Simulation of the Effects of Inertisation of Fires on Mine Ventilation Systems

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ABSTRACT

A research project incorporating a number of mine site exercises to reduce the effects of fire incidents and possible consequent health and safety hazards has been undertaken focused on the application of mine fire simulation software packages for contaminate tracing and fire modelling in coal and metalliferous mines. This paper examines aspects of introduction of inert gases to underground workings to aid recovery of a mine following a fire.

Broad conclusions from work undertaken at individual Australian coal mines are discussed as examples. The effort is built around the introduction of the fire simulation computer program 'Ventgraph' to the Australian mining industry and the consequent 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 jet engine unit. One example has focused on selection of the best surface portal location for placement of the GAG for most efficient suppression of a fire. A second has examined a situation with significant seam gas being emitted on the face. This has shown that under certain face dip angles stopping the mine surface fan to reduce dilution of GAG exhaust gases will cause reversal of face air and consequent mine explosion as gas laden air is drawn across a fire. A third examines inertisation and dilution issues in mains headings. 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 are recognised across the world as a major hazard issue. New approaches allowing improvement in understanding their consequences have been examined. The outcome of the completed 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

Many people consider that mine fires remain among the most serious hazards in underground mining. The threat fire presents depends on aspects such as the nature and amount of flammable material, the ventilation system arrangement, the duration of the fire, the extent of the spread of combustion products, the ignition location and the reaction of personnel present.

A research project incorporating a number of mine site exercises has been undertaken focused on the application of mine fire and ventilation software packages for contaminate tracing and fire modelling in coal and metalliferous mines. This paper in particular examines aspects of introduction of inert gases to underground workings to aid recovery of a mine following a fire.

The study into this complex area has utilised the recently upgraded Polish mine fire simulation software, 'Ventgraph'. There is a need to understand the theory behind the simulation program and to allow mine site use by those already familiar with the main existing mine ventilation analysis computer programs currently popular within the Australian, United States and South African industries such as 'Ventsim', 'VnetPC' and 'Vuma'. 'Ventsim', 'VnetPC' and 'Vuma' were not designed to handle fire effects on mine networks. Under the project a small subroutine has been written to transfer the input data from the existing mine ventilation network simulation programs to 'Ventgraph'.

It is difficult to predict the pressure imbalance and leakage created by a mine fire due to the complex interrelationships between the mine ventilation system and a mine fire situation. Depending on the rate and direction of dip of the entries (dip or rise), reversal or recirculation of the airflow could occur because of convection currents (buoyancy effect) and constrictions (throttling effect) caused by the fire. This reversal jeopardises the functioning of the ventilation system. Stability of the ventilation system is critical for maintaining escapeways free from contamination and therefore available for travel. Reversal of air following fires can have a tragic outcome (Wala, 1999).

Simulation software has the great advantage that underground mine fire scenarios can be analysed and visualised. 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; Dziurzyñski, 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 utilises a colour-graphic visualisation 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).

The primary objective of the study is to use mine fire simulation software to gain better understanding of how inertisation (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? A situation incorporating usage of an inertisation unit with significant seam gas being emitted on a dipping longwall face has been assessed for safety in

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determination of whether a main fan should be turned off or not. 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.

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.

EFFECTS OF FIRES ON MINE VENTILATION

The effects of fire on a mine ventilation network are complex and have been discussed by Gillies, Wala and Wu (2004), Gillies, Wu, and Hosking (2004), Gillies *et al* (2004) and Wu, Gillies and Wala (2004). An open fire causes a sharp increase in the temperature of the air. The resulting expansion of the air produces a number of distinct effects. First the expansion attempts to take place in both directions along the airway. The tendency to expand against the prevailing direction produces a reduction in the airflow. Secondly, the expansion in volume increases air velocity downwind from the fire causing additional pressure loss. This is known as the choke or throttling effect. Finally, the decreased density results in the heated air becoming more buoyant and causes local effects as well as changes in the magnitudes of natural ventilating energy.

The choke or throttling effect

This effect results from an increase in volume of air as it passes through the fire. The effect has been described by Litton *et al* (1987). This increase in volume is due to gas expansion as well as the addition of combustion products such as fire gases and evaporated water. As a result the velocity of air downwind from the fire is increasing and additional pressure loss following the square law results.

