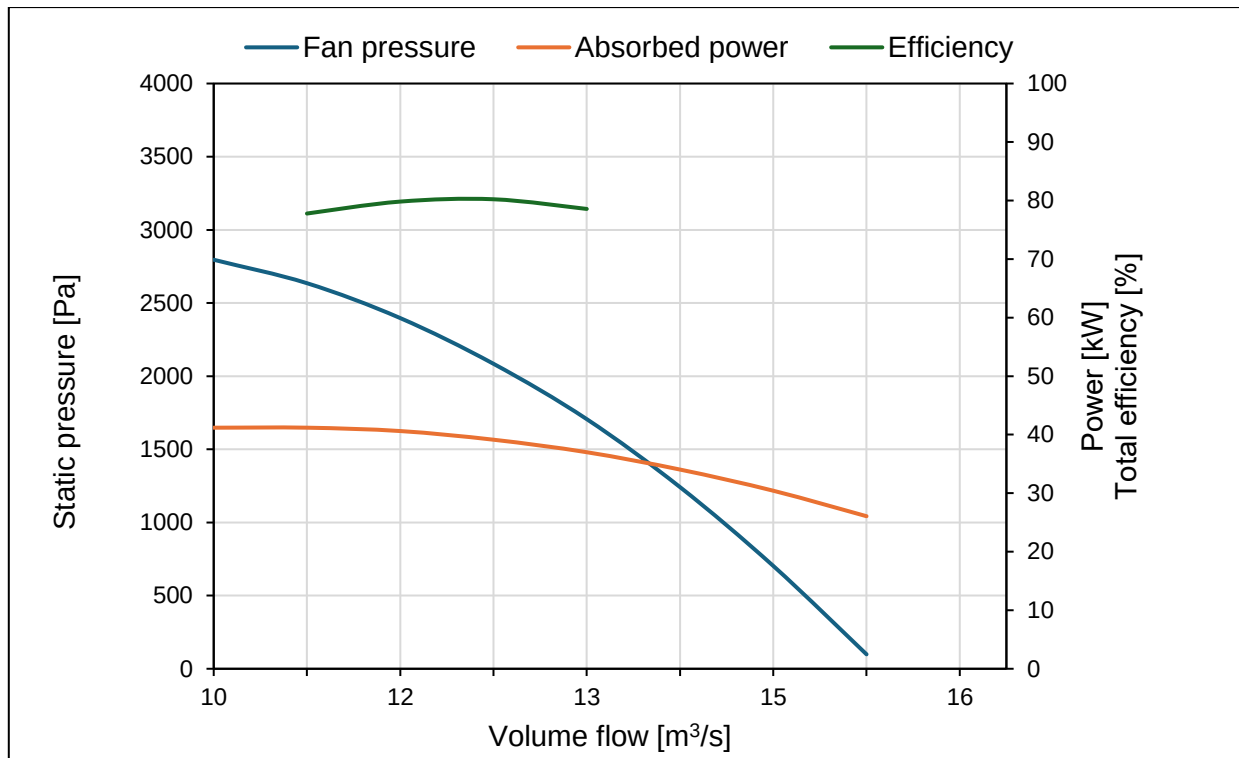


Figure C-3: 45 kW axial fan performance curve

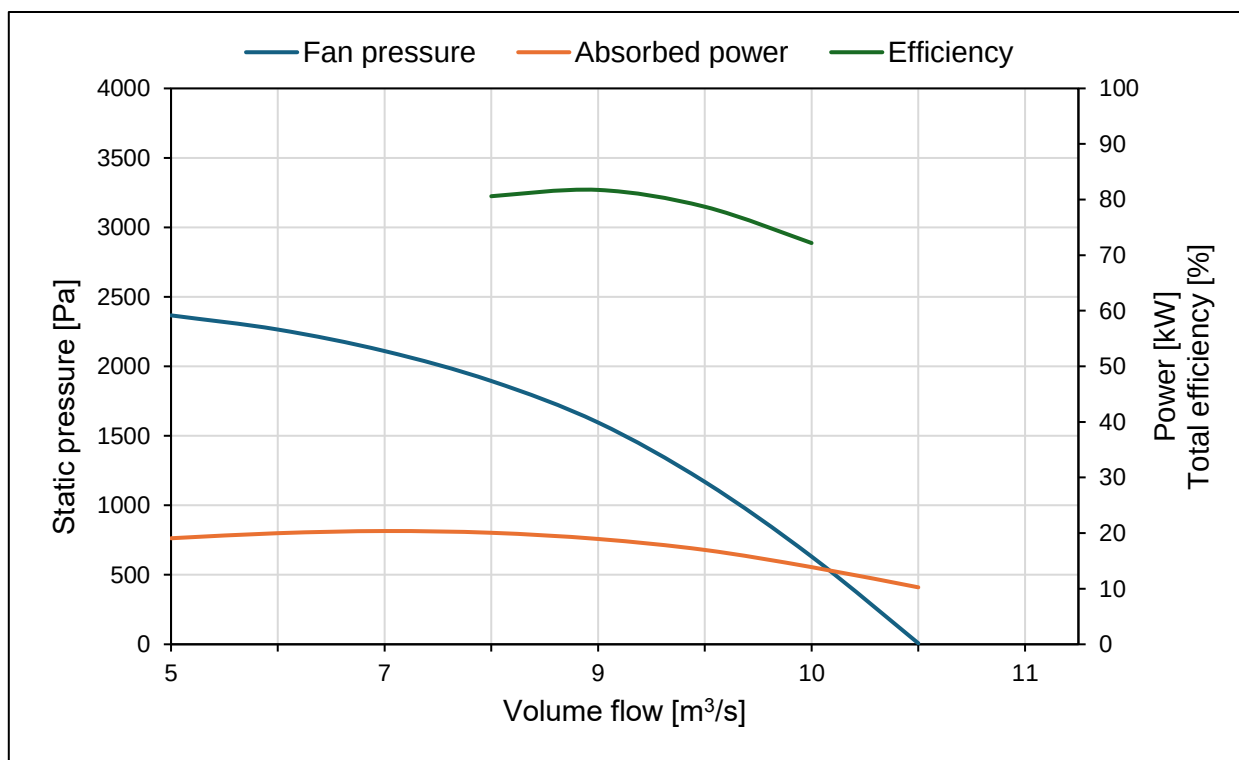


Figure C-4: 22 kW axial fan performance curve

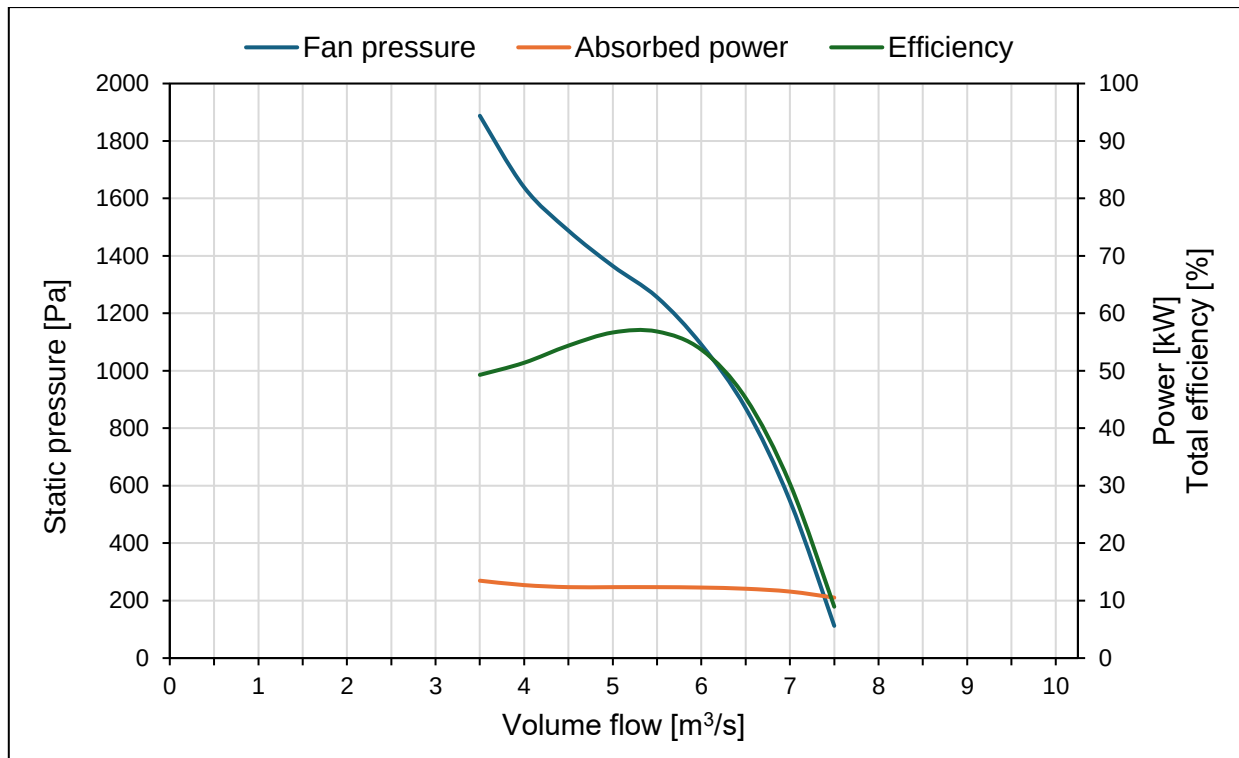


Figure C-5: 15 kW axial fan performance curve

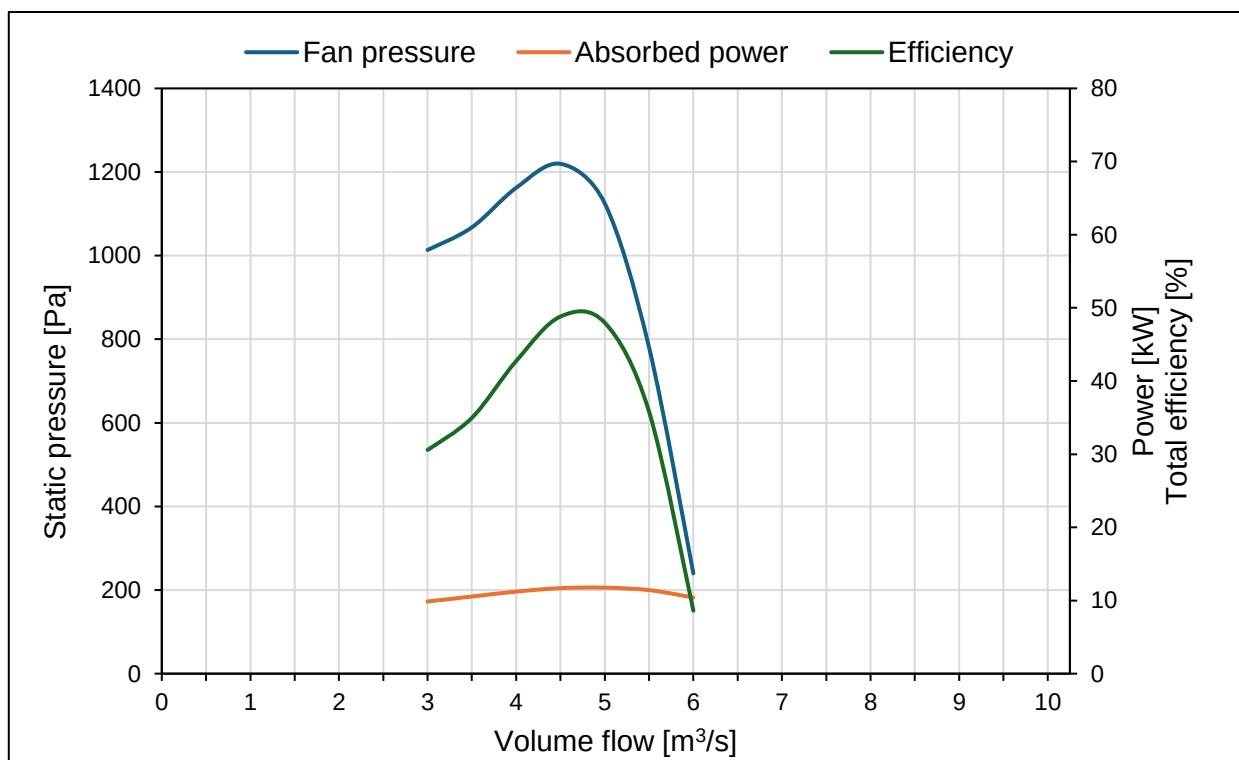


Figure C-6: 75 kW axial fan performance curve

APPENDIX D – TUNNEL COMPONENT SPECIFICATIONS

Table D-1: Rock properties

Parameter	Unit	Value	Description
Region	–	Free state	Region determines the rock properties to be used
Rock type	–	Quartzite	The major portion of the orebody
Rock density	kg/m ³	2 720	Density of the major rock type being mined
Thermal conductivity	kW/m/°C	0.00574	Thermal conductivity of the rock type
Specific heat	kJ/kg/°C	0.837	Specific heat of the rock type
Virgin rock temperature gradient	°C/m	0.015	Virgin rock temperature gradient specific to the region selected
Virgin rock surface temperature	°C	20	Surface starting virgin rock temperature
Age exposure – older haulages	years	10	Age of old haulages; all active mining areas to reflect ago equivalent to advance rate
Wetness – shaft	–	Damp	Main intake shaft wetness (wet, damp, dry)
Wetness – haulage	–	Damp	Main intake shaft wetness (wet, damp, dry)
