# Underground Fire Rollback Simulation in Large Scale Ventilation Models

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Fire in an underground mine poses a serious threat to health and safety of personnel due to the spread of heat, smoke and noxious gases throughout the ventilation system. Predicting the behavior and likely spread of combustion products is important in understanding the potential risk to personnel and assists in developing suitable emergency response plans.

One aspect of fire effects on ventilation that is difficult to predict is a phenomenon known as rollback. Fire rollback causes hot combustion products (smoke and gas) to move along the roof of tunnels in the opposite direction to primary ventilation flow, potentially circulating combustion products into areas upstream from the fire source.

Modelling of fire rollback behavior has been achieved with computational fluid dynamics (CFD) methods, however CFD is not currently practical for mine wide simulation due to model size and speed constraints. Empirical prediction that considers airway size, slope, and air velocity can also be used but it is not ideal for automatic integration into large scale ventilation models.

A feasible solution is to create a single network model to simulate both the large scale ventilation model and the smaller scale rollback behavior. This can potentially be achieved by creating a detailed high density three-dimensional mesh of pathways bounded by the airway around a fire which then feeds into the simpler network of a large scale ventilation model. The high density mesh allows a transient mass balanced Hardy Cross method to simulate air currents independently in three dimensions within the fire region, based on heat and natural buoyancy within each pathway. This paper explores the method, compares with empirical methods, and demonstrates the potential of full integration into conventional whole mine network analysis simulation without the complexity of CFD analysis or empirical equation assumptions.

## 1. Introduction

Mine fires present one of the most serious hazards for underground personnel. Few hazards have such potential for substantial loss of life or damage to property, and the prevention and control of fire is at the foremost of most mine safety management and emergency response plans.

Mine fires generate enormous media scrutiny due to the tragic history of mine disasters and the devastating effects on the surrounding community. Mining history is littered with mine fire incidents and disasters with outcomes varying from massive loss of life to success stories of mine rescue and fire control.

For example, in 2014 an explosion at the Soma coal mine in Turkey caused an underground mine fire resulting in the deaths of 301 people, mostly from carbon monoxide poisoning [1]. In the same year, South Africa's Kusasalethu mine, 486 miners were trapped underground following a fire that occurred about 2.3 km (1.43 miles) underground during maintenance on an air cooler. Fortunately in this case all miners were eventually rescued unharmed [2].

Coal mines, metaliferous mines and civil tunnels are highly exposed to the dangers of mine fires, and while the mechanisms of ignition and resulting fire behavior may differ in some circumstances, the hazards to human life created by heat, smoke and noxious gases are the same.

## 2. Modelling Fire Behavior

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### 2.1 History

Modelling the behavior of a fire and the spread of noxious gases through a mine has long been recognized as an important tool in assisting with emergency preparedness for mines and tunnels [3]. In particular the ability to predict the spread of smoke and fumes can assist in many aspects of mine fire hazard mitigation and control. For example, mine ventilation designs can be improved to be more resilient to fire outbreak with smoke and fumes directed away from work areas, and the operation of vent controls and fans potentially modified in the event of a fire. Emergency refuge stations and fresh air emergency bases can be located in areas that ensure maximum availability and access to mine personnel. In the event of a fire outbreak, fire modelling software may even assist in the real time understanding the spread of gases and changes in ventilation flows and directions.

Mine ventilation software has rapidly developed since the introduction of digital computers in the 1950s, however the advent of more powerful computers in the 1980s, prompted efforts to develop software specifically to evaluate and understand the behavior of fires in mines, as well as the contamination and spread of fire fumes and smoke throughout mines and tunnels. [4]. Fire modelling software can be broadly divided into two categories.

### 2.2 Computational Fluid Dynamics Methods

Detailed fire modelling in three dimensions in tunnels is usually attempted by computational fluid dynamics (CFD) analysis [5]. This approach focuses on the behavior of airflow, heat, smoke and gas fumes in the immediate vicinity of the fire, and works from a finely constructed numerical grid that defines the boundary conditions of the three dimensional environment and the interaction of the air movement to the boundaries and itself. CFD modelling is generally considered for simulation of the area around the immediate fire, but is poorly suited to larger models because of speed and model complexity constraints [6].

