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LESSONS FROM AN UNDERGROUND COAL MINE FIRE IN AUSTRALIA USING RETROSPECTIVE NUMERICAL SIMULATION STUDY

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Abstract. The purpose of this paper is to present a validation study using the mine fire simulation software package VENTGRAPH to examine and reconstruct an underground coal mine fire that occurred in Australia. This fire occurred in November 1976 at the Appin Mine. To perform this study the authors used data collected at the time of the fire, reports and information from those who were involved at the times of the incidents. There are two primary objectives in performing this kind of study. These are the validation of the simulation software and secondly learning more about and from former mine fires. The study and analysis of former fires should prove beneficial in the instruction and training of mine personnel

Introduction Despite remarkable improvements in mine-safety procedures, coal mine fires remain among the most serious hazards in underground mining. How much of a threat that a fire presents depends upon the nature and amount of material ignited, the ventilation system arrangement, the duration of the fire, the extent of the spread of combustion products, the ignition location and, very importantly, the time of occurrence. Wala, at el., (1995), stated that the response to the fire by mining personnel will depend upon all of these factors.

With the increasing complexity of technological and managerial development of mines, the effects of mine fires must be better understood. There should be a continuous effort to better understand the mechanisms of fire and its influence on the mine ventilation system. One of several ways to achieve this goal is the development of a mine fire simulation computer program enabling mining personnel to analyze ventilation systems, and study emergency plans for different mine fire scenarios.

This was emphasized by the Task Group No 4 report arising out of the Moura No 2 Australia coal mine disaster of August 1994 made a number of recommendations including that, "the capability to model ventilation and the mine environment following an incident should be available at mines".

Following these recommendations, sub-committees were formed in 1997 to further progress various findings with Sub-Committee 5 – Incident Management given certain tasks including the question,

"that there is a need for a wider appreciation of current knowledge and improved capability of ventilation management at mines for both routine as well as emergency conditions; guidelines for modeling should include……..

- Computer modeling of post incident mine ventilation
- and atmosphere to be a required element in mine safety management plans,
- Models interface with standard mine planning packages and be kept up-to-date, and
- Development of learned ventilation and fire control responses occur for different incident scenarios and locations, pre-determined for each mine and with plans prepared and personnel trained in appropriate action plans".

A project supported by the Australian Coal Association Research Program is currently being undertaken into applying

VENTGRAPH mine fire simulation software developed and utilized in Poland by Dziurzynski et al., (1991). This simulation program has recently been put in a “Window” format for ease of use and interrelation with other software and with some ability for transferring mine ventilation planning data from programs such as VENTSIM.

The goals of the project are built around the introduction of modern fire simulation computer software to the industry and the consequent modeling of fire scenarios in a number of different mine layouts. The project undertakes simulations of the effects of common fire causes and fire progress rates. It will also undertake further validation of the simulation model through back modeling of past fires where gas and other relevant data recorded are available.

There is a need to understand the theory behind the recently upgraded mine fire simulation software and to allow use by those already familiar with the main existing mine ventilation analysis computer program currently popular within the Australian mining industry, VENTSIM, as an aid to incident and emergency management. However, VENTSIM was not designed to handle fire simulation or in fact compressible flow effects in mine ventilation networks.

The outcome of the project will be that the Australian mining industry is in an improved position in their understanding of mine fires and the use of modern advances to pre-plan actions to be taken in the advent of mine fires and the handling of possible emergency incidents.

Overview of the VENTGRAPH Mine-Fire Simulation Software Package

The VENTGRAPH mine fire simulation software package used to perform these studies was developed by Trutwin, Dziurzynski, and Tracz (1992). The program, coded in Pascal, combines three distinct modules:

- A conventional program for mine ventilation network calculations,
- A network program that accounts for air compressibility, temperature and depth effects and
- A program that simulates fire development rate, products-of-combustion and air temperature changes.

The purpose of VENTGRAPH is to predict the behavior of the ventilation system in the case of a fire. For clear and convenient display of the calculations results, the program provides a dynamic (animated) representation of the fire's progress, including a color-graphic visualization of the spread of combustion products, the temperature, the flow and other parameters throughout the ventilation system in real time.

This program also enables the simulation of fire controlling actions, such as changing an emergency check curtain, opening or closing a regulator (door), breaching a stopping, and changing the fan characteristics. All of these changes can be simulated at an arbitrary instant, which allows for the testing of various fire control and suppression strategies.

Reasons for Validation Exercises and Need for Australian Examples

Validation studies need to be undertaken to build confidence in accuracy and performance of the simulation software. Previous validation studies on VENTGRAPH have been performed by Wala, et al., (1995) using the data gathered from a real coal mine fire which occurred in November 1991 at the Pattiki Mine, White County Coal Corporation, Illinois, USA. The purpose of this paper is to present a validation study to examine and reconstruct underground a coal mine fire that occurred in Australia in November 1976 at the Appin Mine. There are two primary objectives in performing this form of study. These are the validation of the simulation software and secondly learning more about and from mine fires. Such a study and analysis of former fires should be beneficial in the instruction and training of mine personnel.

Case Study - Appin Belt Drift Fire 1976

Introduction - History of fire

Appin Colliery is situated behind the Illawarra escarpment 36 km from Wollongong, New South Wales (NSW), Australia. The Bulli working seam approximately 3m (9.8 ft) in thickness, lies around 570m (1,870 ft) below the surface. At the time of the fire it is accessed by two vertical shafts 5.1m (16.7 ft) in diameter and two drifts at a gradient of 16 degrees. One of the drift is used for track haulage of men and materials and the other has a belt conveyor installation for coal transport. Colliery development is by continuous miners which block out areas for longwall retreating panels. Coal transport underground is by conveyer belt to a 500 tonnes (550 tons) bin at pit bottom which acts as surge to the belt drift.

