IMPROVING UNDERSTANDING OF SPONTANEOUS COMBUSTION THROUGH SIMULATION OF MINE FIRES

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ABSTRACT

The structure of a comprehensive research project into mine fires study applying the "Ventgraph" mine fire simulation software, preplanning of escape scenarios and general interaction with rescue responses is outlined. The project has ACARP funding and also relies on substantial mining company site support. This practical input from mine operators is essential and allows the approach to be introduced in the most creditable way. The effort is built around the introduction of fire simulation computer software to the Australian mining industry and the consequent modelling of fire scenarios in selected different mine layouts.

Application of the simulation software package to the changing mine layouts requires experience to achieve realistic outcomes. Most Australian mines of size currently use a ventilation network simulation program. Under the project a small subroutine has been written to transfer the input data from the existing mine ventilation network simulation program to "Ventgraph". This has been tested successfully. To understand fire simulation behaviour on the mine ventilation system, it is necessary to understood the possible effects of mine fires on various mine ventilation systems correctly first. Case studies demonstrating the possible effects of fires on some typical Australian coal mine ventilation circuits have been examined. The situation in which there is some gas make at the face and effects with fire have also been developed to emphasise how unstable and dangerous situations may arise.

The primary objective of the part of the study described in this paper is to use mine fire simulation software to gain better understanding of how spontaneous combustion initiated fires can interact with the complex ventilation behaviour underground during a substantial fire. It focuses on the simulation of spontaneous combustion sourced heatings that develop into open fires. Further, it examines ventilation behaviour effects of spontaneous combustion initiated goaf and pillar fires. It also briefly examines simulation of use of the inertisation to assist in mine recovery.

Mine fires are recognized 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.

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.

An Australian Coal Association Research Program supported project incorporating a number of mine site exercises, as described by Gillies, Wala and Wu, 2004 and Wu, Gillies and Wala, 2004 has been undertaken focused on the application of mine fire and ventilation software packages for contaminate tracing and fire modelling in coal mines. This paper in particular examines aspects of spontaneous combustion initiated open fires in underground workings.

The study into this complex area has utilized 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 jeopardizes 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 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, Chorosz and D'Albrand, 1985, Greuer, 1988; Dziurzyński, Tracz and Trutwin, 1988). The Ventgraph fire simulation program has been described in detail 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.

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EFFECTS OF FIRES ON MINE VENTILATION

The effects of fire on a mine ventilation network are complex. 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). However, it should be recalled 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, under low air velocity in a level or descentional airway, may back up against the direction of airflow. This has been discussed by Mitchell, 1990. A recent contribution in this area has been made by Hwang and Edwards, 2005.

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.

EXAMPLES OF UNDERGROUND SPONTANEOUS COMBUSTION HEATINGS

UNDERSTANDING HEATINGS IN GOAFS

"Ventgraph" has been trialling a Goaf Extension sub-program to assist understanding of an incident in a goaf. The Goaf software is not fully developed to the commercial phase but has been used within the Polish industry to this point in time with success as a tool for analysis.

The Goaf model has currently been customised to the exploitation systems common in Poland based on an experimental assessment of goaf properties such as permeabilities and porosities, ventilation behaviour, use or otherwise of bleeder or back ventilation systems and so on.

The Goaf extension sub-program establishes a matrix model of the goaf, with methane sources at each junction. This is a two dimensional model and includes ventilation parameters and incorporates fire sources and can allow for the effects of buoyancy and natural ventilation pressure. The model of fire is a unique feature. The simulation model of the fire can "grow" the fire (it builds up over time) and is capable of expanding itself.

Goaf flow is illustrated as colour code gas methane readings (like contours). Manual editing can change methane sources at particular nodes (branch matrix intersections). The model can simulate the operation of the shearer as a gas source moving along face. For this the face resistance to flow is assumed as a constant. Three gas sources are available; the goaf as matrix sources, the shearer as a moving point source and the belt with gas emitted from broken coal. The fire source can be placed at any point.

The fire propagates taking into account heat exchange, hot gases migrating through goaf exchange heat with rocks. A feature for inertisation modelling is incorporated through modelling of injection of inert gases (such as CO_2 N_2 and GAG exhaust) at a constant rate of flow at a given goaf node (in a similar way to introduction of a methane source). Output of results is in graphical form similar to the "Ventsim"/"Ventgraph" style. When a branch is clicked an information window is displayed.

Being part of the "Ventgraph" program set and based on use of Hardy Cross iterative solution techniques, the effects of fire simulated in the goaf on the whole mine network can be understood. In comparison with CFD analysis, the relative simplicity of this model becomes an advantage when applied to complex geometries like the ventilation network of an underground mine which includes a goaf in which migration behaviour must be understood. The models created allow the performance of a series of computations across the whole mine ventilation network in considerably shorter time than possible with CFD analyses.

Figure 1 gives a Polish mine example of use of the program to analyse distribution of methane concentrations within two adjcent goafs within a mine network.