The choke effect is analogous to increasing the resistance of the airway. For the purposes of ventilation network analyses based on a standard value of air density, the raised value of this 'pseudo resistance', R_t, can be estimated in terms of the air temperature as follows (McPherson, 1993).

$$R_t \propto T^2$$

The value of R_t, increases with the square of the absolute temperature (T). It should be recalled however, that this somewhat artificial device is required only to represent the choke effect in an incompressible flow analysis.

Buoyancy (natural draft) effects

Local or roll back effect

The most immediate effect of heat on the ventilating air stream is a very local one. The reduced density causes the mixture of hot air and products of combustion to rise and flow preferentially along the roof of the airway. The pronounced buoyancy effect causes smoke and hot gases to form a layer along the roof and, in a level or descentional airway, may back up against the direction of airflow. This has been discussed by Mitchell (1990).

Whole mine natural ventilation pressure effects

A more widespread effect of reductions in air density is the influence felt in shafts or inclined airways. The conversion of heat into mechanical energy in the ventilation system is called the buoyancy (natural draft, natural ventilating pressure or chimney) effect. The effect is most pronounced when the fire itself is in a shaft or inclined airway and promoting airflow if the ventilation is ascentional and opposing the flow in descentional airways. In the ascentional situation flows can reverse in parallel (bypass) airways to the airway with fire and bring combustion products into these airways. In the descentional case airflow may reverse in the airway with fire, bringing combustion products into adjacent parallel airways and also resulting in non-steady state flow of toxic atmospheres.

Natural ventilating pressure always exists in a mine and its magnitude mostly depends on the mine's depth and difference in air density in the inclined and vertical airways. In the case of fire, this effect is magnified due to high temperatures leading to unpredictable changes in air density and the airflow distribution.

If the air temperatures can be estimated for paths downstream of the fire then it is possible to determine the modified natural ventilating pressures. Those temperatures vary with respect to size and intensity of the fire, distance from the fire, time, leakage of cool air into the airways affected and heat transfer characteristics between the air and the surrounding strata.

INERTISATION

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. Various incidents in 2003 underlined the need for more information on their use and application. The NSW Mine Shield (liquefied nitrogen) apparatus dates to the 1980s and has been actively used a number of times. 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. Nitrogen Pressure Swing Adsorption (Floxal) units are available and in use. Each of these facilities puts out very different flow rates of inert gases with the GAG exhaust and cooling moisture outputting about 20 m^3/s, the Nitrogen Shield about 5 m^3/s, the Tomlinson Boiler about 0.5 m^3/s and the Nitrogen Pressure Swing Adsorption (Floxal) a yet smaller volume. Each is designed for a different application.

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?

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 that was suspected to have been caused by lightning 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 a GAG unit and is developing a commercial mine emergency and recovery business.

The Queensland GAG unit was called to the Southland, NSW mine fire at the end of 2003 but not utilised in full.

In the US an equipment unit fire in the Dotiki mine, Kentucky, in early 2004 was stabilised using a Nitrogen and Carbon Dioxide. In late 2004 a fire at the Excel No 3 mine in Kentucky on a belt conveyor was stabilised through injection of nitrogen gas and foam through four specially drilled boreholes. In addition in early 2004 carbon dioxide was used to stabilise a goaf spontaneous combustion heating in the West Ridge mine in Utah (Fancart, 2004).

The New South Wales Mines Rescue Board and CIG Company developed the Mine Shield system in 1985. It has been used in incidents at five mines in NSW and at Moura No 4 in Queensland. The most recent operation was at the Hunter Valley Dartbrook mine where inert gas was injected into an active goaf exhibiting a heating over a five months period in 2002. This enabled safe recovery of face equipment.

Simulations using '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. 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 that 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.

Operation of a GAG unit requires preplanning in terms of infrastructure requirements for a surface portal docking station and access for operating personnel, jet fuel, water and other operating requirements.

INERTISATION CASE STUDIES

Typical aspects of Australian longwall mining

The examples that follow have been modelled on a layout of a simplified Australian coal mine. The typical layout of an Australian longwall mine is shown in Figure 1. In the figure a raise bore exists behind the current goaf and is shown as a circle with an intake roadway connecting to the longwall face roadway (Mayes and Gillies, 2002). Australian longwalls at present normally use only two roadway maingate developments and have typically between five and seven mains' roadways. In development, A heading is an intake roadway with B heading the return roadway through which the panel conveyor runs.

