Fire Modelling in Underground Mines using Ventsim Visual VentFIRE Software

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ABSTRACT

The risk from fire remains one of the most serious of underground mine disaster scenarios. The impacts of mine fires on the underground ventilation system and the production of toxic gases have been difficult to model and therefore assessments have relied largely on empirical data, historical precedent and subjective opinions. Underground fire modelling software has had limited availability and been technically challenging and time consuming to use especially for routine mine investigations. There has also been no well-accepted set of assumptions for fire modelling in mines, which has resulted in a lack of confidence in adopting its use more widely. This paper describes modelling of three critical fire scenarios in underground hard rock mines: a fire (LHD) in an underground diesel refuelling facility, a fire in an underground explosives magazine and a fire on an underground ore transport conveyor. Modelling was undertaken using Ventsim's VentFIRE™ fire simulation module. It describes the basis of design, the key assumptions, the methodology used and provides examples of the outputs, conclusions and recommendations. It reviews the impacts of these fires on egress and entrapment strategies in the mine. Some general principles regarding improvements to ventilation circuit design based on this analysis are also recommended. Whilst the fire scenarios were based on actual case studies, they have been disguised for this paper.

INTRODUCTION

Fires and explosions are significant contributors to fatalities and high potential incidents in Australian mines. MIHSC (2005) conducted a detailed review of safety incidents in the Australian mining industry over a two-year period from July 2002 and found a high potential incidence rate per million work hours of four and nine respectively for coal and hardrock mines from fires alone. Major explosions in coal mines are not uncommon events in first world countries (Pike River in 2010 and several in the USA in the past ten years); major fires in underground hardrock mines are also not infrequent, with at least two fires widely reported in Australasia in the public media in the past 18 months (Broken Hill truck in fuel bay in late 2011 and Waihi truck fire in mid-2012), but there have been many others that have not had such a high public profile.

The Western Australian *DME Emergency Preparedness for Underground Fires in Metalliferrous Mines Guideline* (1997) states:

> *While there are combustible materials present underground, the risk of fire remains. No hazard is more to be feared, and every underground mine should be prepared for such an event.*

Whilst this paper focuses principally on fires in hardrock mines, it also has application in coal mines. It is based on actual fire modelling studies undertaken by the author, modified for this paper[2].

Fires result in many critical impacts on the underground environment:

- The toxic products of combustion can directly cause injury or death.
- Smoke and irritant gases restrict visibility, disorient the victim and can prevent safe escape or result in injury during egress by falling down vertical openings, etc.
- High temperatures from the primary fire can induce secondary fires or falls of ground.
- Fire can in some cases progress to explosions.
- The fire can put the lives of first responders at risk.
- The fire can result in serious damage to mine infrastructure and therefore loss of production due to the potential long lead times on removing damaged plant and obtaining and reinstalling new plant or creating new bypass accesses or re-supporting existing fire damaged accesses.

In most cases, competent risk assessment combined with good procedures and regular reviews should identify and control fire risks. However, identifying the potential outcomes from a runaway fire event (Hopkins, 1999), especially on the ventilation system generally is very difficult. It is here that modelling tools can be a useful addition for mine ventilation engineers. *Even if every reasonable precaution is being taken, there will always be at least some credible scenarios that can result in a major underground fire in any mine* and therefore careful

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[2] The major differences between fires in hardrock and coal mines are that: coal mines provide an almost infinite source of combustible material (coal); coal mines have the potential (in most mines) for methane explosion; and the main source of serious fires in coal mines is conveyors.

contingency planning for such an event is an essential duty of care at every mine.

FIRE IMPACTS, TYPES AND MANAGEMENT

The modelling of mine fires requires an understanding of *fire chemistry* and *fire dynamics* as well as a suitable *thermodynamic modelling program*. Fire chemistry relates principally to the amount of heat and gases produced by the fire for various types of fuel, etc. Fire dynamics relates to the stages of growth (and decay) of the fire and the heat release rate (HRR). The thermodynamic modelling program then predicts the impact on the mine due to the fire chemistry and dynamics. All three of these are interdependent, for example, all three are very dependent on the amount of fresh air reaching the fire.

Fires produce large amounts of very hot, very low density gas. This results in four main effects on the ventilation system (Chen, Chen and Fu, 2003; Hansen, 2010b; Zhou and Wang, 2002; Gillies *et al*, 2004):

1. a *throttling* or *choking effect* caused by the volume increase of the air passing through the fire zone resulting in higher wind speeds downwind and therefore higher frictional pressure losses
2. a *chimney* or *natural draft* or *natural ventilation effect* caused by the increased buoyancy of the 'air' downwind of the fire effectively giving rise to very large (and potentially unstable) natural ventilation pressures (NVPs) in various parts of the ventilation circuit
3. *flow reversals*: these have been experienced in practice and also shown theoretically via modelling. As an example, in the Belmont fire of 1911, the US Mine Rescue Association (undated) states:

   > *In a fire at this mine, 17 men lost their lives. The fire should not have been a serious one; little damage to the mine resulted. It was discovered while it was still small and was attacked for some time at close quarters, yet the unfamiliarity of the men with fire-fighting methods, together with a reversal of the air currents, permitted an insignificant blaze to develop into an appalling disaster.*

4. *rollback* or the localised reversal of airflow direction above a fire, usually characterised by smoke near the roof moving backwards against the general flow of air over the fire. This is primarily a convection issue with hot, low density gases produced by the fire rising and expanding ('mushrooming') above the fire.

The intensity of a fire (heat release rate, HRR) is largely determined by the rate at which air (oxygen) can reach the fire and the surface area and type of fuel available for burning. Within limits, if more air arrives at the fire, the intensity of the fire increases (and vice versa).

Mine fires can be classified into one of two fuel-oxygen states (Laage, Greuer and Pomroy, 1995; and Laage L W and Carigiet, 1993):

1. oxygen-rich fires: here the oxygen content of the air downwind of the fire remains relatively high (although the carbon monoxide content will still usually be fatal especially with prolonged exposure such as during egress or entrapment). Most mine fires fall into this category
2. fuel-rich fires: in fuel-rich fires, the fire zone becomes so large and so hot that the entire volume of air reaching the fire is heated to a temperature sufficient to cause pyrolysis[3] of the fuel. All or virtually all oxygen is consumed. The fuel that cannot actually burn (due to insufficient oxygen) breaks down directly into carbon residue without consuming oxygen. The oxygen content downwind of the fire is effectively nil. Extremely hot pyrolysed but unburned fuel may be carried into the downstream ventilation where it can combust as soon as it comes into contact with oxygen, providing its temperature is still sufficiently high. NIOSH states that 'fuel rich fires are extremely rare events. It is estimated that less than 0.1 per cent of mine fires reach the fuel rich state'. However, this is not to say that the HRR of a fire does not reduce as the oxygen available reduces.

A classification used in fire chemistry literature is the 'equivalence ratio' which is the defined as the actual fuel/air (oxygen) mass ratio divided by the stoichiometric fuel/air (oxygen) mass ratio (Karlsson and Quintiere, 1999). A ratio less than one means the fire is fuel-rich (poorly ventilated) and greater than one means it is oxygen-rich (well ventilated). If the equivalence ratio is exactly one (the stoichiometric condition), then in theory the fuel and oxygen would exactly consume one another with none of either left over.