The Fire Dynamics Simulator (FDS) is a popular software code in this category, and was released to the public in 2000 by National Institute of Standards and Technology (NIST). It has been used extensively in tunnel fire modeling [5]. An extension to this software is PyroSim™, developed by Thunderhead Engineering Consultants, which adds a graphical user interface to FDS allowing improved integration into CAD software [7].

### 2.3 Network Analysis Simulation Methods

A flow network consists of a series of nodes or junctions connected by pathways defining the potential movement of airflow. The mesh of connecting pathways between nodes is analyzed by considering the pressure or energy balance between closed loops of connecting nodes, using an iterative solver approach. The fundamentals of many popular modern network solving methods were original conceived in the mid-1800s with Kirchhoff's Law and further refined in the 1920s for rapid solving of fluid flow networks with the Hardy Cross algorithm.

Unlike CFD, network analysis only considers the possibility of movement of air along one pathway between nodes, and therefore restricts flow to only the one dimension. The natural ventilation pressures along the pathways resulting from heat affected air densities are included in the pressure or energy balance equations to predict the change in airflow volumes and directions from the fire heat.

Contaminants released by the fire are added to airflow volumes and transported through the mine network using transient time based simulation techniques. The behavior and gas released from the fire can be modified during the simulation based on the fuel source and the amount of oxygen available for the fire. The resultant simulation can provide a complete time based spread of heat and contaminants, together with identification and timing of any ventilation direction and flow changes,

Numerous fire simulators have been developed since the 1980s, however examples of software currently in common use includes MFIRE (originally developed by US Bureau of Mines) [4], Ventgraph (developed by the Polish Academy of Sciences [8]) and Ventsim VentFire (developed by Chasm Consulting [9]).

### 2.4 Rollback Considerations

A significant complication of fire modelling in a confined tunnel is a phenomena called 'rollback'. Rollback occurs when hot gases and vaporized burning fuel from the fire rises to the roof due to heat driven natural ventilation pressures. The combustion products are then forced along the roof and if insufficient forward velocity of ventilation is available, then the gases may spread in either direction, both upstream and downstream from the fire. The heated rollback gases may continue to propagate further (possibly spreading the fire elsewhere) until they have cooled sufficiently to lose natural ventilation buoyancy and re-enter and mix with the lower airstream. The rollback of combustion products in a Swedish fire tunnel test is shown in Figure 1.

Fig. 1. Rollback occurring in a Swedish fire tunnel test [10].

The spread of rollback products effectively creates a bi-directional flow in the same tunnel and may inundate firefighting or mine rescues crews approaching from the upstream direction placing them in potential danger. In addition, the rollback may push back into other intersections that would normally be predicted to be in fresh air in a one dimensional simulation.

Researchers determined that smoke rollback is dependent on the tunnel dimension, the fire intensity, and the air velocity [11], and rollback modeling must at a minimum consider these factors if modeling of the process is to be successfully achieved.

## 3. Analysis of Rollback

### 3.1 Computational Fluid Dynamics

Detailed modelling of rollback behavior is generally accepted as requiring a CFD software approach, which predicts the three dimensional movement of hot gases in a confined space. However CFD models can be time consuming to develop and coupled with lengthy simulation time, this limits the size and complexity of the modelled environment. The method is therefore suitable for only small areas, and cannot currently be used for modelling fire in large whole mine ventilation systems [6].

Figure 2 shows the modelling results of a small diesel fire with a limited velocity of air travelling right to left. Modelling was performed with the Fire Dynamics Simulator (FDS) using the software PyroSim™ for the graphical front end [6]. The model clearly shows the rollback of a heated layer of air and smoke travelling in the opposite direction to the main airflow.

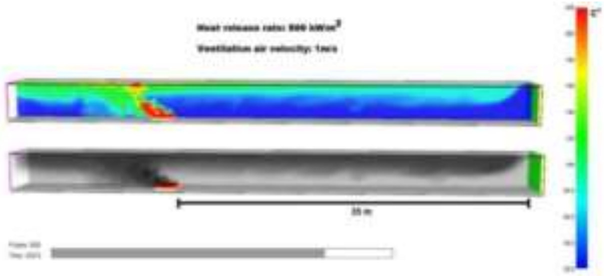

Fig. 2. Example of CFD modelling in PyroSim™ showing smoke and heat [6]

### 3.2 Empirical Analysis of Rollback

Adjiski [6] suggests network analysis methods are considered limited in capability to simulate rollback because tunnels and shafts are only considered as a single uni-directional pathway, and therefore bi-directional airflow movement such as rollback cannot be modelled. Airflows are either fully one direction or the other.