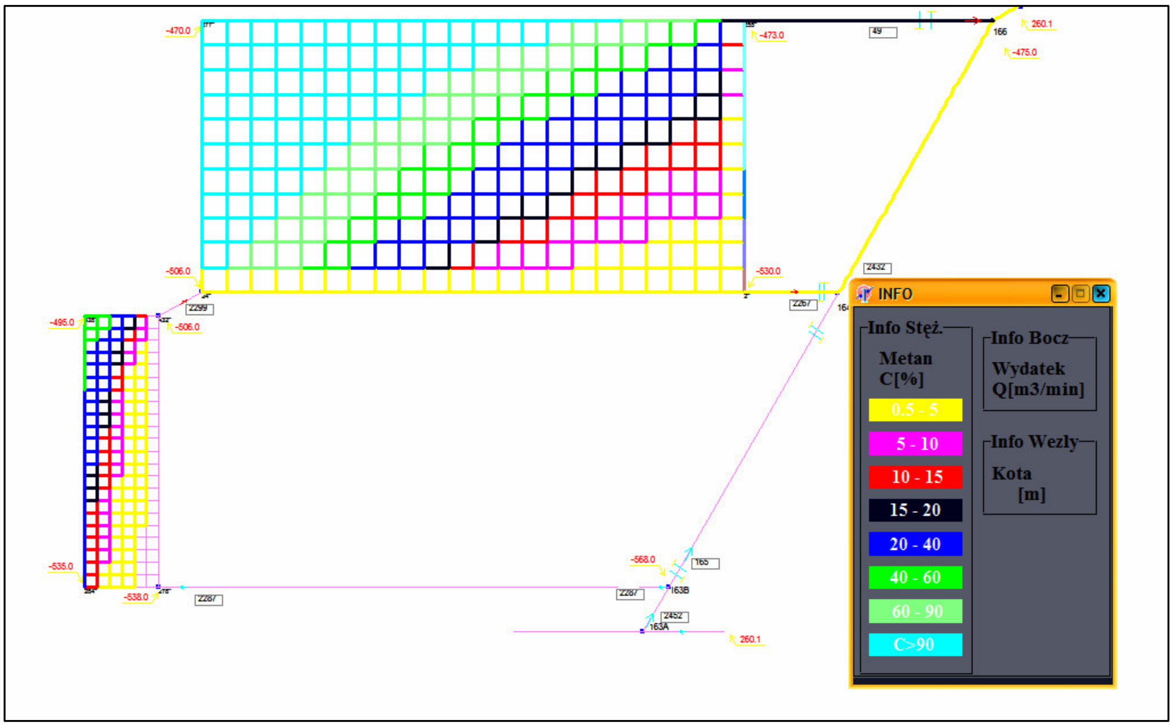

Figure 1 Distribution of methane concentrations within two adjcent goafs within a mine network (after Krawczyk, 2005)

UNDERSTANDING HEATINGS IN PILLARS

All spontaneous heatings require that certain conditions are satisfied for the coal temperature to continue to rise. Primary amongst these conditions is that, at some point within the pile or solid mass of coal, the rate of heat generation from oxidation exceeds the rate of heat loss due to conduction and convection. If ever this condition is not fulfilled, the heating will have reached a maximum temperature and there will be no further increase. The temperature in the pile or mass of coal will henceforth begin to decrease. Whilst the requirement for this condition is well known, it is difficult to predict the characteristics of coal mass or size, coal reactivity, airflow flux and other parameters that will allow the development of a high temperature heating.

MODEL USED TO EXAMINE THE DEVELOPMENT OF A SPONTANEOUS HEATING

Humphreys, 2004 has developed a numerical model to examine the development of a heating within a coal mass, pillar or pile. A brief discussion on this heating development is given in Gillies, Wu and Humphreys, 2005. For the purposes of modelling, it has been assumed that the starting conditions in the coal pile are homogenous; that is with all coal at the same particle size, reactivity and initial temperature. An underground coal pillar or solid mass will have a permeability that allows passage of air as controlled by the mine ventilation air pressure across the pillar. This permeability is likely to be lower than that exhibited by loose coal in a pile although the spontaneous combustion development characteristics will follow the same trend. In Humphreys' analysis of the airflow, flux is constant across the model although obviously there is consumption of oxygen as air passes through the model. For the purposes of examining the nature of a spontaneous heating as it occurs in a pile of coal, a quasi three dimensional model has been run for a representative coal.

DEVELOPMENT OF A SPONTANEOUS HEATING

An example of a heating development is illustrated in Figure 2.

