Practical prediction of blast fume clearance and workplace re-entry times in development headings.

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ABSTRACT: Re-entry into blast fume affected underground areas is a safety and productivity concern for most mines. Lengthy re-entry times may improve clearance of noxious gases, but can result in production delays and decreased overall productivity. Re-entry times into development headings are often standardized based on worst case scenarios, resulting in unnecessary delays. Fume clearance from blast areas can be mathematically estimated using a number of different methods however a complicating factor of fume clearance is considering the volume, efficiency and discharge location of fresh air ducts required to clear development blast areas. This paper proposes a modification to an existing well know method of fume clearance calculation to account for vent duct flow clearance and dilution efficiency. Finally, the paper considers how such an algorithm may be incorporated into modelling software.

1 INTRODUCTION

1.1 *Mine Development & Blasting*

Blasting with explosives is an essential activity for developing tunnels in most underground hard rock mines, however the process introduces a number of hazards that must be controlled to ensure a safe work environment. A major consideration is the release and removal of noxious gases from the mine before the re-entry of workers to areas that may be affected by blasting fumes.

Traditional methods of estimating blast fume dispersal can provide accurate indications of clearance times if carefully calibrated to mine conditions; however these tools are rarely used systematically with blasting activities due to the wide range of variations in ventilation and blasting conditions.

In addition, the traditional calculation methods provide a limited platform for calculating mine wide fume dispersal, where mixing of airflows and dilution limit the use of fume concentration calculations.

1.2 *Explosive Quantities*

Unless specialized properties are required, ANFO (Ammonium Nitrate Fuel Oil) is the predominant explosive used for development blasting due to price and performance characteristics.

Typical explosive quantities used in development headings vary according to rock type and blast practices however powder factors in development rounds typical from 0.6kg to 1.2kg ANFO per tonne of rock blasted.

Larger headings tend to have lower powder factors due to the smaller relative proportion of the high intensity blast in the initial confined center of the development face.

Table 1. ANFO Properties

Ammonium Nitrate	94%
Fuel Oil	6%
Density (unpacked)	820 kg/m3
Gas Volume	1.08 m3/kg (at 25^0C)

A typical heading size of 5m wide x 5m high, 3.5m deep and with a rock density of 2700 kg/m3, would therefore be expected to use approximately 150kg to 250kg of explosives, depending on rock type and fragmentation required.

ANFO explosive gas composition can vary significantly based on moisture content and fuel oil percentage. In addition to complete combustion gases of Nitrogen (N2), Carbon Dioxide (CO2) and water (H2O), ANFO (Ammonium Nitrate with 6.0% fuel oil) will produce the following additional noxious gases on detonation.

Table 2. ANFO Explosive Noxious Gas Composition

Noxious Gases	Gas Yield	Conc.	Gas Density
	l/kg ANFO	ppm	kg/m3
NO2	1.8	1667	2.62
NOx (inc. NO2)	3.5	3241	< 2.62
CO	16.0	14815	1.15
NH3	0.4	370	0.73

Fuel oil percentages less than 6% will produce less Carbon Monoxide (CO) but higher Oxides of Nitrogen (NOx), while higher fuel oil percentages will increase CO yield and decrease NOx yield.

Atmospheric mixed gas compositions will be substantially less than shown in table 2, due to the phenomenon of 'throwback', where the detonation of explosives will cause a discharge of blasted material and gases into the atmosphere well back from the blasted face.

1.3 *Explosive Gas Exposure Limits*

Many documented cases exist of mine worker injuries or fatalities from exposure to explosive fumes. In the Revenue-Virginius mine in Colorado in November 2013, 20 miners were exposed to what is believed to be carbon monoxide from recent blasting, result in two fatalities.

Re-entry into work areas too soon after blasting, or inadequate ventilation can lead to fatal exposure to poisonous gases. The three main gases of immediate concern to human life are the oxides of Nitrogen (NOx / NO2), Carbon Monoxide (CO), and Ammonia (NH3).