The size and nature of a mine fire depends on:

- how long it has been burning
- what is burning
- whether the fire has been spontaneous or was externally initiated
- the air flow to the fire (supply of oxygen)
- the geometry and composition of the material
- where the heat goes.

Fire management in an underground mine has several key principles (DME, 1997; Thyer, 2002):

- Prevent the start of the fire using equipment specifications, fire suppression systems, careful materials selection and careful consideration of ignition sources.
- Detect the fire early and provide effective systems to isolate and/or reduce the impacts of the fire. This includes fire suppression systems, fire containment systems, and an effective ventilation system that prevents or reduces the toxicity of products of combustion entering the main mine workings.
- Provide warning for persons underground and effective egress and entrapment/refuge systems so that personnel can wait safely until the fire is extinguished or they are rescued.

Note that modern 'duty of care' requires, among other things, that the lives of rescuers are not put at unreasonable risk to fight a fire, particularly if no person is at risk from the fire. This means that if a fire starts and is not contained by the fire suppression systems, it is *likely to spread to an out of control (runaway) event.*

Deliberate reversal of flow over fires is a highly risky decision and should never be undertaken except under very

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[3] Pyrolysis is the thermochemical decomposition of organic material at elevated temperatures without the participation of oxygen. It involves the simultaneous change of chemical composition and physical phase, and is irreversible. In a wood fire, the visible flames are not due to combustion of the wood itself, but rather of the gases released by its pyrolysis, whereas the flame-less burning of a solid, called smouldering, is the combustion of the solid residue (char or charcoal) left behind by pyrolysis. Thus, the pyrolysis of common materials like wood, plastic, and clothing is extremely important for fire safety and firefighting [Wikipedia].

carefully considered circumstances (Ray *et al*, 2002; Ryan, 1995).

The prompt and competent response of persons underground and on surface to a reported mine fire is also important in dealing safely with fires. This has also been analysed extensively (Vaught *et al*, 2000; Royal Commission on the Pike River Coal Mine Tragedy, 2012) but is beyond the scope of this paper.

TYPICAL UNDERGROUND FIRE SCENARIOS IN HARDROCK MINES

There is substantial data available regarding the incidence of underground mine fires. In the USA, NIOSH (De Rosa, 2004a; De Rosa, 2004b) compiles regular reports on coal and non-coal mine fire statistics. In Australia, there are no underground fires statistics maintained at a national level, but the major mining states do keep statistics and occasionally put out statistical reports.

In a hardrock mine, the three most critical fire risks are probably:

1. Mobile diesel equipment fire: fires on underground mobile equipment are (unfortunately) still relatively common. Most of these are relatively minor and are extinguished either via on-board suppression systems or portable extinguishers. Major fires (where the vehicle is destroyed) are infrequent but by no means 'incredible'. From this author's experience, the two most common incidents where the vehicle is destroyed are:
    - fire during vehicle refuelling
    - fire due to vehicle rollover.
2. Magazine fire: magazine fires can be especially significant as it common for them to be located adjacent to major intakes, there are often large quantities of explosives stored underground, they have limited direct exhaust or none at all, explosives are oxidising agents (which means they do not need an external source of oxygen to burn) and there is the risk of detonation if the explosives catch fire.
3. Conveyor fire: as the potential fuel load for a conveyor fire (the belt) is spread out over the length of the conveyor, and the conveyor may be moving when it catches fire (making the fire mobile), a conveyor fire can result in a large area being directly affected and a lengthy process to contain or extinguish the fire.

Since the subject of this paper is fire modelling, in all cases it is assumed that the fire suppression systems have failed (either to activate, or to extinguish the fire) and the fire has progressed to a runaway event.

It should be noted that in terms of safe entrapment, the 'worst credible' event means considering how long an entrapment may be required. However, for fire modelling, the 'worst credible' event usually means designing for the most intense fire. These two criteria are not compatible in that an intense fire will burn through its available fuel more quickly (hence requiring a shorter entrapment) and vice-versa. However, both considerations are important; the behaviour of the ventilation system and fire management options is best understood by examining *high energy, intense fires*; the required duration of entrapment provisions is best understood by examining the potential *longest duration of a fire*.

MINE FIRE DYNAMICS AND BEHAVIOUR

Explosion potential of a fire

It is not uncommon for a primary fire to initiate a secondary fire or an explosion, even in hardrock mines.

WA DOCEP (2008) and other authoritative sources recommend that any fire on a vehicle with pneumatic tyres is not approached for 24 hours after the fire starts due to the potential for the tyres to explode.[4] Of course, if it is certain that the tyres have 'failed' (no longer inflated) then there is no longer any explosion risk from them, and this normally occurs fairly early in an intense fire.

It is recommended to not attempt to smother a fire that involves burning explosives.

Orica (2004) states:

> *DO NOT FIGHT FIRES INVOLVING EXPLOSIVES. Attempts to smother a fire involving this product will be ineffective as it is its own oxygen source. Smothering this product could lead to decomposition and explosion. This product is more sensitive to detonation if contaminated with organic or oxidisable material or if heated while confined. Unless the mass of product on fire is flooded with water, re-ignition is possible.*
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> *Water may be applied through fixed extinguishing system (sprinklers) as long as people need not be present for the system to operate.*

Therefore if an automatic water deluge system does not extinguish an explosives fire, these fires must be left to burn out themselves.

Estimates of airblast overpressures from accidental detonation of explosives (Mainiero and Weiss, 1995) or from fires triggering methane explosions (Zipf, Sapko and Brune, 2007) have been undertaken but are not considered in this paper.

Stages of mine fire

A fire goes through three principal stages:

Growth stage

In this stage, the fire starts and its intensity increases until it reaches a maximum determined by either the limit on fuel that is available at any time to be burned, or the oxygen available. In a fire in a constrained area, the end of the growth stage is often characterised by *flashover*, when the hot gases and radiation have heated the temperature of the remaining combustible materials to their auto-ignition temperature and, effectively, these explode simultaneously into flame.

Peak intensity stage

In this stage, the fire burns at roughly the same peak intensity with the rate (of intensity) determine by either the available fuel or the available oxygen. This is the phase with the maximum heat production, maximum temperatures and maximum impact on the ventilation system.

Decay stage

In this stage, the fire is starting to reduce in intensity of its own accord as it is starting to run out of fuel. However if the fire is partially oxygen constrained, then if more oxygen is suddenly made available (eg by opening fire doors), the fire may flare up again. It is often in the decay stage of the fire

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[4] Technically, WA DOCEP states the 24 hour period applies 'after removal of the heat source likely to lead to an explosion'.

life that fire fighting attempts may be made to hasten the extinguishment of the fire.