Wetness – Production area	–	Wet	Main intake shaft wetness (wet, damp, dry)

Table D-2: Tunnel properties

Parameter	Dimensions [m unless indicated otherwise]	Friction factor [ns ² /m ⁴]	Description
Downcast shaft 1	50 m ²	0.011	Properties of downcast shaft (equipped)
Downcast shaft 2	29 m ²	0.011	Properties of downcast shaft (equipped)
Upcast shaft	29 m ²	0.011	Properties of upcast shaft (equipped)
Intake haulages	4 × 3.5	0.011	Properties of intake haulages
Return airway mains	5 × 5	0.011	Properties of return haulages
Return airway half levels	4 × 3.5	0.011	Properties of return haulages
Cross-cut(s)	3.5 × 3.5	0.011	Properties of cross-cut(s)
Travel way(s)	2.4 × 3	0.011	Properties of travel ways
Raise bores	2 m ²	0.003	Properties of raise boreholes
Centre gullies	2.9 × 1.5	0.011	Properties of centre gulleys
Strike gully(s)	2.9 × 1.5	0.011	Properties of strike gulleys
Face	1.5 × 20	0.011	Properties of stope

APPENDIX E – FIRE DESIGN CURVES

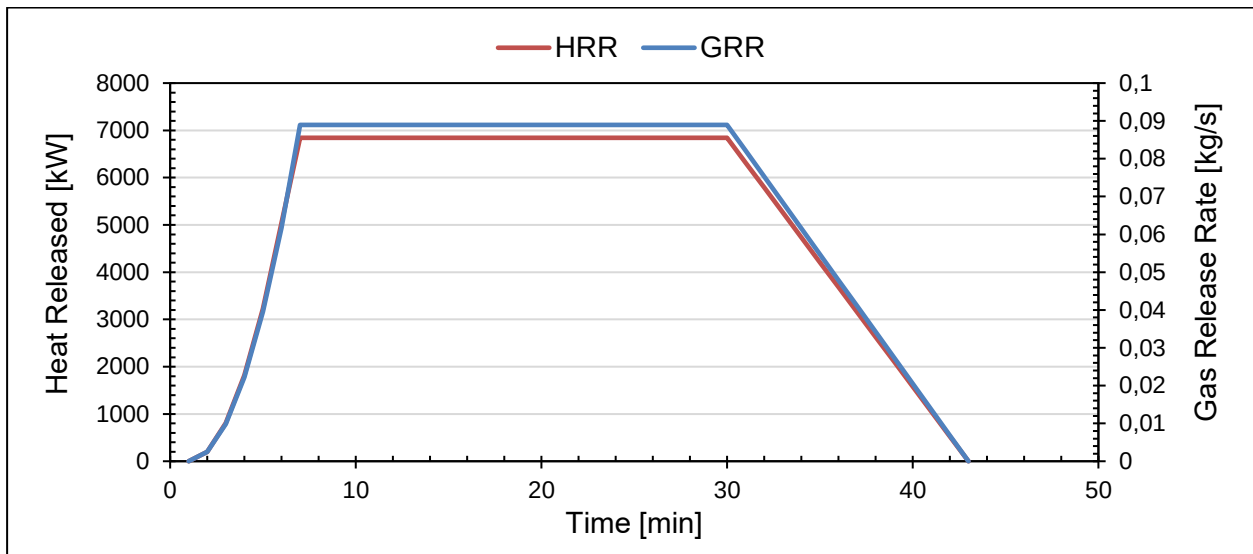


Figure E-1: TB01 design fire curves

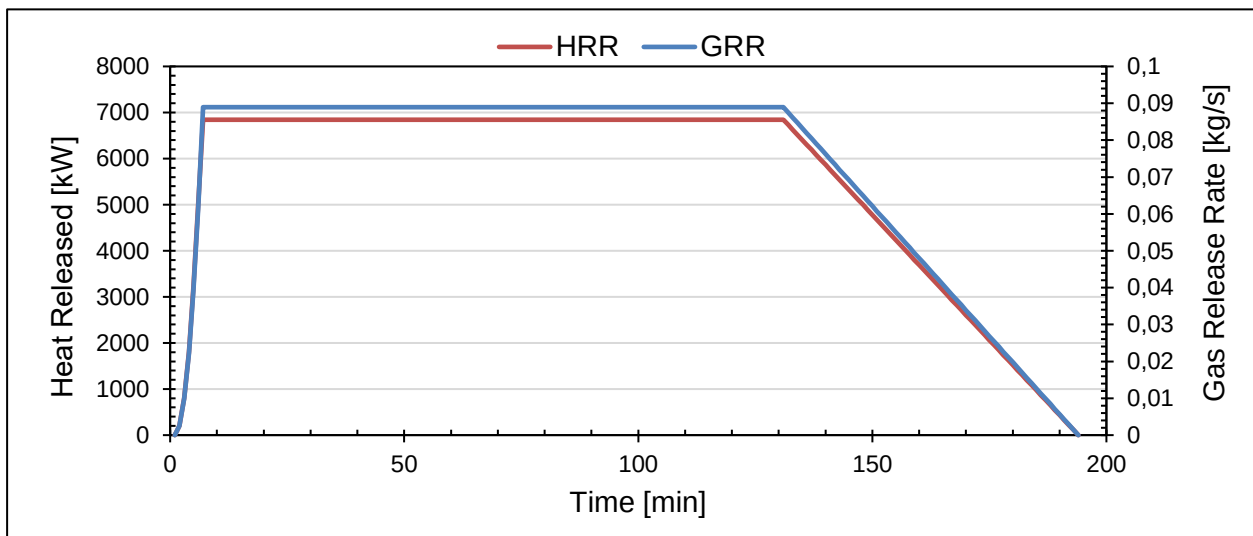


Figure E-2: TB02 design fire curves

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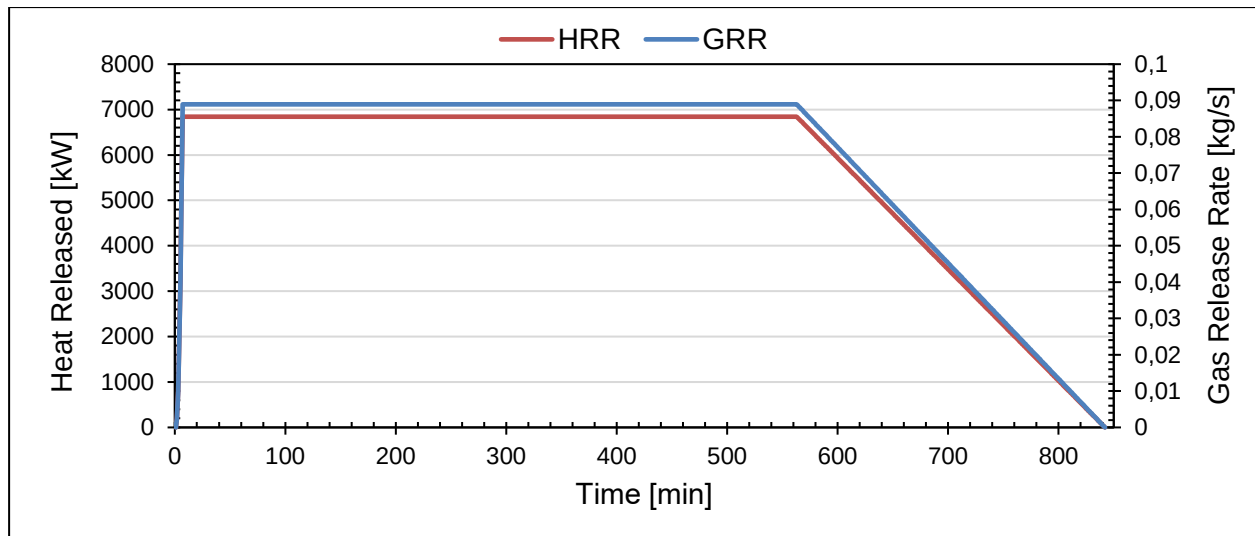