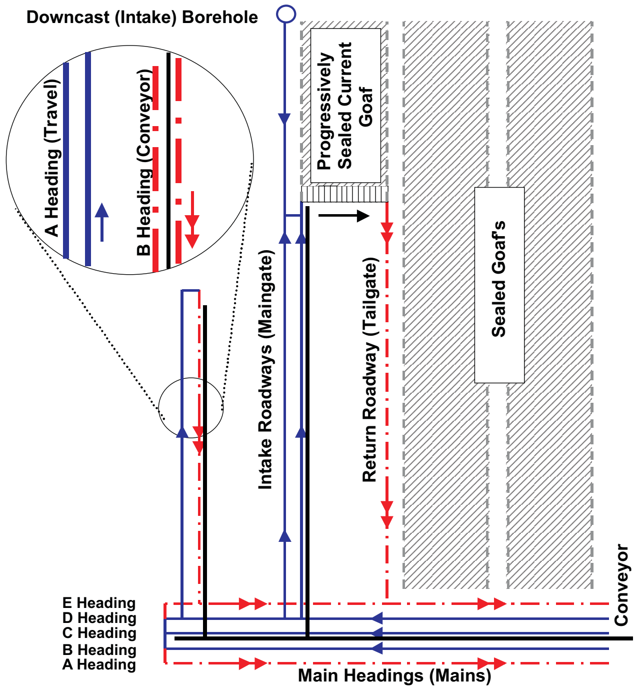

FIG 1 - Typical layout of Australian Longwall Mining.

In the mains, B, C, and D headings are typically intake with flanking return roadways, A and E headings. When all longwalls are being extracted on one side of the mains only, D and E headings may be used as return roadways with A, B and C headings as intake roadways. The conveyor runs in the intake headings, typically in C heading. In Queensland this roadway is segregated from either one or both of the other intake roadways.

Simulating the effects of GAG usage

The simulations selected illustrate some effects of introduction of inert gases to a ventilation system affected by a fire.

Positioning of inertisation units

The examples illustrate application of a GAG jet engine unit placed at a mine surface portal. The best surface portal location placement for the GAG for most efficient suppression of a specific longwall panel fire has been examined. These case studies use a simple Australian longwall layout with the longwall panel driven from the mains entries with mains of length of 2 km and 4 km. A 1.0 m diameter borehole was connected about 400 m from the back of the longwall panel.

Two GAG jet engine unit positions were investigated. The first position was at the portal B heading and the second position at the top of the borehole located at the back of the longwall panel. A diesel fire with a 30 m length of fire zone started 50 m outbye of the current longwall face was simulated.

Procedures to implement the GAG for both positions are as follows:

1. start the simulation and let the fire run for one hour;
2. start the GAG after one hour and close the emergency door at portal B heading just outbye the GAG;
3. shut off the fan and close off the other two emergency doors located at C and D heading; and
4. let the GAG run till the heat production from fire is minimal and the fuel temperature is less than 250°C.

It was found that it made no difference for the second case study GAG position whether the emergency doors at the portal were closed or not.

When the length of the mains is 2 km, the time it takes for the GAG put the fire out was similar whether the GAG unit was at the mains portal or at the top of longwall back borehole. However, when the length of the mains is increased to 4 km, it was found that a GAG unit located at the back borehole has significant advantage in terms of time in reducing the fire to significantly reduced state (see Figures 2 and 3).

