Fire Behavior Analysis of a Mine Future Plan

Ali Haghighat[1], Stewart Gillies[2]

[1]*Virginia Tech, Blacksburg, Virginia, USA*
[2]*Missouri University of Science and Technology, Rolla, Missouri, USA*

No underground peril has the greater potential for the large loss of life than a mine fire or explosion. A study was carried out at the Missouri University of Science and Technology MS&T Experimental Mine to better understand fire behavior in unpredictable incidents. MS&T Experimental Mine is a limestone underground mine. Ventsim Visual software modeling was used to investigate fire behavior through airways of the mine ventilation network planned for the future. Both naturally and mechanically induced ventilation pressures were taken into account. Within different parts of the mine two different scenarios were determined. In all scenarios examined the fire source was a burning Bobcat vehicle. The effect of usage of two different kinds of tires were investigated in all scenarios. Numerous parameters such as levels of CO, CO_2 and psychrometric behavior, visibility and airflow direction were investigated during the study time. Four stations were chosen as the target points to monitor predetermined factors. Various options were considered to confine the fire in a part of the mine. The effect of tires on fire intensity was considered as one of the most important factors for fire control. High risk parts of the mine were identified. An approach to control the fire at different time increments focusing on selected key parameters of lowest levels of toxic gases and dry bulb temperature and high visibility was adopted. Procedures to control fires in two main sections of the mine from external to excavations were proposed. This study has been undertaken to show that the development of an emergency plan ahead of any incident is vital in fire events for all mines.

Keywords: Fire Analysis, Ventism, Visibility, Psychrometric Behavior, Species

1. Introduction

The smoke and gases produced by a fire in a confined space may quickly create a lethal atmosphere for underground workers exposed to the event. For this reason there is a need to predict the effects of underground fires and utilize the results to establish emergency response procedures and systems to ensure the safety of people working underground (Ventsim manual). A study has been carried out to simulate a fire event in the MS&T Experimental Mine future layout using Ventsim Visual software in order to investigate produced noxious gases and select the fastest and safest design to mitigate the percentage of hazard in the mine. Heat simulation and dynamic simulation habeen calibrated for fire simulation commencement. All psychrometric data has been put in to the simulator according to the latest field survey. Two scenarios have been considered to investigate numerous parameters such as CO, CO_2, airflow, and dry bulb temperature at stations. Four different stations have been determined as the target points to monitor fire behavior. Four hours was set as the simulation time for all scenarios. Fire events in all scenarios have been set to 20% diesel and 80% rubber in four main steps. Natural and mechanical ventilation pressures have been considered in all scenarios. The direction of airflow has been investigated in each scenario.

Surface fan operation has been controlled according to the least amount of hazard accomplishment. After three minutes of fire event both booster fans was turned off. Various options have been considered to reduce the amount of dangerous gases at monitored stations in all scenarios. Tire selection has been considered in all simulations. Confining the fire in a limited area and the lowest monitored amount of CO, CO_2, and dry bulb temperature at determined stations and high amount of O_2 in safe areas of the mine have been determined as the key criteria amongst all scenarios for selecting the optimal scheme in emergency situations. The ideal long distance control of fire for mitigation of hazards, temperature and toxic gases has been selected as the most advantageous plan in each scenario.

2. Scenarios specification

The main problem with many mines today is that they are complex often with multiple shafts, ramps and drifts making it difficult to control the way the smoke and heat spread in the instance of a fire. Ventsim Visual program was used to investigate fire behavior in monitored stations of the mine.

Author's email: alih83@vt.edu

VentFIRE in Ventsim Visual program uses a discrete sub-cell transport and node mixing method to simulate moving parcels of heat and gas around a mine. To dynamically model mine ventilation and accurately take into account continual changes in atmospheric concentrations of gases and heat including recirculation, VentFIRE breaks the model into small independent 'cells' which move freely around a model, mixing with other cells at junctions. Heat transfer to and from each cell from rock strata is calculated by the radial heat transfer method, but with strata heat transfer modified by the assumption of exposed rock boundary temperatures at a long term aged average, coupled with a very short time Gibson's algorithm constant to accelerate heat transfer to and from the immediate rock boundaries during the fire simulation as described in Ventsim Manual [9].

Risk analysis may be done in many different ways both qualitatively and quantitatively [5]. To be effective, addressing risk at mines or industry-wide requires such a targeted and systematic approach that is capable of solving the problems permanently, thereby precluding a potential reoccurrence of them [4].

Fire simulations have been designed according to the designed air simulation of experimental mine future ventilation network. In all scenarios main surface fans have been set to the pull system. Heat and dynamic simulation as prerequisite of fire simulation have been designed appropriately. Dynamic increment has been set to 0.5 seconds for all simulations. Both natural and mechanical induced ventilation pressures have been taken into account in all scenarios.

Two different scenarios were considered to investigate airflow behavior and numerous characteristics in predetermined parts of the mine. Rock type has been set to limestone in all scenarios with 1.3 W/m ˚C thermal conductivity, 1.2 m^2/s 10-6 Thermal diffusivity, 840 j/kg ˚C Specific heat and 1.290 kg/m^3 as density. In all simulations, 25˚ C was assigned to the rock temperature. According to the latest pressure and quantity survey, 18.5˚ C and 22˚ C were put in the simulation for surface wet bulb and dry bulb temperatures. The amount of 20% diesel and 80% rubber were put into the program as the fuel type for burning. Four main events with different start and end time periods and initial and ending burning rates have been set as the dynamic events for the creation of the fire simulation. Dynamic event data for the design of a Bobcat burning is shown in Table 1. The smoothing factor for the simulation result has been set to 500. Four monitors as shown in Figure 1, were established to investigate different airflow parameters at those stations. For all scenarios, the amounts of CO_2, CO, and O_2, psychrometric properties, visibility, and airflow were monitored at the four predetermined stations. Numerous procedures have been investigated to control produced fire at selected working face. An optimum way was proposed to reduce hazards in perilous situations at three main spots of the mine. In all scenarios the threshold limit values (TLV) for CO and CO_2 were considered 25 ppm and 0.5% respectively.