At typical explosive gas yields rates, NO2 theoretically has the greatest danger to life. Exposure to high levels of NO2 causes blistering in lungs and ultimately potentially fatal pulmonary oedema can develop from fluid buildup in the lungs. However NO2 is an irritant asphyxiant gas which causes intense irritation to the eyes and respiratory passages, and is normally easily detectable at up to 40 times lower than exposure standards, reducing the chance of accidental exposure (although higher concentrations >4ppm can anesthetize the nose making detection more difficult). NO2 is also a dense gas and brown in color. In the absence of ventilation it will often accumulate near the floor or in low hollows.

Carbon Monoxide is a colorless, odorless gas that, while having lower toxic explosive yield emission than NO2 from blasting, is arguably a greater threat to life due to the increased chance of accidental exposure, particularly in poorly ventilated areas. It mixes better with the atmosphere at normal exposure heights, and can be retained within broken muck piles long after the blast. Most injuries and fatalities from exposure to explosive gases cite carbon monoxide as the prime cause of poisoning.

Ammonia can also cause harm through overexposure, however the yield of this gas is much lower than both NO2 and CO and is easily identified and normally avoided through smell.

Table 3. Explosive Gas Exposure Limits

Noxious Gases	TWA*	STEL*	IDLH*
	ppm	ppm	ppm
NO2	3	5	20
CO	25-35	100	1200
NH3	25	35	300

* TWA – Time Weighted Average
STEL – Short Term Exposure Limit
IDLH – Immediate Danger to Life and Health.

2 GAS CLEARANCE TIME ESTIMATION

2.1 *Methodology of Gas Data Recording*

A number of development headings at the host mine (15 in total) were measured for gas during and after blasting to help understand the potential variance in gas concentrations and clearance times.

The gas data logging handheld monitors (2 Draeger XAM 7000 and 3 Industrial Scientific iBrid MX6 units) were left at a safe distance of 50m – 100m from the face, and collected after the blast.

Carbon Monoxide was the measured gas and was used in the analysis of the estimation method, however other gases such as NO2 or NOx could also have been used. The measured results showed a wide range of maximum concentrations and clearance times, highlighting the problem of estimating theoretical clearance times.

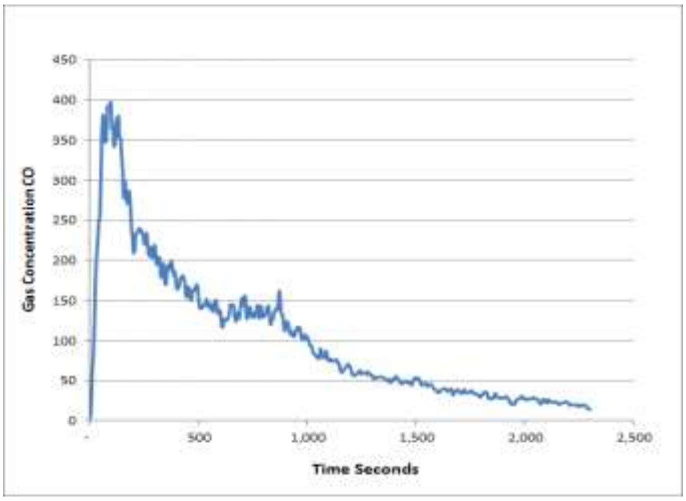

Figure 1. Graph showing a typical gas monitor data log. Results varied widely between faces due vent duct placement, airflow quantity and duct discharge velocity and direction.

The main observed variation factor was the position and velocity of fresh air from the duct. There was also considerable variation when the fans were resumed after blasting (to protect duct).

Due to the limited number of gas recordings available, no attempt was made to quantify and statistically validate the cause of the variations.

2.2 *Methods of Calculating Theoretical Clearance Time*

A number of methods are available to estimate concentration and clearance times from underground blasting. In most cases a variation of a mathematical logarithmic decay series is the basis behind estimations. The data collected from gas sampling strongly supports this methodology.