Figure E-3: TB03 design fire curves

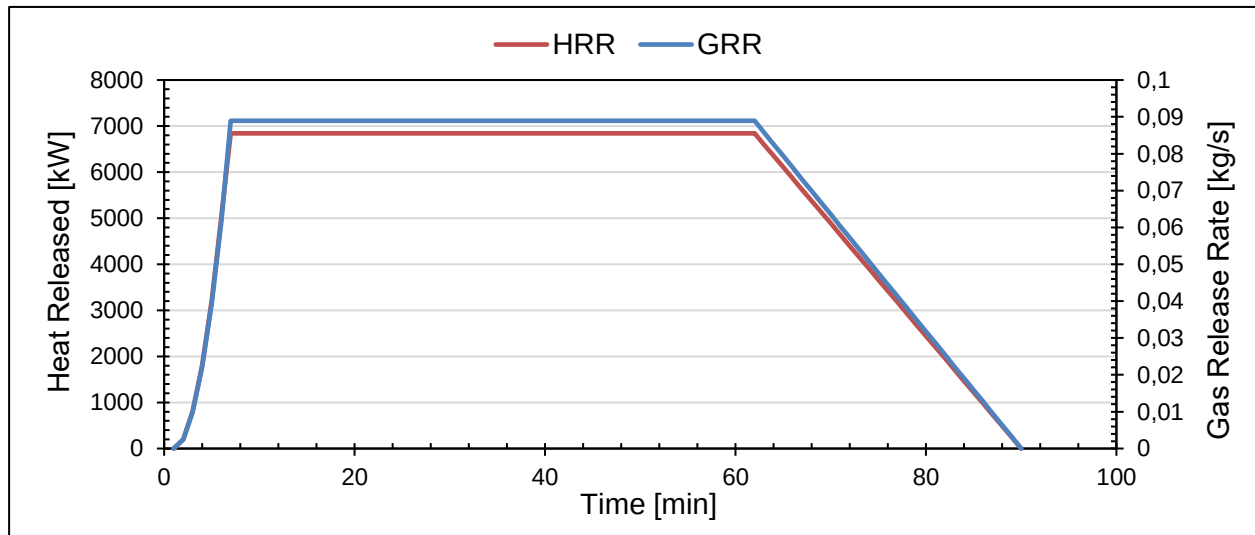


Figure E-4: TB03A design fire curves

APPENDIX F – FIRE SIMULATION SET-UP IN PTB

Table F-2: Fire simulation set-up in PTB

Step	Procedure	Procedure description
1	Under “Thermo Calculate” at the input section of all the tunnel components, set the “Transient Rock Active” to [0].	This ensures that the model reaches steady state.
2	Run the simulation until the outputs of the air node and tunnel components converge. Create snapshot 1.	A snapshot enables user to simulate a scenario from the previous time period.
3	Under “Thermo Calculate” at the input section of all the tunnel components, set the “Transient Rock Active” to [1].	This ensures that the variables change dynamically before converging to a steady-state manner.
4	Run the simulation from snapshot 1 until the outputs of the air node and tunnel components converge. Create snapshot 2.	
5	Change the time periods according to the determined fire duration, with a minimum number of 60 time steps for transient simulations.	
6	At the node where the fire hazard originates, insert the following input values [1]: • Heat released [kW] • Gas flow rate [kg/s] • Airflow at max heat [kg/s] • Fire time constant	These input values are obtained through literature.
7	Run simulation from snapshot 2.	
8	Ensure that the variables exhibit a dynamic response. Thereafter, it should result in steady-state behaviour.	

APPENDIX G – SIMULATION RESULTS: CONVEYOR BELT FIRE IMPACT

This section covers the remaining three conveyor belt configurations and their corresponding fire incidents. The discussion of the results follows the same procedure as described in Section 3.4.3.

Design Fire Scenario 1: TB01

The TB01 conveyor belt is situated at the top of the decline. Fresh air is drawn from 121 level travel way, which flows over the conveyor belt to the rest of the decline. The air mass flow over the conveyor belt is 18.85 kg/s at a velocity of 1.02 m/s. The haulage dimensions in which TB01 operates have a flow area of 16 m². There are no return airways in this area and the air forms part of the intake air towards the work areas on 129 level and 137 level. Figure G-1 illustrates the temperature profile of Mine A following a fire incident involving the TB01 conveyor belt.

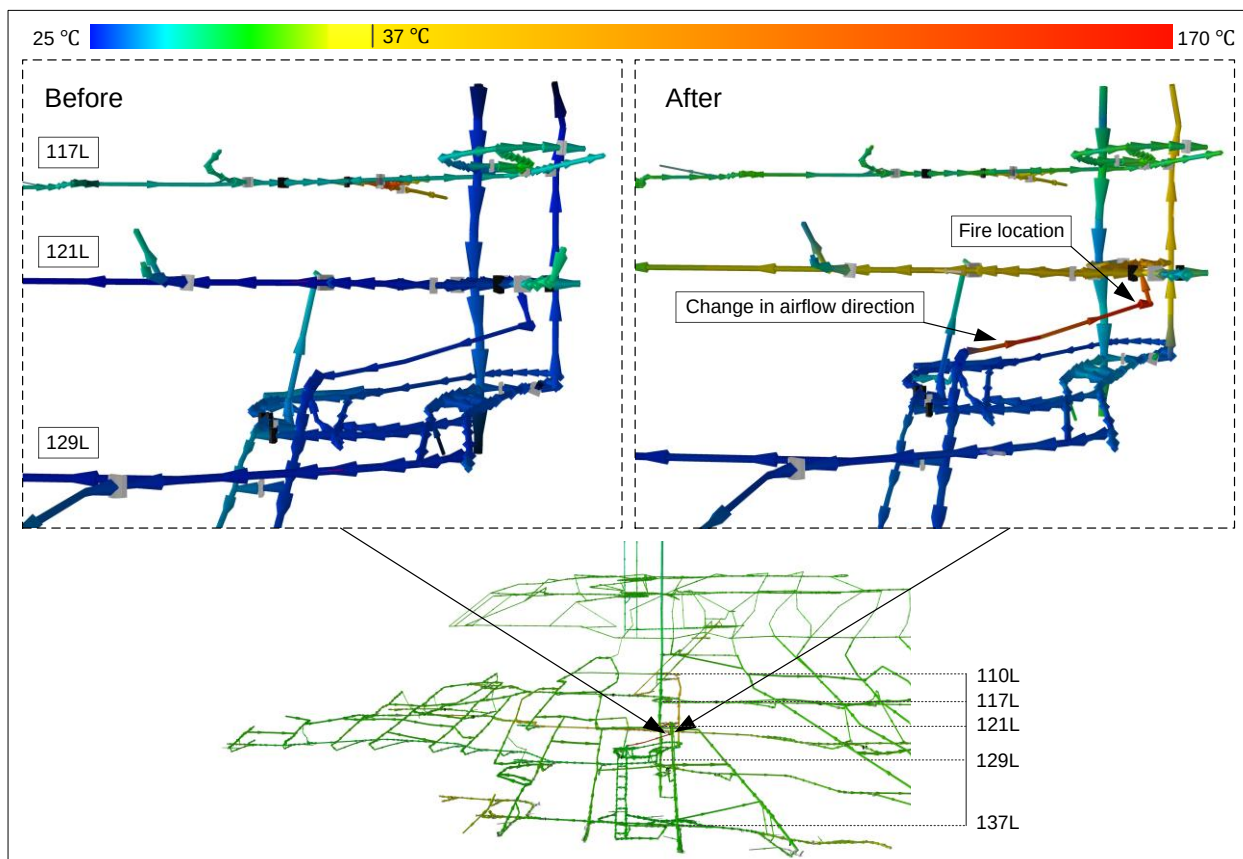


Figure G-1: TB01 temperature results

Simulating underground mine fires for emergency planning

In the event of a fire involving the TB01 conveyor belt, the airflow direction changes, as illustrated in Figure G-1. This change is a result of the throttling or choking effect, which causes a flow reversal. Temperatures reach a maximum of 170 °C, leading to an expansion of gas and an increase in air volume. Consequently, the air velocity peaks at 3.75 m/s. This elevated air velocity results in significant frictional pressure losses, causing contaminated air to rise through the raise bore hole to 121 level.

While the temperature increase is notable, it is not the primary concern due to the relatively high volume of air passing through the fire-affected area. The major concern is the distribution of CO gas as it begins to spread towards the active working areas. Figure G-2 shows the distribution of CO in the ventilation network.