Durations of stages

The duration of each stage (and the associated heat output in each stage) is difficult to predict, but is generally not critical for ventilation modelling for three reasons:

1. The purpose of the modelling is principally to understand what areas of the mine will be affected and how badly affected (in relative terms) by the fire so as to understand impacts on egress and entrapment and therefore search and rescue and fire fighting options. It is not to predict, *inter alia*, the precise carbon monoxide concentration at some point in the mine.
2. Perhaps equally important is to be able to assess the impact of deliberate changes to ventilation controls or fan on/off or volume status, ie management options for the fire, or to understand the importance of unintended changes in ventilation controls such as controls burning out or power being lost to particular fans. It is very important to note that deliberately interfering with the progress of a fire can be very risky (and therefore only used with extreme caution) but can be the best course of action in specific circumstances (Ryan, 1995; Ray *et al*, 2002).
3. If the fire can be modelled easily, then it is a straightforward matter to vary the size and duration of the fire, ie undertake sensitivity studies so as to gain a more comprehensive appreciation of what various sized fires could mean at different locations in the mine.

Based on observations and reports from actual underground fires, the initial phase of fire growth is generally fairly short (less than 30 minutes would be relatively common for a fire to reach peak intensity). The final (decay) phase depends on whether the fire is fought (and if so, how effectively) and could be anything from 30 minutes to four hours (or more for conveyor fires or deep-seated fires such as spontaneous combustion). The peak intensity phase depends very heavily on the amount of available fuel (and its exposed surface area for burning) and available oxygen (and hence airflow over the fire). For mobile equipment fires, it could be as little as two hours for a light vehicle or up to 16 hours for heavy vehicles that are fuel rich and in a poorly ventilated area. In the case of conveyor fires, the 'fuel' is located along a considerable length of drive therefore may proceed for some considerable time if the fire is not fought. In the case of spontaneous combustion fires where there is potentially an unlimited amount of fuel, the peak intensity period may never end unless the fire can be starved of oxygen such as by inertisation.

FIRE CHEMISTRY

The 'yield' (rate) of a combustion gas is defined as the mass of gas (eg CO) produced per mass of fuel (eg conveyor belting) consumed by fire.

As an example, the complete oxidation (burning) of 1 kg (not 1 litre) of diesel fuel (with only a trace of sulfur) would produce (yield) 3.10 kg carbon dioxide and 1.35 kg water vapour. The 3.46 kg of oxygen required to do this would come from 15 kg of air (air consisting of 23 per cent oxygen by mass). Hence the theoretical (stoichiometric) air to fuel ratio for complete combustion of diesel is 15 to 1. At 30°C and 110 kPa barometric pressure, 3.1 kg CO_2 occupies 1.64 m^3 and 1.35 kg H_2O occupies 1.75 m^3. The loss of 3.46 kg of oxygen is a loss of 2.52 m^3. The net increase in gas over a diesel fire is 0.87 m^3/kg of diesel fuel consumed (at the above temperature and pressure).

Of course, a fire produces carbon monoxide and other gases as well, but these are usually minor in terms of volume flows (but very significant in terms of toxicity, discussed later).

A fire producing 1 MW of heat from diesel fuel will be burning 0.0222 kg/s (or 0.0261 l/s) of diesel fuel and will produce about an extra 0.019 m^3/s of gas (over and above the ventilating air through the fire zone). Therefore, for example, a major 18 MW fire would only produce *about* an extra 0.35 m^3/s of combustion gases, in addition to the ventilating air passing over the fire. The corollary to this means that even a large fire of 18 MW requires only a relatively small airflow to support combustion (18 × 0.0222 × 15 = 6 kg/s or about 5 m^3/s). The conclusion being that even a relatively poorly ventilated area can support a significant fire (eg truck burning at 18 MW heat release rate).

It can be seen from this analysis that in almost all cases, even large underground mine fires will be oxygen rich and in this case, the net increase in gas flow due to POCs is negligible. However, the volume flow rate over the fire increases dramatically due to the increase in temperature, which is accompanied by a reduction in density and an increase in volume flow rate for the same gas mass flow rate.

Note that the thermal capacity of air is about 1 kJ/kg/K so that a 20 MW fire into an airflow of 40 m^3/s (48 kg/s) will increase the air temperature by about 410°C with smaller or larger airflows changing the air temperature proportionally. The potential for secondary fires to be initiated immediately downwind of the main fire is evident.

Toxic gases, gas concentrations and visibility

Airborne products of fire include smoke (airborne solid particles), carbon dioxide and other more toxic gases.

Smoke irritates and obscures vision, while toxic gases cause mental and physical impairment and disorientation. Carbon dioxide is produced in large quantities in a fire and is also toxic in high doses.

Toxic gases

Numerous studies have been conducted into fire chemistry. In one major study, the USBM investigated the toxic gases given off by various types of fires (Egan, 1990). The key gases were carbon monoxide (CO), hydrogen cyanide (HCN) and hydrogen chloride (HCl). CO is considered to be the most toxic in practical terms followed by HCN because HCN also interferes with the body's ability to use oxygen. HCN is generated when nitrogen-containing materials are burnt. HCL irritates the eyes and upper respiratory tract and is produced when materials containing chlorine are burnt, such as PVC. The equivalence ratio is known to be a key determinant of the production of carbon monoxide and hydrogen cyanide in particular (Stec *et al*, 2008).

Where CO concentrations from a fire are not calculated from the fire chemistry itself (eg using the equivalence ratio), a CO concentration of ten per cent by volume (10000 ppm) is often used as a conservative assumption (ie upper value) (Pitts, 1995). However, a value of ten per cent CO would generally only apply for a fire in an enclosed or severely ventilation constrained situation concentration; in most circumstances CO values are much lower than this, but still highly toxic.

Toxic gas proxy

Due to its practical toxicity described above, and the fact that it is always present in carbon-based fires, carbon monoxide

(CO) is considered to be a good proxy for the toxicity of an underground fire.

A CO concentration of 1200 ppm is considered to form an immediate danger to life or health (IDLH) which is the benchmark for emergency egress (NIOSH, undated), whilst the IDLH for CO_2 is four per cent (40 000 ppm). The Australian NOHSC (Safe Work Australia, undated) recommends any CO exposure (in an occupational *not* emergency setting) to not exceed 100 ppm CO for a 30 minute duration and on no account to exceed 400 ppm CO. All exposure limits should be adjusted where the oxygen partial pressure varies significantly from the sea level standard.

It is important to remember that underground fire modelling should *not* be used to forecast actual toxicity of the air; rather its role is to examine the impacts of a fire and different control strategies on the ventilation circuits and the relative safely of various airways to POC contamination.

FIRE MODELLING SOFTWARE

Mine fire modelling options available

As noted earlier, any fire prediction program needs to model fire chemistry, fire dynamics and the thermodynamics of the ventilation system—all three of which are interrelated. Whilst fire chemistry and fire dynamics have been extensively studied in laboratory tests and some larger scale testing has been conducted, it has generally been in a highly controlled and simplified environment; overall there is no model at this time that can take as an input (say) a certain model of underground loader and confidently predict the progress and chemistry of a fire which starts in a certain way at a certain location on that loader. There are simply far too many variables involved.