De Souza, Katsabanis, Roberts and Heidrich (1991) proposed a logarithmic decay method incorporating dispersion factors for distance away from the face. Gillies, Wu, Shires (2004) proposed modified logarithmic constants to improve correlation. Agasty, Clausen, Kellner and Langefeld (2013) proposed computational fluid dynamics (CFD) to solve and analyse the problem.

All methods have significant merit and can closely represent the dilution behavior of blast gases, but can be difficult for the site engineer to calibrate to local mine conditions. This paper will focus on the use of one of the more traditional approaches using a blast throwback approach.

2.2.1 *Throwback Method*

A simple and well-documented method appearing in many texts is to calculate the theoretical blast throwback distance from the development face, and then use a log natural decay series to estimate the reduction in gas concentration over time. The blast throwback is the distance the blast material and gas expands (throws back) and contaminates the atmosphere immediately after the blast.

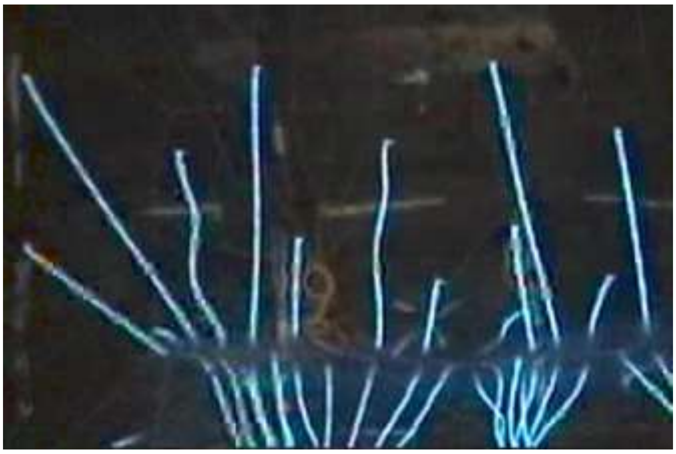

Figure 1. Initiation of an underground development blast video (nonel tubes sending blast signals to detonators)

Figure 2. Subsequent throwback of gases and rock material during the underground development blast (video).

A number of simplified assumptions are made for the throwback method;

- The throwback volume is assumed to be uniformly mixed with blast gases.
- A flow rate of fresh air is then assumed to mix evenly with the contaminated volume, diluting the gas uniformly over time. Fume throwback length L can be estimated from the equation;

$$L = \frac{KM}{FaD\sqrt{A}} \tag{1}$$

Where: L = Length of fume throw back (m), K = Constant (usually 25), M = Mass of explosives used (kg), Fa = Face advance (m), D = Density of rock (t/m3) and A = Area of face (m2)

The time t taken for gas to disperse to a defined level can be defined using;

$$t = \frac{V}{Q} \ln\left(\frac{Gc}{Gt}\right) \tag{2}$$

Where: t = Time to achieve target concentration (s), V = Volume of gas filled space (m3), Q = Flow rate of fresh air (m3/s), Gc = Initial gas concentration (ppm), Gt = Gas concentration at time t (ppm)

If the initial gas concentration (Gc) of the throwback region is unknown it can be calculated from the diluted theoretical gas yield of the explosive product as follows;

$$Go = \frac{1000\, y_{gas}}{y_{anfo}} \tag{3}$$

Where: G_o = Initial undiluted (no throwback) gas concentration. y_{gas} = yield rate of noxious gas (l/kg explosive), y_{anfo} = total gas yield of explosive (m3/kg)

$$Gc = \frac{M \times y_{anfo}}{V} \times Go \tag{4}$$

To estimate gas concentration *Gt* at any specific time after the blast, equation (2) can be rearranged as;

$$Gt = \frac{Gc}{Exp\left(\frac{tQ}{V}\right)} \tag{5}$$

2.3 *Estimation Errors*

The application of theoretical formulas to estimate gas concentration and clearance time often shows a poor correlation to actual gas readings.

