ISSUES IN USE OF INERTISATION OF FIRES IN AUSTRALIAN MINES

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ABSTRACT

An ACARP funded research project has been examining use and potential applications of inertisation within the Australian coal mining industry.

The project has reviewed the variety of inertisation system available in Australia and their technical specifications. Particular attention has been given to the GAG, Mine Shield, Tomlinson and Floxel approaches.

Exercises which involved "evaluation or auditing" of selected mines as to the ability to deliver inert gases generated from GAG units to high priority underground fire locations have been undertaken in a number of mines. These exercises have been built around the use of the fire simulation computer program "Ventgraph" and modelling of fire scenarios in selected different mine layouts. A coding system has been developed from these audit exercises.

Designs have been developed of high pressure/compressor fans to allow delivery of high volumes of inert gases down "emergency drilled" mine bore holes of 200 to 3,000mm diameter. Information about available borehole sizes has been gathered from drilling contractors. Various tables have been developed relating borehole diameter and depth, fan compressor pressure and inertisation unit output.

Inertisation and dilution issues in Mains headings are examined. Mains headings present a complex ventilation network with often numerous parallel headings, hundreds of cut-throughs and a variety of ventilation control devices. In such a complex system (with additional interference from a fire), maintaining control of the movement of inert gas is more difficult than elsewhere in the mine. Some illustrations of this issue are given.

Mine fires and heatings are recognised across the world as a major hazard issue. New approaches allowing improvement in understanding their use of inertisation techniques have been examined. The outcome of the project is that the mining industry is in an improved position in their understanding of mine fires, use of inertisation and the use of modern advances to preplan for the handling of possible emergency incidents.

INTRODUCTION

The primary objective of the study is to use mine fire simulation software to gain better understanding of how inertisation approaches such as Engine Exhausts, Nitrogen, Carbon Dioxide, Pressure Swing Adsorption and Tomlinson Boiler units can interact with the complex ventilation behaviour underground during a substantial fire. Inertisation systems for handling underground fires, spontaneous combustion heatings and elimination of the potential explosibility of newly sealed goafs have been accepted as important safety approaches within the many parts of the international industry. Examples of the recent use of inertisation systems to assist in stabilising mine fire situations are given.

Case studies have been developed to examine usage of inertisation tools and particularly application of the Polish developed jet engine unit, the Gorniczy Agregat Gasniczy (GAG). Gorniczy Agregat Gasniczy loosely translates to Mine Fire Extinguisher. Considerations for selecting the best surface portal location placement for the inertisation unit for most efficient suppression of a fire have been examined. Introduction of inert gases can present difficult emergency management decision making. Should the main mine fans be turned off to reduce dilution of the inert gas, or will this action cause, in conjunction with fire induced buoyancy effects, airflow reversal and the drawing of combustion products or seam gases across a fire leading to an explosion?

The possibility of a wider and proactive application of GAG in Australian mines responding to or recovering from mine fires or spontaneous combustion heatings or elimination of the potential explosibility of newly sealed goafs is examined. The primary focus here is on systems involving delivery of GAG exhaust through docking to surface boreholes connecting into underground workings. Attainable designs for panel boreholes and how GAG docking to boreholes can improve delivery of GAG exhaust are discussed.

Mains headings present a complex ventilation network with often numerous parallel headings, hundreds of cut-throughs and a variety of ventilation control devices. In such a complex system (with additional interference from a fire), maintaining control of the movement of inert gas is more difficult than elsewhere in the mine. Some illustrations of this issue are given.

Simulation software has the great advantage that underground mine fire scenarios can be analysed and visualized. A number of fire simulation packages have been developed to allow numerical modelling of mine fires (such as Greuer, 1984; Stefanov et al, 1984; Deliac et al, 1985, Greuer, 1988; Dziurzy ski, Tracz, and Trutwin, 1988). Details of the Ventgraph program have been described by Trutwin, Dziurzynski and Tracz (1992). The software provides a dynamic representation of a fire's progress in real time and utilizes a colour-graphic visualization of the spread of combustion products, O_2 and temperature throughout the ventilation system. During the simulation session the user can interact with the ventilation system (eg, hang brattice or check curtains, breach stoppings, introduce inert gases and change fan characteristics). These changes can be simulated quickly allowing for the testing of various fire control and suppression strategies. Validation studies on Ventgraph have been performed using data gathered from a real mine fire as undertaken by Wala, et al (1995). Wu, Gillies and Wala (2004) examined application of fire simulation to modern Australian mines. Gillies, Wala and Wu (2005) examined some aspects of understanding use of inertisation through use of Ventgraph simulation.