A Davidson Sirocco 2.9 m (9.5 ft) diameter double inlet centrifugal fan, normally exhausting approximately 225 m^3/s (476,325 cfm) at pressure 2000 Pa. (7.9 in W.G.), was situated on one of the shafts. The other shaft and both drifts were intakes. Figure 1 illustrates the layout of the drift bottom which shows the belt and man drifts, the bin, the bin elevator drift to the top of the bin, the ventilation line (tubing), and the emergency fire doors.

The belt drift is approximately 3.2m (10.5 ft) wide and 2.5m (8.2 ft) high and is 1912m (6,298 ft) long. It is supported by roof bolts with mesh in the shale beds and is gunited throughout its length. A clouth steel cord rubber belt approximately 940mm (37 in) in width was installed in the drift in 1963. Approval has been granted to use this type of belt on the basis that no fire resistant steel cord belt was then available to operate on a single lift at the load and on the gradient of Appin drift. A total of 101 manholes approximately 20 m (65 ft) apart had been built into the side of the drift. Figure 2 shows a schematic of the belt along the drift. It can be seen from this schematic that during the fire the belt burned out all the way from manholes #80 to manhole #30.

A steel emergency door in the connection road between the two drifts was installed. A steel fire door was also installed in the bin elevator drift partly sealing between the rib on one side and the conveyor belt leaving a gap over and round the belt itself and around a ventilation tube running the length of the bin elevator drift and continuing to the bottom of the return shaft. There was, in addition, a door situated at the surface portal of the belt drift. It was made in two parts and fitted round the conveyor belt and structure.

It was estimated that a 180 Pa (0.7 in W.G) air pressure difference existed between the top and bottom of the drift belt. The top of the bin was connected by a ventilation line (tube) directly to returns (upcast shaft) so that a flow of 5 m^3/s could be maintained up the bin elevator drift to the top of bin (Kininmonth and Fisher, 1981).

On Sunday morning, 7 November 1976, at approximately 1:40 a.m., smoke was discovered emitting from the belt drift. It was later determined that the fire had caused airflow in the belt drift to reverse. Emergency procedures were set in motion. The rescue station was notified at 2:25 a.m., and rescue station personnel arrived at the mine at about 3:00 a.m.

Immediate fire fighting consisted of an attempt to convey water to the site of fire by using fire hoses directed onto the top and bottom belts at surface. At 4:20 a.m., a rescue team traveled into the mine on the haulage in the men and materials drift in which air was downcasting as normal. While they were underground, they closed and sealed the fire door in the connecting roadway near the bottom of the belt drift, broken and sealed the ventilation line leading to the top of the bin and closed and sealed the part door in the bin elevator drift. Sealing of the belt drift at the surface was improved by throwing bags of stone dust and loose dust against the partial doors around the belt. High expansion foam was pushed into the belt drift via a small access door in the concrete portal of the belt drift from 9:45 a.m.

Air samples were taken from the sealed belt drift from 1:30 p.m. onwards. The initial readings indicated approximately 0.39% CO and 0.45% CH_4. By 6:15 p.m., the readings were 0.45% and 0.8% respectively. At 7:00 p.m., both readings were dropped to zero which was take to indicate that the foam plug and the stone dust were being effective. A summary of the chronology of the event and activity during the incident is shown in Table 1.

Table 1 Summarized Chronology of the Appin Belt Drift Fire.

DATE/TIME		EVENT/ACTIVITY
07/11/76	1:40 am	Smoke found around the mine
	4:20 – 6:53am	The fire door in the connecting roadway near the bottom of the belt drift was closed and sealed, the ventilation line leading to the top of the bin was broken and sealed, and the part door in the bin elevator drift was closed and sealed.
	9:45 am	Belt drift sealed and high expansion foam was implemented.
	1:30 pm	Air sample readings at the top of Belt Drift: CO 0.39%, CH_4 0.45%.
	6:15 pm	Air sample readings at the top of Belt Drift: CO 0.45%, CH_4 0.8%.
	7:00 pm	Air sample readings at the top of Belt Drift: CO 0%, CH_4 0%.
	9:55 pm	Foam machine stopped (3700 liters used)
08/11/76	4:30 am	Air sample readings at the bottom of Belt Drift: CO 1100 ppm, CH_4 0.45%.
09/11/76	3:30 pm	Air sample readings at the bottom of Belt Drift: CO 3000 ppm, CH_4 4.0%. No smoke but haze. Belt drift became downcasting.
	5:15 pm	Air sample readings at the bottom of Belt Drift: CO 340 ppm, CH_4 0.2%.
	7:00 pm	Active fire reported between 40 and 58 manhole and water was used to fight the small fire from the top of Belt Drift.
	10:30 pm	Two members of first rescue team reached the pit bottom through the Belt Drift.
10/11/76	2:25 am	A full team reached the bottom after further mopping up operation.