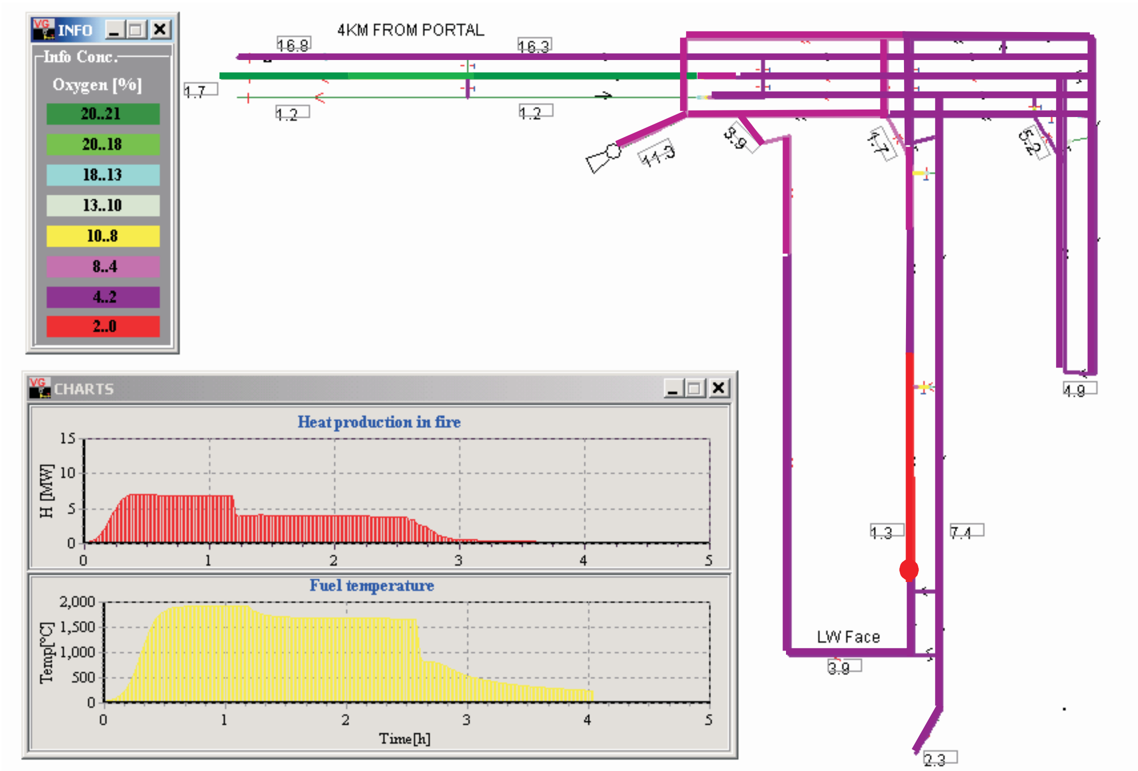

FIG 2 - GAG position at the portal B heading for 4 km mains length.