Table 1. Bob cat with EarthForce™ compact tires burning event information through 4 hours.

Events	Time Range (sec)		Burn Rate (Kg/hour)	
Name	Start	End	Initial	Final
starts	0	1800	0	200
escalates	1800	3600	200	480
maximum	3600	13800	480	480
ends	13800	14400	480	0

Twenty percent diesel and eighty percent rubber have been assigned to be burnt. During the first 30 minutes, 2500 kW energy has been produced by burning of that fuel. The second step of the fire event is when it escalates. The period of this step was set to 1 hour. The amount of energy has increased to 6000 kW. During the third step of the fire event (fire maximum) 6000 kW has been produced by the fire. The period of this step was set to two hours and fifty minutes. During the fire termination step, 6000 kW has reduced to zero in the last 10 minutes.

The intensity of a fire or heat release rate is largely determined by the rate at which oxygen can reach the fire and the surface area and type of fuel available for burning. Within certain limits, if more oxygen reaches the fire, the intensity of the fire increases and vice versa [2].

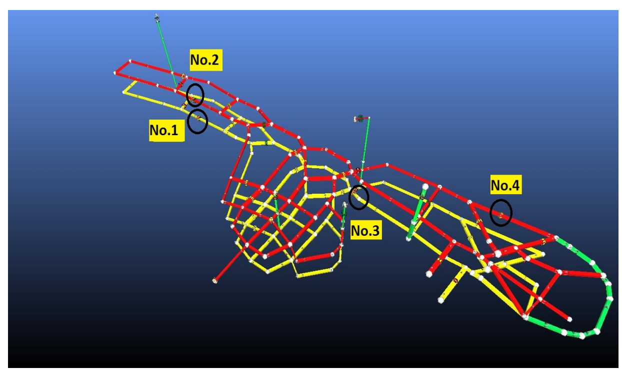

Figure 1. Monitors position through airways.

3. Tire specifications in the mine

The Bobcats in MS&T Experimental Mine have been using two different types of solid tires. All Scenarios have been simulated according to the EarthForce™ solid press-on tire. The use of standard duty pneumatic tires were compared to the EarthForce™ solid tires too.

3.1 EarthForce™ solid press-on tires

These kinds of tires with their sidewalls are designed to prevent cuts and cracks in aggressive terrain. They are made of heavy duty rubber compounds for increased service life and have advantages as following:

- Deep lug treads provide traction in an assortment of terrains
- Great shock absorption for machine longevity and operator comfort
- Super smooth tires also feature air-cushioned design

The use of this tire in the Experimental Mine is shown in Figure 2.

Figure 2. EarthForce™ solid press-on tire.

By the use of this kind of tire, the money spent due to flat tires has been eliminated and the longer tire life time has been achieved. Specification of this kind of tire has been shown in Table 2.

Table 2. EarthForce™ solid press-on tire specifications in experimental mine.

Model	EarthForce™
Style	Dirt Terrain with Rim
Outside Dia. (mm)	838
Tire Width (mm)	305
Rim Dia. (mm)	406
Tread Depth (mm)	51
Weight (kg)	113

3.2 Standard duty pneumatic tires

These tires are created for long wear during normal machine-hour applications. The use of this tire in the Experimental Mine is shown in Figure 3.

The special rim guard and thick sidewalls provide protection against punctures. They're constructed with natural and synthetic rubber. Specification of Standard Duty Tires is shown in Table 3.

Figure 3. Standard Duty pneumatic tires.

Table 3. Standard Duty pneumatic tire specifications.

Model	Skid-Steer Loader
Style	Standard
Outside Dia. (mm)	787
Tire Width (mm)	254
Rim Dia. (mm)	419
Tread Depth (mm)	14
Weight (kg)	36

As Thyer in 2002 [8] explained, the key principles of fire management in an underground mine are as following

- Prevention of the fire commencement by the usage of appropriate suppression materials or systems
- Early detection of fire and provision of effective system to isolate/reduce the impact of fire.
- Providing warning for persons underground and applying the effective egress and refuge systems

The identification of potential fire locations and fire types and the associated consequences are the main focus of every fire study. In order to do this a hazard analysis is necessary. To conduct fire modeling, it is necessary to evaluate the risk of a fire in the mine and its consequence [6]. According to the conducted hazard analysis study, two main locations have been selected for fire analysis in the MS&T Experimental Mine.

4. Scenarios

4.1 Scenario 1, fire at the west working face (down level).

Fires rarely start in shafts, because these are generally damp or wet. In slopes or drift entrances fire are as likely to occur as in any mine passage or level [7].

In this scenario, fire has been set at the west working face on the lower level. The pull system of surface fans has been considered to investigate the behavior of fire and different characteristics through the airways in four hours real time. The fire event has been set to act as shown in Table 1. EarthForce™ solid tires have been used in the Bobcat burning simulation. Six minutes after fire event commencement, the east surface fan has been set off. Three minutes after initiation of the fire event, booster fans in lower and upper levels have been turned off. Two blocked raises at the center and the east part of the network and two closed adits at the east panel of the experimental mine, as shown in Figure 4, have been opened after ten minutes in simulation. The west portal was closed 10 minutes after the fire started. All of the times for this scenario were selected according to the distance and the action of the mine's work force. The distribution of noxious gases through the airways after 1 hour is shown in Figure 5.

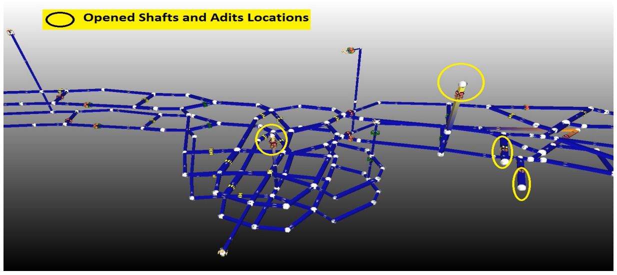

Figure 4. Opened adits and shafts 10 minutes after fire starts.