Development of the numerical model of the ventilation system at the Appin Mine

A numerical model representing the Appin Mine ventilation system was developed using the VENTGRAPH software package. This model was developed based on the available limited historical information concerning the geometry of the mine and mine openings (Figures 1, and 2). Due to the location of the fire (descentionally ventilated belt drift) and its effect on the entire ventilation system it was considered sufficient to create a simplified model of the ventilation system to perform the simulation study. The line schematic of the simplified model of the Appin Mine ventilation system is shown in Figure 3. The numbers in the boxes shows the calculated airflow in m^3/s and the arrows at the nodes shows the pressures in Pa. This model is adequate to simulate all control measures concerning this particular fire.

Model of the Fire Source

Development of an adequate mathematical model of the fire is still considered as one of the major problem in computer simulation of a mine fire. Because of the nature of the combustion material, the oxygen availability, and the way fires are started and developed, there are no identical or even similar fires. The mathematical model of the mine fire has to take this diversity in behavior into account. Although a lot of data concerning mine fires behavior has bee collected, a fully satisfactory mathematical model for them does not exist.

The fire source model used by the authors in this study is similar to the model validated by Wala et al., (1995).

Mine Fire and Descensional Ventilation System

Before any simulation study of the Appin Belt Drift Fire will be performed, the authors would like to present the criteria for airflow reversals, developed by Budryk (1956,1976). According to Budryk (1976) any mine ventilation system can be presented by a simple schematic called the closed schematic. The closed schematic for the Appin Mine is shown in Figure 4. As can be seen from Figure 4 branch “c”, named internal subnetwork, represents the Belt Drift with fire. Branch “b'' represents airway(s) parallel to the branch with fire, named bypass subnetwork. In the case of the Appin Mine, these are the Man Drift and Intake Shaft. The stability of these airways is to be investigated or maintained. The bypass branch is the boundary (divider) between the external and internal subnetworks. The last branch of the closed schematic is branch “a”, which represents the rest of the ventilation system, named external subnetwork. All these three branches have associated resistances Ra, Rb, and Rc and pressures Pa, Pb, and Pc. These pressures represents the sum of fan(s) pressure(s) and heat energy (buoyancy) generated by the fire.

Budryk developed a method for the detection of unstable airways using simple “closed schematic” network explained above. By analyzing this simple network, without having to perform a full network calculation Budryk was able to come with qualitative answers which can be of great importance. These answers (criteria) besides indicating where and in which sequence airflow stands still or reversals occur can also give valuable advice as to how threatened airways can be stabilized. The practical implications for escape ways for miners or advance routes for firefighting teams are obvious. These criteria (theoretical relationships) can be used to choose proper rescue and firefighting strategy in case of fire in an underground mine and minimize the any trial and error processes.

Fires in ascensional and descensional ventilation airways act in different ways and so will be discussed separately. In this paper the emphasis is on the descensional ventilation system because this was the case in the Appin Mine. The same criteria could be determined for ascensionally ventilated system. However, for the descensonal system the control process is more complicated than for ascensional. For the descensional system, there are three scenarios depending on the magnitude of the buoyancy generated in a particular airway in which the flow reversed. Within the Appin Mine the branch “c” is not directly (physically) connected with branch “b” at point “A”. (This connection exist in the system, but it is done through the outside atmosphere.) The hot, reversed air, from the belt drift is not getting into the Intake Shaft and Man Drift and generate buoyancy Pb acting in the “bypass” branch. Therefore, the scenario analyzed in this paper will be for relations between these pressures as follow:

$$Pa > Pc > Pb \qquad (1)$$

As mentioned before the Belt Drift in the Appin Mine is ventilated descensionally which means that the air flowing along the drift is flowing from the surface (top) to the bottom. It is known that in case of fire in such an airway (entry) the buoyancy effect (chimney effect, heat energy) will act again the flow. If this heat energy is high enough it could reverse the flow in this airway and in addition could bring the hot air and products of combustion into an intake site of the parallel, adjacent (bypass) airways.

By solving analytically this simple closed network, presented in Figure 4, the criteria for airflow reversals in branch with fire, assuming that conditions described by relation (1) prevail, are as follow:

$$\frac{P_a - P_b}{P_c - P_b} < \frac{R_b + R_a}{R_b} = 1 + \frac{R_a}{R_b} \qquad (2)$$

Because there is no direct connections between the inner branch “c” and the bypass branch “b” at point A, the buoyancy pressure generated in “b” branch will be zero Pb = 0. So the final criteria for flow reversal in branch with fire can be expressed as follow:

$$\frac{P_a}{P_c} < 1 + \frac{R_a}{R_b} \quad (3)$$

To bring the flow in the branch with fire (belt Drift) to the normal direction as it was before fire started and be able to attack fire directly with water waking down along the drift in the fresh air the criteria (3) must be changed to be as follow:

$$\frac{P_a}{P_c} > 1 + \frac{R_a}{R_b} \quad (4)$$

To be able to make this happen the resistance of the outer system Ra must be decreased or resistance of the bypass branch Rb must be increased. If it is possible both resistances could be used to stabilize the system.

Computer simulation of the Appin's Mine Fire

As insufficient gas sampling data available during the 1976 Appin Belt Drift fire incident, it is impossible to try to re-enact step by step what was occurred during the incident and to validate the model based on the comparison of the measured and predicted gaseous levels in the mine.