In terms of the behaviour (thermodynamic response) of the ventilation system, fire modelling of civil structures such as tunnels and underground train stations is conducted regularly using general computational fluid dynamics (CFD) or specialist CFD programs such as the public-domain Fire Dynamics Simulator or SmokeView developed by the National Institute of Standards and Technology (NIST, undated) of the US Department of Commerce. The older (1975) Subway Environmental Simulation program developed by the US Department of Transportation is also available (US Dept of Transport, 1976). However, setting up a model using these tools is impractical in the vast and complex system of leaky underground tunnels and caverns such as occurs in a mine.

Over the past 20 years, two modelling tools specifically to assess underground mine fires have become available. These were MFIRE (developed by the USBM originally in the 1980s (Laage, Greur and Pomroy, 1995) now under the control of NIOSH) and Ventgraph™ (from the Strata Mechanics Research Institute of the Polish Academy of Sciences, originally developed in 1988). MFIRE is freely available at no charge (OMSHR, undated); Ventgraph is a commercial program (IMG, undated).

Hansen (2010a) provides a very useful discussion of the merits of the three different approaches (CFD, FDS and mine fire simulation programs), including testing against empirical data. A particularly interesting discussion of the difference in ventilation design, and egress strategy factors, in public tunnels versus underground mines is given by Duckworth (2008).

> *Unlike workers in the mining and civil construction industries, the general public are neither trained nor equipped to fight fires or evacuate under deteriorating smoke conditions. Accordingly, for the majority of modern transportation tunnels the ventilation infrastructure is sized on the requirement to control the combustion products from worst-case fire scenarios and to provide a tenable evacuation route for the tunnel users. It is common for these same emergency ventilation systems to be employed, often in a reduced capacity, for other operating modes such as the dilution of pollutants during congested traffic conditions. This is one of the fundamental differences to mine ventilation, where primary ventilation systems are not typically sized based on fire scenarios.*

In more recent times, VnetPC™ is now available with a modified version of MFIRE as an add-in and sold as MineFire™ (MVS, undated). Ventsim has also recently introduced a fire modelling module called VentFIRE™ (Ventsim, undated).

Subsequent to the Moura No 2 disaster, the Task Group No 4 Report stated that 'the capability to model ventilation and the mine environment following an incident should be available at mines'.

Later on, Sub-Committee 5 (Incident Management) noted the following:

> *There is a need for a wider appreciation of current knowledge and improved capability of ventilation management at mines for both routine as well as emergency conditions; guidelines for modelling should include …*
>
> - *Models interface with standard mine planning packages and be kept up-to-date'.*

In this regard, there are two main problems this author sees with MFIRE and/or VENTGRAPH:

1. They are standalone packages and do not integrate at all easily into the major ventilation modelling software used in Australian mines which is Ventsim.
2. They require specialist skills to set up the fire models and run the packages. This removes the application from use in most Australian mines at least on a regular basis, although Ventgraph has been used for some coal mines in Australia (Gillies *et al*, 2004).

The VentFIRE module is a seamless integration into Ventsim Visual and therefore readily available for mine ventilation engineers. It is fully interactive with the same graphical interface familiar to users.

All three programs have attempted to validate outputs against the results from known mine fires: VENTGRAPH used a retrospective validation against the USA fire at Pattiki in 1991 (Wala *et al*, 1995) and both MFIRE and VentFIRE using results from a purpose-designed test program at the US Waldo experimental mine (Laage and Carigiet, 1993; Stewart, 2012). No comparison of the results of the three programs against either a known or contrived fire scenario has been performed to date, although this would be a useful exercise.

As noted above, no current fire modelling program can be said to fully and accurately describe all fire scenarios. A number of particular limitations exist in one or more of the fire modelling programs and should be noted:

- 'Rollback' is either not modelled, or where it is, is based on very approximate and simplified empirically derived equations. Rollback typically peaks at an incoming wind speed of about 1.5 m/s with negligible rollback evident at incoming wind speeds above 4 m/s (Verakis, 1991; Tarada, 2010). Rollback is not usually significant outside the immediate area of the fire, but can be an important factor at and near the fire site (Chen, Chen and Fu, 2003) and it has been found that rollback can affect other areas of the mine if the rollback retreats upwind sufficiently far to contaminate an intake.

- Fire spread (eg the spread of a fire along a conveyor belt or the spread of a fire along a coal entry) is either not modelled, or where it is, is based on very approximate and simplified empirically derived equations.
- Whether air density varies along any given airway or is fixed along the length of a given airway.
- Whether the fire model is a genuine thermodynamic model, for example, one program starts every fire simulation with every airway in the mine initially at 20°C irrespective of actual conditions which may vary considerably in an extensive underground operation and impact on starting NVPs.
- Are inputs specified as actual values or a non-dimensional subjective scale, eg one program uses a dimensionless ‘fire intensity’ scale of one to ten rather than a MW value.
- How CO_2 yield and hence CO concentration is calculated, eg is it via a fixed CO/CO_2 ratio which does not vary through the fire duration.
- How CO_2 yield changes (as it should) with the fuel-oxygen ratio during the stages of the fire.
- How easy is it to set up the fire model, and then perform ‘what ifs’? Some programs require a series of modules to be run, firstly to input the data, then to undertake the thermodynamic modelling and finally for the fire modelling. Sensitivity analyses involving changes to the network are lengthy.
- Can the software allow the progress of the fire to be interrupted by the user and the network changed to simulate the effect of fans or ventilation controls deliberately changed, or burnt out, etc or to interrogate gas concentrations in any airway in the model at that time.
- All of the programs rely on the Hardy Cross algorithm for solution. The Hardy Cross method effectively assumes that, at any instant, the mass of air entering the mine (plus gases produced in the mine, eg POCs, strata or diesel gases or water vapour) equals the mass of air plus introduced gases leaving the mine. In reality, in a mine fire that is rapidly increasing in intensity, this will not strictly be the case. However, reducing the ‘increment time’ between simulations to a low value (such as less than one second between simulations) allows a steady state simulation to achieve a close approximation to a non-steady state program. This is what VentFIRE is referring to when it describes its simulation as being ‘dynamic’.

To remove some of these constraints and limitations, there is certainly the scope, and need, for more work to be done to quantitatively understand and characterise mine fires and apply this to fire modelling. This is particularly the case for full-scale diesel equipment fires and large-scale magazine fires as there is little or no comprehensive empirical data available for such fires.

Operation of VentFIRE

VentFIRE allows the dynamic nature of the fire to be modelled as it takes into account the change in density as the air passes over the fire due to the heat added, the consumption of oxygen and the generation of products of combustion using published (or user-set) gas yield values and the equivalence ratio (in the case of CO).

In VentFIRE, fire ‘events’ are added to an airway. There can be multiple *events* in an airway, and any number of airways can have *events* in them. Each stage of the fire is set up as an event but *events* can be used in any airway to change the fire behaviour, eg by changes to ventilation controls, turning fans on or off, introducing inertising gases, etc. However, the user can manually interrupt the fire simulation (which is viewable in real-time) at any time and evaluate the impact of such changes and then resume the simulation.