One method proposed by Lihong and Smith [12] is to consider rollback within a network analysis model by incorporating semi-empirical equations to predict the circumstances in which rollback may occur. The method was implemented into the US Bureau of Mines MFIRE program in 2011 and validated in fire tunnel tests.

Lihong and Smith proposed using a method incorporating the tunnel hydraulic height, fire temperature, heat release rate, and tunnel inclination into a formula that establishes the critical velocity under which rollback will be likely to occur during an MFIRE simulation. In the event of rollback, a further formula can then be used to predict and report the length of rollback.

A limitation of this method is that rollback occurrence is only reported during simulation and not used or simulated within the greater model. In addition, complex geometry such as changing airway inclinations, nearby intersections and variations in rock properties are not considered by the calculations.

## 4. Rollback Modelling with Network Analysis Simulation

Network analysis is generally considered only suitable for representing models with unidirectional pathway. This study was conducted to test whether unidirectional pathways could be split within a network model to allow bi-directional airflow along the upper and lower regions of the airway. Danko [13] proposed a similar concept for energy and moisture flow movement within large cavities and development headings using a network model, but restricted the use for non-fire related heat flow and moisture distribution.

The use of an interconnected mesh of horizontal and vertical airway paths within a large bounded airway allows two or three dimensional natural pressure driven movement of airflow within the larger volume. The properties of the split airways are maintained such that the combined boundary and resistance parameters of the pathways still mimic the original airway path for unidirectional flow.

### 4.1 Overview

The method of using a high density mesh of pathways within defined airways in a network was explored using an unmodified version of the Ventsim Visual™ VentFire™ module [9] , however it may be possible that other network simulation software incorporating fire heat and natural ventilation may also be able to utilize this method. VentFire™ is a module integrated into Ventsim Visual™ mine ventilation software that uses network analysis for large scale mine simulation of the effects of a defined fire situation. The software uses heat driven natural ventilation pressures, and transient simulation of fire heat and gases to predict fire behavior in a mine [14].

### 4.2 Constructing the Pathways

To create a high density three dimensional mesh within a defined airway, an algorithm was developed to automatically split the airway both lengthways and vertically to create an upper and lower pathways, interconnected by regular vertical pathways. This allows the user to manually select a region immediately around the fire location to split before the simulation.

Figure 3 shows a single airway that has been split to upper and lower horizontal pathways. These pathways were sized exactly half the height of the original airway. Using Ventsim Visual™ wall exclusion option, the facing boundaries of the upper and lower boundaries were removed from the airway resistance and heat transfer calculations. This created an overall combined parallel resistance nearly identical to the original single airway, and limits heat transfer from fire to only the immediate rock surface surrounding the upper and lower airways. Simulating airflow *without* fire, therefore gives identical airflow results to the original single linear path.

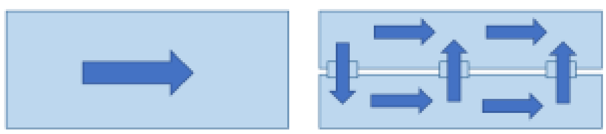

Fig. 3. Splitting single airway into bidirectional flow meshes

To facilitate the buoyancy driven air transfer between the upper and lower horizontal pathways, vertical pathway connections at a frequency of a minimum 4 m were created, although higher frequency could be used for more detailed analysis. The vertical airways are established at minimal size, assume no boundary resistance or heat transfer, and have a fixed resistance of 0.001 $Ns^2/m^8$ to allow relatively low resistance movement of air between upper and lower layers. Further testing found that resistance values for the vertical connections were reasonably insensitive providing they were a magnitude lower or more than the horizontal resistances.