In many cases the main source of correlation error is the efficiency of the fresh air from the duct in penetrating the full throwback blast zone. Coupled with the potential lack of uniformity in the concentration of the throwback gas cloud (with higher concentrations more likely at the face), the potential for estimation error increases.

If the duct is discharging some distance from the face (even if the duct discharge is within the throwback zone), only a portion of the supplied fresh air will reach into the region close to the face, resulting in lesser amounts of cleared gas, and longer clearance times.

3 A CALIBRATED APPROACH

3.1 *Defining a calibration factor*

To improve correlation with recorded results, it is advantageous to consider the delivery flow of fresh air from a duct into the heading (which can be easily measured) separate to the portion of the flow that effectively clears the gas (which cannot be easily measured). Assuming we treat flow Q as the full discharge flow from the duct, the equations in section 2 can be modified to account for observed differences by applying a calibration or 'dilution efficiency factor'.

3.1.1 *Goals for a calibrated method*

To achieve improved correlation with actual results, and to provide a useful tool for mine wide simulation, some key requirements must be met;

- Easy calibration to actual blast conditions measured in a mine, to account for the dilution efficiency of duct air at the face.
- Volumetric and mass balance of explosive gas products released into the mine atmosphere must be preserved.
- The ability to incorporate into mine ventilation simulation software using dynamic (transient) simulation methods.

3.1.2 *A Factored Solution*

Clearance times and concentrations will change significantly based on the proximity of the fresh air duct from the blast face and how this duct is directed into the heading. The fresh airflow must penetrate the explosive gas region and 'scavenge' the blast gases at the face, carrying the gases in the return air stream.

This scavenging behavior is a complex 3D flow dynamics problem depending on many factors and prediction would require complex computational fluid dynamics (CFD) methods or extensive empirical data. However the aim in this case is to only calibrate this behavior to produce a reasonable basis for predicting future blast activities with similar ventilation configurations at the mine.

A dilution efficiency factor (f_d) can be considered by modifying equation 2, 4 and 5 as follows;

$$t = \frac{V}{Q \times f_d} \ln\left(\frac{Gc}{Gt}\right) \tag{2a}$$

$$Gc = \frac{M \times y_{anfo}}{V} \times Go \times f_d \tag{4a}$$

$$Gt = \frac{Gc}{Exp\left(\frac{t \times Q \times f_d}{V}\right)} \tag{5a}$$

Where: f_d= dilution efficiency factor

If the initial gas concentration (Gc) and any future concentration (Gt) at time (t) are known, equation (2a) can be rearranged such that any point along the data logged curve can be used to calculate the dilution efficiency factor;

$$f_d = \frac{V \times \ln\left(\frac{Gc}{Gt}\right)}{t \times Q} \tag{6}$$

The best estimate of the dilution efficiency factor will occur if a point is near the center of the curve (where concentration is 50% of maximum).

3.2 *Worked Data Example*

An example blast was selected for calibration. Approximately 220kg of explosive was fired at 5m x 5m x 3.5m deep development heading.

3.2.1 *Gas data collection*

The gas monitor was placed near a junction approximately 60m from the face. A 1070mm duct supplied approximately 20m3/s of air to within 35m of the face. Large tears were observed at several locations along the vent duct between the monitor and the face.

This location was chosen due to consistent data collection quality that was not affected by blasting in other nearby headings. Some other locations measured were found to be contaminated with gases from upstream blasts. On other occasions there were lengthy delays in turning the ventilating fans on which affected data quality.

3.2.2 *Measured Results*

Shortly after firing, the data logging gas detector quickly rose to a maximum of 448ppm from the face, reducing to 83.73ppm after 600 seconds.

3.2.3 *Calculations*

The throwback length L can be calculated from equation 1.

$$L = \frac{25 \times 220}{3.5 \times 2.7 \times \sqrt{25}} = 116.4\ m$$

The throwback volume V = 116 x 25 = 2806 m^3

The dilution efficiency factor f_d can be calculated from equation 6.

$$f_d = \frac{2806 \times \ln\left(\frac{448}{83.73}\right)}{600 \times 20} = 0.392\ or\ 39\%$$

A corrected concentration graph can now be calculated from equation 5a. Figure 3 shows a graph of the actual measured data, the uncalibrated curve, and the calibrated result using the dilution efficiency factor. As expected, the calibrated curve closely matches the actual results.