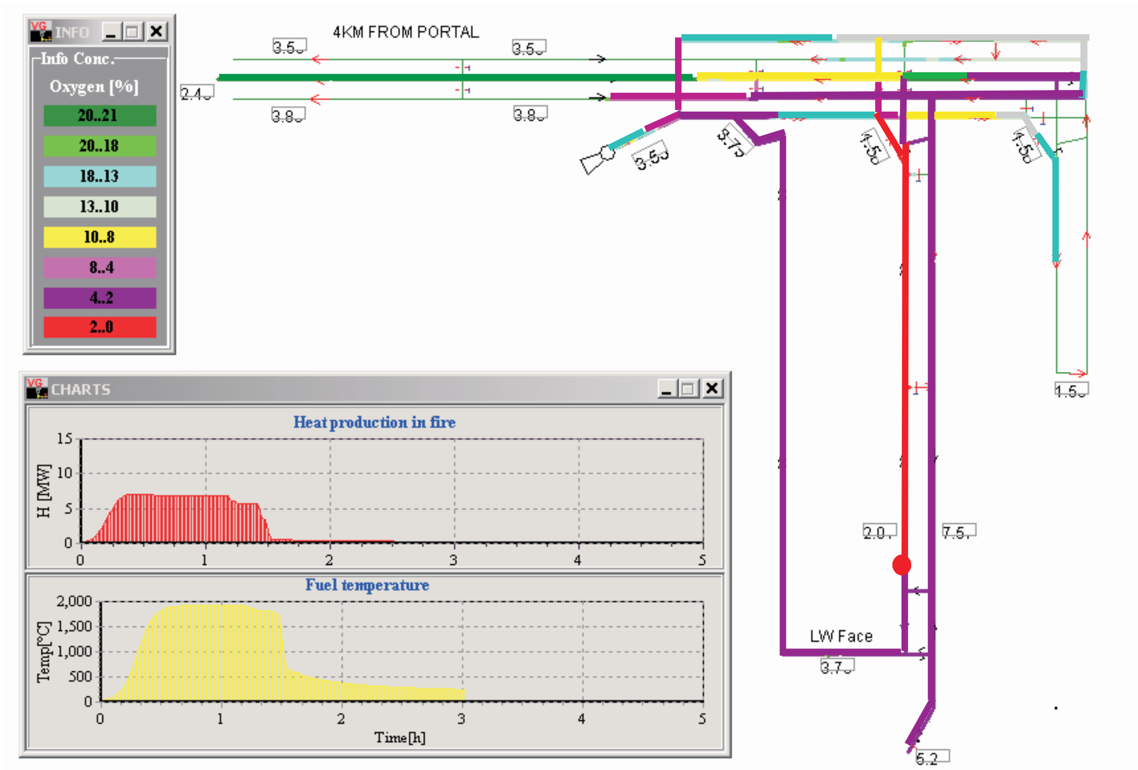

FIG 3 - GAG position at the top of back LW borehole for 4 km mains length.

It should be noted that the advantages that can be gained from use of various GAG positions depends on a number of considerations including the location of the fire, the relative distance from the GAG placement 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, jet fuel, water and other operating requirements.

The same conclusion from GAG studies also applies to use of other inertisation units. It would be advantageous for investigations to be undertaken by any mine contemplating use of inertisation for use with fires in priority locations. This require detailed study of the mine's ventilation and fire simulation model to identify optimum unit position placement for various priority fire locations.

Fire with high gas level at face

Investigations were undertaken to examine usage of the GAG jet engine in a mine with high gas emission levels at the longwall face. The layout of a simple Australian longwall examples used in the previous section was modified. A seam gas face source of methane of 400 L/s was introduced in the middle of the longwall face line in the model. This gives a methane concentration level of about one per cent on the tailgate return side of the longwall face. In the simulation a diesel fire of 10 m length of fire zone was started 50 m inbye the maingate end of the current longwall face.

The longwall face was examined under two situations of dip angles of 2.5 per cent and five per cent (minus 6 m and minus 12 m respectively on a longwall face 240 m long) down from maingate to tailgate. This gives descentional ventilation effects on the face. The fire in this situation will work against the main ventilation flow direction along the longwall face from maingate to tailgate. The GAG unit is positioned at the portal B heading.

Procedures to implement the GAG for both positions were as follows:

1. start the simulation and let the fire run for one hour;
2. start the GAG after one hour and close the emergency door at portal B heading just outbye the GAG;
3. close off the emergency door located at C, shut off the fan and then close off the emergency door located at D heading; and
4. let the GAG run till the heat production from fire is minimal and the fuel temperature is less than 250°C.

It was found that when the longwall is dipping at 2.5 per cent, the GAG unit is successful in reducing the fire to minimal heat production and fuel temperature of less than 500°C around four hours after the GAG was started as indicated in Figure 4. No airflow reversal was observed at the longwall face.

When the dip angle increased however, to five per cent for the same fire situation the airflow on the longwall face reverses as soon as the fan is turned off. This leads to a high concentration of face methane flowing back across the fire with high likelihood of an explosion occurring as shown in Figure 5. A sharp drop in the heat produced from the fire is observed.

As soon as a simulated explosion 'occurs' in the Ventgraph simulation program, the program will no longer simulate the heat production from fire. The program assumes that if an explosion occurs, there is no point in continuing the simulation. Addition of the inert gas stream adds another level of complexity to the already complicated interrelationships between the mine ventilation system, the presence of seam gases and a mine fire.

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?

