Validation of the Ventgraph program for use in metal/non-metal mines

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ABSTRACT: The mine ventilation program Ventgraph has been utilized and validated extensively in coal mines in Europe, Australia, and the United States. Ventgraph is used for studying coal mine fires, fighting fires with inert gases, spontaneous combustion, and mine emergency exercises. However, it has been used to a much lesser extent in metal/non-metal (M/NM) mines. Its application to hardrock mining methods would be beneficial for studying M/NM ventilation effects, mine evacuation training, risk analysis of potential mine ventilation changes, airborne contaminants, recirculation, and mine fires. In order to determine its applicability to M/NM mine fire modelling, Ventgraph was utilized to simulate the 1972 Sunshine Mine fire, where 91 miners perished. The Sunshine Mine was selected due to its deep, complex ventilation system, involving ventilation thermal effects and recirculation not normally found in single-level coal mines. Information sources such as the United States Bureau of Mines (USBM) accident reports, ventilation surveys, books, and publications were examined to recreate the pre-fire Sunshine Mine ventilation system. Next, Ventgraph's network and fire simulation were run using assumptions from a USBM contract report to re-create the early stages of the mine fire and contaminant flow. Options to better control the ventilation system, evacuation, and early mine rescue attempts were tested. Calibration of Ventgraph's fire simulation module to known events of the fire showed close correlation to contaminant levels observed and real-time movement of fire combustion products through the mine. This study's conclusions validate the use of Ventgraph in a deep M/NM mine fire and illustrate its use as a valuable tool in mine ventilation, fire, and evacuation planning.

1 Introduction

In 2008, the National Institute for Occupational Safety and Health (NIOSH) began a research project to reduce the incidence rate and severity of fires in metal/non-metal (M/NM) mines and to reduce the potential consequences of fires in M/NM mines through a better understanding and consideration of the products of combustion (e.g., smoke and heat) in ventilation and escape planning.

After examining the available ventilation modelling programs for mine fire simulation capability, NIOSH researchers chose Ventgraph, developed by the Polish Academy of Sciences (Wala *et al.*, 1995, Dziurzynski *et al.*, 2006). Ventgraph includes features similar to other ventilation programs, such as network simulation and contaminant dispersal, but also has additional capabilities such as mine fire simulation, compressible flow modelling, and real-time on-screen visualization of mine ventilation and fire effects. In addition, Ventgraph offers modellers considerable flexibility for displaying multiple fire product gasses, ventilation system pressures, airflows, and other information important to mine safety professionals. Most importantly, Ventgraph models can be halted anytime during execution, allowing for on-screen changes to ventilation system parameters such as fire intensity, ventilation structure adjustment, and fan operation. This feature is especially beneficial for training, mine evacuation, and fire fighting options.

To demonstrate the capabilities of Ventgraph for modelling a M/NM operation, the 1972 fire at the Sunshine Mine in Kellogg, ID, was chosen. Ninety-one miners lost their lives at the Sunshine Mine, making it the second worst hard rock mining disaster in U.S. history. The Sunshine Mine fire also represents a turning point in public attitude towards mine safety, helping to trigger the passage of the Mine Safety and Health Act of 1977. Unlike previously studied coal mine fires, the Sunshine Mine was a deep operation influenced by significant natural ventilation thermal effects (Wala *et al.*, 1995). The Sunshine Mine had a complex ventilation system incorporating two surface main fans, eleven underground booster fans, and compressed air injection. The underground booster fans caused high pressure differentials, leakage, and recirculation. This, coupled with fire-induced bulkhead failures, contributed greatly to the large number of fatalities. In essence, due to the above factors, the smoke could not be cleared from the mine in an effective manner.

The Sunshine Mine fire had been previously modelled by early digital ventilation programs (Hall *et al.*, 1977), but without inclusion of fire combustion products and thermal effects. At that time, mine ventilation programs balanced airflows and pressures, but did not have the capability to model mine fire effects and flow of combustion products. Natural ventilation effects could be calculated and manually inserted into the network.

Since the early 1970s (Greuer, 1977), the United States Bureau of Mines (USBM), in cooperation with Michigan Technological University (MTU), pioneered efforts to define mine fires, their effects on mine ventilation systems, and to develop the MFire software to aid ventilation engineers in modelling mine fires (Laage *et al*., 1995). Support for MFire was severely reduced with the elimination of the USBM in 1995. NIOSH has recently begun updating the MFire program code (Yuan, 2008).