The paper examines the effects of fires and introduced inertisation on mine ventilation systems using numerical fire simulation software “Ventgraph”. Various case studies based on the modelling of fire scenarios with introduced inertisation in a number of different Australian longwall mine layouts are discussed.

INERTISATION SYSTEMS

Simulation of inertisation usage

Inertisation has been accepted to have an important place in Australian mining emergency preparedness. The two jet engine exhaust GAG units purchased from Poland by the Queensland government in the late 1990s for the Queensland Mines Rescue Service have been tested and developed and mines made ready for their use in emergency and training exercises. Their use in real and trial mine fire incidents has underlined the need for more information on their application. The NSW Mine Shield (liquefied nitrogen) apparatus dates to the 1980s and has been actively used a number of times particular in goaf heating incidents.. The Tomlinson (diesel exhaust) boiler has been purchased by a number of mines and is regularly used as a routine production tool to reduce the time in which a newly sealed goaf has an atmosphere “within the explosive range” and for goaf spontaneous combustion heatings. Nitrogen Pressure Swing Adsorption (Floxal) units are available and in use both for reducing time in which goafs are “within the explosive range” and for goaf spontaneous combustion heatings. Each of these facilities puts out very different flow rates of inert gases. Each is designed for a different application although there is some overlap in potential applications. Table 1 examines some typical characteristics of the outlet flow of examples of these four units.

Table 1 Characteristics of the outlet flow of the GAG, Mine Shield, Tomlinson and Floxal inertisation units.

	Flue Gas Generator (Tomlinson Boiler)	Mineshield Liquid Nitrogen System	GAG unit	Membrane System AMSA Floxal Unit
Inert Gas Output Quantity Range, m^3/s	0.5	0.2 – 4.0	14 – 25	0.12 – 0.7
Suggested Default Quantity, m^3/s	0.5	2.0	20	0.5
Delivery Temperature, ^oC	54	Atmospheric	85	20
Oxygen, %	2	0	0.5	3
Nitrogen, %	81.5	100	80 – 85	97
Carbon Dioxide, %	15.3	-	13 – 16	-
Carbon Monoxide, ppm	0	-	3	-
Water Vapour, %	1.2	-	some	-
Water droplets			significant	

Underground mine fires lead to complex interrelationships with airflow in the mine ventilation system (Wala, 1996). Addition of the gas stream from an inertisation unit adds another level of complexity to the underground atmosphere behaviour. Important questions are raised such as should the main mine fans be turned off so as not to dilute the inert gas or will this action cause, in conjunction with buoyancy effects, airflow reversal and the drawing of combustion products or seam gases across a fire leading to an explosion?

The GAG and Mine Ventilation Systems

Simulation of the introduction of the GAG or other apparatus has indicated that there is a substantial lack of knowledge on use of these facilities. The Queensland GAG units were first used actively in 1999 at the Blair Athol mine to handle a spontaneous combustion issue in old underground workings that were about to be mined by surface techniques. The GAG unit was subsequently used successfully in an underground mine fire at the Loveridge mine, West Virginia in early 2003 (Urosek et al, 2004). On this occasion the GAG ran for approximately 240 hours over 13 days and was successful in stabilising the mine so that rescue teams could enter the mine and seal and fully extinguish the fire affected zone. Much was learnt about the ventilation network behaviour and the need to have an upcast shaft open. Observations were made on the effects of natural ventilation pressure, barometric changes and rock falls on the backpressure experienced by the operating GAG.

A fire which was suspected to have been caused by lightening strike at the Pinnacle mine, also in West Virginia, was out of control from October 2003 to May 2004. A Polish owned GAG unit was successfully used to stabilise the situation although there were a number of underground gas explosions during the course of the incident (Campbell, 2004). Following these experiences the US Micon company has purchased GAG units and has developed a commercial mine emergency and recovery business.