### 4.3 Applying Fire Heat

The heat generated from fires can be calculated by considering the heat of combustion properties and burning rates of the fuel. The heat release rate (HRR) and moisture calculated can then be applied to the energy content (as sensible and latent heat) of the air surrounding the fire to calculate the temperature and the resulting air density calculated from a modified ideal gas law equation (Equation 1)

The natural ventilation pressure can then be calculated by considering the difference in air density between the internal network pathways heated (or otherwise) by the fire, and an external reference column of air at equivalent external elevation and atmospheric temperature outside of the mine influence (Equation 2).

$$\rho(humid) = \frac{p_d M_d + p_v M_v}{RT} \qquad (1)$$

Where:

$\rho(humid)$ = Density of the humid air (kg/m³)

$p_d$ = Partial pressure of dry air (Pa)

$p_v$ = Pressure of water vapor (Pa)

R = Universal gas constant, 8.314 J/(K·mol)

T = Temperature (K)

$M_d$ = Molar mass of dry air, 0.028964 kg/mol

$M_v$ = Molar mass of water vapor, 0.018016 kg/mol

$$NVP = \Delta\rho g h \qquad (2)$$

Where:

NVP = natural ventilation pressure

$\Delta p$ = air density difference between networked column and reference column, kg/m3

h = height of airway column, m

The NVP calculation can be applied to every networked branch with a vertical variation (including the interconnecting vertical rollback branches) to calculate the flow within a pressure balanced Hardy Cross network approximation of flow quantity and direction.

### 4.4 Transient (Dynamic) Simulation

Flow direction and volumes can be initially calculated by a steady state Hardy Cross simulation, and the resulting airflow velocities can be used to calculate the average speed of movement of gas and heat through the model.

Ventsim Visual™ uses a sub-cell transport method for transient modelling (labelled dynamic simulation in Ventsim Visual™), where airway pathways are split into smaller cells, each carrying a portion of the airway products through the model and over the fire.

Oxygen within cells that pass over the fire is consumed and replaced with combustion gases. The cells continue to move through the model, distributing heat and gases to pathways away from the fire.

The combined temperature and density of each group of cells in a branch airway is then used to recalculate NVP for the model, and further steady state flow balance simulations are periodically performed. Transient cell movement periods were set to every 0.1 s during simulation, and steady state flow simulations were set to every 1.0 s to assess changes in flow direction and volume.

Cells entering junctions between branches are mass balanced and mixed uniformly with other cells entering the junction and the combined heat and gas is delivered into cells downstream from the junction (Figure 4).

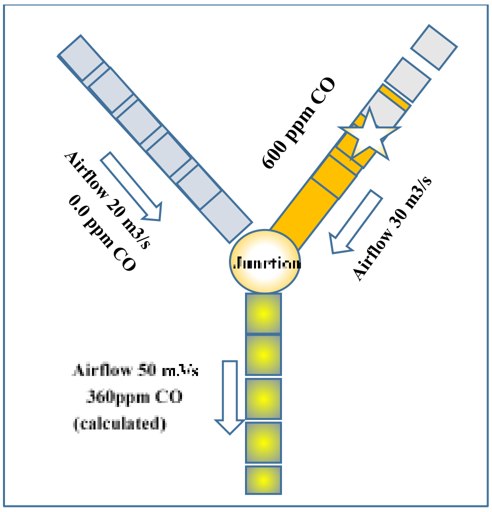


Fig. 4. Plan section showing transient flow and mixing simulation using sub cells

The results of the steady state simulation are transferred back into the transient simulation to alter the speed and direction of the cell movements. The global mine model joins seamlessly with the high density meshed part of the model where the fire is located, and mixed cells are free to move around the upper rollback layer, as well as in and out of the fire zone (Figure 5).

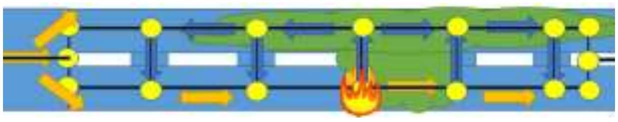

Fig. 5. Vertical section showing possible transient flow and rollback simulation around fire zone

## 5. Model Validation

### 5.1 Overview

An MFIRE model developed by Lihong and Smith [12] was used to validate the empirical rollback equation implementation in MFIRE. This model (Figure 6) is the basis for the high density network simulation in Ventsim Visual™.

The model incorporated a simplified representation of a number of connecting panels of an experimental mine, where a small diesel fire was ignited, producing a heat release rate (HRR) of approximately 520 kW (equivalent to around 50 l/hr burn rate of diesel fuel). The model was validated comparing actual rollback observations in the real mine fire versus MFIRE simulated results and the empirical rollback equations.

The Ventsim Visual™ model (Figure 7) was developed used identical sizes, resistances and lengths to the MFIRE model and a fix flow in the C-Butt exhaust was used to duplicate the initial flow velocities.