The user also sets *monitors* in important airways that do not have *events* already in them. This effectively tells VentFIRE to ‘log’ the required fire output parameters (gas concentrations, airflow, HRR, temperature, humidity, visibility, etc) in that airway during the simulation. The reason for this is that if the model has hundreds or thousands of airways, then collecting all the fire-related data on every airway is excessive and unnecessary.

Up to 250 different types of combustible fuels can be added to the Ventsim preset database. Each type of fuel can have a defined heat of combustion output, oxygen consumption rate, and yield rates of various gases per kg fuel burned. To simplify this, a standard (default) series of simple fuels with laboratory estimated heat and gas yields is also provided.

The VentFIRE module describes the algorithm strategy used in the software as follows:

- *VentFIRE uses a discrete sub-cell transport and node mixing method to simulate moving parcels of heat and gas around a mine. To dynamically model mine ventilation and accurately take into account continual changes in atmospheric concentrations of gases and heat including recirculation, VentFIRE breaks the model into small independent ‘cells’ which move freely around a model, mixing with other cells at junctions. Each airway may be broken into dozens of cells (creating potentially hundreds of thousands of cells for a large model), and each cell independently contains information on gases, heat, moisture and density at that location within the airway. The cells are moved around at directions and speeds calculated by the global airflow simulation (a Hardy Cross simulation based on compressible flows and density driven natural ventilation).*
- *As each cell of air passes over a fire, oxygen from the cell is consumed (based on fuel properties) at a defined combustible fuel burning rate. Heat from combustion (also defined in the fuel source properties) is added to the cell. If oxygen is reduced below a predetermined concentration the fire is throttled if excess fuel is available, and heat and gas output is limited. Other gases are added to cells based on the yield rates specified in the combustible fuel properties. For critical gases such as carbon monoxide, an upper and lower limit can be specified to simulate the carbon monoxide emission effects of an oxygen or fuel rich fire; however this can be overridden to produce maximum carbon monoxide if a cautionary (‘worst case’) scenario is desired.*

Regarding heat transfer from the hot gases to/from the rock surface of airways, VentFIRE uses a proprietary approach involving the Gibson algorithm and the long-term steady-state calculated surface rock temperature to simulate short-term rapid transfers to and from a limited thickness boundary rock mass (Stewart, 2013).

VentFIRE gives an indication of the visibility of a light-emitting or light-reflecting sign at an arbitrary 25 m distance based on the soot yields of combustible materials and the theory described by Mulholland (1995).

STEPS TO CREATING A FIRE MODEL IN VENTSIM VENTFIRE

The following steps are required to create a fire model in Ventsim:

- Set up the yields of combustion gases (and soot, if desired) under SETTINGS>PRESETS. Either the default values can be used or other data sources such as provided by NIOSH (Egan, 1990).The yield of combustion products can vary for different fuel types. For CO, both a maximum and minimum yield can be specified for each fuel type; the maximum yield is used when the fire is approaching the fuel-rich status (oxygen deficient). The minimum yield of CO is used when only half the total oxygen passing over the fire is consumed in the fire. A sliding scale is used for intermediate values.

- Set up the fire simulation settings under SETTINGS>SETTINGS>AIRFLOW>FIRE. These are described in the Ventsim™ user guide but can probably be left as the defaults in most circumstances. This author recommends, however, using an *equivalence shift* ratio of one for most underground fires.
- Set up the dynamic modelling settings under SETTING S>SETTINGS>AIRFLOW>DYNAMIC. These affect how long the computer simulation will take. It is usually best to choose a dynamic increment of about 1 second for the 'first pass' simulation as this increases the speed of the simulation. If desired, this setting can be reduced to 0.2 seconds or even lower for the final pass to produce smooth curves otherwise there may be a somewhat sawtooth effect.
- Estimate the duration of the various stages of the fire and the fuel burn rates at the start and end of each of these stages. The fuel burn rates allow calculation of both the heat release rate and gas production via the gas yields. Some advice has been presented earlier regarding fuel burn rates; however, the estimate is not critical as it is easy to vary both the intensity and duration of the fire, making sensitivity study a straightforward operation.
- Set up one or more fire events in one or more airways. Usually each stage of the fire is an event; with several events in the airway in which the fire occurs to model the progress of the fire. This input screen is also used for other types of dynamic *events* such as preprogrammed changes to regulators or fans (although exactly the same result can be achieved by pausing the simulation and manually making the same changes to the underlying network).
- Add in *monitors* (sensors) at key locations in the mine at which the user wants to examine fire related data. Monitors are automatically added to airways which have fire *events* in them.
- Ensure the SETTINGS>COMPRESSIBLE FLOW and SETTINGS>NATURAL VENTILATION PRESSURE options are selected.
- Run the fire simulation from the main toolbar. A small dialogue box will appear to the side of the screen and the values displayed in the model will start to change in real-time (flow volumes, arrow directions, etc). The dialogue box contains a PAUSE button which, if pressed, causes the simulation to pause so the user can make changes such as changing ventilation controls, stopping or starting fans, etc; the only exclusion is that airways cannot be added or removed from the model at this time. The simulation can then be RESUMED.
- Once the fire simulation is complete (or during it), interrogate any of the monitors for any fire parameter. These provide time-related data in graphical form for the entire simulation and can be exported as a CSV file. Examples of outputs are shown in Figures 4, 5 and 6.

CASE STUDY

Three credible worst-case fire scenarios are identified below. In all cases, the fire suppression systems are assumed to have failed to extinguish the fire.

Fuel bay

The refuelling facility has two fuel bays (light and heavy vehicles) sharing one common entry and has a single RAR at the back (Figure 1). It is assumed the fire occurs on a 17 t LHD and only the LHD burns out, ie that the main diesel fuel bulk tank storage does not catch on fire. This is not a worst case scenario as if the fuel storage is downwind of a major fire, air temperatures could possibly result in the fuel tank catching fire, depending on the design of the tank and its connections and the water suppression systems in place.

The fuel content used for this LHD fire is shown in Table 1.

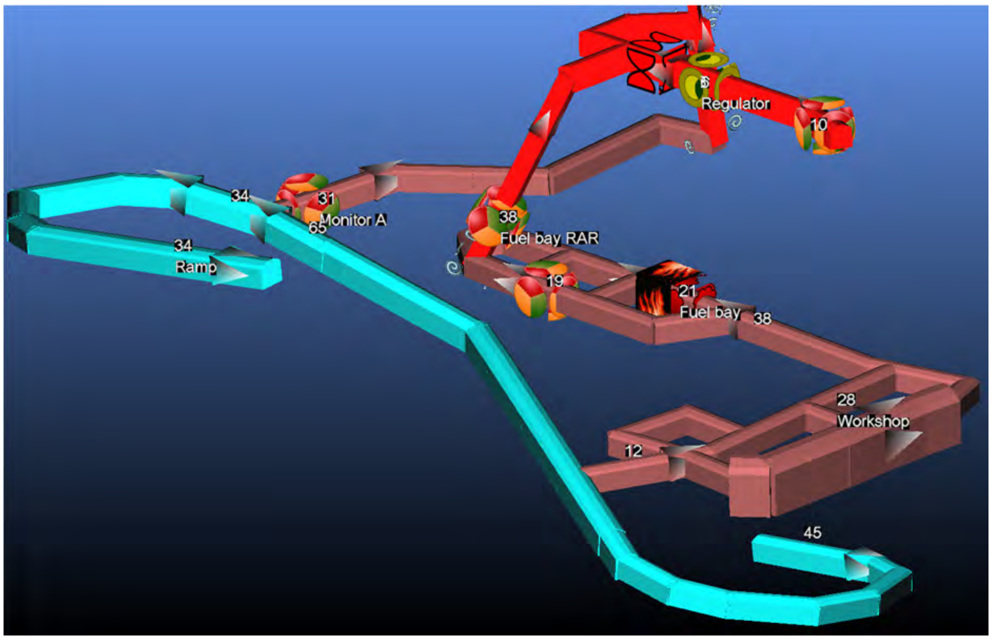

FIG 1 - Fuel bay location and fire. Numbers are original airflows (m^3/s) before fire.