A new generation of ventilation programs that include user friendly data entry and graphics has evolved in the last 20 years, of which Ventgraph is one. Ventgraph's capabilities to simulate mine fires and make changes in real-time make it a valuable tool and its abilities have been extensively tested in coal mine applications. The opportunity to apply these tools to deep metal mines is attractive and a potential benefit to the health and safety of underground M/NM miners. Using previous ventilation modelling data with Ventgraph will hopefully validate its usefulness in this difficult environment which includes mine heat sources, natural ventilation effects, fire thermal effects and flow of contaminants through the mine.

2 Description of the Sunshine Mine fire

2.1 Ventilation System

An effective model of the Sunshine Mine fire requires an understanding of the ventilation system and the sequence of events during the fire and rescue. Therefore, this section will describe the underground mine and summarize the initial fire events.

The Sunshine Mine was located west of Kellogg, Idaho, in the Silver Valley of the Coeur d'Alene mining district. Figure 1 shows a schematic of the ventilation system at the time of the fire. Primary access to the mine was through the Jewell intake shaft at 823 m elevation MSL to the 3700 Level (elevations are depth below shaft collar in feet), across this level approximately 1.6 km east by track haulage to the underground winze vertical No. 10 Shaft (10 SH) and then to lower work areas. At that time, 10 SH was extended to the 5800 Level. Raises were connected east and west of 10 SH as secondary escapeways. Most support services were located on the 3700 Level at 10 SH. These services included the four-deck "chippy" cage operated from the 3700 Level, a larger double drum hoist that could hoist 9 men was located above on the 3100 Level (secondary escapeway), pipe shop, supervisor's office, safety room, maintenance shop, electrical shop, and substation.

Intake air was coursed down the Jewell shaft, across the 3100 Level and 3700 Level to 10 SH, and down to the working areas. Air was distributed to the levels by booster fans. Additional air to the work areas was provided by compressed air from the surface. Exhaust return air from the bottom workings was coursed up east and west of 10 SH shaft through raises and ultimately joined on the east side of 10 SH at the 3400 Level, where mine level boosters were installed immediately above the 3700 Level shop areas. The return air proceeded west, then up No. 3 Shaft (3 SH) to other booster fans at 1900 Level, and to surface exhaust fans at 3 SH and Big Hole.

A new recently completed raise, the No. 12 Shaft borehole, (12 BH) located off the Jewell shaft at 3700 Level was connected to the west end of the 4800 Level. This raise was planned to be widened and used as an intake airway to the lower mine.

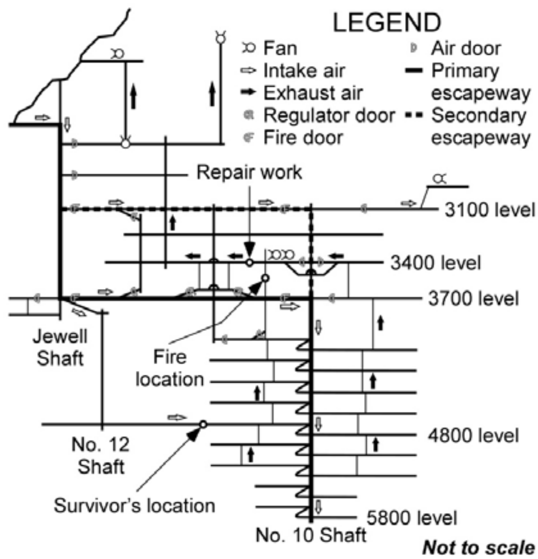

Figure 1 Sunshine Mine ventilation and escape system.

The location of the 3400 return airway between two intake levels, combined with high booster fan pressures, caused leakage primarily between the 3400 and 3700 Levels. Because this problem was noted in the fall, a 1971 USBM ventilation survey (Foster & Andrews, 1971) at the time of the fire the USBM's recommendations to reduce leakage and improve mine airflow capacity were being carried out 100 m (340 ft) west and downwind of the 3400 Level booster fans. Further, at the time of the fire, the 3400 return airway was being enlarged and leakage prevention work was being performed. This work involved sealing wooden bulkheads between levels that isolated mined-out stopes and sealing raises that contained mine waste and combustible materials. Drift areas west of the 3400 Level booster fan installation were smooth-lined with wood stulls, covered with plywood and asphaltic mastic, and sealed with polyurethane foam to promote smooth airflow through airways with rough walls (Day, 2007).