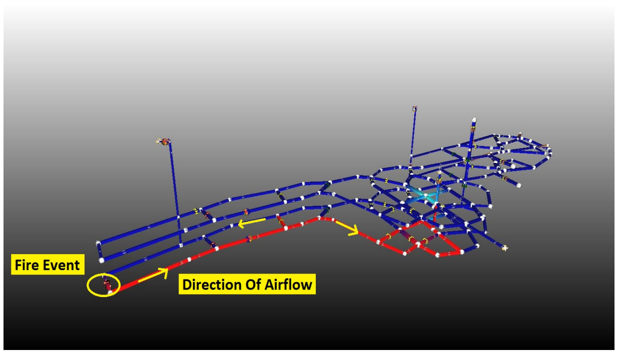

Figure 5. Fire distribution, 1 hour after fire initiation (pull system).

The slope of the tunnel, combined with its reduced height, causes a predominant propagation of the smoke in the ascending direction. Thus, the exhaust openings placed in the descending direction with respect to the fire location do not aspirate smoke, but clean air. In the case of an emergency, the individual operation of the exhaust openings should be allowed. Also, their number should be increased, in order to open more exhaust openings located in the ascending direction from the fire location [1].

4.1.1 Airflow and O_2 behavior at monitored stations

Fires produce large amounts of very hot, very low density gas. This results in four main effects on the ventilation system as following [3]:

- Throttling or choking effect
- Chimney or natural draft or natural ventilation effect
- Flow reversal
- Roll back

Natural ventilation pressure, opened adits, shafts, and fire affected the direction of airflow at all stations. The airflow direction has been changed at station 1 about 1 hour after the fire began. The airflow result at station 1 during the whole burning time is shown in Figure 6.

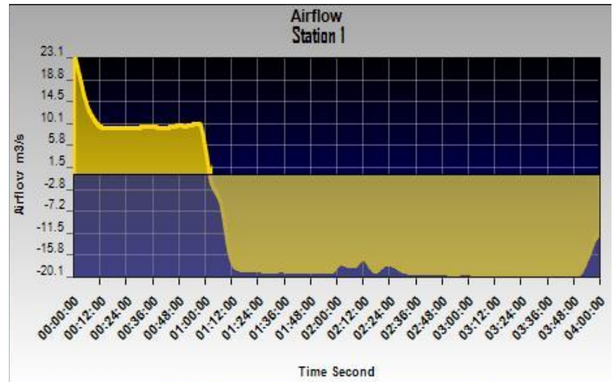

Figure 6. Air flow behavior at station 1.

It is evident from Figure 6 that the maximum amount of airflow at station 1 in the reversed direction was 20.1 m^3/s. As it can be seen in this figure, the graph exhibits sharp drop during the first 12 minutes when booster fans and east surface fan have been turned off and the adits and raises have been opened completely at 10 minutes and then remained constant up to 1 hour. The airflow has been decreased dramatically at that time because airflow has been reversed and it almost leveled off up to the last 10 minutes. The last drop happened in the last 10 minutes of the fire event. The graph under the zero line is showing the reversed direction of airflow at that station through the time. The airflow decreased near the end of the fire.

Airflow at stations 3 and 4 behaved the same. The least amount of airflow has been recorded at 8.1 m^3/s at station 4 (furthest monitor to the fire source) in the reversed direction. An airflow diagram at station 4 is plotted in Figure 7. At 10 minutes, the airflow direction at station 4 has been changed and then increased marginally to 8.1 m^3/s up to the end of 1 hour and almost remained constant up to the end of simulation. The minimum and maximum amount of airflow at station 3 has been recorded as26.3 and 26.7 m^3/s.

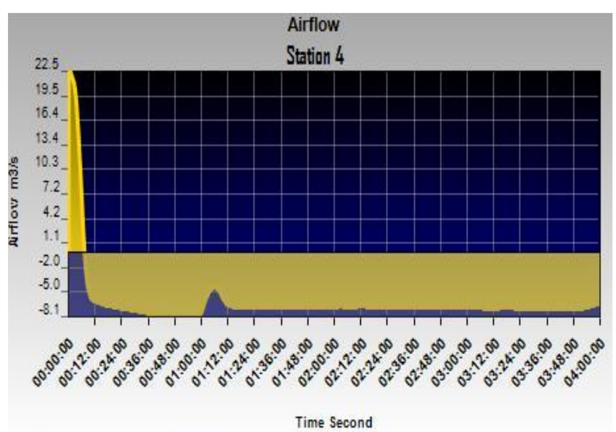

Figure 7. Airflow distribution in 4 hours at station 4.

According to the airflow data at station number 2, it is evident that the airflow graph decreased when the fans were turned off. Then the airflow increased conspicuously, across the period from 10 minutes to 1 hour, to 22.4 m^3/s. Because of the fire behavior, the direction has been changed again at 1 hour after fire initiation and reached to 5.5 m^3/s at which it remained constant up to the end of event. The results are illustrated in Figure 8.

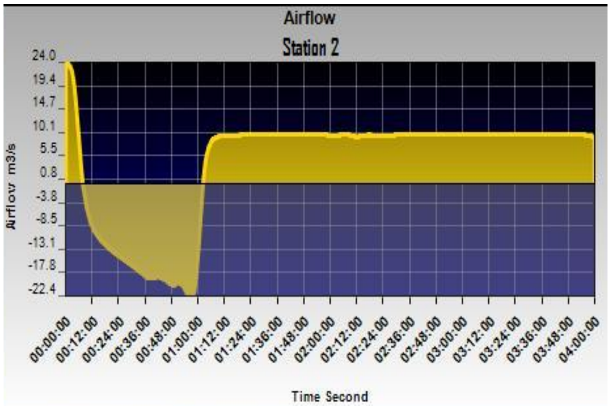

Figure 8. Airflow distribution at station 2.