However, it should be noted that some of the phenomenon of the fires observed during the 1976 Appin incident can be seen during the simulation session following the list of major events, see Table 1, during the firefighting action at the Appin Mine. The whole time period between the first smoke occurrence on November 7, 1976, 1:40 am, till November 9, 1976, 3:30 pm when the Belt Drift flow was still unstably, switching back and forth, because problems with sealing the portal at the top of the Belt Drift. To be able to show similarity between real scenario and simulated one the authors are going to show three snapshots of the computer screen for following timings:

- the first five hours of the event, November 7, 1:40am – 7:00am (fire started – flow reversal in Belt Drift – sealing both fire doors at the bottom of the drift, and blocking the tubing ventilation, see Figure 5.
- time between 6:00am – 10:00am on November 7, 1976, when the sealing of the Belt Drift took place, see Figure 6,.and
- period between 9:50pm – 4:30am on November 8,1976, when other attempt for better sealing of portal stared again, see Figure 7.

This is based on the following assumptions:

- A Belt fire occurs at location of manhole #80, approximately 450m up from the bottom of belt drift.
- Belt burning to a maximum length of 100 m along the Belt Drift with a medium fire intensity of 5 in the scale of 1-10.
- Assume 10% ratio between the CO to CO_2, in the combustion product.
- Time constant of the fire development is 4 hours (14,400 seconds).

Based on the simulation, the airflow reversal was observed about 1 hour 47 minutes after the fire simulation initiated. Figure 6 shows a snapshot of the fire simulation result 2.5 hours after fire started. It can be seen that there is a reduction in heat production when the airflow reversal occurred. It is understood that as the products of fire are forced passed or over the fire at the moment when airflow reversal occurs, the amount of oxygen available to the fire is decreased.

The timing of airflow reversal occurrence will depend on many factors such as size and intensity of the fire as well as the location of the fire. By the time the Appin fire was noticed on the surface (there was no one underground at the time), the airflow in the Belt Drift was already upcasting, so it is impossible to determine the actual timing of the reversal of airflow. However, it is important for the model to be able to demonstrate this potential phenomena aithough in this case reversal prevented combustion gases traveling into the mine.

Generally the whole firefighting activity was about to bring the flow in the belt drift back to the direction as it was before fire started to be able to actively fight the fire with water from the top in the fresh air. To achieve this goal actions was taken of closing both fire doors (bottom of the drifts and bin drift), disconnection of tubing ventilation. Figure 7 shows the flow and fire behaviors after both fire doors were sealed off and ventilation line blocked. Figure 8, and 9 show the flow and fire behaviors after cutting off oxygen to the fire to retard by sealing of the portal of the Belt Drift. These three actions increased resistance of the external part of the system while the fourth action did not achieved any advantage, according to the criteria expressed by formula (4).

To be able to show the fire control procedure according to formula (4) the fire simulation was performed again following the actions which agreed with the above mentioned conditions. The resistance of the external system could be reduced by opening the fire doors. Simulation shows that this is not enough and breaching the stopping between intake and return branch between nodes (43 – 10) will assist this objective. In addition this reversing of the flow in the belt drift and establishing stability may be achieved by increasing the resistance of the bypass branch (intake shaft) by hanging a curtain. Figure 10 shows the flow behaviors in the ventilation system by applying the plan presented above.

Conclusions

- This study is the next step on the road to prove that software developed to simulate a mine fire and its interactions with a ventilation system, particularly VENTGRAPH, can be used for training and instruction of mining personnel, Wala, (1992). After more studies like this confidence will be achieved that numerical simulation can be used as a tool for decision making during real mine fires

- By comparing the behavior of the real fire at the Appin Colliery, as described by Kininmonth, and Fisher (1981), the simulation results were very close (at least quantitatively) to that seen at the mine.
- The authors would like to emphasize the importance of collecting valuable information during real mine fires. This information can help to perform further validation studies of the simulation software.
- The real Appin Colliery belt drift fire provided an opportunity to develop a model of the mine fire in a descensionally ventilated mine. This model is an excellent “textbook example” to teach students, engineers, managers and rescue personnel about controlling the ventilation system in the case of a fire using Budryk’s method of applying a closed schematic.
- This study shows the advantage of using Budryk’s method for the detection of unstable airways in the ventilation system in the event of a fire.

Acknowledgment

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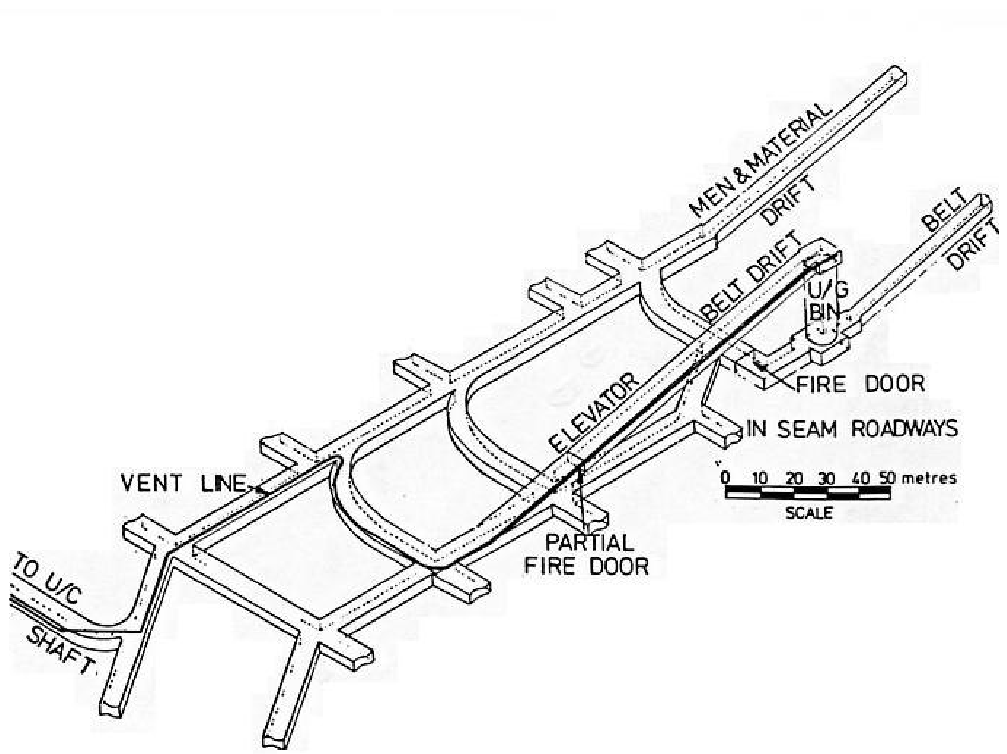