New and innovative approaches to mine recovery are occurring. In the US an equipment unit fire in the Dotiki mine, Kentucky, in early 2004 was stabilised using a Nitrogen and Carbon Dioxide (Wesley et al., 2006). Also in early 2004 carbon dioxide was used to stabilize a goaf spontaneous combustion heating in the West Ridge mine in Utah (Stoltz et al., 2006).

Simulations using the fire simulation software “Ventgraph” can be undertaken to gain better understanding of how inertisation units or systems interact with the complex ventilation behaviour underground during a substantial fire or hating. Aspects worthy of examination include:

- Location of the introduction point for inert gases for high priority fire positions; eg. portal docking position, special boreholes;
- Size (diameter) of borehole or pipe range required to deliver inert gases and back pressure issues;
- Time required for inertisation output to interact with and extinguish a fire;
- Effects of seam gas on fire behaviour with inertisation present;
- Changes which can be safely made to the ventilation system during inertisation including switching off some or all fans;
- Need for remote controlled underground doors to channel inert gases to the fire location;
- Complications caused by underground booster fans; and
- Spontaneous combustion issues.

EFFECTIVE DOCKING POSITIONING OF INERTISATION UNITS

Positioning of the inertisation units is a major determinant of potential success for most efficient suppression of a specific fire. Traditionally in Queensland docking points have been placed on intake ventilation headings (either travel roads of conveyor belt roads). Some mines have prepared docking points on boreholes of about 1.0 to 2.0m diameter placed at the back of longwall panels.

The advantages that can be gained from use of various inertisation docking positions depends on a number of considerations including the location of the fire, the relative distance from the inertisation docking portal location and the attributes and complexity of the mine ventilation network. Operation of a GAG unit requires preplanning in terms of infrastructure requirements for a GAG surface portal docking station and access for operating personnel, fuel, water and other operating requirements.

A current ACARP supported project has been examining this aspect. Priority fire locations at mines with a developed and current Ventgraph simulation model have been examined as to the ability of a GAG inertisation unit to inert a fire in the mine recovery stage. In the study it was assumed that the GAG would be docked at a prepared position designated by the mine (most commonly the current fabricated docking installation.

A total of 71 potential priority mine fire locations that had had scenarios simulated were reviewed. From these 35 scenarios were considered worthy of incorporating utilization of the GAG. Table 2 shows results of the outcome of the 35 scenarios from the study.

Table 2 Effectiveness of GAG delivery

Code	Description	Results out of 35 scenarios simulated	Percentage %
A	GAG exhaust delivered efficiently (without significant dilution) to fire.	0	0
B	GAG exhaust reaches fire with no fan changes but diluted and not fully effective.	7	20
C	GAG exhaust reaches fire only after fan change and potentially effective after ventilation air (incl. fire fumes) local reversal across fire.	16	46
D	GAG exhaust will never reach fire.	5	14
E	GAG exhaust only reaches fire after fan change and working section methane and ventilation air (incl. fire fumes) reversal across fire.	7	20

Analysis of these situations leads to the following comments.

- Category A covers fire in which the inertisation product is directed fully over the fire. No mine priority fire examined achieved the situation in which the simulated fire is directly controlled to aid recovery in a timely manner.
- Category B covers situations in which the inertisation product goes straight to the fire but there is significant dilution from other ventilation air or leakage through stoppings. 20 percent of mines are in this category and under these situations the fire should, over time, be abated or stabilised to a point where conventional recovery approaches can be initiated.
- Category C covers priority fires in which the GAG output will never reach the fire location without stopping of one or more main surface fans to rebalance ventilation within the pit. In many of these cases requiring fan changes to put GAG output across the fire location effective ventilation air velocity has been reduced to the extent that local reversal across the fire occurs and fire fumes are pulled across the fire. This is an unsatisfactory situation as fire smoke and fumes can carry combustible products. This situation broadly prevails for 46 percent of the cases examined
- Category D covers priority fires in which the GAG output will never reach the fire location. These are fire locations within panel sections in which either the fire behaviour stops normal intake ventilation flow into the section headings or the GAG docking point is in an airway that is segregated from the section. This situation is seen in 14 percent of the cases examined.
- Category E covers priority fires in gassy mines in which section production gas make has been included in the simulation modelling. GAG exhaust will never reach the fire location without stopping of one or more main surface fans to rebalance ventilation within the pit.