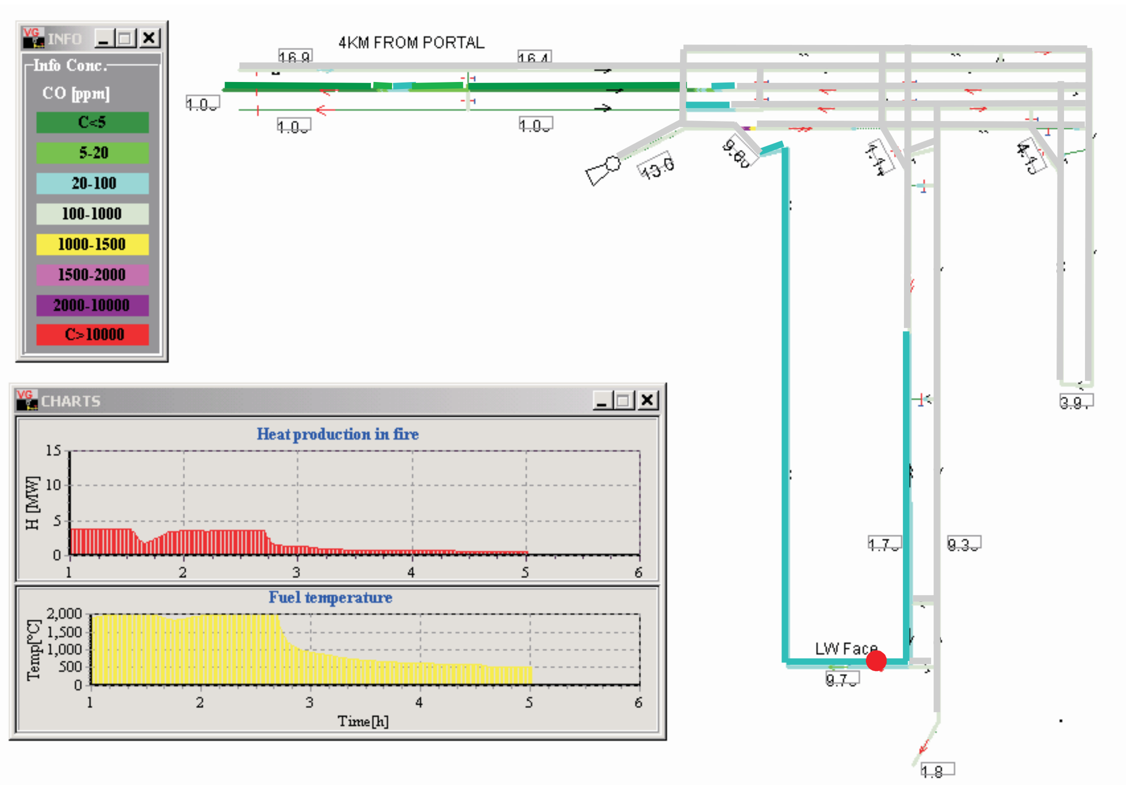

FIG 4 - Fire on gassy longwall dipping at 2.5 per cent from maingate to tailgate.