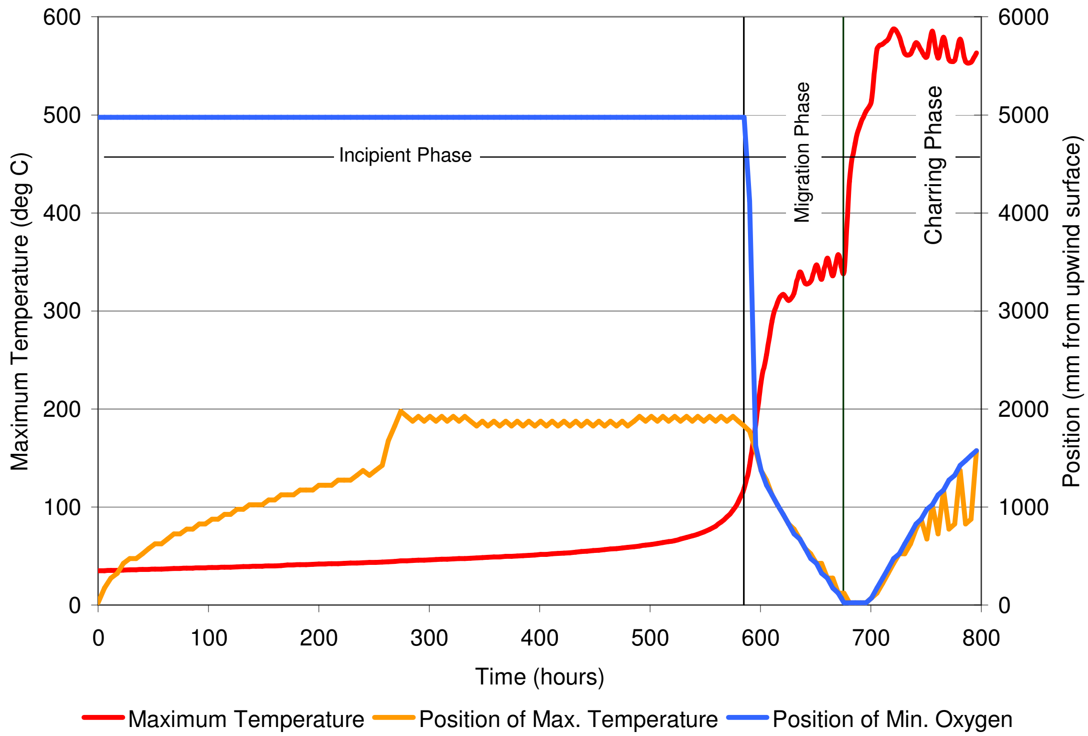

Figure 2 Base case of heating development – temperature and oxygen (after Humphreys) 2000

This example has been discussed in detail in Gillies, Wu and Humphreys, 2005. The peak temperature in the pile, the position of the peak temperature (the hotspot) and the position of the minimum oxygen concentration in the pile are shown. At the very start of the heating, there is a moderately rapid increase in temperature, with the "hotspot" located at the upwind surface of the pile and the minimum oxygen concentration at the back surface. The rate of temperature rise moderates (not visible on the figure but occurs nevertheless) and the position of the peak temperature moves gradually downwind. The position of the minimum oxygen remains at the back surface of the pile, although the minimum oxygen concentration is decreasing. After 275 hours, the peak temperature has moved to the furthest downwind position at about 1900mm. The hotspot remains in this position until its temperature exceeds 125ºC. This triggers a change in the behaviour of the heating and the hotspot begins to migrate forward. Shortly afterwards, the minimum oxygen concentration in the pile falls to zero, as does the oxygen concentration at the hotspot. Despite this, the peak pile temperature is increasing rapidly, at approximately 8ºC/hour.

Once the positions of the peak temperature and minimum oxygen concentration coincide, they begin to migrate together toward the upwind surface. This can only begin when the temperature profile in the coal ahead of the hotspot is sufficient to consume all the oxygen entering that part of the pile. The forward migration of the heating is limited by the upwind surface which triggers another increase in the coal temperature. A short while after this, the temperature of the coal is sufficient to cause charring and a charline is formed in the pile. The final phase of the heating is the lateral expansion and downwind migration of the charline, as all the reactive elements in the coal are consumed by oxidation.

From this analysis, it is possible to divide the development of this heating into three distinct phases:

1. The incipient phase characterized by peak temperatures up to about 125ºC. During this phase a hotspot develops from the upwind surface, migrates downwind to a maximum depth and remains static in that position.
2. The migration phase characterized by the forward migration of the hotspot. During this phase the oxygen concentration falls to 0 percent and there is a very rapid increase in the peak coal temperature. Without remedial action, the heating continues to develop and could lead to the outbreak of fire at the upwind surface of the pile.
3. The charring phase, when the temperature in the pile is sufficient to cause the formation of unreactive char. Without remedial action the heating will continue to develop until the hotspot and charline encounter the downwind surface when an open fire could break out.

These phases have been set out for clarity in Figures 2. The most significant phase in any heating is the initial incipient phase to about 125ºC. Any spontaneous heating which is sufficiently large as to pose a threat to safety will have to pass through the incipient phase. Most of the time required for a dangerous heating to develop will be in reaching 125ºC. There may be circumstances in which a coal can be exposed to airflow and such a heating will not develop. For example, if the mass or thickness of the coal pile is insufficient, heat losses will predominate at some temperature and a spontaneous heating will not occur. However, for heatings of significance, the incipient phase time period will be significant and there are a number of important factors in determining whether spontaneous combustion will occur in a particular coal.