3 Fire Event

On May 2nd, 1972, at around 11:40 a.m. after the lunch break, smoke was discovered in the 3700 Level shop and office area close to the underground hoist at 10 SH. Management officials in the nearby office were notified immediately. Smoke was traced to about 270 m west of 10 SH, emanating from the 910 raise (910R), indicating that the fire was located above the 3700 Level. As per the mine fire procedures plan, the decision was made quickly to evacuate the mine using the 3100 Level secondary escapeway, and to close the fire door to the west on 3700 Level by the Jewell shaft (Figure 1). Mine supervisors feared the smoke would contaminate the intake air to the lower levels.

At noon, surface employees were notified of the fire and told that mine evacuation had begun, and the safety engineer was directed to bring the McCaa mine rescue breathing apparatuses to the 3100 Level. This level was where the evacuating miners would be sent, avoiding the 3700 Level smoke. The 3700 Level was the primary travelway into and out of the mine used by miners. Stench gas was released into the surface compressor system to notify miners of evacuation at 12:05 p.m. Smoke was observed coming from the mine exhaust on the surface at that time. Underground, smoke levels increased and spread quickly from the 910R raise into intake air on the 3700 Level, and into the active mine workings below.

At about 12:15 p.m., miners evacuating on the 3100 Level to the Jewell shaft encountered light smoke caused by recirculation from the 3400 Level booster fans below. Around 12:18 p.m., an examiner on a routine check of the 1900 Level return fans above encountered impassable smoke, precluding access to the upper level return fans. By 12:30 p.m., smoke was leaking from multiple bulkheads into the 3100 Level, inhibiting evacuation. Due to smoke-reduced visibility and unfamiliarity with the evacuation route on 3100 Level (Note: 3700 Level was the primary route), many miners had difficulty finding their way out.

When the McCaa breathing apparatuses arrived at the 3100 Level at 1:00 p.m., carbon monoxide (CO) levels over 3000 ppm were measured by the rescue team advancing towards 10 SH near No. 5 shaft. The last cage was hoisted to the 3100 Level just after 1:00 p.m., at which time the hoist operator was overcome by CO. The rescue team encountered and brought out two miners from the 12:43 p.m. hoist load, and one of those rescuers perished due to cumulative CO exposure.

Miners evacuating on the lower 3700 Level had closed the fire door east of the Jewell shaft at 12:00 noon, then later (1:15 p.m.) opened the cover that restricted airflow down the recently completed 12 BH raise near the Jewell shaft and 3700 Level (Figure 1). The 3700 Level was connected to the lower levels of the mine at the west end of the 4800 Level. This change provided by the open shaft would supply the only fresh air, although in small quantities, toward the 10 SH area. Saved by this single split of fresh air, two survivors were found eight days later by rescuers using an emergency hoist capsule down the 12 BH to 4800 Level.

4 Modelling

4.1 References Used

Information used to generate the Sunshine Mine network for Ventgraph was acquired from multiple sources. J.W. Andrews (2008), former Mine Safety and Health Administration (MSHA) and USBM ventilation engineer, maintained an extensive file on the incident. He also participated in the original USBM ventilation surveys (Foster & Andrews, 1972) of the mine, and the USBM Contract Report (Hall *et al*., 1977) on *Ventilation Analysis of the Circumstances of the Sunshine Mine Fire*. Contract participants were ventilation experts from the Colorado School of Mines, University of Idaho, MTU and the Pennsylvania State University. Other information was gleaned from the USBM Final Report on *Major Mine Fire Disaster, Sunshine Mine* (Jarrett *et al.*, 1972), the books *The Price of Silver* (Day, 2007) and *The Deep Dark* (Olsen, 2005), and the online report, *The Sunshine Mine Fire Disaster – A View from the Inside* (Launhardt, 1997). These sources were helpful in establishing and corroborating timelines during initial stages of the fire and evacuation.