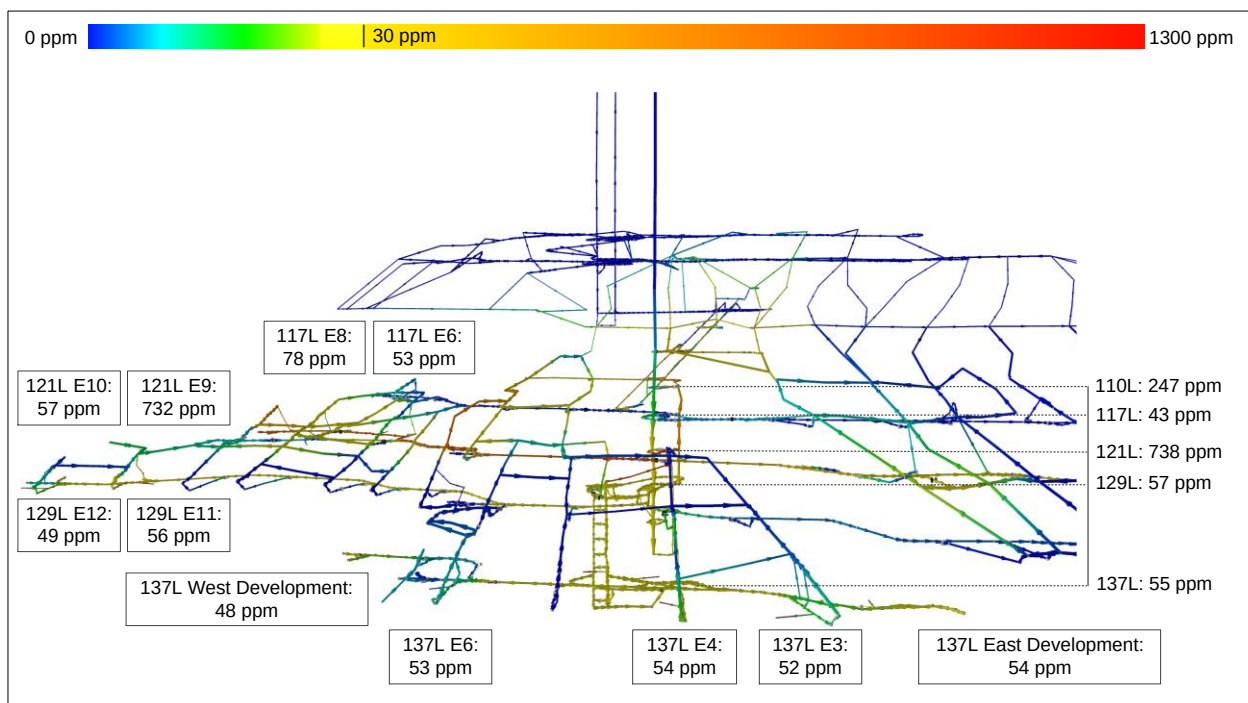


Figure G-2: TB01 CO results

Figure G-2 depicts the CO concentration at each active work area when the fire reaches its peak 29 minutes after ignition. Air is recirculated on 121 level, resulting in air being pushed back into the main shaft. The contaminated air makes its way into the intake air flowing towards 129 level and 137 level. The OEL of 30 ppm is exceeded in all work areas, highlighting the need for remediation strategies.

Simulating underground mine fires for emergency planning

Design Fire Scenario 2: TB02

The TB02 conveyor belt runs from the end of TB01 to the start of the decline between the 129 and 137 level tips. The same air mass flow that passes over TB01 also flows over TB02, which is measured at 18.85 kg/s with a velocity of 1.81 m/s. The haulage where TB02 operates has a cross-sectional area of 9 m², which explains the increase in air velocity. As with TB01, TB02 does not have a return airway, and the air mass flow supplies fresh air to the 129 and 137 level work areas. Figure G-3 shows the temperature profile for Mine A in the event of TB02 conveyor belt catching fire.

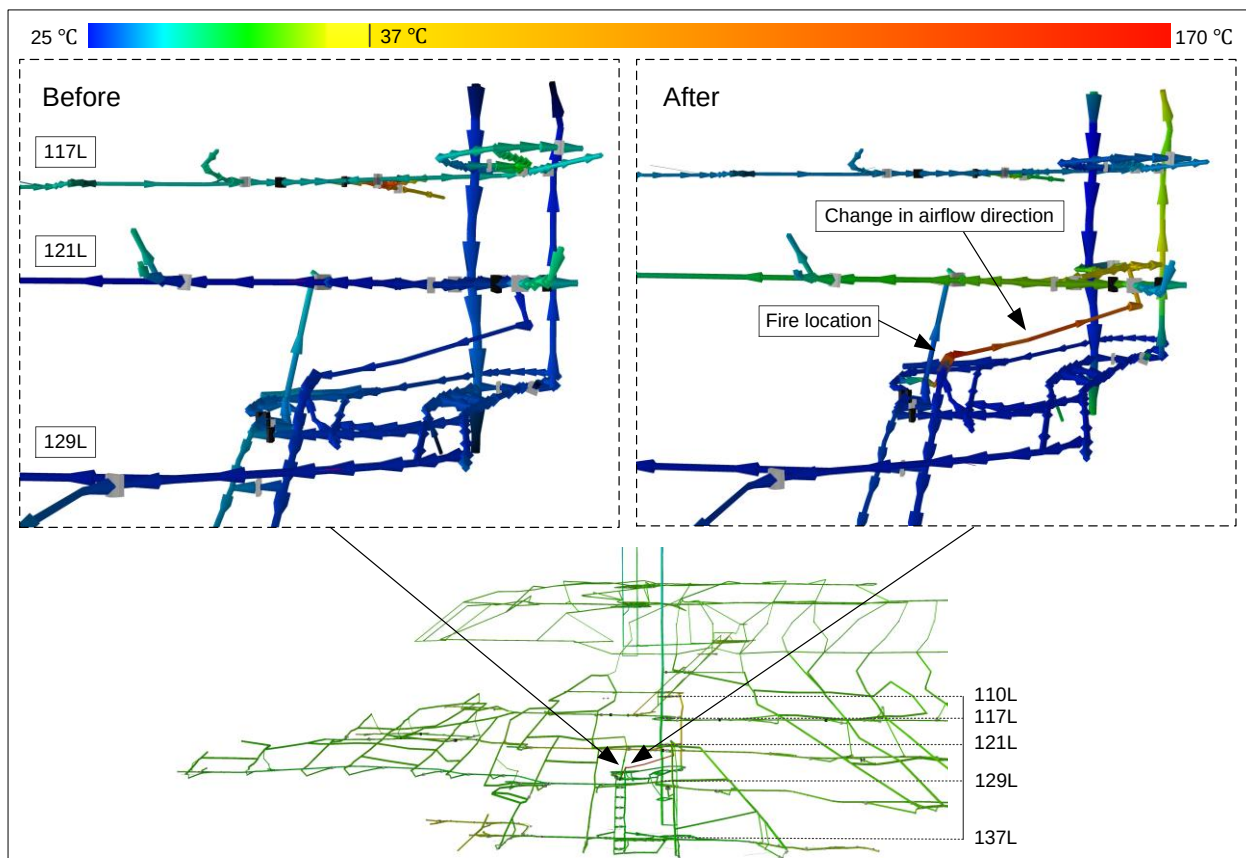


Figure G-3: TB02 temperature results

It is clear that in the event of a fire occurring on the TB02 conveyor belt, the airflow direction shifts, as observed in the case of TB01. The temperature peaks at 165 °C, causing gas expansion, which leads to an increase in air volume flow. The velocity reaches a maximum of 6.7 m/s, with the hot air rising through the raise bore hole to the 121 level intake. This change in airflow direction is primarily driven by frictional pressure losses due to the sudden rise in air velocity.

Simulating underground mine fires for emergency planning

Once again, the major concern is not the temperature but rather the CO distribution to active working areas. Figure G-4 shows the distribution of CO throughout the ventilation network following the TB02 fire incident.

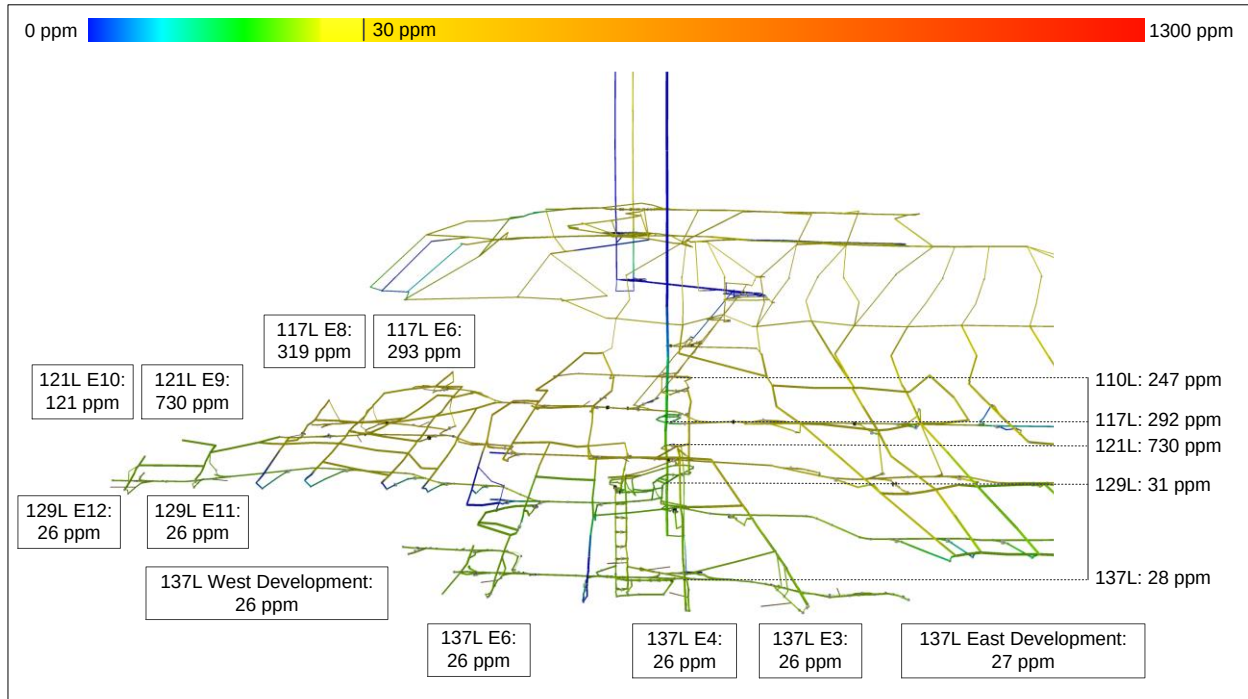


Figure G-4: TB02 CO results

The CO concentration from 121 level and above exceeds the exposure limit of 30 ppm, highlighting the urgent need for remediation strategies. The lower CO concentrations on 129 level and 137 level is due to the absence of air recirculation into the main shaft on 121 level, unlike in the TB01 fire scenario. Consequently, no air is pushed towards the intakes of 129 level and 137 level. The increased air quantity on 121 level results in higher CO concentrations at that level, contributing to an overall increase in CO distribution throughout the ventilation network of Mine A.