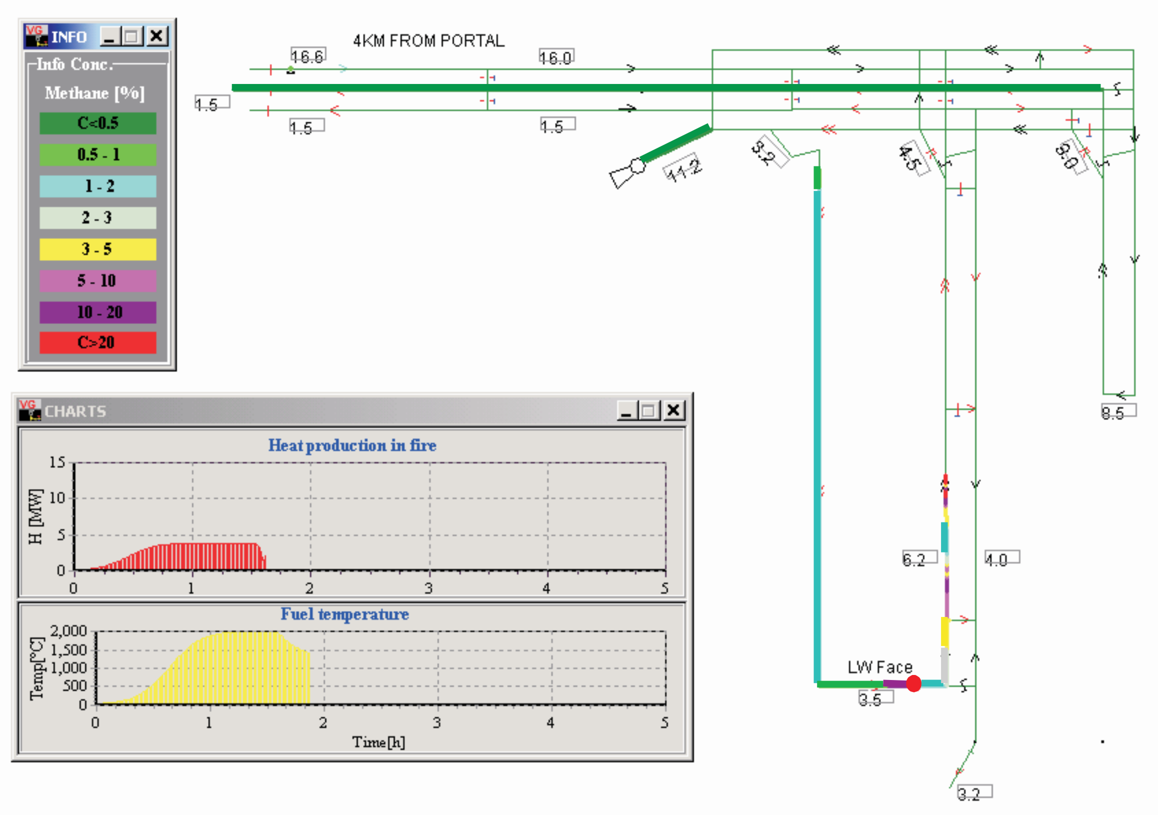

FIG 5 - Fire on gassy longwall dipping at five per cent from maingate to tailgate.

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; and
- 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 (C heading in Figure 1) had a regulator placed outbye to reduce airflow and cause leakage flow into it from surrounding headings A GAG unit was connected to the beltway drift and run at 11 000 rpm to give an exhaust stream with an oxygen level less than five 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 6 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.

Considering the contour for ten 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 than 10 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 ten per cent for the first 400 m of the mains.

Figure 7 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.

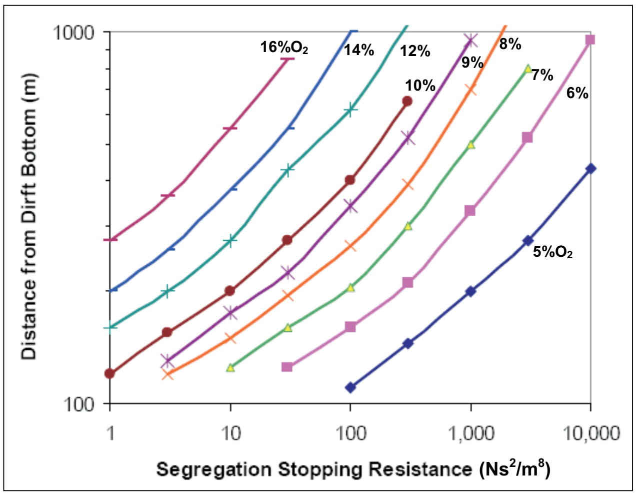

FIG 6 - Dilution of inert gas at varying segregation qualities and distance.

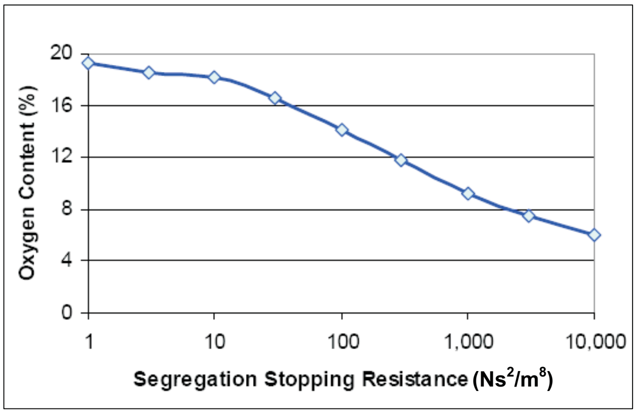

FIG 7 - Dilution of inert gas at 1.0 km from drift bottom.

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 and possible emergency incidents. Work undertaken so far at individual 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 example has focused on selection of the best surface portal location for placement of the GAG for most efficient fire suppression. A second has examined a situation with significant seam gas being emitted on the face. This has shown that under certain face dip angles stopping the mine surface fan to reduce dilution of GAG exhaust gases may cause reversal of face air and a consequent mine explosion as gas laden air is drawn across a fire. 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. Some illustrations of this issue have been given.

Mine fires are recognised across the world as a major hazard issue. New approaches allowing improvement in understanding their consequences have been developed as an aid in handling this complex area.

The mine fire simulator Ventgraph has been shown to be an important tool in planning for mine fires and the use of inertisation. The capability to visually display the spread of effects of a fire quickly and reliably provides a strong aid to those involved in developing emergency plans or contributing to emergency management. The active use of mine fire simulation in emergency planning should continue to be encouraged.

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