Figure 1. The layout of the drift bottom at Appin mine 1976 (After Kininmonth and Fisher, 1981)

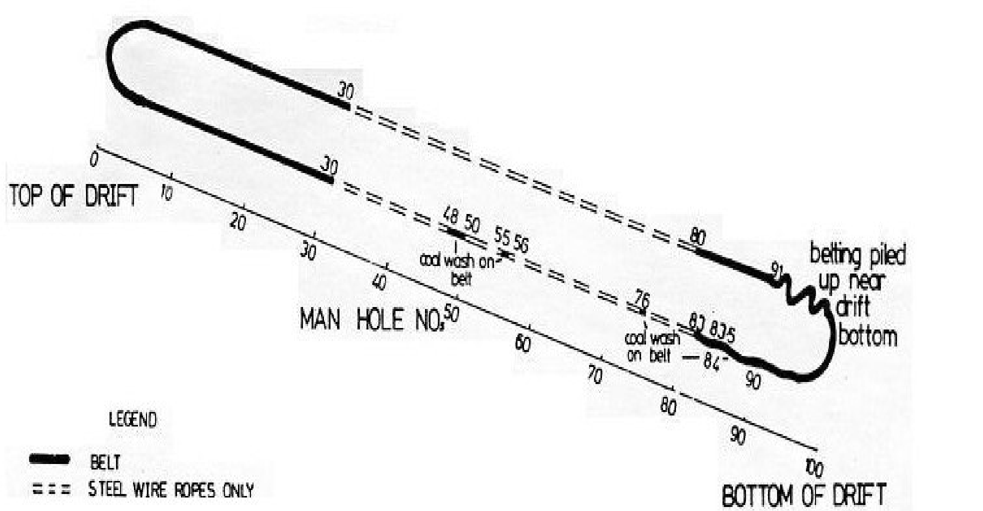

Figure 2. Schematic of the drift belt arrangement in the Appin Mine, 1976 (After Kininmonth and Fisher, 1981)

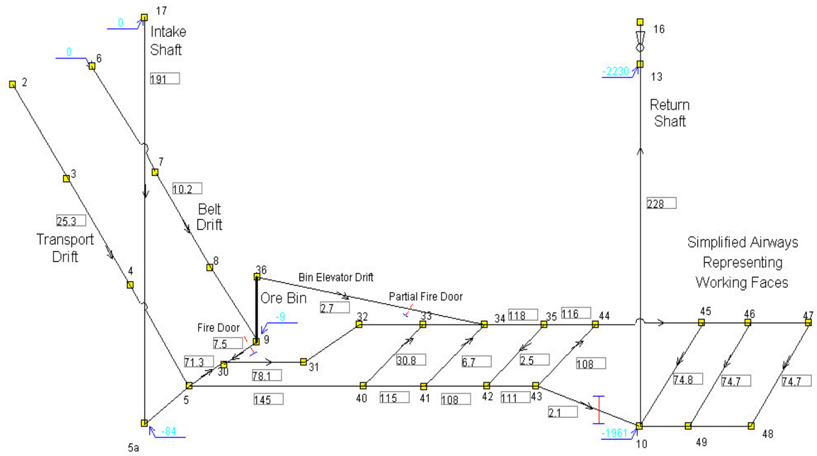

Figure 3. A line schematic of the simplified ventilation system of the Appin Mine

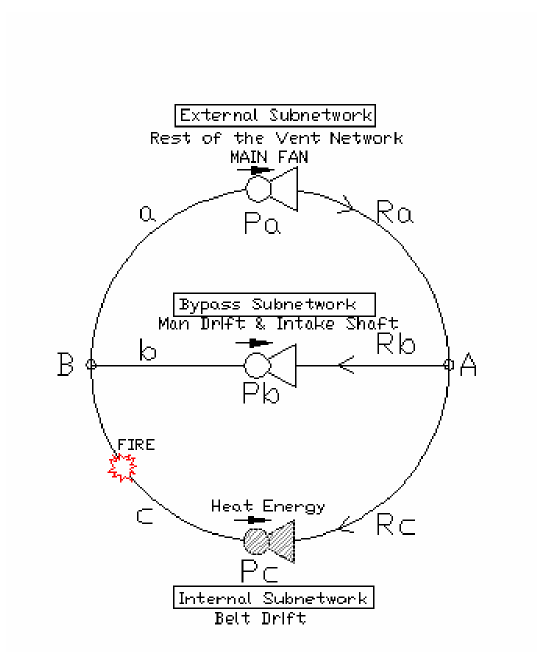

Figure 4. The Closed Schematic of the Appin Mine ventilation system with fire in the Belt Drift