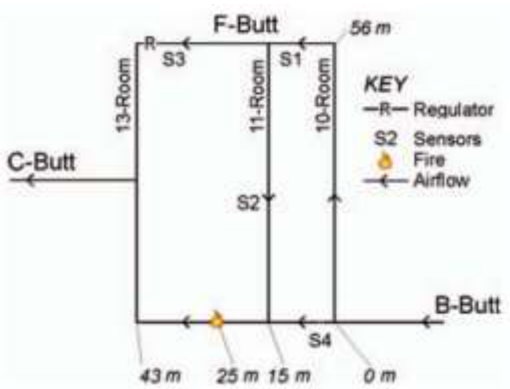


Fig. 6. MFIRE Validation Model [12]

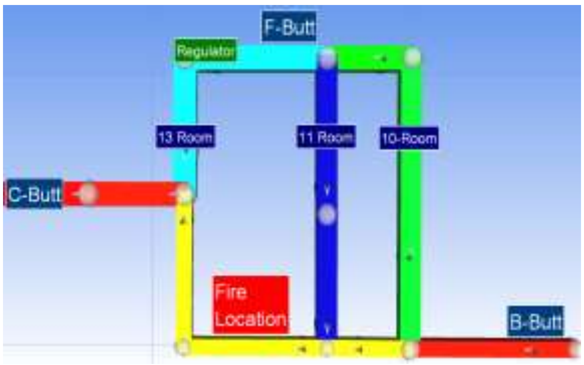


Fig. 7. Ventsim Visual™ model equivalent

### 5.2 Splitting Airways

Once the model is created, the airway splitting algorithm is used to manually select and split the pathways around the fire region into upper and lower pathways with vertical connection between. Approximately 40 m of airways each side of the fire were split to allow rollback (Figure 8).

The split length varies between 5 and 10 m depending on the length of the original branch. Finer splits can be specified however did not necessarily produce better results. Arguably, the splits create only a two dimensional flow network along the airways, however given the exact position of the fire across a tunnel may be unknown and rollback tends to be uniformly spread across the roof of a tunnel, this approach is seen as valid, and a three dimensional mesh (longitudinal, height and width pathways) would unlikely create additional value.

A current limitation of Ventsim Visual™ VentFire™ is that smaller lengths require a smaller dynamic time increment to allow creation of sufficient sub cells for accurate simulation and therefore the size of the split will adversely impact simulation time, particularly for large models.

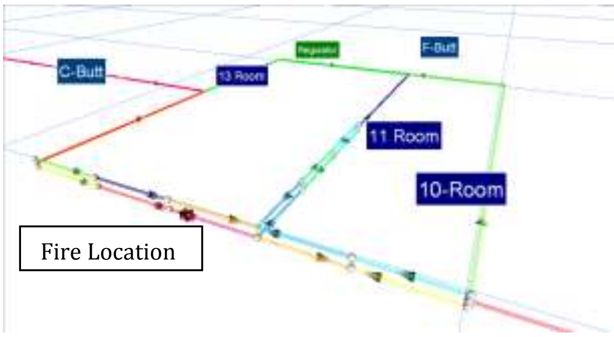


Fig. 8. Airway branches split into bi-directional upper/lower layers with vertical joins.

### 5.3 Varying Model Parameters

Three different flow velocities were specified to test against the MFIRE model validation results. In addition, the effect of slope was analyzed in the model by sloping all airways at 12% from left to right, and then from right to left.

Finally, a test example was done on a full mine model. While this example wasn't validated, the technique and outcomes were observed for relevance in a real mine simulation or emergency analysis.

## 6. Comparison with MFIRE Empirical Approach

The simulations demonstrated results broadly consistent with the MFIRE empirical equations. It was difficult to directly compare results as the empirical equations suggest a definite exact critical velocity at which reversal will occur, whereas the VentFire™ simulation with the bi-directional airways created different upper and lower velocity flows, as well as a slightly chaotic simulation output where airflows directions oscillated as natural ventilation pressures and heat was dynamically balanced. Only a few units (Pa) of pressure difference may exist in natural ventilation during simulation, and the oscillating reversal of individual airways and vertical joins may result because of this changing small variance.