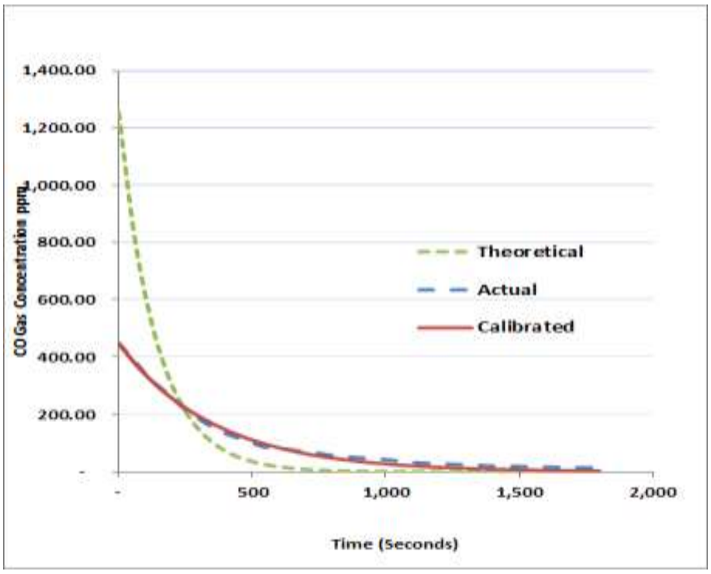

Figure 3. CO Gas comparison of measured concentrations, uncalibrated calculations, and calibrated calculations.

3.2.4 *Summary of Example Results*

The calculated results were compared again to actual data. The calculated gas concentration at 5 minutes from equation 5a is calculated;

$$Gt = \frac{448}{Exp\left(\frac{300 \times 20 \times 0.392}{2806}\right)} = 181\ ppm\ CO$$

- The five minute concentration compares well at 181pm calculated vs 185ppm measured.
- The 15 minute sample shows some variation with 29ppm calculated versus 39 ppm measured, however this is accounted by a background mine concentration of 10ppm CO.

The calculated line shows that while the theoretical estimation based on the un-factored throwback formula is not accurate, the calibrated curve using the dilution efficiency factor shows a very close match to the measured data.

If contaminants are already part of the fresh air stream (from upstream blasting for example), then the new concentration Gt can be added to existing fresh air contaminant levels in the airflow providing the relative portions of the contaminant gas are small compared to the overall airflow.

As a final check, total CO gas volumes were calculated using actual data, estimated CO gas volume from ANFO mass (@16 l/kg), and theoretical calculation from the above equations.

- Measured CO gas volume = 3900 litres
- Theoretical Explosive Volume = 3520 litres
- Calibrate Calculated Volume = 3480 litres

Given limited accuracy in airflow estimations and ANFO mass, the differences are negligible and support the factored method of gas clearance estimation. The difference between measured and theoretical can be attributed to background levels of approximately 10pmm from other areas of the mine (approximately 540 litres over the measured time intervals).

3.3 *Practical Gas Concentration Prediction*

Provided basic parameters such as explosive mass and the quantity of ventilating fresh air are known, the only factor required to predict gas levels is the dilution efficiency factor.

3.3.1 *Estimating the Dilution Efficiency Factor*

Since this factor is an indication of the efficiency of the airflow in clearing the gas from the area we must consider the configuration and location of the airflow into the heading. From a practical perspective, a factor of 100% indicates the duct airflow will initially push the maximum concentration contained in the throwback volume, while lesser amounts indicate penetration of the fresh air flow into the gas zone is less efficient, and hence will result in decreased clearing efficiency and longer clearance times.