4.2 Modelling Process Used

Airway data (airflow, resistance, airway, and junctions) were generated from the MTU contribution to the USBM Report (Hall *et al*., 1977). The Penn State University and University of Idaho also modelled the Sunshine fire and their data sets from this report provided equivalent confidence when compared to each other and thus would have provided similar results if used.

Airways (Hall *et al*., 1977) were not to scale and data needed for establishment of contaminant transient times were unavailable. Data were correlated from USBM Report descriptions and schematics to full-scale digitized mine drawings (Andrews, 2008). Airway locations were determined from descriptions and manually scaled.

Mine temperature data are required by Ventgraph for determination of natural ventilation and fire thermal effects. Information on temperature was gathered from 1971 USBM ventilation survey measurements. These temperatures may have been lower than at the time of the fire in May; nevertheless, they would not have significantly altered the natural ventilation effects and airflows in the fire area, and the same data were used by Hall *et al*. (1977). Temperature and elevation data were input for each junction, and barometric pressure was computed from standard atmospheric tables at elevation and not corrected for in-mine pressures.

5 Model Development

5.1 Network Model Comparison

The 1977 USBM model data was modelled in Ventgraph with airflow results comparing within 1.6%. Efficiency was calculated by summing the differences between Ventgraph and the USBM model airflows, and dividing by the sum of all airflows. Because all three USBM researcher's models were comparable, the Ventgraph model was believed to provide a good correlation to the initial Sunshine conditions. The MTU/USBM model utilized fixed pressure airways for fans (no fan curve), assuming no short-term change during the initial fire stages. As per the USBM ventilation survey estimate, mixed-quantity injection airways were used to simulate compressed air for mining work areas in multiple locations.

5.2 Ventgraph Fire and Fan Simulation

Based on the USBM accident investigation, the fire was located in the upper 910R (Figure 1). Ventgraph allows for the choice of fuel (oil, wood, coal, or belt) for heat value, length of fire, and relative fire intensity in the range of zero through ten (Dziurzynski et al., 2006). Concentrations of CO and hydrogen in combustion products are given as 10% and 1% respectively as a default value, but may be modified. Fire ramp-up time from start to full strength is specified by the operator. Specific modelling choices made by the author will be discussed in Section 5.2.

An important asset of Ventgraph is that real-time simulation can be started and stopped at any time. Fire characteristics can be altered, ventilation structures installed, resistances changed, and fan operation adjusted on the interactive screen schematic. As the simulation advances, smoke movement, various contaminant concentrations changes, and other data may be observed visually and in on-screen output boxes. These boxes are chosen by the modeller to visualize desired specific information in real-time. Figure 2 shows a snapshot of smoke advance in the early fire stage at the time smoke was discovered (arrived) at the 10 SH 3700 Level area at around 11:40 a.m. The network schematic view may be zoomed in or out for more or less detail.

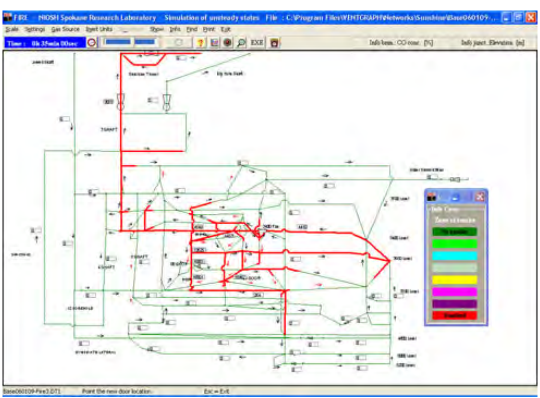

Figure 2 Ventgraph schematic visualization of smoke travel at the 11:40 a.m. smoke discovery (evidenced by bold airways).

Because a fixed pressure fan could not be used to represent drastic changes in the model caused by a failed bulkhead, fan curves for the 3400 Level booster and two main surface fans were generated from USBM simulations. Non-critical fans were left as fixed pressures. Accuracy comparison after fan curves changes was 3.3%.