It was also observed in the Swedish train fire tunnel test [10], that fire and rollback simulation in real life can also be chaotic and unpredictable due to the direct behavior of the fire and inconsistent supply of oxygen to the fire in the event of low airflow. It must be noted that VentFire™ will deliberately throttle back a fire if insufficient oxygen is temporarily available to the fire, resulting in a 'flaring' of the fire as new oxygen enters, and an uneven application of heat and NVP to the air.

### 6.1 Simulation Observations

The initial MFIRE study [12] suggested a critical velocity of 0.88 m/s of airflow velocity towards the fire under which rollback would occur. Actual observations showed smoke rollback into 11-Room and some evenly mixed smoke present back to 10-Room.

The VentFire™ simulation with an initial airflow of 0.68 m/s (decreasing by volumetric expansion during the simulation to around 0.35 m/s) showed a clear rollback situation into the proceeding junction and then into 11 Room, however smoke did not penetrate fully back to 10-Room. The discrepancy can perhaps be explained by the more even distribution of fire heat applied in VentFire across the full tunnel section which may have reduced the peak temperature in the rollback layer. This potentially could be resolved by increasing network mesh density or rollback thickness but was not tested during the project.

Without the rollback function, it would have been assumed that all heat and gases from the fire would have continued to travel out towards C-Butt, and no contamination of 11-Room would have occurred. Figure 9 shows rollback past into and past 11-Room junction.

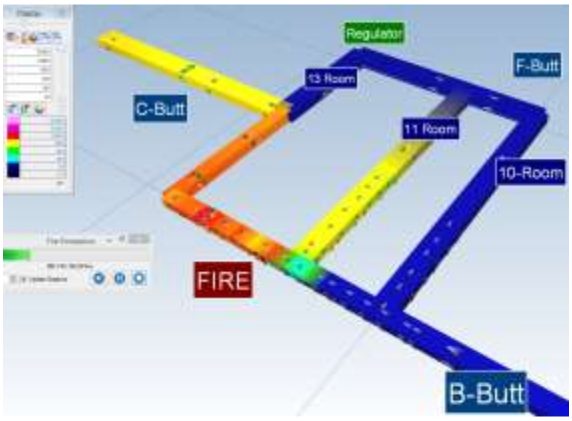


Fig. 9. Air velocity initially 0.68 m/s into fire (colors represent carbon monoxide level estimation, red=high, blue = low), rollback occurs.

A further test increasing the velocity of flow into the fire was performed with the VentFire™ simulation. The initial airflow was increased to 1.0m/s (again this decreased during simulation due to air expansion) and showed partial rollback immediately around the fire, but ultimately no contamination of 11-Room (Figure 10).

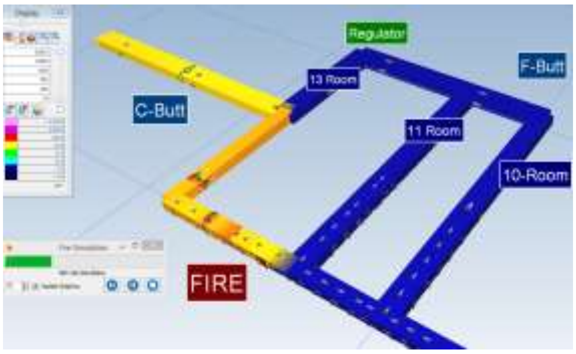


Fig. 10. Air velocity initially 1.0m/s into fire, partial rollback

A VentFire™ simulation with an initial airflow of 1.5 m/s showed no evidence of rollback, and no contamination of 11-Room (Fig. 11).

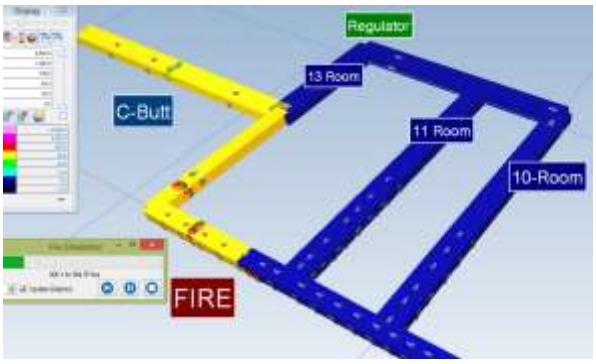


Fig. 11. Air velocity initially 1.5 m/s into fire, no rollback

### 6.2 Inclining the model

No validation of the inclined results could be made because the actual validation test work was not performed on inclined airways. Nonetheless, Equation (1) from the MFIRE empirical equation suggest that slope should have a clear effect on the rollback critical velocity, and therefore the occurrence of rollback, and this was tested in the VentFire™ model.