However this change in ventilation causes working section methane and ventilation air (incl. fire fumes) to reverse across the fire. This is clearly a potentially dangerous situation. This situation was found in 20 percent of the cases examined

These simulation exercises undertaken with a wide range of Australian mines focuses attention to the situation that many potential underground mine fire sources cannot be successfully inertised with the GAG docked at the current specified point. This point is most commonly at the Mains Travel or Conveyor Heading portals.

This inability to deliver GAG output is particularly so for fires in extended areas of workings or in panels. Two important conclusions are

- Sucessful delivery of GAG output from units on the surface must consider other (that is alternative to Mains Travel or Conveyor Heading portals) delivery conduits directly into workings near the fire through existing or purpose drilled boreholes.
- During a fire the stopping of the main surface fan or fans will lead to rebalancing of pit ventilation and in some cases potential explosions through air reversals bringing poorly diluted explosible seam gases or fire products across the fire site..

The next section examines some considerations in use of boreholes for delivery of inertisation products.

INERTISATION THROUGH BOREHOLES

The potential use of appropriately sized boreholes to deliver inertisation output directly to a fire or heating has advantages. Economic installation of well placed boreholes could allow the proactive use of larger inertisation units such as the GAG in a wider application in Australian mines responding to or recovering from mine fires or spontaneous combustion heatings or elimination of the potential explosibility of newly sealed goafs.

Australian coal mines have experienced significant goaf heatings or goaf fires in recent years. Incidents at mines such as Dartbrook in 2002 and 2005/06, Austar in 2003/04, Moranbah North in 2004, North Goonyella in 2004/05 and Newstan in 2005/06 have caused significant loss of production time and in some cases mine reserves. Mine inertisation approaches using the Mine Shield, Nitrogen Pressure Swing Adsorption (Floxal) and Tomlinson Boiler units have been used in these Australian recent mine incidents involving goaf heating. The low output of 2 m^3/s or less of these units has limited their success. The GAG has the ability to supply a much higher output at an operating cost advantage but has not been considered to date for these applications due to inability to deliver the inert exhaust to the affected area.

There is potential for an increased role for the GAG built on experience gained in the use of the GAG and other inertisation units in recent years. This can encompasses

- How GAG docking to boreholes can improve delivery of GAG inert gases to high priority potential fire locations particularly in working panels.
- How GAG docking to boreholes can be used to economically inert goaf spontaneous combustion incidents. More than five Australian collieries has experienced major goaf heatings in recent years and the small inert gas units have not been of sufficient capacity.

- How GAG docking to boreholes can be used to inert goafs on sealing to avoid explosible atmospheres and movement of atmospheres into the “Coward Triangle”.

Boreholes placed within panels or more remote areas of mine workings have the capability of being used to deliver inert gases to nearby fires and so aid in mine recovery. Since the early 1990s drilling of boreholes through the overburden overlying worked underground seams has come a long way. Some major challenges with unstable strata have been overcome and a number of drilling companies service the market. Many collieries currently utilise one or more boreholes for ventilation or road base delivery purposes. Boreholes can also be used for man escape or delivery of GAG inert flow if necessary.

The challenge faced is how to effectively design these holes cost efficiently. The GAG has capability of delivering an exhaust stream of about 20 m^3/s although some of this is water vapour that quickly drops out of the air stream. There are limits to delivery of GAG output through different diameter holes at varying depths. Deeper holes naturally require larger diameter openings to overcome back pressure. Some require very large diameter boreholes of greater that 1.5 m that are prohibitively expensive.

Inertisation exhaust flow in deeper or smaller diameter holes faces significant back pressure. What is needed is a variable pressure fan that can be placed in line with the GAG flow and overcome substantial back pressure to allow holes of economical dimensions to be utilised.

A primary requirement is to examine attainable designs for panel boreholes under Australian conditions with current drilling technology. Part of this is to calculate design considerations for a variable pressure fan that can assist flow against back pressure. There is a limit to the contribution a variable pressure fan can make to assisting flow. An objective will be to define the

- Hole designs (diameters and depths) that can deliver directly without assistance of any fan,
- Hole designs that can deliver with assistance of a fan and the pressure required for this delivery to be attained, and
- Specifications of boreholes design parameters that cannot achieve delivery even with fan assistance.