TABLE 1

Heat released when a 17 t payload LHD is burnt (indicative values).

Fuel	Quantity	Calorific value	MJ
Diesel fuel	400 l = 340 kg (≈70% of full tank)	45 MJ/kg	15300 MJ
Hydraulic oil	360 l = 306 kg	45 MJ/kg	13770 MJ
Rubber tyres	550 kg each = 2200 kg (allowing for some wear and non-combustibles in tyre)	32 MJ/kg	70400 MJ
Other plastics and flammable materials	2000 kg (based on 5% of total vehicle tare weight of 40 tonnes)	32 MJ/kg	64000 MJ
Total			163 GJ

This modelling exercise assumes the LHD fire is not fought until at least the period of maximum intensity has passed and the tyres (if present) have been consumed or at least breached and therefore cannot explode. To be conservative (near worst case), it is assumed the fire reaches peak intensity in 30 minutes and 80 per cent of the combustible material for the LHD burns out in the peak intensity phase lasting a further two hours and then to nil over a further five hours. Hence the HRR during the peak phase of the LHD is 163 GJ × 80 per cent/two hours = 18 MW (LHD). These values are conservative compared to the 9 MW used by Hansen (2011) for a Toro 0011 LHD (21 t).

The fire is not approached for 24 hours due to the potential for an explosion on a tyre, unless it is otherwise confirmed that all tyres have burnt through.

Magazine

The magazine has two accesses from a main travelway with a single RAR at the back (Figure 2). There is a connection between the two entries in which the bulk explosives are stored.

The maximum quantity of explosives stored in the magazine and its associated fuel content are shown in Table 2.

TABLE 2

Heat released from explosives magazine.

Fuel	Quantity	Calorific value	MJ
ANFO[a]	40 000 kg	3.750 MJ/kg	150 000 MJ
Detonators	10 000 each	n/a	nil
Ammonium nitrate emulsion	10 000 kg	3.750 MJ/kg	37 500 MJ
Other plastics and flammable materials	Nil	32 MJ/kg	nil
Total			187 GJ

a) ANFO and other ANFO-based explosives are not technically a 'fuel' as they will burn even in the absence of oxygen in air, as ANFO contains all the necessary oxygen for burning. The 'calorific value' in this case is the energy content or 'explosion power' quoted by Orica as being 350 to 400 kJ per 100 g ANFO (Orica, 2004).

For this magazine fire, it is assumed the fire will not be fought until the explosive material has burnt out (so there is no possible risk of detonation impacting on fire fighting crews) and this is likely to be 24 hours. Similar time assumptions are used as for the LHD fire resulting in a peak heat release rate of 187 GJ × 80 per cent/two hours = 20 MW.

Conveyor

The conveyor is inclined and has several open connections at various points to a service drive running along its length (Figure 3). The crusher above the conveyor tail end is fed by an LHD that collects ore from several orepasses, some of which are occasionally partially open. The conveyor catches fire at the head end of the belt.

There are a wide range of underground conveyors and hence conveyor fires. The credible worst case scenario for each needs to be established after review of the individual circumstances. In this particular case, the following was considered to be the worst credible scenario:

- conveyor belt length of 300 m, 2 m wide and 30 kg/m^2. Total weight 36 000 kg.

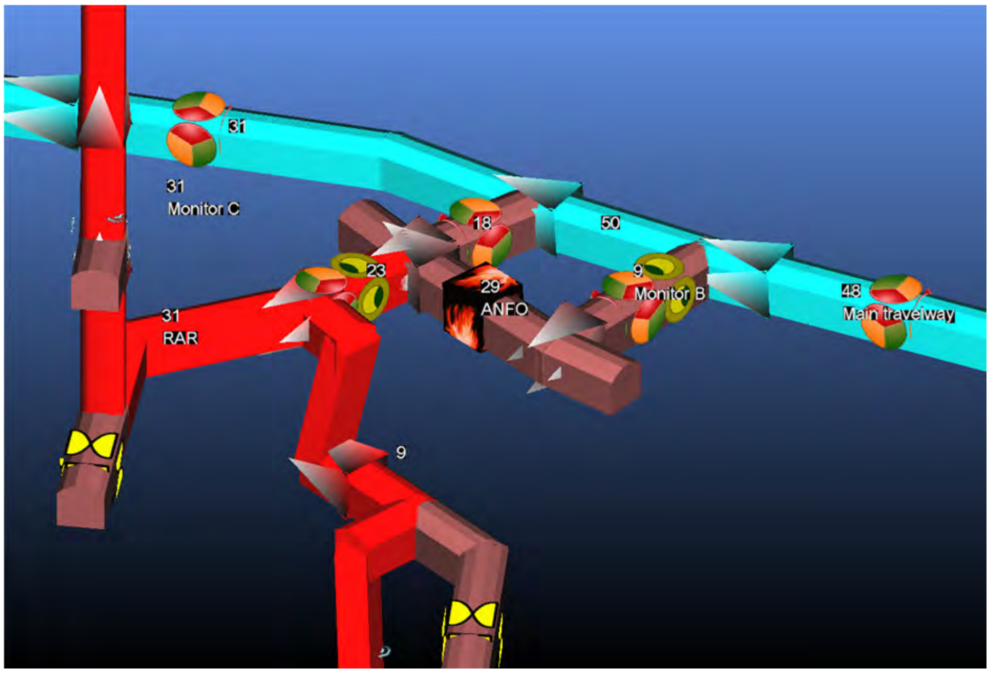

FIG 2 - Magazine location and fire. Numbers are original airflows (m^3/s) before fire.