Figure 12 shows that inclining the model at 12% away from the fire, resulted in the smoke and heat travelling away from the fire with no rollback occurring. For rollback to occur, sufficient pressure would have had to be available to force the heated air downwards against its own natural ventilation pressure, and into the oncoming air velocity.

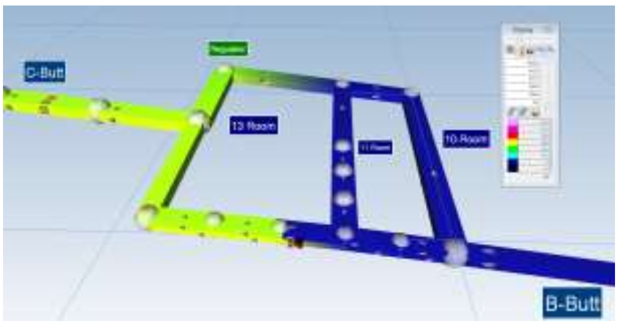


Fig. 12. Inclined at 12% to the left (0.68 m/s initial)

Figure 13 shows that inclining the model at 12% towards the fire causes rollback and reversal to occur all the way to the 10-Room intersection and into 10-Room, as the natural ventilation pressure of the heated air can now be used to assist in the rollback direction.

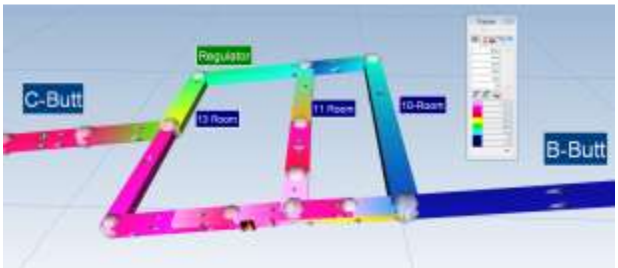


Fig. 13. Inclined at 12% to the right (0.68 m/s initial)

## 7. Comparison with CFD Approach

The opportunity was also taken to compare the results of a CFD study of a 3000 kW fire in a tunnel by Goce Delchev University [6]. The tunnel was modelled in CFD at 4 m wide by 3 m high, with a length of 50 m. A diesel pool fire was assumed generating a heat release rate of 500 kW/m$^2$ over a 6m$^2$ area.

An equivalent 3000 kW HRR diesel fire was built in an identical size tunnel in Ventsim Visual™ VentFire™ to compare results.

### 7.1 CFD Results

The CFD study compared fire rollback with three (3) different air velocities at 1.0 m/s, 1.5 m/s and 2.0 m/s (Figure 14). The CFD results suggested extensive (30 m+) rollback would occur in the 1.0 m/s case, partial rollback (9 m) in the 1.5 m/s case, and no rollback in the 2.0 m/s case.

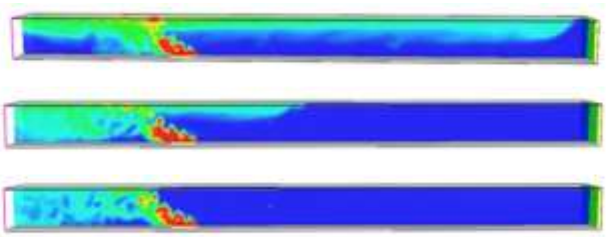

Fig. 14. CFD Modelling of 1.0 m/s (top), 1.5 m/s (mid) and 2.0 m/s (bottom). [6]

### 7.2 Ventsim Visual™ VentFire™ Results

The equivalent Ventsim VentFire™ simulation showed broadly consistent results, although considerable variability was observed during simulation (Figure 15). The 1.0m/s case generated rollback ranging from 20-40 m in length, the 1.5 m/s case generated rollback ranging from 10-15 m in length, and the 2.0 m/s case generated only minor rollback directly above the fire, with occasional 5 m extensions into the wind.