It is evident from the above figures that natural ventilation pressure, effects of opened adits and shaft and fire effect have had a large effect on the direction of airflow at all part of the mine.

Before the fire event, the amount of O_2 ranges from 21.1% to 21.7% in all scenarios. The least amount of O_2 that has been monitored was 18.8% at the closest station to the fire when the fire has been simulated for 4 hours. The closest station to the fire was station 1. The range of O_2 in all stations is shown in Table 4.

Table 4. Oxygen percentage in all stations through 4 hours.

Station	Min O_2 %	Max O_2 %
1	18.8	21.3
2	20.5	21.4
3	21.6	21.7
4	21.0	21.1

4.1.2 CO and CO_2 behavior at stations

At all stations, the amount of CO and CO_2 has been recorded in order to get a better understanding of fire behavior through the airways. At station 1, the amount of CO has increased dramatically and approached 2200 ppm as the peak point after 1 hour and then it remained constant up to the last 10 minutes. The graph exhibits a sharp decrease during fire termination period. The amount of CO at the end of the fire event after 4 hours was approximately 700 ppm.

By briefly glancing at the CO_2 graph from this station, it is evident that the CO_2 is behaving the same as CO behaved in the period of the fire. The highest amount of CO_2 at this station was 1.86 % and at the end of 4 hours this amount has been diminished to 0.220% conspicuously. The highest amount of CO and CO_2 were recorded in this station.

The amount of CO has escalated dramatically in the first 72 minutes of the event at station number 2. The highest concentration during the fire was 1427 ppm and then it decreased sharply to 714 ppm. A direction change has been determined to be the main reason for the great change in the amount of CO between 60 and 72 minutes. After 72 minutes, the amount of CO has decreased sharply to 714 ppm and then almost leveled off until the last 10 minutes. A sharp decrease happened during the last 10 minutes. The amount of CO at the end of 4 hours was 350 ppm. The results are gathered in Figure 9.

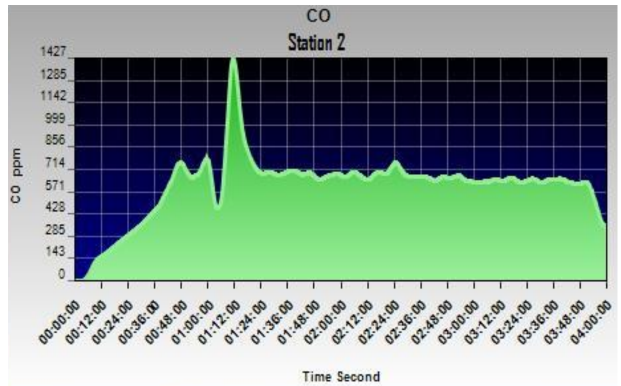

Figure 9. Amount of CO at station 2.

When the CO_2 graph at this station was studied, it was discerned that the behavior of CO_2 was the same as CO at this station. The maximum amount of CO_2 at station 2 was 0.438% as shown in Figure 10.

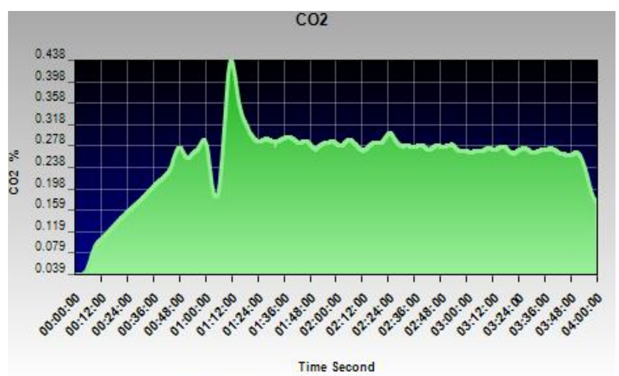

Figure 10. CO_2 behavior at station 2.

It is clear that the furthest station had the least amount of toxic gases compared to the other stations.

Due to its distance, the least amount has been recorded at station 4. The monitored amount of CO and CO_2 at the east part of the mine was not considerable. Stations 3 and 4 have been determined to be the safest place amongst all determined stations in this scenario. At these stations, the amount of CO and CO_2 has been kept less than TLV. As has been seen at the previous stations, the graph behavior of CO and CO_2 were the same as each other at both 3 and 4 stations. The result of CO and CO_2 at stations 3 and 4 are shown in Table 5.

Table 5. CO and CO_2 results at stations 3 and 4.

Station	3	4
Min CO (ppm)	0	0
Max CO (ppm)	7	4
Min CO_2 %	0.039	0.038
Max CO_2 %	0.063	0.054

4.1.3 Psychrometric behavior at stations

In this study, all dry and wet bulb temperatures and the rock temperature have been investigated at all stations. The highest temperature was recorded at station 1. The temperature changes during the 4 hour fire event at stations 3 and 4 were not considerable. During the first hour, the dry bulb temperature graph remained at its lowest amount. During the next 12 minutes, the temperature reached its highest point at 201˚C at station 1. Then it decreased to 183.4 ˚C and it plateaued until the last 10 minutes of the simulation. During the last 10 minutes, the graph has decreased noticeably to 78 ˚C at the end of the 4 hour simulation. The result of dry bulb temperature at station 1 is plotted in Figure 11. The wet bulb temperature behaved the same as the dry bulb temperature. The minimum and maximum wet bulb temperatures were 19.8˚ and 52.7 ˚C.