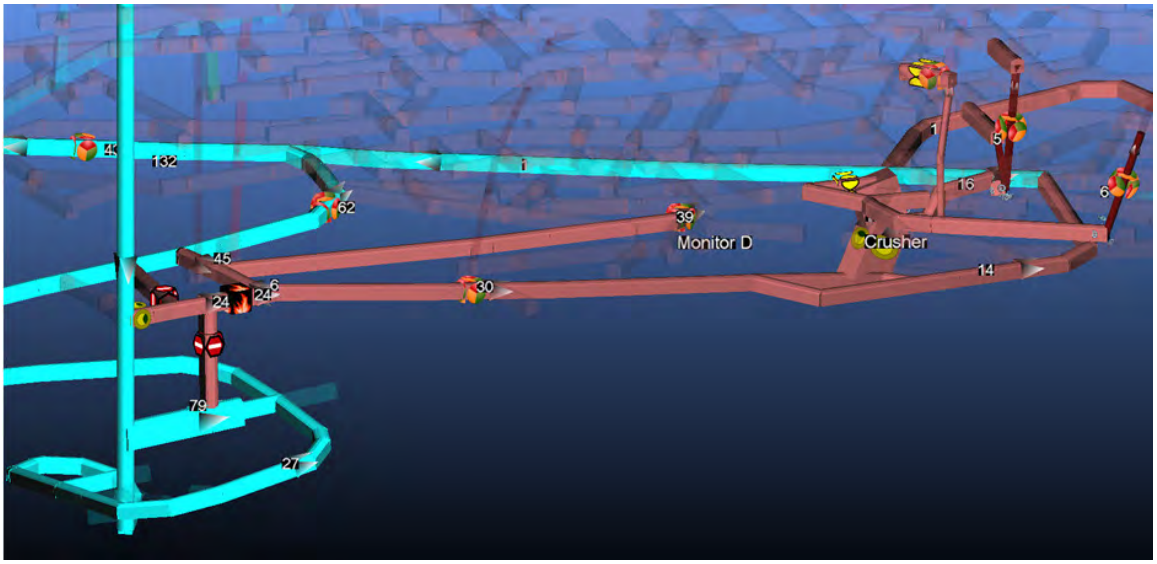

FIG 3 - Conveyor location and fire. Numbers are original airflows (m^3/s) before fire.

- calorific content 23 MJ/kg or total of 828 GJ.
- flame spread rate of 1 m/min. A good discussion of this is provided by Verakis (1991) and also by Perera and Litton (2012) . At 1 m/min spread rate, it would take 300 minutes (five hours) for the entire belt to have caught fire.
- the conveyor belt is empty when on fire. This represents the worst case (fastest) rate of spread of the flame along the belt.

For a fire on a conveyor, it is assumed fire fighting will commence once crews are mobilised and ready. It is assumed this will take two hours. This assumes the fire can be approached from the upwind side, where visibility, toxicity and air temperature will not be quite so critical. Fire fighting commences two hours after the fire starts and is extinguished in six hours.

The peak heat release rate for the conveyor fire is taken to be 11 MW (reached after 30 minutes) based on Lowndes *et al* (2006). This is somewhat higher than the value used by Hansen (2011) of 8 MW. At this rate, the conveyor fire would burn for about 20 hours if not externally extinguished.

RESULTS AND CONCLUSIONS

The results of the case study are discussed below. Whilst these results will not be applicable to all situations, they are certainly 'contra-intuitive' in some respects and indicate that fire modelling should be an important future type of analysis undertaken in hardrock mine ventilation planning and review.

Fire in fuel bay

Closing the fire doors at the entry to the fuel bay will greatly reduce the heat release rate (intensity) of the fire as it partially starves the fire of oxygen. However, if the doors are effective, this reduces the equivalence ratio which greatly increases toxic carbon monoxide levels. It also results in a hotter fire and may trigger downwind fires due to the elevated temperatures or, if the fire becomes significantly fuel-rich, by the transfer of pyrolysed fuel to downwind areas. Closing the doors also significantly extends the duration of the fire, which will increase entrapment times and delay fire fighting assuming the fire is only to be fought during its decay phase. It also runs the risk of producing an explosive 'backdraft'[5] if fire fighters open the fire doors to fight the fire. Closing the doors does, however, reduce the risk of downwind connections into the RAR 'reversing' flow and pushing POCs into other areas.

It should be noted that even if the chosen strategy was to close the fire doors, the doors would need to be a very good seal to have a substantial effect on the fire; as noted earlier, an 18 MW fire only needs about 5 m^3/s of air to sustain itself.

The conclusion, which is probably likely to apply generally, is that fire doors *should not generally be used to reduce the intensity of a fire, but rather to isolate POCs from a fire entering escape routes*.

With the fire doors open, modelling of this scenario also showed that ventilation connections *into* the return air raise *downwind* of the fire (especially those close to the fire), and which are normally open, should be designed to close automatically in the event of a fire otherwise it is possible for the high buoyancy created in the RAR by the fire to push POCs out of the RAR against the normal direction of airflow and contaminate airways that the mine would not expect to be contaminated. The alternative (apart from closing the fire door at the entry to the refuelling bay) would be for any such nearby downwind connection into this RAR system to have its own fan pushing air into the RAR (rather than relying on a regulator), and in the event of a fire in the fuel bay, for that fan to trip and then self-close, preventing POCs leaving the RAR system. It is again likely that these conclusions are applicable to most situations similar to this.

Fire in magazine

The presence of the two short access entries into the magazine off the main travelway, combined with the fixed orifice regulator at the back of the magazine, was found to result in recirculation of the POCs out of the magazine into the travelway, and then into other areas of the mine. Effectively, the expansion of the POCs at the fire location, combined with the bottleneck/throttling created by the regulator and the short distance between the main travelway outside the magazine and the magazine fire, results in POCs backing up into the

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[5] Backdraft is defined by the US NFPA as 'The explosive or rapid burning of heated gases that occurs when oxygen is introduced into a building that has not been properly ventilated and has a depleted supply of oxygen due to fire'