Inertisation users in Australia and in particular GAG operators such as Mines Rescue organisations need the answers to these questions for future planning. In particular detailed designs are needed by operating mines. Borehole drilling into operating mines has become common place in recent years and designs that allow multiple use for ventilation requirements, delivery of road base, potential man escape and delivery of inert gases provide a step forward for the industry.

A systems involving borehole delivery of GAG exhaust is set out in figure 1.

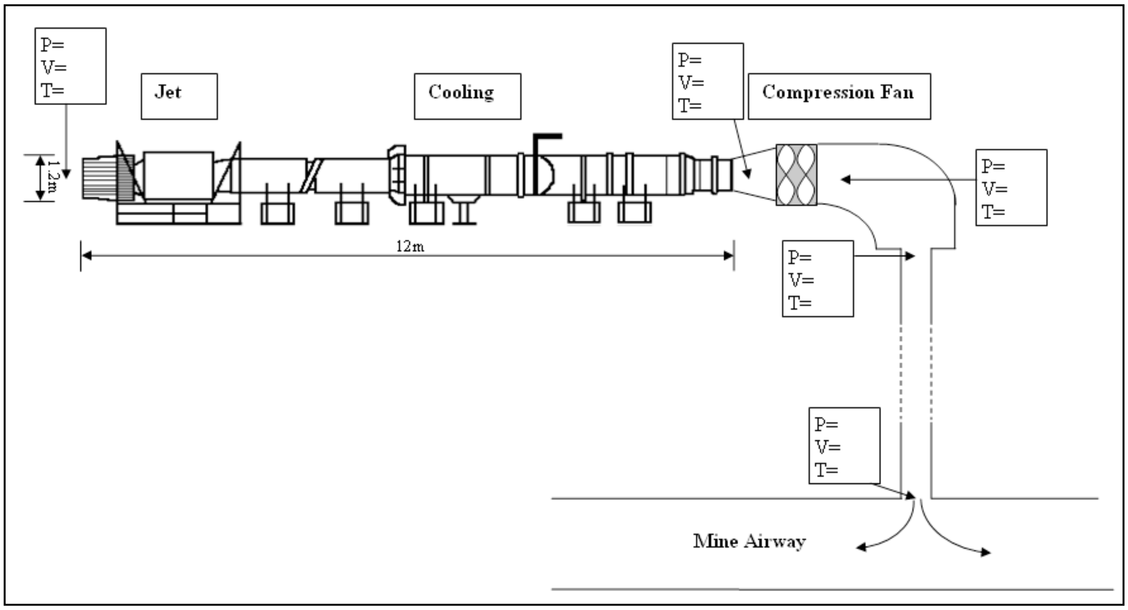


Figure 1 Schematic of system comprising GAG unit and compressor fan for borehole delivery

Development o such a system needs enhanced engineering understanding in a umber of areas.

- Borehole design parameters need to be established applicable to Australian conditions based on the complex fluid flow theory that describes the dynamic, hot, pressurised exhaust carrying a superheated vapour. To investigate the possibility of using GAG in small diameter boreholes for either production inertisation or fire fighting purposes, it is necessary to understand GAG exhaust fluid behaviour. Steady flow energy equation based on Bernoulli's equation made applicable to compressible flow can be put in a form to describe the behaviour of GAG exhaust fluid being pushed down the borehole. Work needed to overcome resistance to flow exiting the GAG outlet can be evaluated as *Work to handle any issues of energy loss due to compression, work to overcome frictional rubbing drag on outlet walls, work to overcome shock losses, work to overcome elevational buoyancy effects and finally work to overcome water vapour super heating issues.* In the system of passing GAG exhaust down mine boreholes all components will be additive. These can be put in the form of an equation

$$W_{12} = \int_1^2 VdP + F_{12} + \left(\frac{u_1^2 - u_2^2}{2}\right) + (z_1 - z_2)g + \text{superheat effects}$$

Where W = Work to achieve flow, VdP = Compression Work, F_{12} = Friction Impedance to fluid passing through pipe, u_1, u_2 = Fluid velocity terms, z_1, z_2 = Elevation terms. Each component in the equation can be established separately by knowing various fluid flow conditions or parameters.

- Determinations need to be made of the relationships between borehole back pressure and GAG thrust relationships.
- Determinations of the best variable pressure fan design that can be coupled to the system to overcome bask pressure need to be made.
- Determinations of how a variable pressure fan can be powered either through external sources or by direct coupling to the jet engine and utilisation of its potential power need to be made.