SIMULATION OF A SPONTANEOUS COMBUSTION INDUCED PILLAR MINE FIRE

Ventgraph fire simulation software has been used to examine and illustrate the effects on the mine ventilation network of an open fire on a pillar sidewall rib induced by a spontaneous combustion heating developed from within the pillar. The simulation illustrates the effects of the fire on the whole mine ventilation network after an incubation period of about 700 hours following the outbreak of the pillar fire following a long incipient period and a migration phase upwind. The pillar under examination is positioned separating a mains intake heading from a return heading and so the heating has initially migrated toward the intake air. A fire development is examined in two stages within the case study mine.

1. An open fire that has broken out on the intake side of the pillar.
2. A subsequent stage when an open fire has broken out on the return side of the pillar (the charring phase, when the heating has continued to develop until the hotspot and charline encounter the pillar rib on the return side).

This hypothetical spontaneous combustion incident is reported as a simulation scenario that focuses on effects across the whole mine network. It is written up as a series of developments against time from the outbreak of the open fire in the pillar rib.

FIRE SCENARIO DEVELPOPMENT

Spontaneous combustion fire in fractured pillar coal in the rib of a mine Mains F Heading inbye 27 c/t. There is a very high pressure of about 1200Pa across the F to G (Intake/Return) pillar. Heating started as deep-seated oxidation. In the initial stages of heating, moisture transfer and coal oxidation predominate. Mains entry nomenclature is as follows:

- Headings C and D are Intake Transport roads.

- Heading E is the Intake Belt road
- Heading F is another Intake road (second means of egress).
- Headings B, G, H and I are Returns

INTAKE SIDE FIRE FOLLOWING THE MIGRATORY PHASE

As the coal dries out, a substantial local hot spot develops near the air inlet and begins to migrate upwind. Heating front has moved upstream in search of oxygen to the F Heading pillar rib. It has just developed to the point of an open fire. Prior to running the Ventgraph simulation mine ventilation and gas characteristics and monitoring controls that may be required are pre-entered.

- CO and CH_4 electronic sensors inbye the fire at 4 N LW and 5 N Dev TG Dog Legs
- CO sensors in E Hdg 10 – 11 C/T and 38 – 30 C/T
- CH_4 sources of 0.4 m^3/s from 4N LW face and 5N Development face.

Assume CO sensors in Control Room have alarm set at 8ppm

Simulation

Step 1 Time 0 – 30 minutes: Simulate 1m length open fire over entry width. Smoke first reaches 5N development face at 22 minutes. Smoke path and extent shown in Figure 3

Control Hypothetical action of Development face crew. Crew see smoke and phone Outbye Deputy at 30 minutes. Crew contact Control Room Operator (CRO) and CRO ask LW crew to evacuate mine. Crews drive out in smoke. Crews reach surface at 45 minutes since fire outbreak.

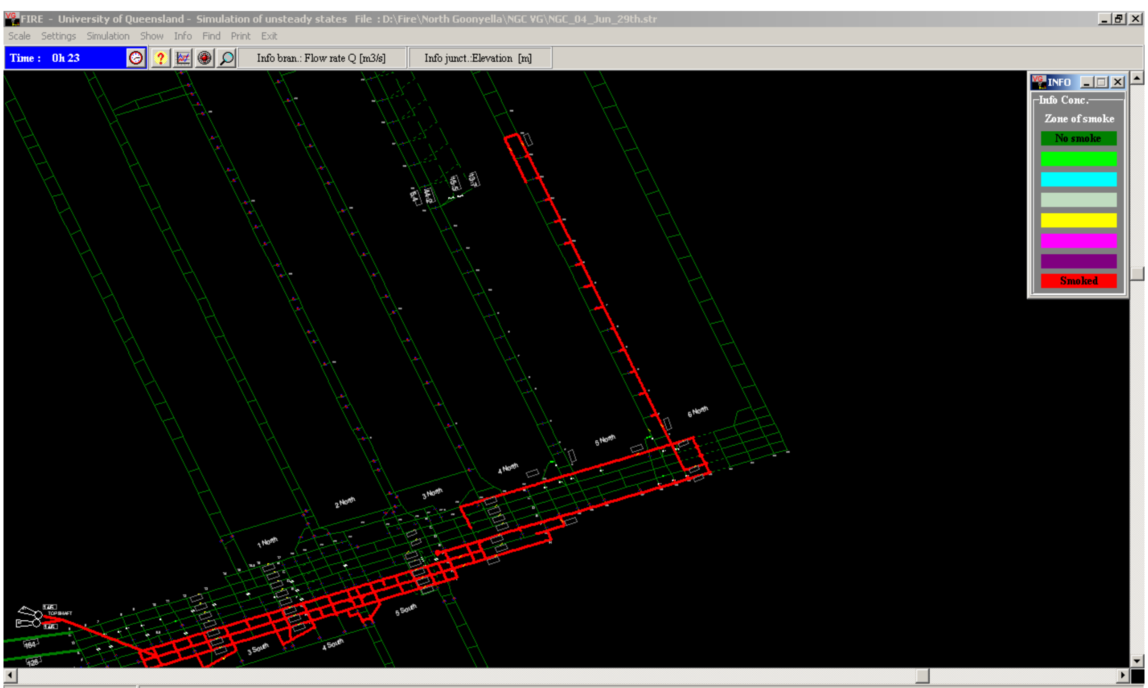

Figure 3 Smoke distribution at 22 minutes. Some smoke reaching surface exhaust main fans outlets.