It is important to note that the dilution efficiency factor is independent of the amount of airflow quantity from the duct. It is the efficiency of whatever air is available to clear the gas. On several tests where the fan was not turned on, the clearance factor was still recorded at over 90% due to slow but efficient natural diffusion of air.

It is just as important to note however that while the dilution factor may not change, the actual clearance times are still dependent on the quantity of clearing airflow. In the measured examples the blast headings without ventilating flow took many hours to clear.

It is proposed that mines could develop their own set of a dilution efficiency factors based on observed differences in measured data. While the amount of airflow from the duct does not theoretically impact the estimation of a dilution efficiency factor, the amount of air leaking from the duct between the detector and the face is important. Duct leakage lowers the dilution efficiency factor because a portion of the duct air is no longer available to clear the fumes.

An example demonstrating one approach to dilution efficiency factor estimation could be as simple as the table 4 shown below which sets different factors based on the distance of the duct from the face. Other factors such as velocity of air from the duct may also need to be empirically considered if gas testing at the mine indicates it is important.

Unfortunately there was not enough quality data in this study to offer further recommendation on factors to use, however it is expected most mines could fairly easily establish factors to suit their ventilation practices. The measured data set gathered for this study, showed clearance factors typically ranging from 30-40% for headings with duct 35m from the face in fair condition.

Table 4. Example Dilution Efficiency Factors *

Vent Duct Distance To Face	Dilution Efficiency Factor, Duct Condition: Good	Average	Poor
10m	85%	75%	65%
15m	78%	70%	58%
20m	70%	62%	50%
30m	50%	42%	34%
40m	34%	26%	20%
50m	25%	18%	15%

*Example only – do not use. These figures are highly dependent on mine ventilation and duct practices. This table shows one approach to utilizing empirical data results to predicting future clearance times.

One heading measured with duct much closer to the face showed over 80% efficiency. In fact in theory, if the duct was place at the face with even distribution of air pushing back the fumes as a 'plug', or the blast occurred in a flow through ventilated area, an efficiency of 100% could be assumed.

3.4 *Using different factors*

To calculate a concentration versus time curse based at a (for example) 50% dilution efficiency factor, the following process can be used.

Assuming the same physicals as the previous example, equation 4a can be used to estimate the initial gas concentration before throwback dilution.

$$Go = \frac{1000 \times 16}{1.08} = 14814 \ ppm\ CO$$

From the undiluted concentration, the throwback concentration (and hence the initial clearing concentration from the heading) can be calculated.

$$Gc = \frac{220 \times 1.08}{2806} \times 14814 \times 0.5 = 627 \ ppm\ CO$$

Now that the initial blast clearance concentration is calculated, the concentration of gas from the face any time after the blast can be calculated from equation 5a. For example, the gas concentration from the face at time = 10 minutes (600 seconds) is.

$$Gt = \frac{627}{Exp\left(\frac{600 \times 20 \times 0.5}{2806}\right)} = 74 \ ppm\ CO$$

The time for gases to dilute to a safe level of 25 ppm* at the face can be calculated from equation 2a.

$$t = \frac{2806}{20 \times 0.5} \ \ln\left(\frac{627}{25}\right) = 904s \quad or \quad 15 \text{ min}$$

*Note: CO gas at 25ppm may not be the limiting re-entry consideration as NOx may have a higher TWA risk.

4 APPLICATION TO MINE NETWORK SIMULATION

Blasting gas concentration estimation methods in mine wide ventilation network simulation is potentially very useful. By combining the results of one or more blast locations, the concentration and travel time of fumes through an entire mine can be predicted, and re-entry times can be estimated, not only for individual headings, but for mine regions.

4.1.1 *Mine Wide Re-entry Times*

The complex interactions between multiple headings in the same ventilation stream and the dilution of gases through the remainder of the mine is an important consideration for re-entry time.

While the re-entry time for a specific heading (for example) may only be 15 minutes, if the same gases from the cleared heading travel through other travelways in the mine, the actual re-entry time to access the area may be much greater.