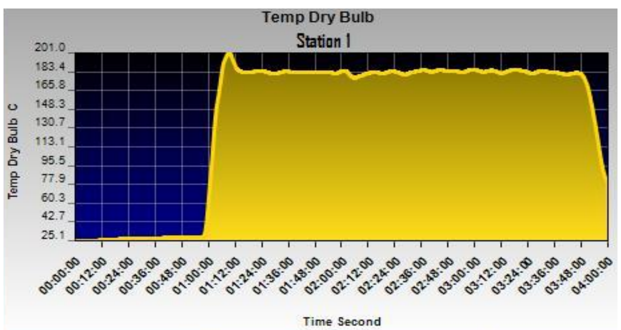

Figure 11. Dry bulb temperature graph at station 1 in 4 hours fire event.

The rock temperature continued to increase from the beginning of the fire event until the end. The highest rock temperature amongst all of the stations was 67.4˚ C at station 1. The result of rock temperature at station 1 has been shown in Figure 12.

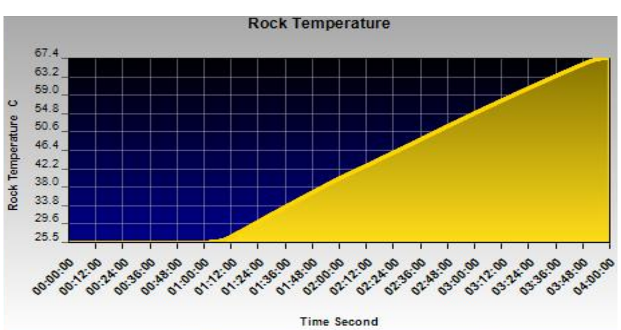

Figure 12. Rock temperature changes at station 1.

The range of psychrometric behavior at the other stations has been recorded and is illustrated in Table 6.

Table 6. Various temperature result at stations 2, 3 and 4.

Station	2	3	4
Min DB Temp ˚C	24.8	25.1	24.5
Max DB Temp ˚C	77.2	28.8	26.1
Min WB Temp ˚C	19.6	19.9	19.6
Max WB Temp ˚C	34.8	20.0	20.6
Min Rock Temp ˚C	25.1	21.5	24.6
Max Rock Temp ˚C	28.4	25.2	24.6

It is evident from Table 6 that the fire has not had a significant impact on temperature changes at the eastern part of the mine.

4.1.4 Visibility at stations

With the exception of stations 1 and 2, all of the stations' visibility have not been affected by the fire. This was evident from the fact that the eastern part of the mine was devoid of smoke. Visibility at station 1 decreased from 25 m to 0.1 m during the first hour and then it remained the same until the last 10 minutes. During the final step of the fire, the visibility at that station increased to 2.6 m. The visibility graph is plotted in Figure 13.

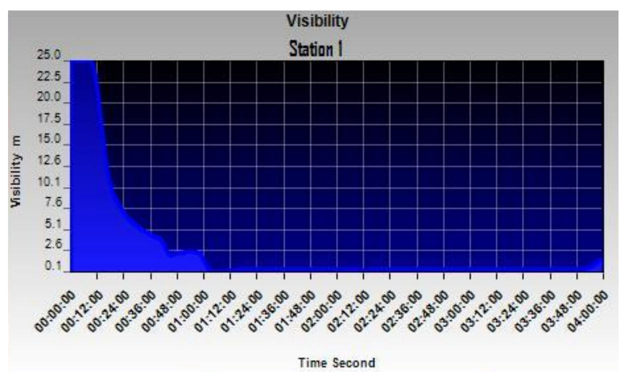

Figure 13. Visibility graph at station 1.

The visibility graph at station 2 was recorded the same as it was at station 1. The visibility was 25 m before the fire event and it decreased spectacularly to 0.6 m where it remained constant until the last 10 minutes. Visibility increased to 3 m during the fire termination step.

In summary, it is noteworthy that the fire was controlled in the western part of the mine by opening the specified adits and shafts. By this action, half of the mine was saved from noxious gases. The other options were examined in order to get the safest atmosphere throughout the mine. It is not recommended to turn all of the fans off. The amount of toxic gases were too high when all of the fans were turned off. The following procedure was determined as the best approach to diminish the hazard level in emergency situations at that working face:

- **(a)** East surface fan has been turned off.
- **(b)** Booster fans in lower and upper levels have been turned off.
- **(c)** The two blocked raises at the center and eastern parts of the network and the two closed adits at the eastern panel have been opened.
- **(d)** West portal has been closed.

This approach has been determined as the optimum reaction to decrease the hazards of the fire at the bottom west panel in an emergency situation.

By changing the EarthForce^{TM} compact tires to standard duty pneumatic tires in the simulation, the amount of burning has decreased and also hazards have decreased respectively. The results are shown in Tables 7 and 8.

Table 7. Average CO according to 2 different tires at all stations.

Tire Type	EarthForce^{TM}	Standard Duty
Property	Average CO (ppm)	Average CO (ppm)
Station 1	1100	308
Station 2	350	174
Station 3	3.5	1
Station 4	2	0.5

Table 8. Average DB temperature according to 2 different tires at all stations.

Tire Type	EarthForce^{TM}	Standard Duty
Property	Average DB Temp ^{o}C	Average DB Temp ^{o}C
Station 1	113	48
Station 2	51	40
Station 3	27	25.7
Station 4	25.3	24.6

4.2 Scenario 2, fire at the east working face

The fire has been set at the ramp on the east part of the mine. Surface fans pulling air have been considered in this investigation of fire behavior and different characteristics through the airways for, four hours real time. Six minutes after fire event commencement, the west surface fan has been turned off while the east surface fan has not. Booster fans on the surface and lower levels were not deactivated during the whole time of the fire event. Both of shafts at the central part of the network have been opened 10 minutes into the fire event. The east adit, drainage adit, and shaft have been opened 10 minutes after the fire initiation time too. All times for this scenario have been selected according to the distance and reaction of the mine's staff. The distribution of fire and the determined adits and shafts for the pull system of the surface fans through the airways is shown in Figure 14.