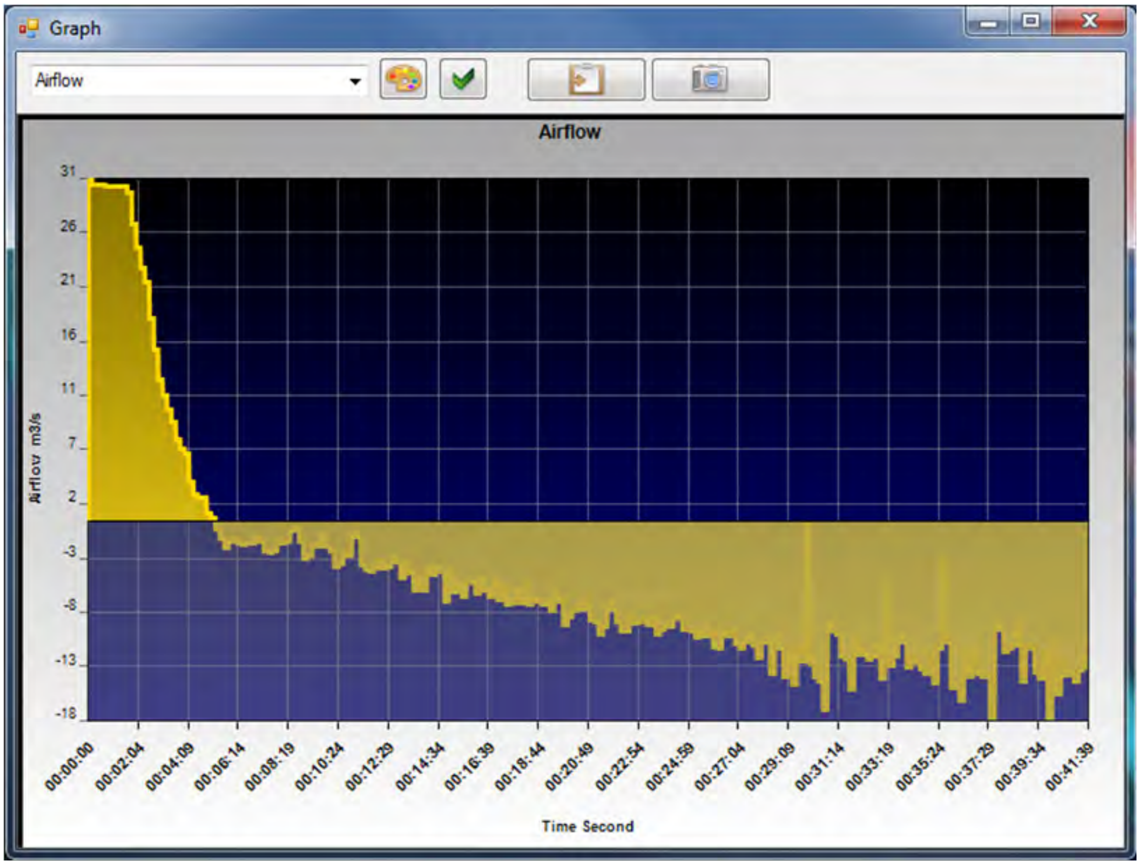

FIG 4 - Fuel bay output data at monitor A showing flow reversal.

FIG 5 - Magazine output data at monitor C showing CO.

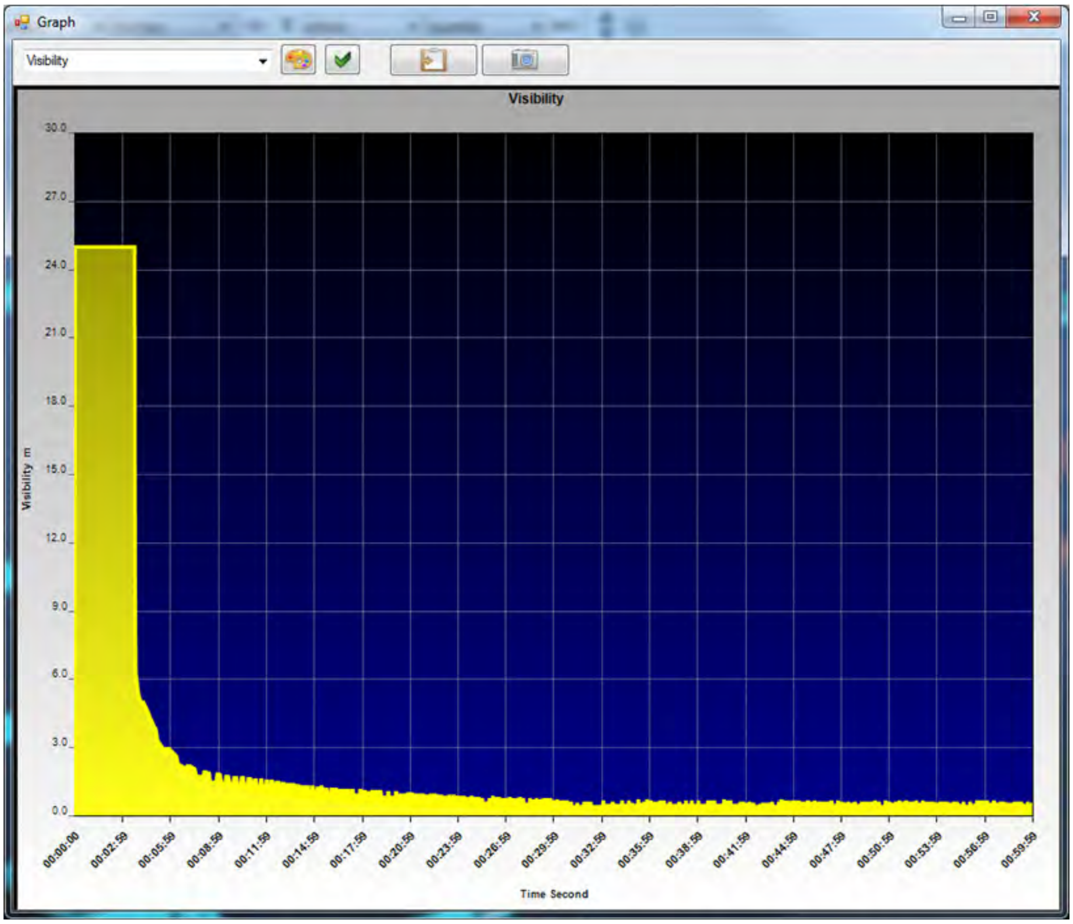

FIG 6 - Conveyor output data at monitor D showing visibility (reduces to about 4 m after four minutes and 1 m after 15 minutes).

travelway and actually circulating around the magazine via the common portion of travelway. In reality, this scenario would also be a likely candidate for rollback of POCs into the travelway, even if an access did not fully reverse.

Solutions to this problem would be either to have one fire door to the magazine close at the start of the fire (allowing air to only enter the magazine via the other door and then to the exhaust), or to open the regulator at the back of the magazine to ensure both magazine entries incast (assuming this will result in sufficient airflow through the magazine to stop it outcasting to the main travelway). The best access door to close would be the one that maintains airflow over the fire. This is also likely to be a general conclusion for intense fires in an area which has two entries off a shared airway.

Fire in conveyor

The main problems with the conveyor fire stem from:

the numerous open connections into the conveyor drive from the adjacent semi-parallel service drive for access and maintenance, some of which are very high or wide and all of which have no ventilation controls

the descentional nature of the ventilation in the conveyor ramp aggravates the problems of NVP produced by the fire resulting in fluctuating airflow conditions in the conveyor ramp

- the proximity of the conveyor to the shaft bottom, given the shaft is a major fresh air source for the operation

the location of the LHD tramming route directly above the crusher (feeding the crusher from various locations) and the potentially open passes above the crusher, resulted in POCs significantly impacting on the mine

- rapid loss of visibility downwind of the conveyor fire affecting potential egress options.

Apart from reinforcing the critical importance of fire prevention and suppression systems for conveyors, this modelling reinforced that it is highly desirable for conveyors to be set up in their own self-contained ventilation district that can be isolated in the event of a significant fire. It would also suggest that ascentional ventilation for a conveyor with an exhaust near the high point of the conveyor is preferable to the descentional system used here.

General observations

In some cases, the NVP produced by the fire results in choking to the point where further development of the fire is oxygen-constrained; however, not enough NVP may be produced to actually reverse the flow over the fire.

Where a fire does reverse direction, the low oxygen content of the POCs now being drawn back over the fire decreases the heat output from the fire which reduces the NVP that the fire is producing. In some cases, this loss of NVP causes the flow over the fire to revert to its original direction. However, in certain circumstances an unstable situation may develop where the airflow reverses back and forth. In practice, rollback could potentially develop in such a scenario drawing fresh air to the fire and potentially restarting the sequence.

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