- Designs for automation of GAG operations need to be made. The GAG-3 gas turbine is a thrust engine and as such can be used against pressure for inertisation through a reduced diameter borehole. To accomplish this aim the GAG-3 has to be electronically controlled with spare I/O capacity for butterfly valve and proportional control on a tee piece in the exhaust delivery duct. The control system needs to react to duct pressure measurement input and output PID control of the engine rpm and afterburner fuel flow with dynamic measurement of backpressure against the turbine section.
- Mine layout and application of inert gases to fire or heating or to keep sealed area atmospheres out of the explosive range need to be considered. Any use of the GAG must examine its interaction with the complex ventilation behaviour underground during a substantial fire. Ventgraph simulation can be used to examine critical issues which include location of the GAG and boreholes for high priority fires or other issues, design dimensions of borehole or other passages required to deliver inert gases and back pressure issues, time required for inertisation output to interact with fire or other issues, effects of seam gas on fire behaviour with inertisation present, changes that can be safely made to the ventilation system during inertisation including switching off of some or all fan, and spontaneous combustion time frame issues.

INERTISATION EFFECTIVENESS IN MAINS HEADING FIRES

Mains headings present a complex ventilation network with five or more parallel headings, numerous cut-throughs and a variety of ventilation control devices. In such a complex system with additional interference from a fire, maintaining control of the movement of inert gas is more difficult than elsewhere in the mine. There is added emphasis in Queensland where most mines have inertisation injection portals (docking stations) connected to Mains entries. At present most Australian collieries have limited control over flow of air in Mains intakes. The quality of segregation stoppings and doors varies greatly between sites. Some states have limited legislative requirements regarding segregation.

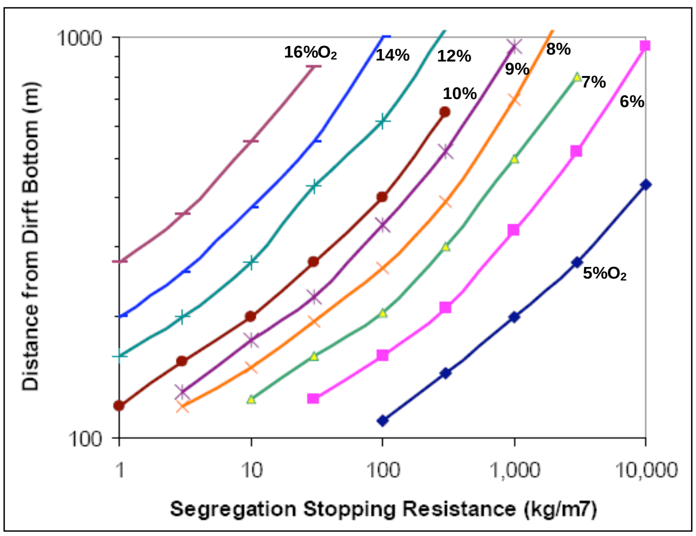
Causes of fires in mains headings include:

- Belt fires (including transfer points and motors)
- Vehicle fires
- Spontaneous combustion in pillars (particularly pillars with large pressures differences across them)

It is not always practical, or safe, to turn off the main fans and flush the mine with inert gas in the event of a fire. Given this limitation, use of segregation can allow fans to be kept on while inert gas is delivered to a particular fire site without dilution and without inertising the other airways. On the other hand, without adequate segregation inert gas will spread between all intake airways and be diluted by fresh air.

To determine the impact of the quality of segregation (stopping resistance) on GAG effectiveness in a quantitative manner, Hosking (2004) undertook “Ventgraph” simulations using a fully segregated belt heading with a range of segregation stopping resistance values. The belt way carries intake air and had a regulator placed outbye to reduce airflow and cause leakage flow into it from adjacent intake headings A GAG unit was connected to the beltway drift and run at 11 000 rev/min to give an exhaust stream with an oxygen level less than 5 per cent. The oxygen level found at each cut-through was then measured for each stopping resistance. To keep the scenario simple no doors were included and no fire was actually placed in the drive. The mine fans were kept on throughout the simulations. Existing overcasts in the model were retained and cut-throughs were spaced at approximately 50 m intervals.