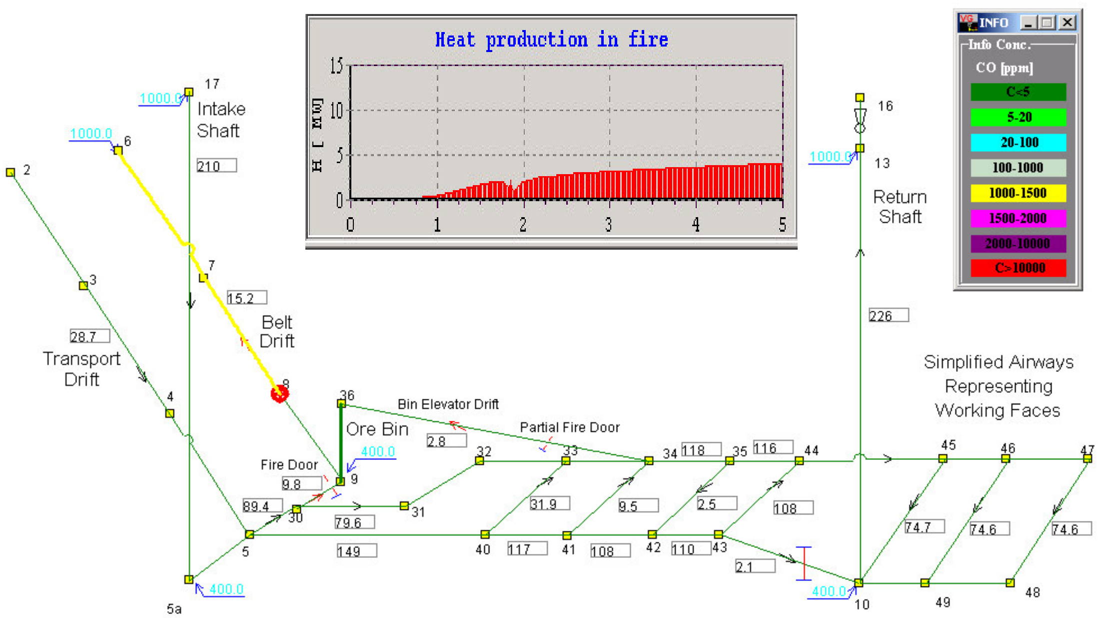

Figure 5. Snapshot of the VENTGRAPH fire simulation showing CO level and heat production.

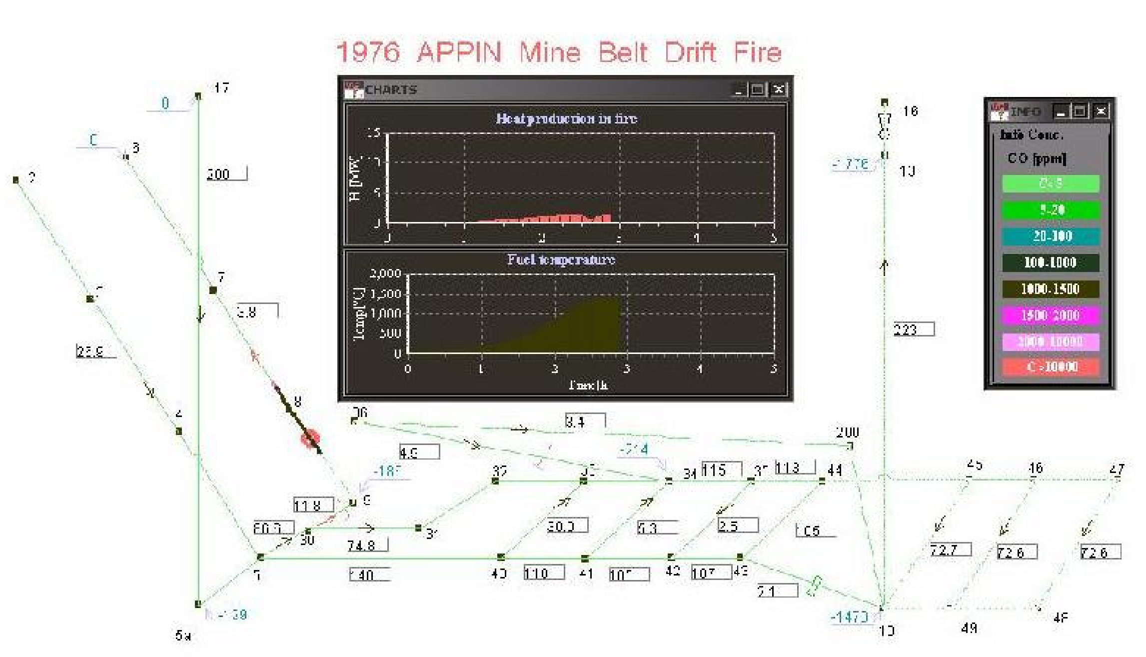

Figure 6. Snapshot of the VENTGRAPH fire simulation, showing CO level and heat production around three hours since the fire started and few minutes after flow reversal in the belt drift.