Design Fire Scenario 4: TB03A

The TB03A conveyor configuration is situated at the lower end of the decline, just below the 137 level tips. A total of 18.92 kg/s of air flows over TB03A at a velocity of 1.35 m/s, moving up a raise bore to 137 level. The cross-sectional area where TB03A operates is 12 m². Figure G-5 shows the temperature profile in the event of a fire involving TB03A.

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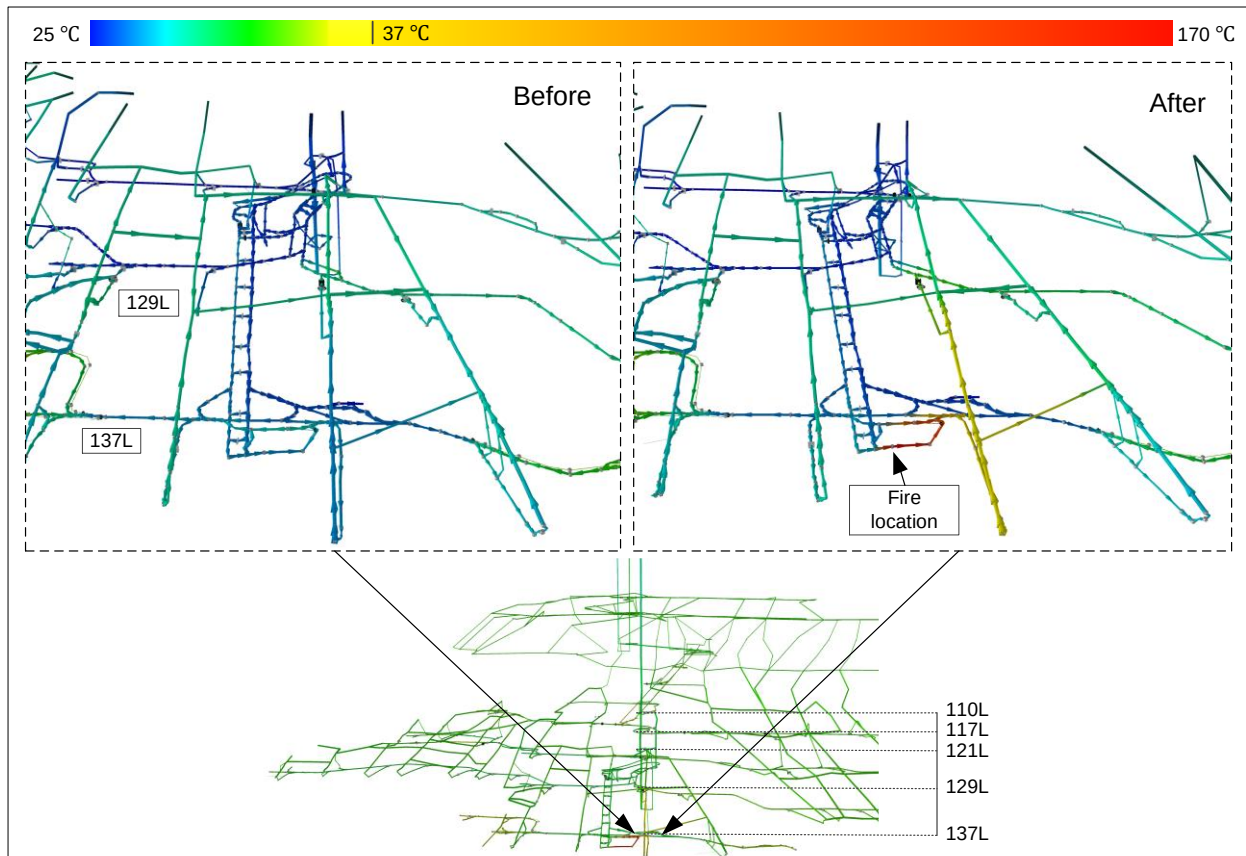


Figure G-5: TB03A temperature results

In the event of a fire involving conveyor belt TB03A, the rising temperature leads to gas expansion, causing an increase in the volume of air. This effect is observed in all simulated scenarios. However, in this case, the air pressure on 137 level is lower than at the fire location, allowing the hot, contaminated air to still rise up the raise bore to 137 level. The temperatures peak at 632 °C.

Despite the extreme local temperatures, the primary concern, as with previous scenarios, remains the spread of CO. Figure G-6 illustrates the CO distribution resulting from the TB03A fire incident.

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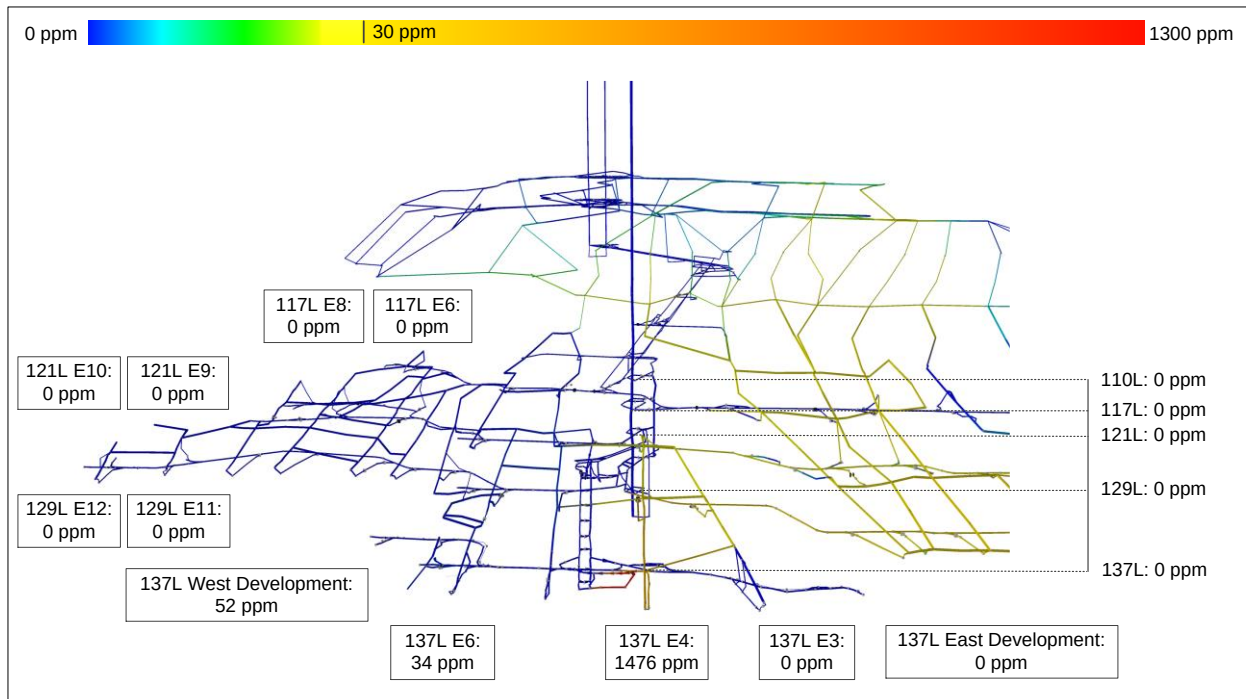


Figure G-6: TB03A CO results

The CO distribution in Mine A's ventilation network is significantly lower in the event of a TB03A fire, as shown in Figure G-6. This is largely due to cross-cut E4 functioning as a chimney and exhausting the contaminated air into the return airway. It is clear that only 137 level is affected by the TB03A fire. The role of cross-cut E4 in exhausting the air provides valuable insight for developing effective remediation strategies.

Results summary

The simulation of the remaining three conveyor belt fire scenarios contributed to the completion of the first step of Objective 3. The implementation of the design fire curves allowed for a detailed evaluation of the impact on the level intakes and active work areas. The time it took to exceed the OEL and the time it took for each working area to reach a maximum were recorded.

Table G-1 lists the simulated temperature results for each identified area in the remaining three scenarios that exceeded the OELs.

Simulating underground mine fires for emergency planning

Table G-1: Simulated design fire temperature results

Conveyor configuration	Location	Time to exceed OEL [h:mm]	Time to reach maximum	
			Time [h:mm]	Temperature [°C]
TB01	121L Intake	00:07	00:15	62.93
TB02	121L Intake	00:09	02:09	48.05
TB03A	137L E4	00:06	00:13	100.80

Although Table G-1 identifies areas where the temperatures exceeded the OELs,, as previously discussed, these temperatures are not the major concern. The simulated CO concentration results are presented in Table G-2.

Table G-2: Simulated design fire CO results

Conveyor configuration	Location	Time to exceed OEL [h:mm]	Time to reach maximum	
			Time [h:mm]	Maximum CO concentration [ppm]
TB01	117L Intake	00:40	00:42	43.58
	121L Intake	00:06	00:25	738.15
	129L Intake	00:12	00:23	57.00
	137L Intake	00:18	00:33	55.85
	117L E6	00:38	00:42	53.07
	117L E8A	00:34	00:42	78.21
	121L E9	00:12	00:33	731.60
	121L E10	00:35	00:42	57.07
	129L E11	00:24	00:38	55.99
	129L E12	00:33	00:42	49.44
	137L E3	00:32	00:42	52.01
	137L E4	00:28	00:41	54.09
	137L E6	00:40	00:42	33.33
	137L E Dev	00:30	00:42	54.36
	137L W Dev	00:34	00:42	48.49
TB02	117L Intake	00:41	02:34	291.79
	121L Intake	00:07	00:29	730.45
	129L Intake	00:17	00:17	30.99
	117L E6	00:39	02:33	292.75
	117L E8	00:35	02:28	318.86
	121L E9	00:12	00:36	722.10
	121L E10	00:37	02:28	120.89
TB03A	137L E4	00:05	00:13	1 475.68
	137L E6	01:27	01:29	33.75
	137L W Dev	01:27	01:29	52.22

Simulating underground mine fires for emergency planning

The results in Table G-2 outline the time that each area exceeded the OEL and when maximum CO concentrations were reached. These findings highlight the substantial impact of each conveyor belt fire scenario on Mine A's ventilation network. The simulations, based on worst-case scenarios, provide a baseline for evaluating the risks associated with such incidents.