Figure 2 shows the results as a set of contour lines for oxygen concentrations. It can be seen that on a log-log plot the dilution rates form a clear relationship with stopping resistance and distance. As would be expected higher resistance segregation stoppings will maintain a reduced the oxygen content of the atmosphere at fixed sensor points in the belt road, and the oxygen content increases with distance from the drift (as the number of leakage paths increases). As the pressures across stoppings are lower further inbye, the leakage rate drops and the contours become steeper.



(Ns^2/m^8)

Figure 2 Dilution of inert gas at varying segregation qualities and distance

Considering the contour for 10 per cent oxygen (a level below which open flames will not occur), the quality of segregation has a dramatic effect on the range of the inert gas. If flaps/used conveyor belt are used for segregation (less than10 Ns^2/m^8) this concentration of inert gas will only travel 200 m – the first four cut-throughs after the drift bottom. On the other hand a quality stopping that is well maintained (resistance of 100 Ns^2/m^8) will keep the oxygen level at 10 per cent for the first 400 m of the mains.

Figure 3 illustrates how effectively the ventilation network can deliver inert gas to a fire at 1.0 km distance. Stopping resistances less than 10 Ns^2/m^8 are unable to stop dilution of the heading air at this distance. Above 10 Ns^2/m^8, the oxygen content steadily declines with higher quality segregation.

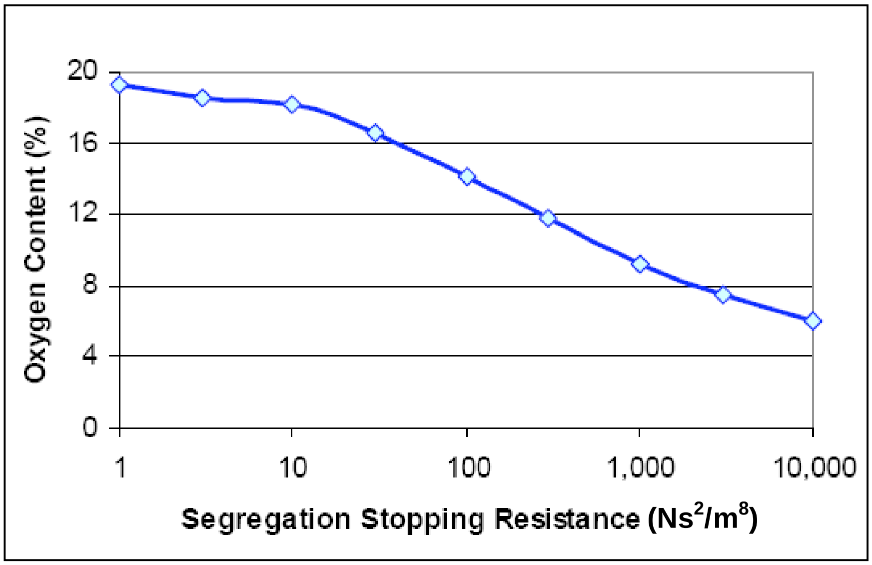


Figure 3 Dilution of inert gas at 1.0 km from drift bottom.

These plots are relatively simple to generate for a ventilation network once the model exists. While it may be technically unrealistic or impractical to consider changes to segregation stoppings in an existing mine, diagrams of this form are useful as a planning tool for future developments. Good quality segregation restricts the spread of contaminants (heat, dust and gas on a routine basis and smoke and fire products in an emergency) in addition to assisting the movement of inert gases.

CONCLUSIONS

A study has examined the potential for simulation of the effects of inertisation on fires within a mine ventilation network. The project involved applying the "Ventgraph" mine fire simulation software to preplan for mine fires. Work undertaken to date at some Australian coal mines is discussed as examples. The effort has been built around the modelling of fire scenarios in selected different mine layouts.

Case studies have been developed to examine usage of inertisation units and particularly application of the GAG unit. One section has focused on selection of the surface portal location for placement of the GAG for effective fire suppression. The difficulties that some current approaches present are highlighted. Another section has looked at issues involved with delivery of GAG output through boreholes. A third examines inertisation and dilution issues in Mains headings. These present a complex ventilation network and with additional interference from a fire, maintaining control of the movement of inert gas is more difficult than elsewhere in the mine.

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