6 Examination of References for Fire Details

6.1 Fire start and smoke arrival times used to calibrate fire to observations

The time of observation of smoke is essential to recreating the fire event (Jarrett *et al.*, 1972); (Day 1976, 2007); (Olsen 2005); (Launhardt, 1997). The day of the fire, downwind (west) of the 3400 Level return booster fans, miners were blasting to enlarge the return airway until the 11:00 a.m. lunch time and did not notice any smoke. Miners leaving the 10 SH 3700 Level just after 11:30 a.m. traveling west to the Jewell shaft passing by the 910R also noticed no smoke. Miners on the 3700 Level stated that they first observed smoke at around 11:40 a.m. in the shop area (illustrated in Figure 3), and on the upper 3100 Level at about 12:10 p.m. At 12:18 p.m., heavy smoke was observed in the upper return shafts on the 1900 Level.

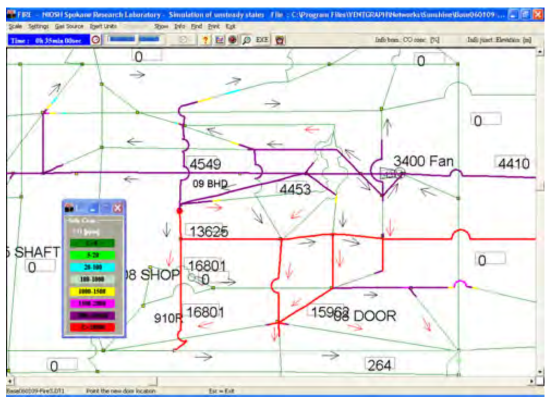

Figure 3 Visualization of fire area (carbon monoxide levels) during the early stages of contamination.

Ventgraph allows the modeller to follow smoke travel through the system to ascertain arrival times. After arrival times are known, back calculation to fire start-up may be determined, and then modelled to fit observations. Hall *et al*. (1977) envisioned a small fire smoldering until it burnt through the bulkhead from the backside, with rapid failure and increased fire activity driven by high airflows from the short circuit caused by bulkhead failure from the 3400 to 3700 Levels.

6.2 Fire Event Sequence Development

USBM investigators determined that the 910R bulkhead failed, but how rapidly and its effect on the ventilation system needed to be determined for modelling purposes. Experimenting with Ventgraph showed that almost total failure needed to occur to force smoke and high CO to the lower 3700 Level and overcome fire thermal buoyancy forces.

To illustrate this scenario, at a 2007 Trona Mine fire incident in which the author participated, a small ember flew through a wood bulkhead vent hole, landing in between bulkhead cribbing, starting a fire that totally consumed the structure in 10 minutes. Pressure across this bulkhead from the ventilation system was 1500 Pa (6"wg), and after failure 85 m^3/s (180,000 cfm) short-circuited to the return. Fire and high pressure differentials can rapidly consume a bulkhead and very quickly compromise its integrity. The Sunshine Mine 910R bulkhead had twice this pressure and was modelled to partially fail 5 minutes after the fire began and totally fail in 15 minutes. Hall *et al.* (1977) modelled the failure in increments, but no start time or timeframe was given.

In the simulation, Ventgraph fire intensity settings from 1 to 10 were used to vary the fire strength. However, no defined heat flow values are given for these ranges, which are calculated internally. Various fire intensities and lengths (extents) were modelled to obtain CO levels and ventilation system effects to correspond to USBM study results and observations. To adequately model alternate or defined fire scenarios, these values need to be quantified by Ventgraph or empirically determined by the researcher. In this case, the modelled fire was determined to be equivalent to a 35 kW fan source upon the ventilation system. Heat was also added to the air and rock, making determination of the total fire heat output difficult.

Using Ventgraph fire modelling tools, the following scenario was developed to simulate the initial stages of the Sunshine Mine Fire: a "Level 10" intensity wood fire 65 m long in 910R raise starting at 11:05 a.m., ramping up to full strength in 5 minutes, and the 910R bulkhead totally failing in the next 10 minutes with the fire growing to 100 m and then 200 m in length. This scenario matches smoke arrival times and observed CO levels in Hall *et al.* (1977).