These results form the basis for understanding how fire events influence mine ventilation and air quality. They further serve as a starting point for developing remediation strategies aimed at managing CO levels and maintaining safe airflow in Mine A.

APPENDIX H – SIMULATION RESULTS: IMPLEMENTATION OF EMERGENCY PLAN

This section reports on the implementation of the defined emergency plan on the remaining three conveyor belt configurations. The discussion of the results follows the same procedure as described in Section 3.5.2.

Design Fire Scenario 1: TB01

1. Implementation after time t

In Table G-2, cross-cut E9 on 121 level exceeded the OEL for CO first in the event of TB01 catching fire. After 12 minutes, personnel are exposed to CO concentrations of above 30 ppm. The emergency plan was simulated to occur after 12 minutes. The evaluation of the variation of CO concentration is illustrated in Figure H-1.

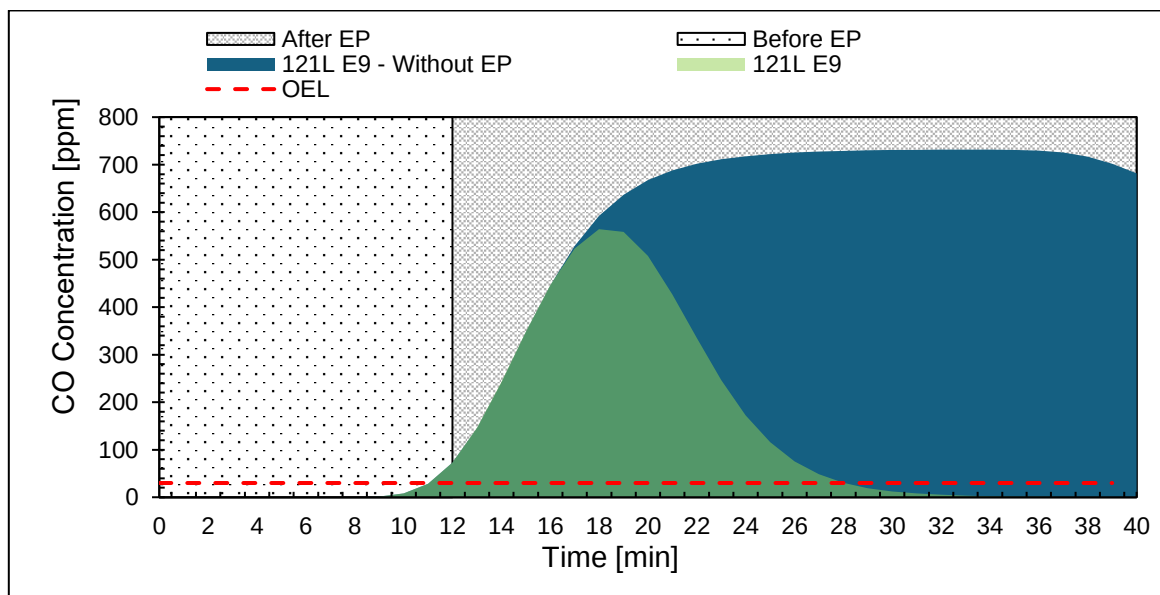


Figure H-1: Effect of emergency plan on CO concentration after time t – TB01

Figure H-1 illustrates the CO concentration profile for cross-cut E9 on 121 level. It compares the scenario where the fire scenario was left to burn out to the scenario where the emergency plan was implemented once the OEL is exceeded. Once the emergency plan has been implemented, a significant decrease in the CO concentration was experienced.

Since 137 level still required ventilation demand, the air mass flow in the chairlift decline increased as experienced in the simulation scenario of conveyor belt TB03. The chairlift decline therefore

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experienced a higher pressure. The results followed the same trend as presented in Figure 3-21. The contaminated air is therefore prevented to reach active working areas once the emergency plan is implemented.

2. Implementation of defined set point

The implementation of the defined set point demonstrated the effectiveness of the emergency plan, with the fire doors automatically closing upon detecting a CO concentration of 25 ppm. The simulation of the TB01 design fire curve, together with the emergency plan, ensured that no active working areas were affected by contaminated air, as shown in Figure H-2.

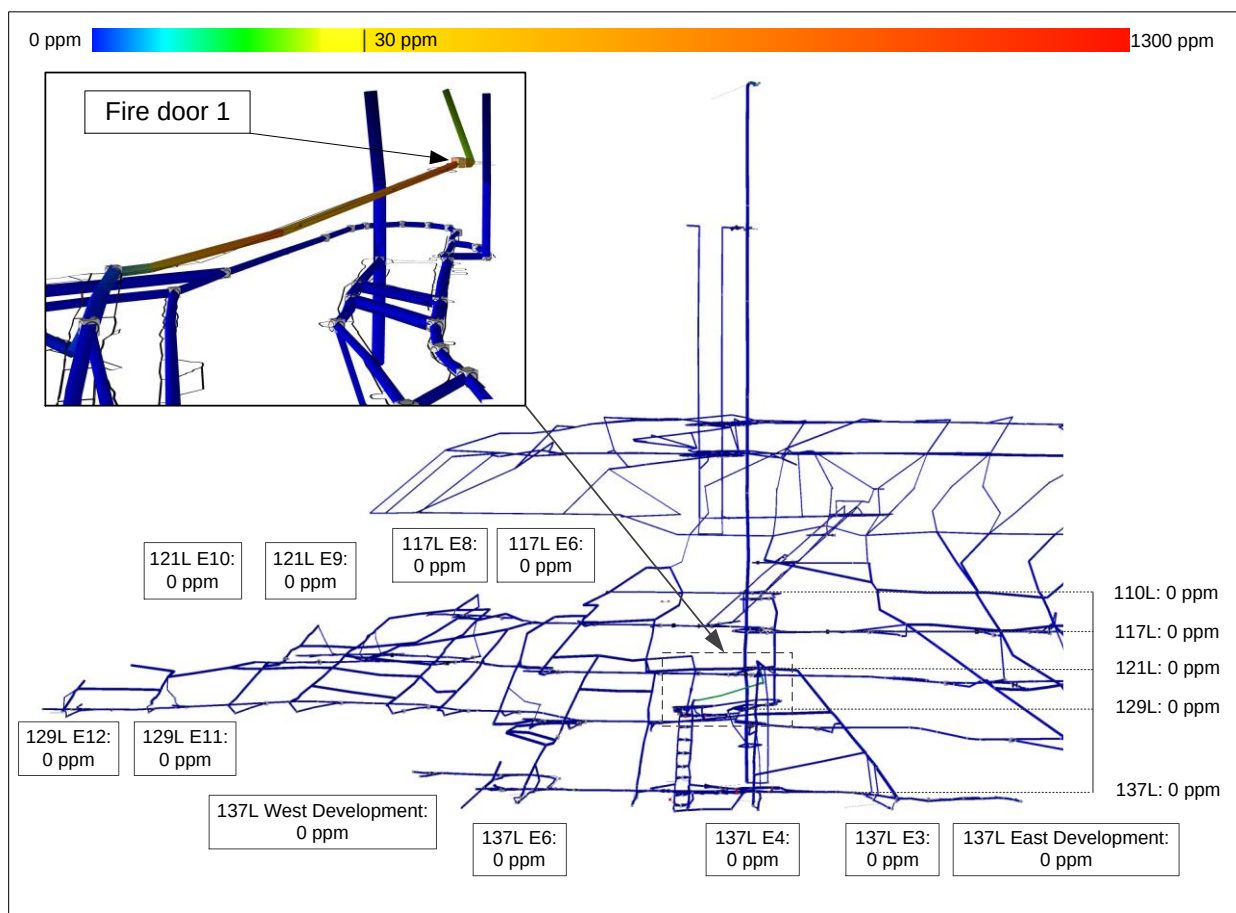


Figure H-2: Effect of CO results after implementation of defined set point – TB01

As shown in Figure H-2, no working areas were affected by the simulation of the TB01 fire incident. Given TB01's location, with no additional connections and only one air supply route from 121 level, the closure of Fire Door 1 led to the suffocation of the fire. Without air supply to sustain it, the fire was extinguished before the CO concentration could reach the OEL.

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However, it is important to consider that if any leaks occur in the fire door, causing a ventilation drift, flow reversal may occur and cause contaminated air to rise through the raise borehole to 121L intake. Therefore, it is essential to investigate a scenario where fire door 1 is open and airflow is provided through the conveyor decline towards the chimney. This scenario aims to validate the effectiveness of smoke extraction through the dedicated chimney while the TB01 conveyor belt is burning.

3. Smoke extraction

The emergency plan was implemented once a CO concentration of 25 ppm was detected, successfully extinguished the fire before the OEL was exceeded. In theory, it may not be necessary to extract contaminated air through the dedicated chimney. The concentration is low enough to simply open Fire Door 1 and dilute the contaminated air with fresh intake air from the 121 level.

However, as mentioned earlier, potential leakages could sustain combustion. Therefore, a simulation of the dedicated chimney in a tight circuit with the conveyor decline, with Fire Door 1 open to create through-flow, was conducted to assess its effectiveness in allowing the fire to burn out. It took 42 minutes for the TB01 fire incident to burn out. About 90 minutes after ignition, the contaminated air was removed from the entire conveyor belt decline. Figure H-3 illustrates the CO concentration profile at the intake of the chimney.