4.1.2 *Gas Transport and Mixing*

The movement of gas throughout a mine can be a complex predictive process. The physical processes of gas diffusion, layering, imperfect mixing at junctions, and boundary drag can all have an impact on accurate prediction of gas movement. De Souza (1991) suggests using a diffusion factor to spread and dilute gas concentrations over distance travelled. However, for large mine wide network models such factors add significant complexity to a simulation, and may not necessarily add significant value in terms of providing a tool to improve ventilation.

Therefore, for large scale mine wide prediction of gas transport can be simplified by assuming linear gas movement at average flow velocities, no diffusion of gas once it has left the blast area, and complete homogenous mixing at junctions of airflow. The time to travel along any airway in the mine assuming constant cross sectional area is;

$$t = \frac{L}{v} \quad or \quad t = \frac{L \times A}{Q} \tag{10}$$

Where: t = time to travel the length of airway (s), L = length of airway (m), v = velocity of airflow (m/s), A = cross sectional area of airway (m2), Q = airflow quantity of air (m3/s)

Where two airways meet at a junction or 'node', the gas compositions of the two airflows can be mixed homogeneously as a weighted average and (assuming perfect mixing) the newly calculated mixture can be predicted downstream from the junction as follows.

$$Gm = \frac{\sum (G_{1..n} \times Q_{1..n})}{\sum Q_{1..n}} \tag{11}$$

Where: Gm= mixed airflow gas concentration, $Q_{1..n}$ = Flows into junction from connecting airways, $G_{1..n}$ = Concentrations of gas into junction from connecting airways.

4.1.3 *A Mine Network Simulation Method*

To calculate changing gas concentrations within a ventilation simulation network, a transient or dynamic form of simulation method is needed to transport gas and predict concentrations in all parts of the model at any time.

Gas movements can be calculated assuming the network simulator has first correctly balanced the ventilation network such that;

- all airflows are calculated and balanced so that the airflows into each junction are equal to the airflows from the junction, and;
- average airflow velocities are available or can be derived from airflow and airway size.

4.1.4 *Discrete Cell Transport*

A method (used by Ventsim Visual™) is discrete cell transport. This method divides each airway up into multiple cells containing individual information about the gas concentrations at that point in the airway. Fresh air flow into blind headings is carried by ducts modelled as separate small airways. The throwback volume of blast fume is assumed to be a point source of gas fumes that is fed at the calculated concentrations into the returning fresh air flow. The method works as follows;

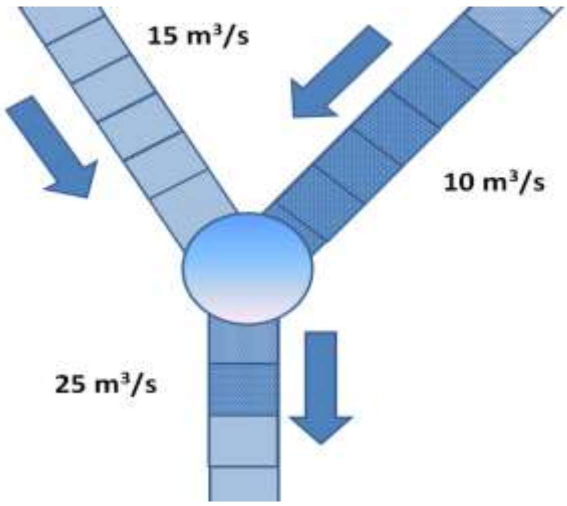

Figure 5. Discrete cell method of flow transport and mixing.

- The cells are shuffled in position along the airway at a time based on the average airflow velocity described in equation (10).
- As cells exit the airway, the junction node collects the cell concentration and flow rate information.
- New cells enter the airway from the entry end. The concentration contained in the new cells is based on the volume weighted average concentration entering the junction from other airway cells (as per equation 11).
- The cells which travel through the explosive clearance area has gas added using concentrations defined by equation 5(a). This can be done using simple addition assuming relatively small concentrations; a mass balance method may need to be used for higher concentrations.
- The simulation continues until the explosive clearing concentration has fallen below threshold levels and gas levels in the remainder of the mine have decreased to acceptable levels.
- Data can be recorded over time at specified locations in the model, to display after the simulation completion as a graph.