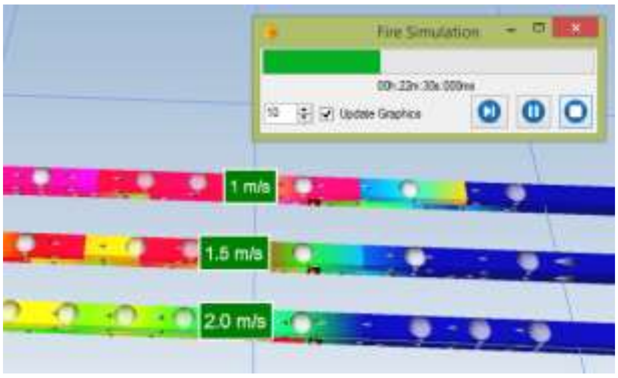


Fig. 15. VentFire™ Modelling: 1.0 m/s (top), 1.5 m/s (mid) and 2.0 m/s (bottom).

## 8. Full Complexity Model Testing

The method presented was tested on a full mine ventilation model. Although not validated, the speed at which the method could be applied and the rapid results that can be obtained, gives credence that this method may be suitable for real time emergency evaluation, instead of the usual post-event analysis of a fire outcome. Ventsim VentFire™ shows results graphically as it progresses allowing visual inspection during the simulation.

Figure 16 shows a mine ventilation model where a truck fire was assumed on a main ramp. The combustibles on the truck were assumed burned over four (4) hours, and the ventilation model observed for changes during the simulation.

Fig. 16. Full Scale Mine Ventilation Model

### 8.1 Results

It was immediately observed that rollback of fumes occurred uphill on the ramp approximately 40 m above the truck against the main ventilation flow (Figure 17). Later in the simulation, complete reversal of the main ramp flow occurs, directing smoke and fumes into previously clear areas. Even after complete reversal occurs in the ramp, rollback *against* the reversed flows directed fumes unexpectedly into an area just downhill from the fire.

The complexity of results of this simulation suggest that a variety of unexpected conditions could occur should this have been a real fire. In the event of trapped personnel or a mine rescue excursion into the area, these conditions may have placed personnel in further danger, and would have been well worth considering during the planning phase of any rescue or evacuation scenario.

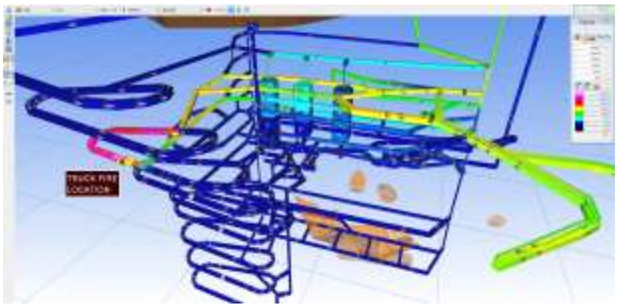

Fig. 17. Rollback then flow reversal uphill from the truck fire location.

Assuming a valid ventilation model is already available, a VentFire™ fire simulation can be quickly constructed with initial results from the simulation achieved within minutes.

## 9. Conclusions

Utilizing a high density mesh of rollback branches within a broader network analysis model to simulate rollback zones appears to be a useful method for rapid rollback simulation and integration within a global mine ventilation fire model. Despite the time based variability of the VentFire™ results, the method provides results which are broadly consistent (but not exactly the same) as empirical and CFD analysis.

The method must be recognized as a highly simplified simulation that ignores much of the detail of a real fire such as radiant heat and convection within the 3D space. However while the method does not provide the accuracy or detail of CFD modelling, neither does it require the extensive inputs and assumptions of CFD methods, and given the amount of uncertainty in the estimation or measurement of fire variables, this may provide a perfectly acceptable initial analysis of the situation.

While CFD analysis promises detailed results around the immediate fire zone, the limited area possible to simulate, and the time taken to create and simulate models rule this method out for larger simulations or when quick results are required. Empirical analysis (with MFIRE for example) only provides an indication of the possibility of occurrence of rollback, but does not provide any additional analysis of the effects of the rollback on the remainder of simulation model.

In the event that results must quickly be known or estimated, the proposed integrated network analysis method has the potential to provide one of the most rapid ways to integrate and obtain results of rollback simulation details into a broad and extensive mine ventilation model. Ultimately, the effective use of such a method relies on a mine having an accurate model of the ventilation system, however most mines now have these models for ongoing planning and design purposes.

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