Step 2 Time 30– 60 minutes: Coal fire grows. 5 m entry length coal burning

Control Hypothetical action of Deputy. Deputy finds fire source at 45 minutes after fire start. Deputy has hose ready to fight by 60 minutes.

Step 3 Time 60 – 90 minutes: Coal fire grows. 25 m entry length coal burning.

Control Deputy cannot extinguish fire at 90 minutes and drives out of mine. Reaches surface at 105 minutes. Fire out of control. Decision reached that underground ventilation control will be ineffective. Decision made to shut down the 2 underground booster fans and 1 Main fan

Step 4 Time 90 - 120 minutes: Continue coal fire, 25 m entry length coal burning. No CO sensors in mine have alarmed yet. Smoke path and extent shown in Figure 4. CO path and extent shown in Figure 5

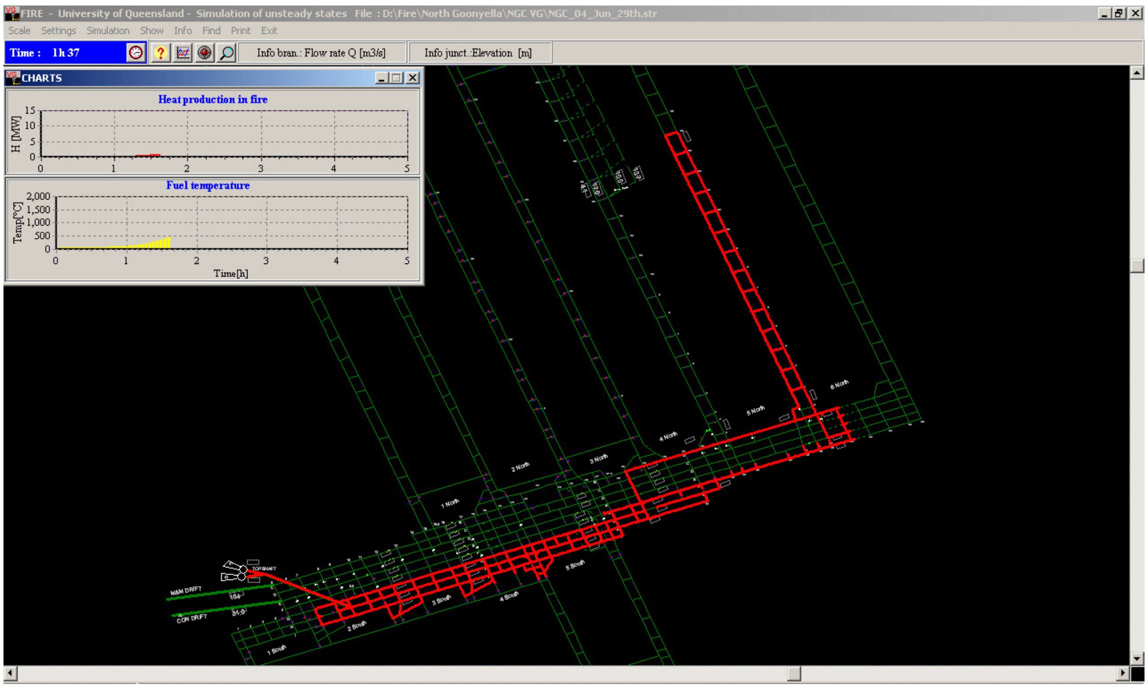

Figure 4 Smoke distribution, heat production and fire temperature after booster and mine fans turned off 97 minutes after fire started.