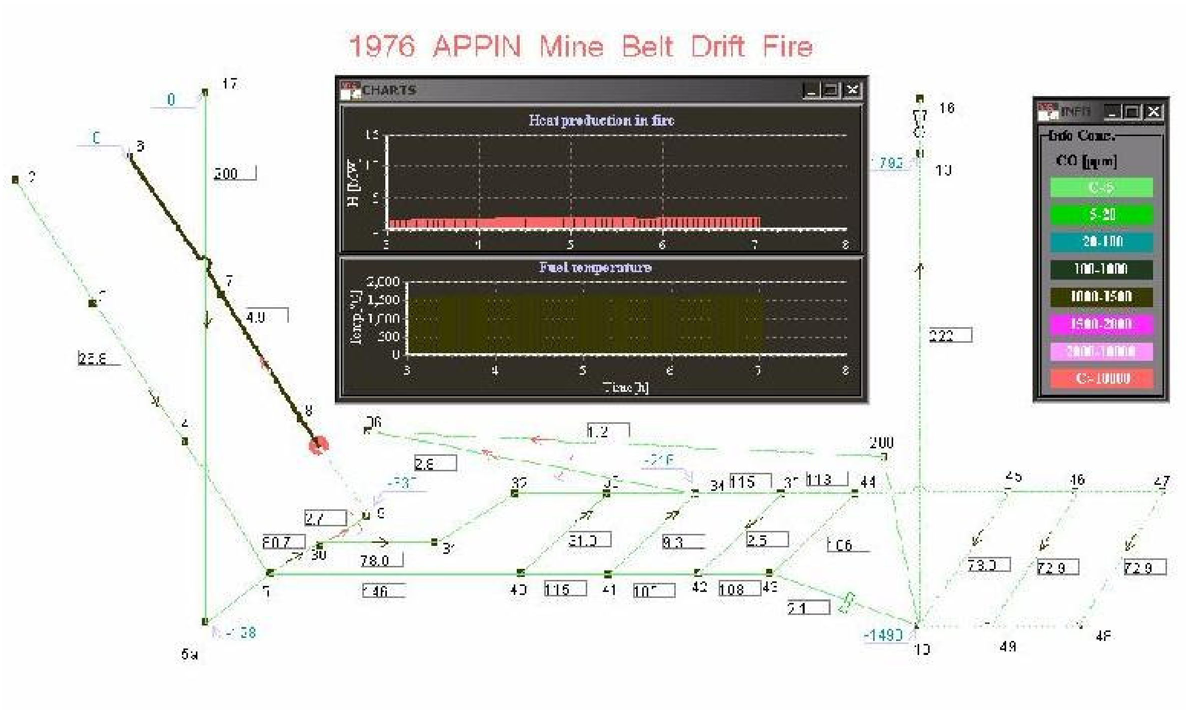

Figure 7. Snapshot of the VENTGRAPH fire simulation, showing CO level and heat production around seven hours since the fire started and after both fire doors being sealed and ventilation line being disconnected.

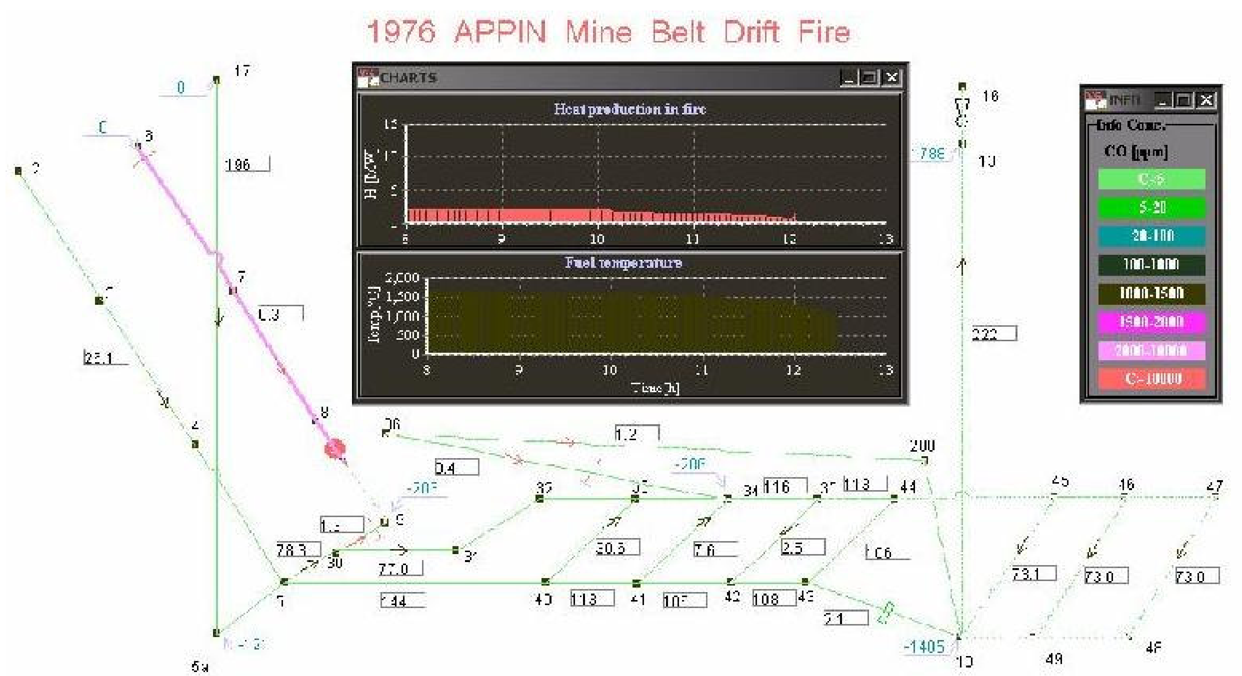

Figure 8. Flow and fire behaviors after twelve hours and limiting oxygen into the fire by sealing the portal.