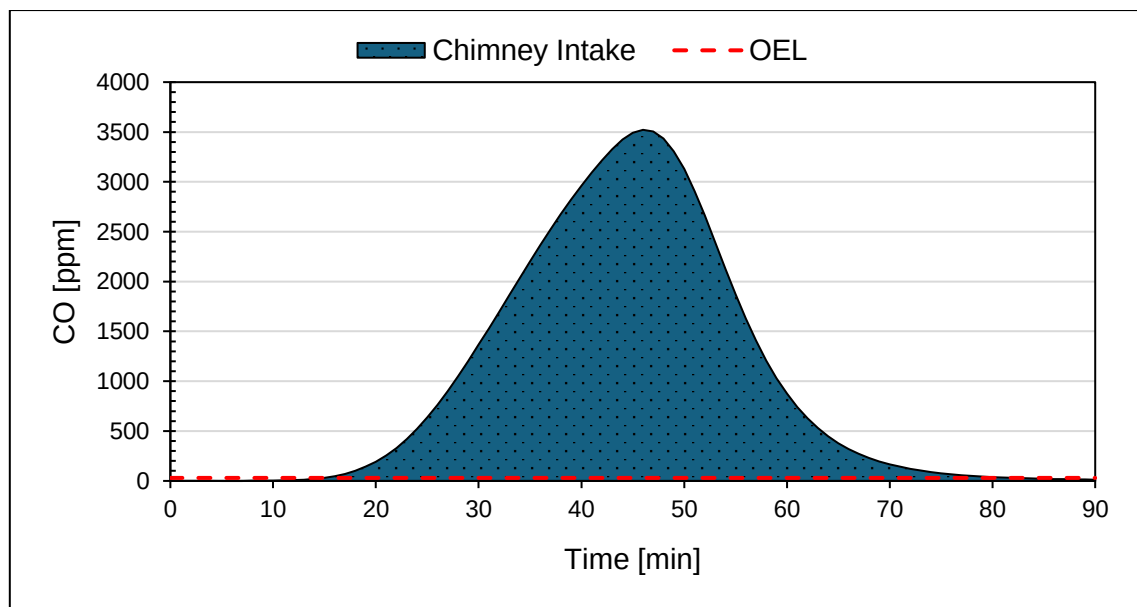


Figure H-3: Time to extract contaminated air – TB01

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The extraction of the contaminated air through the chimney effectively directed it to the eastern side of Mine A. The effectiveness of the smoke extraction is illustrated in Figure H-4.

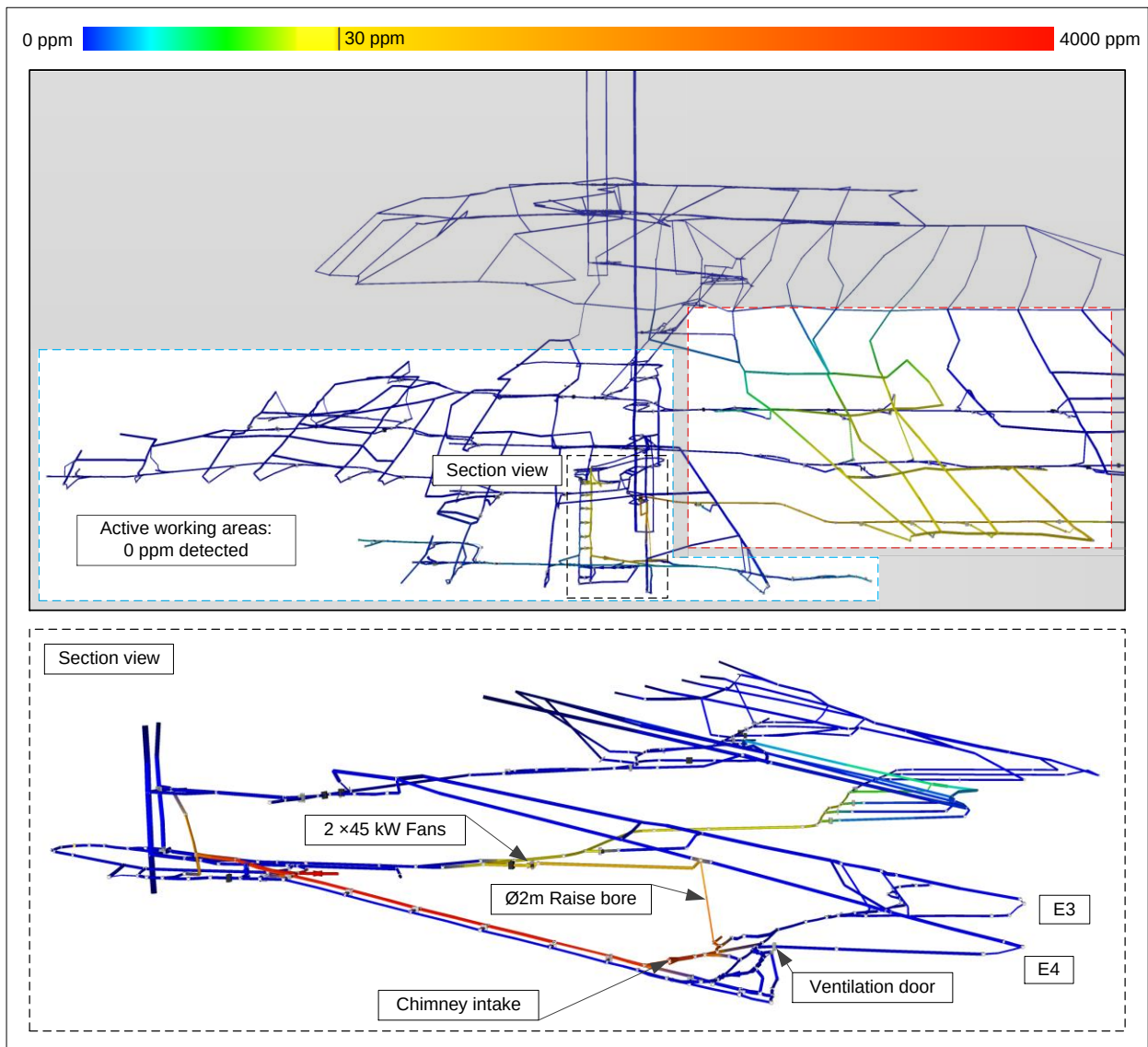


Figure H-4: Smoke extraction simulation results – TB01

The dedicated chimney efficiently extracted contaminated air from the decline, even when the fire was left to burn out. However, as noted in the TB03 conveyor belt fire simulation, this approach is not ideal. Opening Fire Door 1 may sustain or reignite the fire if it has not been fully extinguished. Therefore, it is critical to ensure that the fire is completely extinguished before opening Fire Door 1 to minimise infrastructure damage and reduce risks to employee safety.

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Design Fire Scenario 2: TB02

As with Design Fire Scenario 1, cross-cut E9 on 121 level exceeded the OEL after 12 minutes. Given the proximity of TB02 to TB01 and the similar impact simulation results, the implementation of the emergency plan resulted in outcomes similar to Design Fire Scenario 1. The focus now shifts to evaluating the emergency plan in the event of a fire at TB03A.

Design Fire Scenario 4: TB03A

1. Implementation after time t

Table G-2 shows that cross-cut E4 on 137 level exceeded the OEL for CO first in the event of TB03A catching fire. After 5 minutes, the CO concentration exceeded the OEL of 30 ppm. The emergency plan was simulated to be implemented after 5 minutes. The evaluation of the CO concentration in cross-cut E4 is illustrated in Figure G-6.

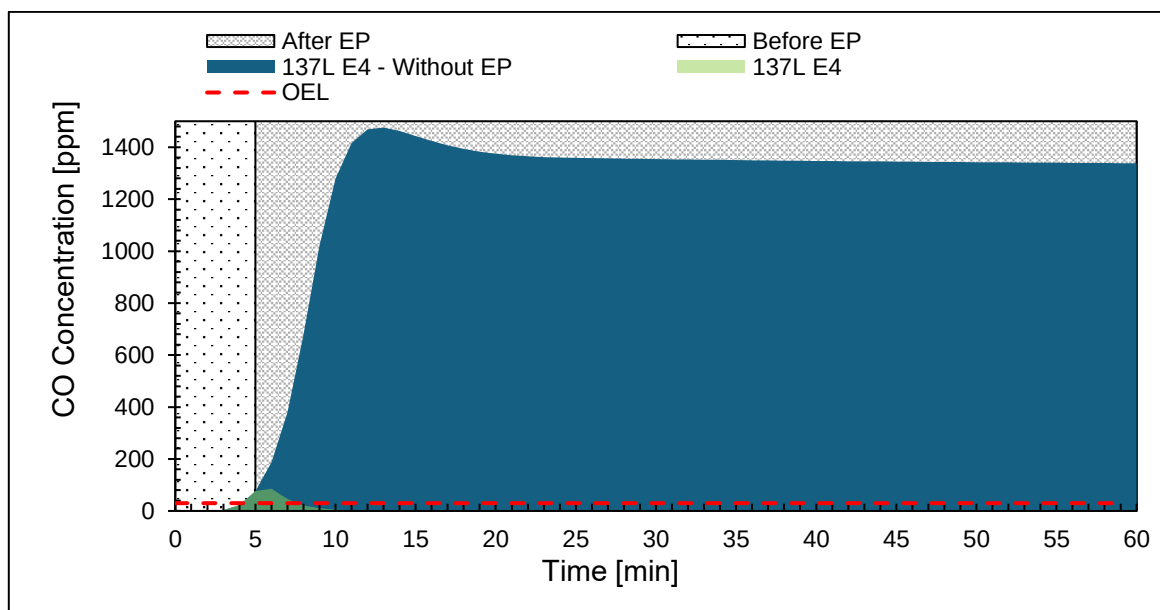


Figure H-5: Effect of emergency plan on CO concentration after time t – TB03A

The CO concentration profile in cross-cut E4 significantly dropped below the OEL limit after the emergency plan was implemented. Closing the fire doors when a CO concentration of 25 ppm is detected cuts off airflow to the fire, effectively stopping the combustion process.

The fire incident occurred below the 137 level intake, and the closure of Fire Door 5 effectively prevented contaminated air from reaching active working areas. This demonstrates that the

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emergency plan is successful in isolating contaminated air and safeguarding all working areas from contamination.

2. Implementation of defined set point

As with the previous simulated scenarios, the goal of implementing the defined set point is to demonstrate the effectiveness of the emergency plan, which closes the fire doors once a CO concentration of 25 ppm is detected. The simulation results showed that no active working areas were affected when the design fire scenario of TB03A was mitigated, as shown in Figure G-6.