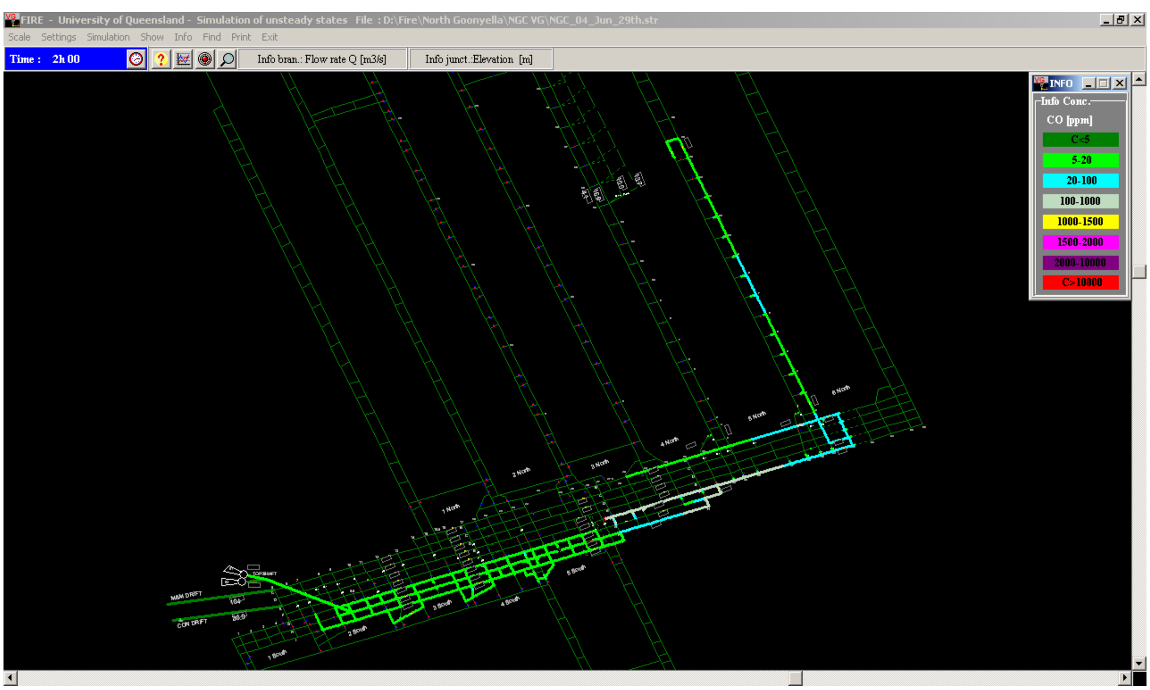

Figure 5 CO distribution after 120 minutes.

Step 5 Time 120 – 180 minutes: Coal fire grows. 50 m entry length coal burning.
CO sensors on 5 N Dev Dog Leg first alarms at 130 minutes. Methane path and extent shown in Figure 6

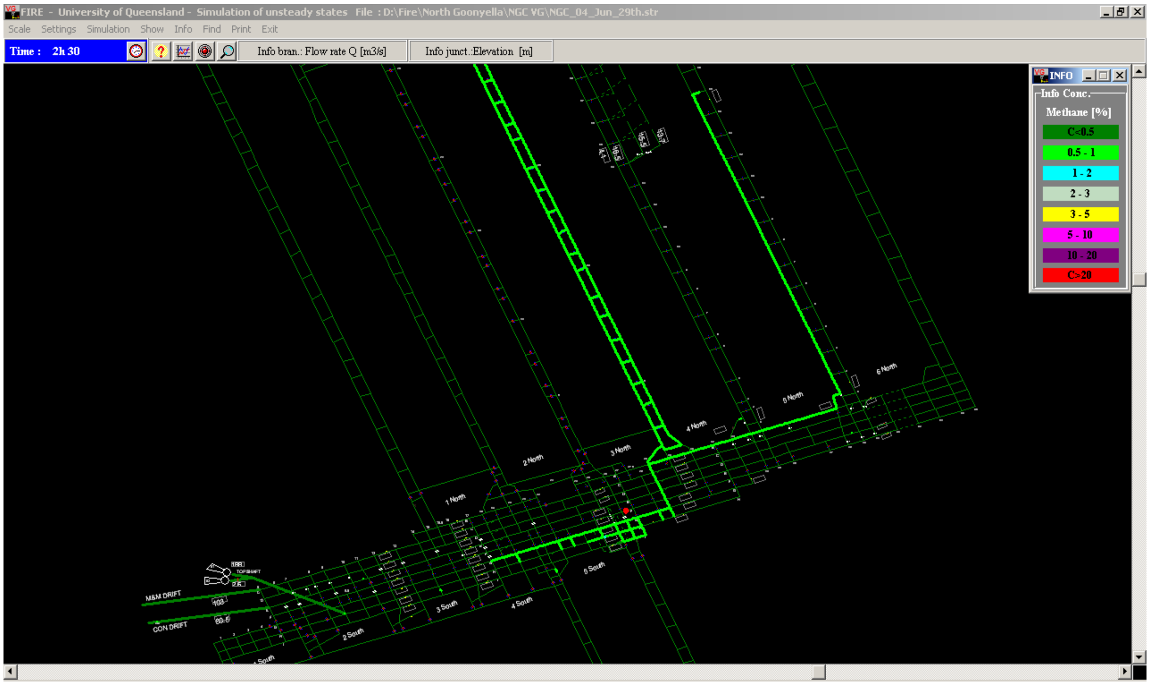

Figure 6 CH_4 distribution after 150 minutes

Air carrying significant CH_4 never reaches the fire zone during the simulation. CO sensor 4N LW Dog Leg has not alarmed after 180 minutes

Step 6 Time 180 – 240 minutes: Coal fire grows. 100 m entry length coal burning. CO sensor 5N Dog Leg is alarming at 240 minutes.