To reach approximately 4,000 ppm CO at the surface (Jarrett *et al.*, 1972), a considerable fire is needed. The fire simulated above resulted in surface fan return CO levels of 3,600 ppm, rising slowly after 2 hours. Concentrations at 10 SH bottom were 1,000+ ppm, which would be fatal to life in short time. CO levels on 3100 Level initially were 500 ppm, deteriorating quickly. These figures seem reasonable based on the actual fire conditions. USBM gas samples about 30 hours after the fire began at the surface exhaust were around 4000 ppm CO. Miners at 400 ppm can survive 1-2 hours, with death in 4 hours. At 1,000 ppm, survival is for 30 minutes with death in 2 hours. The 1,500 ppm level is immediately dangerous to life and health (IDLH) (Hartman, 1961).

6.3 Time Events in Final Ventgraph Sunshine Scenario

Time	Event
11:05	Start wood fire in 910R, 65 m long, ramp up time 5 minutes to "Level 10"
11:10	Fire increases to 100 m long, 910R bulkhead partially failed
11:15	Fire increases to 200 m long, 910R further failure, 08 shop door blown open
11:20	Fire constant, 910R wide open
11:40	Smoke arrives at 3700 Level and at 08 shop door
11:42	Smoke at 10 SH 3700 Level
11:47	Smoke arrives at surface
11:49	Smoke to bottom of 10 SH
12:00	3700 fire door shut at Jewell Shaft
12:10	Smoke leaked into 3100 Level
12:30	Electricians hoisted to 3400 Level to wait for instructions to turn booster fans off
1:15	No. 12 BH cover removed to allow additional fresh airflow to 4800 Level.

Modelling the Sunshine Mine fire in this timeframe and intensity gives good correlation to observed smoke arrival times, evacuating miner CO exposure, and miner behavior. Confidence in the developed base model allows further use in analyzing various options regarding the effectiveness of choices that were made or could have been made during the disaster.

7 "What if" Scenarios of the Sunshine Mine Fire Model

NIOSH's goal is to effectively model mine fires to aid in evacuation and fire fighting, minimizing injury, loss of life, and risk to mine rescue teams. All these goals fall within Ventgraph's capabilities. "What if" scenarios allow for analysis of events prior to, during, and after a fire, identifying reactions that would have been better for escaping miners and factors that would have aided mine rescue teams in fighting the fire and locating survivors. The following examples illustrate how Ventgraph was used to stop the real-time fire simulation and make adjustments to fire strength, location, ventilation structures, and fan operation. This approach allows the researcher to study the applicability and effectiveness of each adjustment.

7.1 Turning Off the 3400 Level Booster Fan

A serious question raised by USBM investigators was why the 3400 Level booster fans were allowed to continue operating, recirculating contaminated mine air. Unfortunately, the fan shared its power supply with the 10 SH 3100 Level hoist and could not be stopped remotely. Further, shutting off that power would have eliminated evacuation of miners to the upper 3100 Level. The only other power disconnect was at the 3400 Level fan location, not on the surface. Electricians were hoisted there at 12:30 p.m. and succumbed to CO while awaiting further instructions.

Using the Time Event Scenario outlined previously and stopping the 3400 booster fan at 12:35 p.m. would have cleared the majority of the 3100 Level roadway in less than 15 min. The CO level at the 10 SH hoisting station remained at approximately 140 ppm for over 80 minutes until clearing. Hoistmen and personnel at that location had nearly all succumbed to CO by then. Most of the miners that were hoisted on the last trip at 12:45 p.m. did not make it out and may have had too high a CO saturation level by then. Lower in the mine, 1000 ppm CO was still arriving at the 4800 Level 34 min after the fan could have been stopped, with 737 ppm after an hour, indicating that the working levels of the mine continued to be heavily contaminated. Even after the change, smoke still occasionally pulsed into the 3700 Level travelway from 910R and fire above.

With quick booster fan stoppage, CO levels would have improved to allow a better chance of escape if miners could have gotten to the 3100 Level and partway towards the Jewell shaft to escape localized contamination.

The improved conditions on the 3100 Level may have allowed Sunshine Mine rescue personnel to access the hoist room with the McCaa apparatus and continue evacuation and travel down into the mine much more quickly. Continued booster fan operation surely contributed to maintaining a high fire level by supplying increased oxygen to combustible material in mined-out stopes and the subsequent deterioration of the mine workings that impeded rescuers.

It should be noted that shutting down main fans is a difficult decision, especially for supervisors in the mine, who are often without essential information regarding the emergency. As a comparison, it took the USBM officials over five days to decide to turn off the same fans.