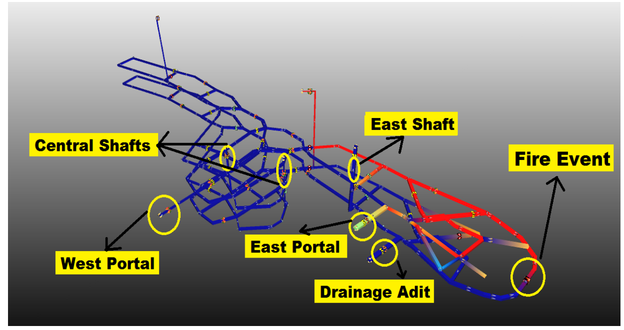

Figure 14. Fire distribution and effective mine's component on airflow direction.

4.2.1 Airflow and O_2 behavior at stations

Because of the east surface fan and two booster fans' pressure, natural ventilation pressure has not influenced airflow direction at any of stations. The maximum airflow changes in the period of the fire event were monitored at station 3. The airflow results during the four hours at station 3 are shown in Figure 15. The amount of airflow through the west part of the mine decreased by turning the west surface fan off. The amount of airflow at the east part of the mine increased noticeably and then it remained constant. The maximum amount of airflow at station 3 was 40.5 m^3/s. The amount of airflow was constant from 15 minutes until the end step of the fire event.

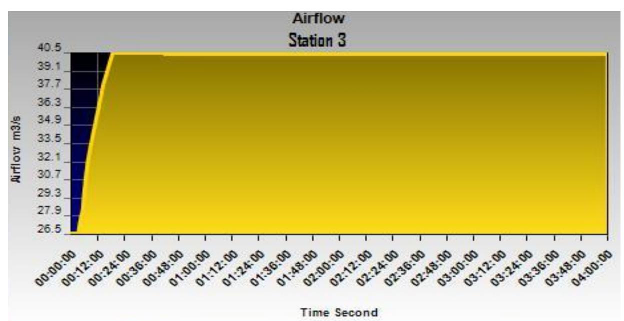

Figure 15. Airflow distribution at station 3.

The direction of airflow at stations 1 and 2 was not changed. During the first 6 minutes, the amount of airflow decreased to 20.0 m^3/s and then started to increase sharply to 21.7 m^3/s in the first 15 minutes and then it leveled off until the end of event. It is evident from airflow diagrams at all stations that the behavior of airflow at the two stations in the west part of the mine and two stations in the east part of the mine are the same.

Before the fire event, the amount of O_2 ranged from 21.1% - 21.6% in all scenarios. The highest change was 1% at station 4. The percentage of O_2 at the other stations did not change considerably. The ranges of O_2 from all stations are shown in Table 9. The amount of O_2 decreased conspicuously at the closest station to the fire, however the TLV was not reached, as illustrated in Figure 16.

Table 9. Oxygen percentage at all stations.

Stations	Min O_2 %	Max O_2 %
Station 1	20.9	21.3
Station 2	21	21.4
Station 3	21.1	21.6
Station 4	20.1	21.1

When the west surface fan was turned off, the amount of airflow decreased. The level of O_2 did not go below the O_2 TLV.

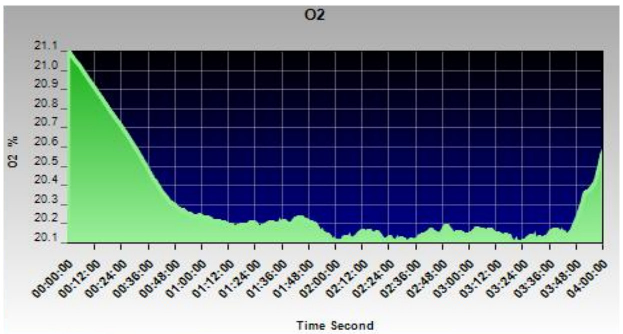

Figure 16. O_2 percentage at station 4 during the fire event.

The direction of airflow changed when all of the fans were turned off. The direction of airflow when the fans have been turned off is plotted in Figure 17.

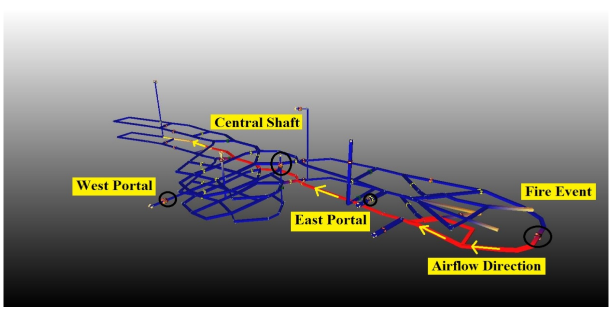

Figure 17. Direction of airflow when all fans are off.

4.2.2 CO and CO_2 behavior at stations in scenario 2

At all of the stations, the amount of CO and CO_2 was recorded in order to determine the toxic atmosphere and fire behavior through the airways. At station 4, the amount of CO increased to 809 ppm dramatically when the west surface fan was turned off. The graph reached the highest point at 2 hours and then remained almost constant until the last 10 minutes, at which point the concentration dropped to 490 ppm. If all of the surface and booster fans would be turned off, the amount of CO would be increased in the mine and also the direction of fire would be changed. The monitored result for CO at station 4 is shown in Figure 18. The highest amount of CO was recorded at station 4. When the amount of CO is high at station 4, the amount of CO at the other parts of the mine were zero.

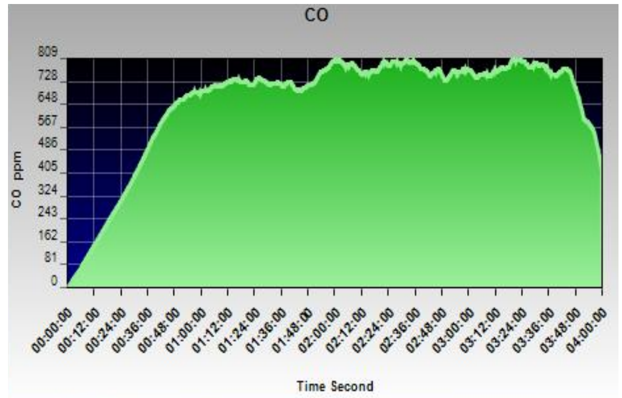

Figure 18. CO distribution at station 4.