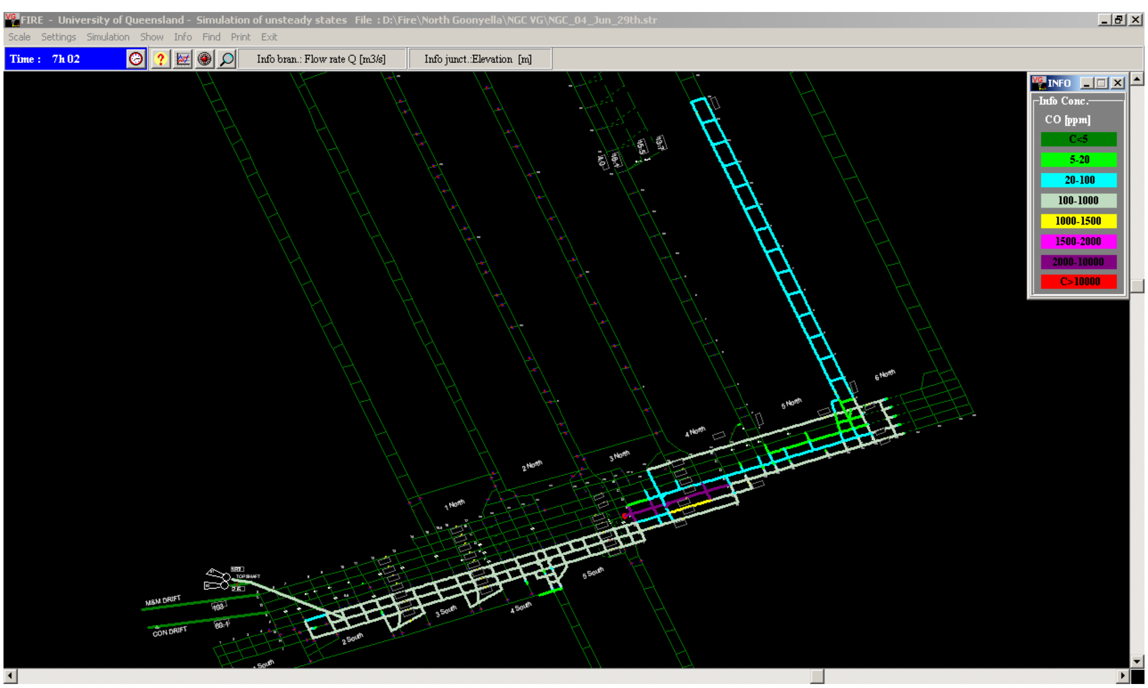

Figure 7 CO distribution after 420 minutes

Step 7 Time 240 – 420 minutes: Continue coal fire, 100 m entry length coal burning. CO sensor in E Hdg 32c/t alarming and smoke has reached LW face. CO path and extent shown in Figure 7.

Turning off the booster fan and one of the main fans changes the ventilation equilibrium within the mine. Air passing inbye the pillar fire in F Heading now courses into the intake airways to the Longwall panel as well as those servicing the development headings. This can be seen in Figure 8.

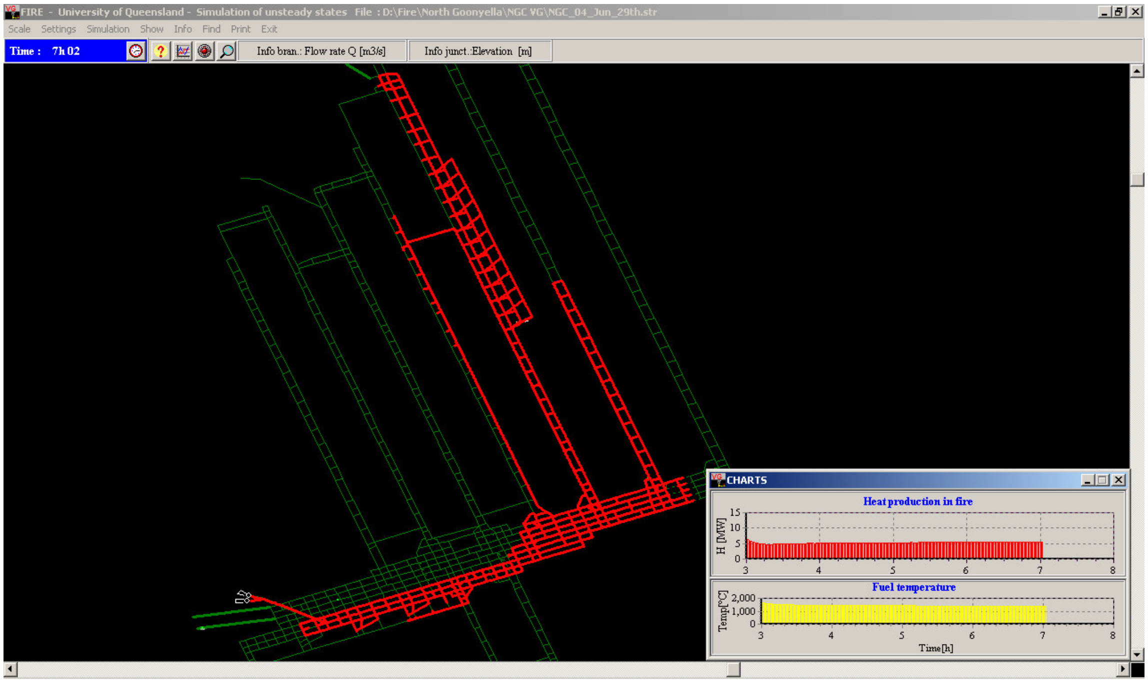

Figure 8 Smoke distribution, heat production and fire temperature after 420 minutes

RETURN SIDE FIRE FOLLOWING THE CHARRING PHASE

Following the charring phase, when the heating has continued to develop until the hotspot and charline encounter the pillar rib on the return side an open fire has broken out on the downwind side of the pillar.