- If gas diffusion needs to be considered, a portion of the gas can be withheld between each cell movement based on length travelled.

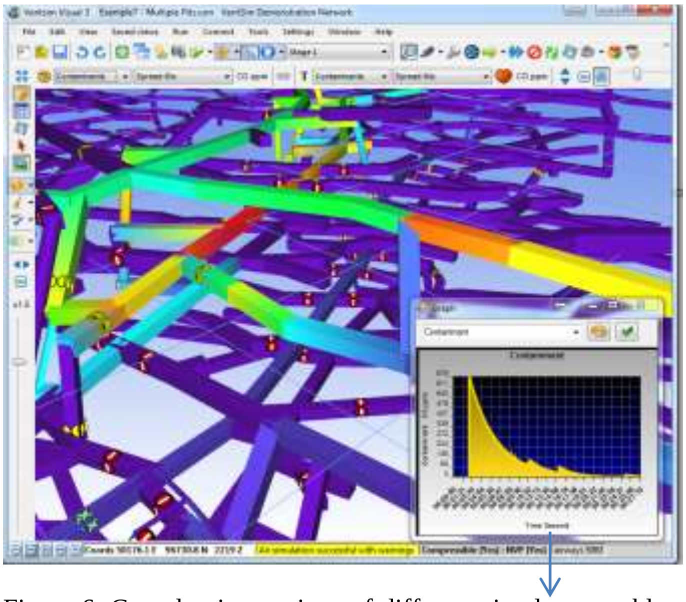

Figure 6. Complex interactions of different simultaneous blast locations and clearance time modelled in Ventsim Visual.

4.2 *Improving Clearance Times using Simulation*

It is not suggested that simulation methods be used for all blasting in a mine. Nor is it reasonable to suggest that simulation alone should be used to predict safe re-entry times. Re-entry formulas and simulation models can never replace safe work practices and measurement of gas in risky atmospheres.

Much of the blast gas dispersion and clearance time results will be an inevitable consequence of the mine ventilation design. Therefore, it is valuable to use ventilation network simulation as a tool to improve ventilation design, so that gas clearance and re-entry times can be improved. A good simulation model can also demonstrate the presence of recirculation which is a common factor in mines that experience lengthy blast fume clearance times.

Increasing airflows, preventing recirculation, diverting gases away from re-entry pathways and sequencing blasting activities to limit higher gas buildups are all valid design approaches to removing blasting fumes and improving re-entry times.

By simulating design vent circuits and testing a variety of possible blasting scenarios, a benchmark of clearance times can be established and other design options can be considered which may reduce clearance times or improve access into the areas. In addition, temporary solutions such as short-term changing of ventilation controls like regulators can also be examined for effectiveness.

5 CONCLUSION

The wide variation observed in blast fume monitoring results precludes the recommendation of fume clearance formulas as a single tool to calculate safe and accurate re-entry times. There are too many variables to consider and too greater chance of unforeseen changes occurring with the blasting process and the ventilation circuit.

Standard re-entry procedures and gas detection and monitoring will remain important parts of safe blast fume management. However calibration and prediction of typical blast fume clearance from typical headings can give greater certainty to re-entry time procedures and can help build confidence in the performance of the ventilation circuit. It can also assist in identifying poor ventilation or blasting practices occurring at the mine which may result in longer clearance times.

Of most practical use however, is the ability to use calibrated blast fume clearance formulas in mine wide simulation, where fumes concentration in many areas can be simultaneously observed over time. Even if the clearance rates fail to accurately describe every blast, the relative merits of different ventilation designs can be assessed against each other.

The simulation results can be used to benchmark and improve ventilation design, and potentially reduce the downtime and lost productivity that occurs when blast fumes are poorly ventilated from the mine.

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