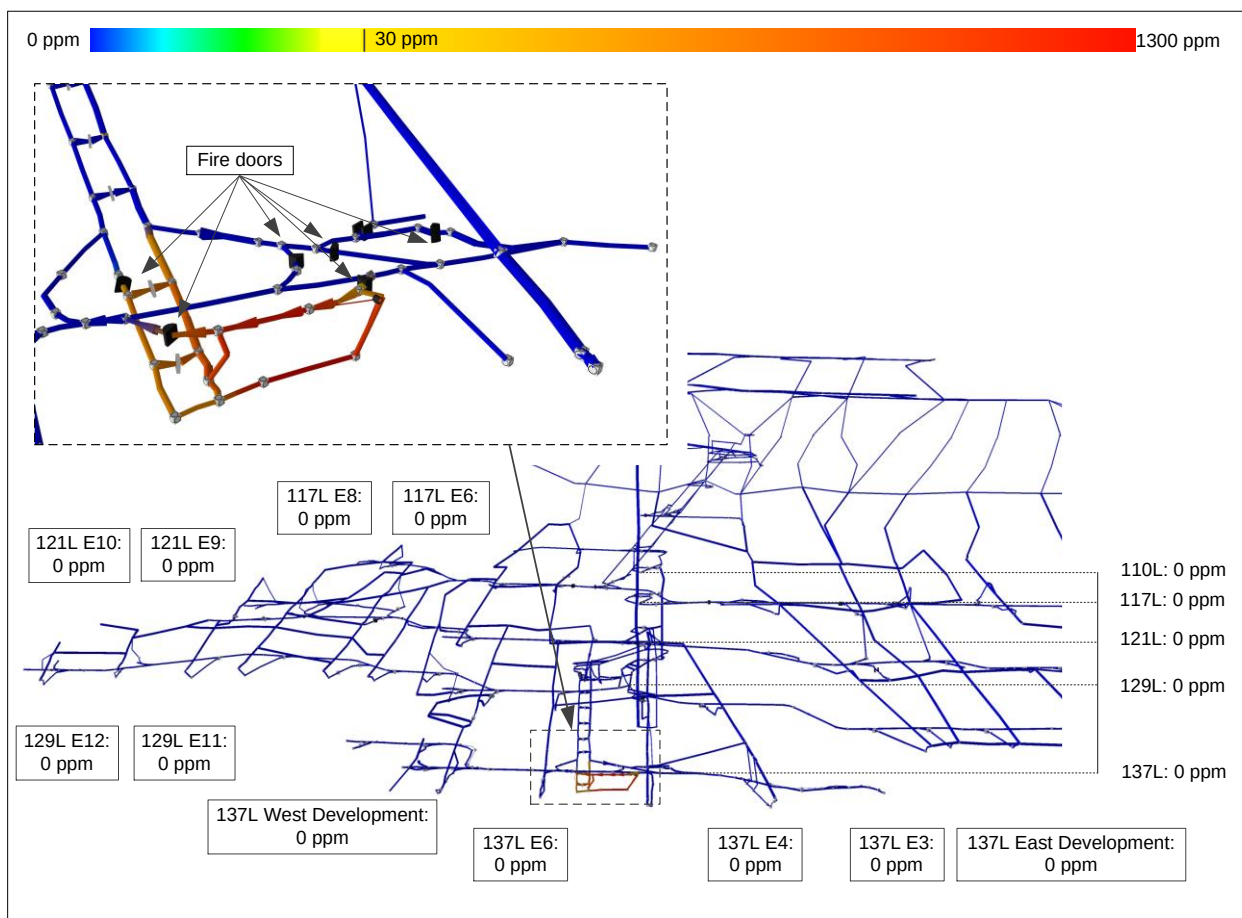


Figure H-6: Effect of CO results after implementation of defined set point – TB03A

Figure G-6 clearly illustrates that no active working areas were affected by contaminated air. The chairlift decline still provided the active working areas on 137 level with fresh air, while the closed fire doors ensured that the contaminated air was isolated inside the conveyor decline. However, the isolated area around TB03A was filled with contaminated air, which had to be removed from the system and extracted through the dedicated chimney.

3. Smoke extraction

The contaminated air from below 137 level in the bottom of the conveyor decline was extracted following the same design configuration as the previous scenarios. As mentioned earlier, through-flow ventilation is necessary to supply the 45 kW fans with sufficient airflow for effective extraction. To establish the ventilation drift, Fire Door 5 had to be opened, while the ventilation door in cross-cut E4 was closed. With all other fire doors sealed, the contaminated air was directed straight towards the chimney intake. Figure H-7 illustrates the CO concentration profile at the chimney intake.

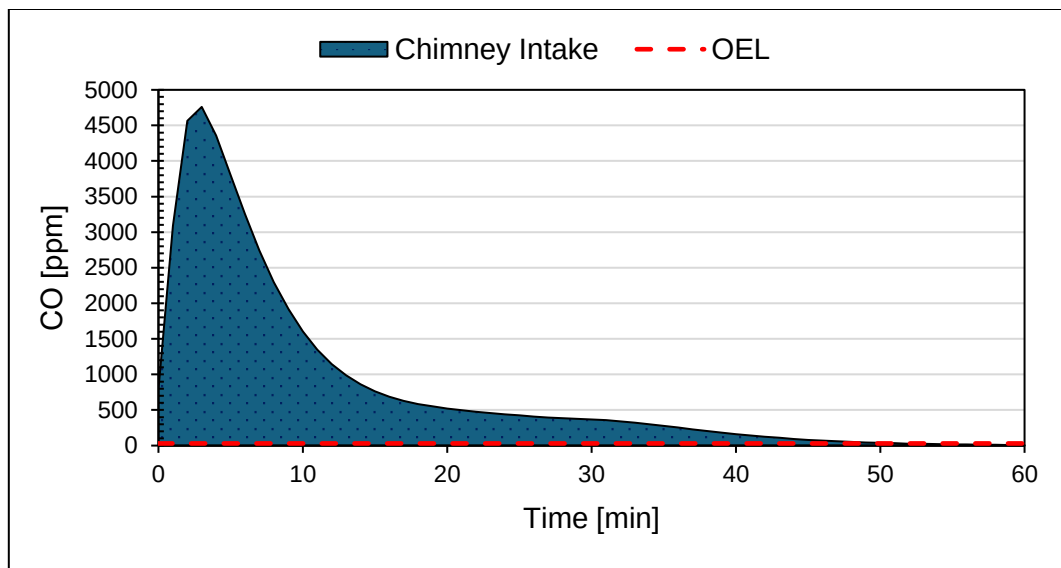


Figure H-7: Time to extract contaminated air – TB03A

After 60 minutes, the contaminated air was cleared from the conveyor decline and directed towards the eastern part of Mine A. Figure H-8 shows the effectiveness of smoke extraction through the chimney.

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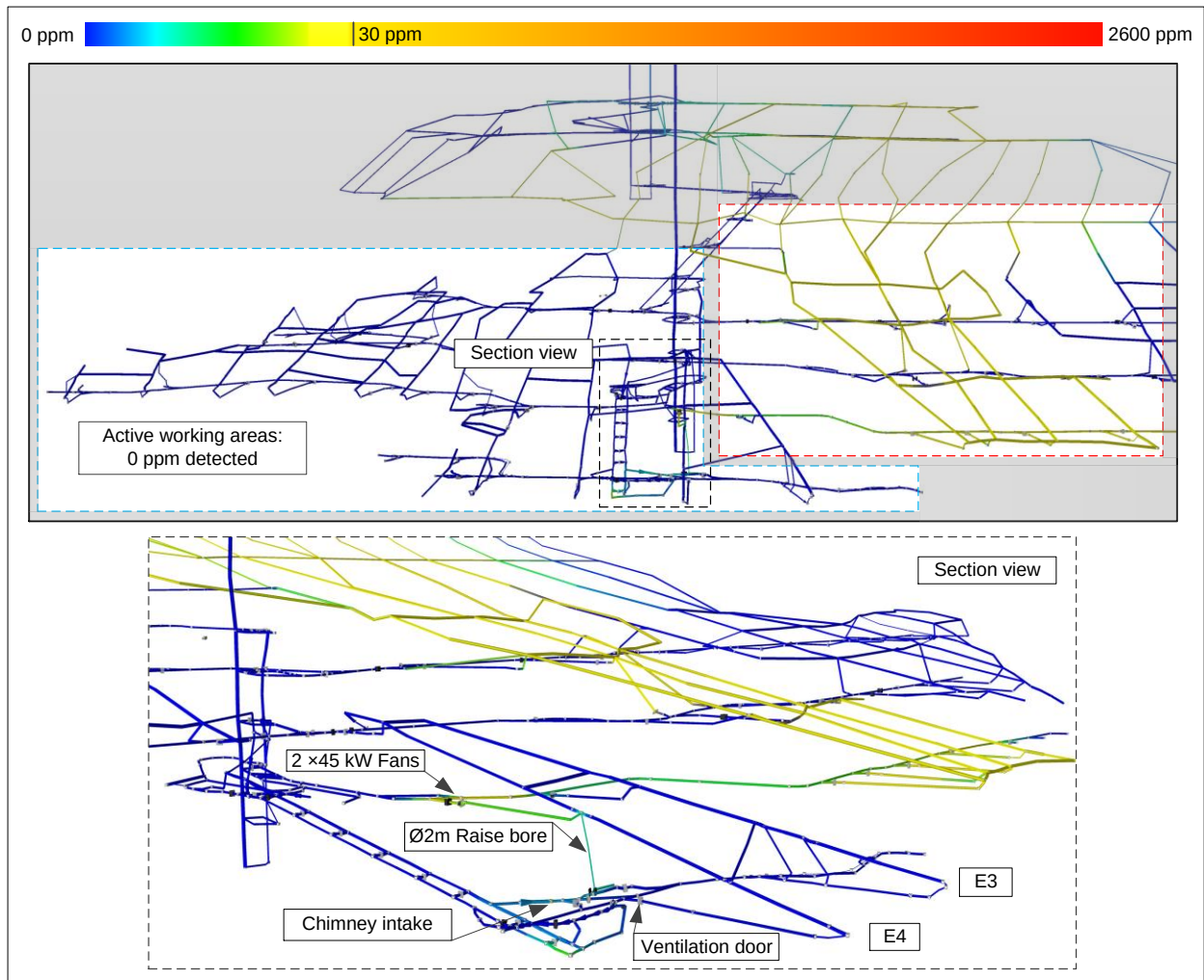


Figure H-8: Smoke extraction simulation results –TB03A

Figure H-8 shows that the dedicated chimney effectively extracted the contaminated air from the conveyor decline, preventing any impact on active work areas. The air was successfully directed towards the eastern part of Mine A. Once the decline was cleared, the results confirmed that the emergency plan effectively mitigated the fire incident, allowing for the safe implementation of re-entry protocols.