A spontaneous combustion initiated fire in fractured rib pillar coal in G Heading (return) outbye 27 cut through and near the No 2 booster fan. There are no electronic sensors inbye the fire.

Simulation

Step 1 Time 0 – 360 minutes Simulate 1m length fire over entry width. CO path and extent shown in Figure 9

The return side fire builds up gradually and only affects ventilation air in the returns.

Both these intake and return side scenario simulation could be undertaken for much longer on the assumption that coal within the mine continues to burn and no remedial action such as flooding or introduction of gas inertisation occurs. It has shown how a relatively common form of mine fire, a spontaneous combustion initiated coal pillar fire (with the pillar separating intake and return air and with substantial pressure differences) can affect the mine workings. It has shown how CO levels in mine airways increase over time for a specific fire build up scenario.

In the intake side fire significant CO levels reach the Mains and 5N Development faces early but also eventually reach the 4N LW face if the fire is not stabilised and extinguished. The fumes from the fire have only limited effect on the LW face as it receives most of its intake air from Mains C and D transport roads.

In the return side fire significant CO levels build up. However these pollutants are restricted to the return airways and so do not directly imperil miners who are evacuating the mine.

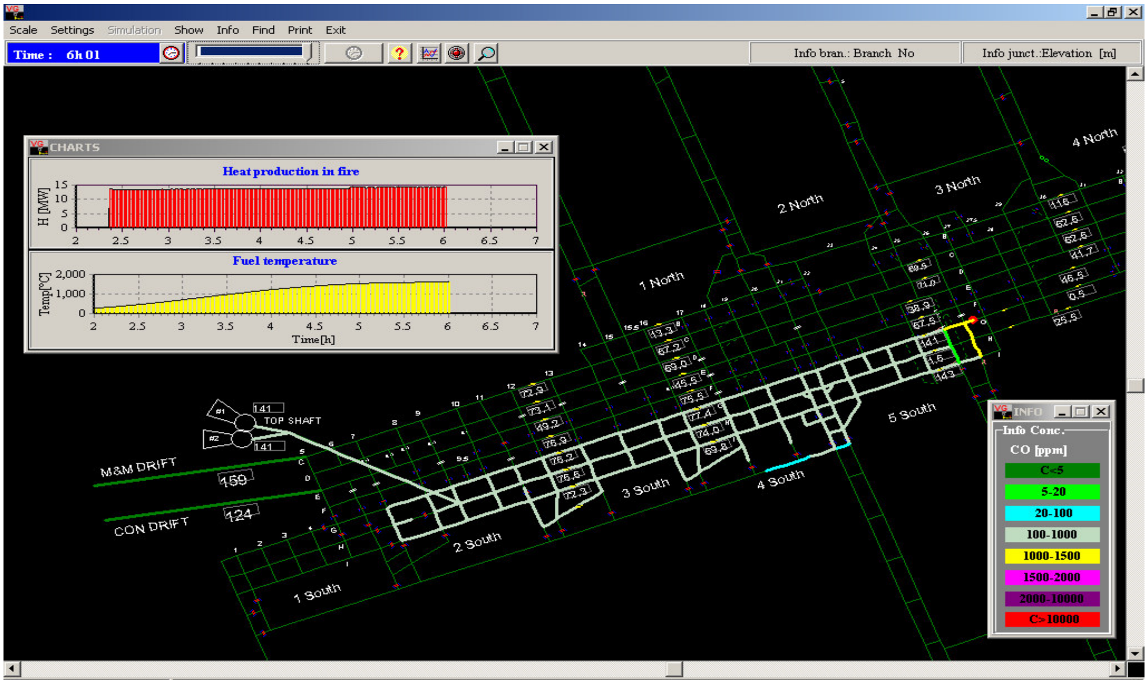

Figure 10 CO distribution levels, heat production and fire temperature after 360 minutes

CONCLUSIONS

A study has examined the potential for simulation of the effects of a relatively common form of mine fire, a spontaneous combustion initiated coal pillar fire on a mine ventilation network. The project involved applying the "Ventgraph" mine fire simulation software to preplan for mine fires and possible emergency evacuations.

The background to this approach to simulating the effects of mine fires on the mine ventilation network has been examined. Approaches to goaf modelling have been examined. The anatomy of a spontaneous combustion heating has been analysed. The three stages in the development of a mine pillar or pile heating, namely the incipient phase, the migration phase characterized by the forward migration of the hotspot and possible open fire on the forward surface and the charring phase, when without remedial action the heating will continue to develop until the charline encounters the downwind surface when an open fire could start.

A case study of the simulated effects of fumes from a fire on the ventilation of a modern Australian mine has been examined. Mine fires are recognized 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 developed from spontaneous combustion heatings. 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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