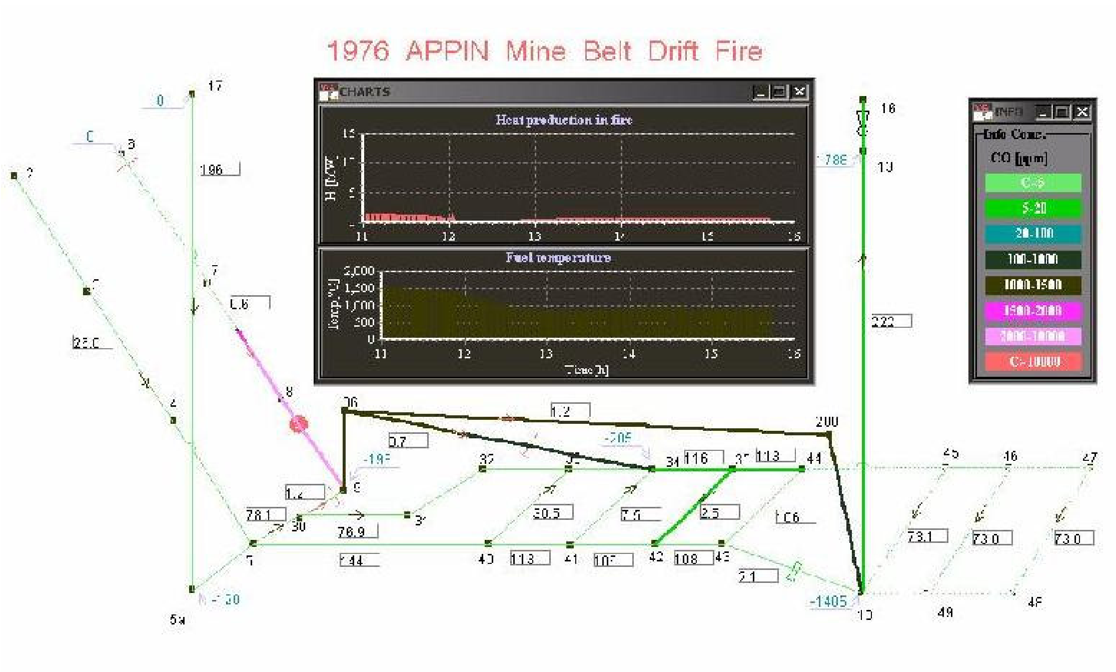

Figure 9. Flow and fire behaviors after fifteen hours sine the fire started.

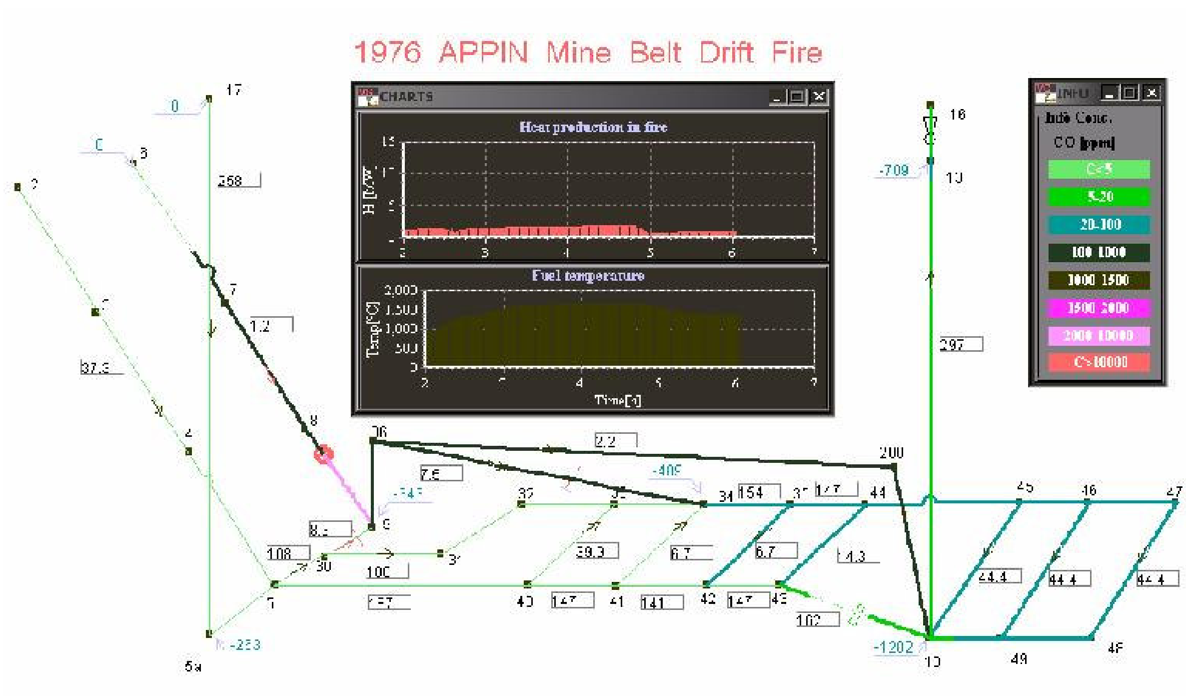

Figure 10. Flow and fire behaviors after stopping in branch, between nodes 43 – 10, was breached (resistance Ra of the external subnetwork was decreased).