By this action the fire was controlled at the east part of the mine without any hazardous effect on the other parts of the mine.

If we take a closer look at CO_2 graphs from all of the stations it is evident that CO_2 is behaving as CO behaved in the period of the fire event. The highest amount of CO_2 was 0.36 % at station 4.The highest amount of CO and CO_2 were at that station. The results of CO and CO_2 at stations are shown in Table 10.

Table 10. CO and CO_2 results at all stations.

Station	1	2	3	4
Min CO (ppm)	0	0	0	0
Max CO (ppm)	1	1	1	809
Min CO_2 %	0.038	0.038	0.039	0.038
Max CO_2 %	0.039	0.039	0.04	0.359

Consistent with the data in Table 10, it is seen that the TLV for CO_2 and CO at the central and eastern part of the mine has not been reached. Hence those parts of the mine were selected as the safe parts in an emergency situation. The result of CO_2 at station 4 is shown in Figure 19.

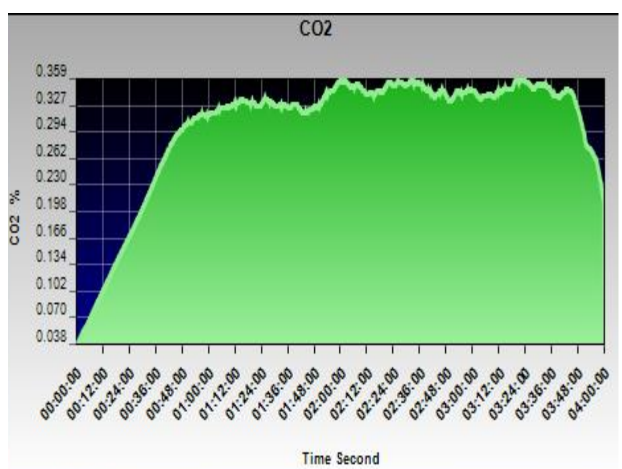

Figure 19. CO_2 distribution at station 4.

When all of the fans were turned off, the amount of CO at station 4, increased dramatically. The approximate amount of CO at that station had reached 2750 ppm. The amount of CO at the other stations was inconsequential. The average amount of CO and CO_2 at station 4, is shown in Table 11.

Table 11. CO and CO2 amount at station 4, when all fans are off.

Station	4
Average DB ˚C	120
Visibility (m)	0.3
Average CO_2 (%)	1.2
Average CO (ppm)	2750

4.2.3 Psychometric behavior at stations

In this study, all dry and wet bulb temperatures and rock temperature were investigated at all stations. Obviously, the highest temperature was monitored at station 4. Temperature changes during the 4 hour fire event at other stations were not considerable. After 2 hours, the dry bulb temperature reached its peak point at 112.3˚ C at station 4 and then it remained constant during the next 1 hour and 50 minutes. The graph is exhibiting a sharp decrease in the last 12 minutes of the fire event. The dry bulb temperatures at station 4 are shown in Figure 20.

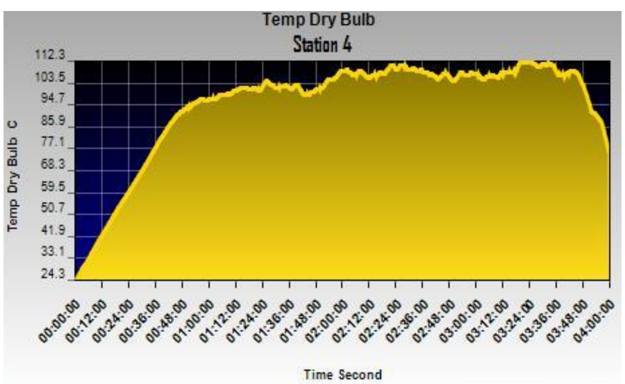

Figure 20. Dry bulb temperature at station 4.

The wet and dry bulb temperatures behaved the same at all stations, just as they did in previous scenarios. The minimum and maximum wet bulb temperatures at station 4 were 19.9˚ and 39.8˚ C. The highest rock temperature amongst all stations was 38.5 ˚C at that station. The rock temperature at station 4 is illustrated in Figure 21. The rock temperature increased dramatically up to the termination time of the simulation.

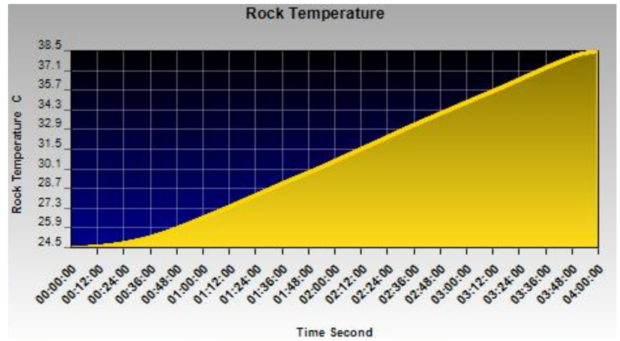

Figure 21. Rock temperature behavior at station 4.

The dry and wet bulb temperatures did not experience any important changes at stations 1, 2, or 3. The fire did not have any impression on the rock temperature at those stations either. The changes in temperature at other stations are illustrated in Table 12.

Table 12. Various monitored temperatures at stations 1, 2 and 3.

Station	1	2	3
Min DB ˚C	25.2	24.8	24.8
Max DB ˚C	25.4	25	24.9
Min WB ˚C	19.9	19.6	19.9
Max WB ˚C	20	19.7	20.1
Min Rock ˚C	25.4	25.0	24.8
Max Rock ˚C	25.4	25.1	25.1

From Table 12 data it can be seen that the fire has not changed temperatures at those stations significantly.

4.2.4 Visibility at stations

With the exception of station 4, none of the stations' visibility were affected by the fire. Visibility at station 4 decreased from 25 m to 1 m during the first 30 minutes and then it remained the same until the last 10 minutes. During the final step of the fire, the visibility at that station increased to 3.4 m. The visibility graph is plotted in Figure 22.

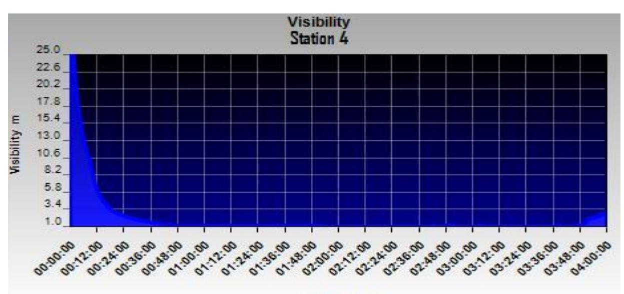

Figure 22. Visibility graph at station 4.

The amount of burning and hazards were decreased respectively by the change of EarthForce™ compact solid tires to standard duty pneumatic tires in simulation. Results. The average CO was monitored 400 ppm at station 4 when EarthForce™ tire was used while with the usage of Standard Duty tire, CO decreased to 170 ppm. Besides, the DB temperature at station 4 decreased from 68.3° C to 45.2° C when the Standard Duty was used.

All in all, the fire was controlled by turning the west surface fan on. Although by this action east and central parts of the mine have been saved from noxious gases, the effect of opened adits and shafts and also fan management in emergency situations cannot be ignored. The other options, like opening closed shafts and adits, or turning the east surface fan off, have been examined in order to get the safest atmosphere through the mine. If all of the fans have been turned off, the direction of fire does not change and the amount of toxic gases and temperature increase considerably in all parts of the mine. The following procedure should be considered for mitigation of hazards when the fire happens at the decline in an emergency situation:

- **(a)** West surface fan should be off.
- **(b)** East surface fan and booster fans should be turned on.
- **(c)** All adits and shafts should be opened.

5. Conclusion

It is noteworthy that distance and airflow direction have played key roles in the amount of CO and CO_2 and temperature changes. Unfortunately, the anticipation of a fire before the event is extremely difficult, not only the location (which to some degree may be predicted using risk assessment techniques on possible combustible sources), but also to the nature, size and behavior of the fire. This study was carried out for better understanding of airflow behavior and fire behavior when a Bobcat vehicle began burning at working faces. The highest amount of toxic CO gas was 3000 ppm at the closest station to the fire when all fans have been turned off.

The west working face at the bottom level was determined as the most perilous part of the mine for executing more safety issues. It is very hard to control the fire when it happens at that part of the mine. By turning all of the fans off, noxious gases have been trapped in the mine. So turning all of the surface and booster fans off wasn't selected as the ideal approach to control the fire. The highest temperature was 200° C at station 1 in scenario 1. CO and CO_2 behaved the same as one another at every station. Numerous applications (such as closing or opening different doors and shafts and turning on or off of different fans) were investigated to discern the optimum procedure for controlling the fire.

However, the best approach was achieved in each scenario by the proposed procedures. This study has shown that tires of vehicles are one of the most important factors in a fire event. Despite this fact, the least consideration has been employed for choosing the tires of vehicles in the mines. The lifetime of tires always pulled the focus of purchasers in industry while burning hazards were neglected. Standard duty pneumatic tires were selected as the Experimental Mine Bobcats' tires for working in underground. The reversed direction of surface fans was considered in this study while in real mines it is very hard to employ this application. In addition, mismanagement and lack of emergency layout in emergency situations can lead to malignant consequences for a mine. This study was carried out to show that the emergency plans for fire events ahead of any emergency are needed for every mine and also underground fires which have were initiated by mobile equipment are still relatively common and likely to be underestimated.

Acknowledgment

This paper was prepared with support from the National Institute of Occupational Health and Safety.

References

[1] Ballesteros-Tajadura, R.,Santolaria-Morros, C., Blanco-Marigorta, E. Influence of the slope in the ventilation semi-transversal system of an urban tunnel, Universidad de Oviedo, A ´ rea de Meca´ nica de Fluidos, Spain.

[2] Tunnelling and Underground Space Technology 21 (2006) 21–28R. Anderl et al., Hydrogen isotope retention in beryllium for tokamak plasma-facing applications, Journal of Nuclear Materials 273 (1) (1999) 1-26.

[3] Brake, D. J., Fire Modelling in Underground Mines using Ventsim Visual VentFIRE Software, Australian Mine Ventilation Conference / Adelaide, SA, Australia, (2013).

[4] Gillies, A. D. S, Wu, H, Reece, D and Hosking, R., Use of Mine Fire Simulation for Emergency Preparedness, Proceedings Qld Mining Industry Health and Safety Conference (2004), pp 13-20 (Qld Resources Council).

[5] Grayson, T. L., Kinilakodi, H., Kecojevic, V., Pilot sample risk analysis for underground coal mine fires and explosions using MSHA citation data" Safety Science 47 (2009) 1371–1378.

[6] Joy, J., Griffiths, D.,National Industry Safety and Health Risk Assessment Guideline, Version No. 7, Minerals Industry Safety and Health Centre (MISHC), University of Queensland, Australia, p. 157 (2007).

[7] Prosser, B., Ruckman, R. Conducting a fire modeling study, 13th United States/North American Mine Ventilation Symposium, (2010) – Hardcastle & McKinnon365–370.

[8] Rice, S. George, Mine fires: a preliminary study. Dept of Interior, Bureau of mines. (1912).

[9] Thyer, A., Development of a fire and explosion risk assessment methodology for underground mines [online], Science Group (Fire and Explosion), Health and Safety Laboratory. Report HSL, (2002). 24. 61 pp.

[10] Ventsim Visual™ 3, 2014, Ventsim Visual Tm User Guide, Ventsim Company.