7.2 Opening and Closing Jewell Shaft Fire Doors

Evacuating miners on 3700 Level closed the Jewell shaft fire door around 12 noon as per the Sunshine Mine Fire Plan. This action forced more air across the 3100 Level to aid evacuation, but actually increased contamination on 3700 Level and to the lower mine.

Later, USBM investigators asked if closing the fire door was the correct choice. The question was posed: “Should the doors have been left alone, or shut on the 3100 Level and reopened on the 3700 Level, as was done by rescue crews at around 1:30 p.m. when they left the mine?”

Analysis by Ventgraph showed that the best choice to maintain fresh air supply to the 3100 Level was to close the 3700 Level door per the Sunshine Mine Fire Plan. If both doors would have been left open, the 3100 level escape route would have suffered from reduced dilution, and CO would have increased by almost 70%. Ventilation in the lower mine would have been aided by the increased airflow and CO would have been reduced by 40%. However, since the evacuation was directed toward the 3100 level, this decision to close the 3700 Level door was the correct choice at that time.

If the 3100 Level door had been shut instead of the door at the 3700 Level, CO would have more than doubled on the 3100 Level; however, the lower mine areas would have seen a decrease in CO due to more air bypassing the fire zone. This would have precluded using the 3100 Level as an escape route, and neither of the hoist operating sites would have had a survivable atmosphere. Miners might have survived longer below, but hoist operators and others on the 3100 Level would have perished sooner with any other door option than the one chosen at the time of the disaster.

The combination of turning off the 3400 Level booster fans when electricians were hoisted to the fan level (12:30 p.m.) and leaving both doors open would have been the best choice. This would have had the effect of rapidly lowering CO on 3100 Level from 551 ppm to 260 ppm in 30 minutes, and to 94 ppm in 45 minutes. This action would have been too late for the hoist operator and miners at 10 SH, but it may have allowed rescue personnel to make it to the 3100 Level hoist room to evacuate more miners. It also may have allowed others to escape on the 3100 Level as conditions would have improved towards the Jewell Shaft. Any option that shut the 3400 Level booster fans off regardless of fire door choices would have improved CO levels deep in the mine due to less recirculation of fire combustion products into intake air.

7.3 Opening the No. 12 BH Cover Earlier

Opening the 12 BH cover at 1:15 p.m. increased airflow to the lower west mine from 0.9 to 2.1 m^3/s, and was the only source of fresh air to miners near 10 SH waiting for evacuation. The survivors’ safe location was west of the shaft, where fresh air arrived from the west and return air from the level below flowed up the return raise system. Investigators asked the question: “What would be the benefit of opening the shaft cover earlier than 1:15 p.m.?” The earliest it could have been changed was noon, which will be the reference point.

Based on the Ventgraph analysis, opening up the 12 BH earlier would have only provided a slight advantage of 90 vs. 87 ppm CO at 10 SH on the 4800 Level, where the mine atmosphere continued to deteriorate rapidly. Airflow down 10 SH is reduced and CO is at a higher concentration with 12 BH open, adding to contamination from recirculated lower level air. In the short term, while miners were evacuating, opening No. 12 BH intake earlier would have made no difference at the. 10 SH assembly point nor to the lower mine.

7.4 Placement of Bulkheads to Fight Fire

Fire growth on the 3700 Level caused ground failures, which severed the main power feeder cable and compressed air line. If fumes and heat could have been diverted from infrastructure critical to mine evacuation and recovery, miners may have been able to be saved, or the mine may have been recovered earlier. Simulations were run with options for opening or closing the 3100 and 3700 Level doors to see if airflow could be forced to flow from 3700 to 3400 Levels, moving the fire away from the 3700 Level facilities at the bottom of the 910R. Unfortunately, with the 3400 Level booster fans either running or turned off, no combination of doors opening or closing would accomplish this goal. A stopping would have needed to be installed past (east of) the 910R raise to force air away from the infrastructure, which could not have been done by rescue teams for a considerable period of time.

The accuracy of the Ventgraph simulation was only deemed valid during the initial stages of the fire before too much damage to the ventilation system had occurred. Ventilation planners should practice with various bulkhead placement scenarios to better prioritize mine rescue efforts and protect critical mine infrastructure through control of airflow to mine fires.

8 Summary and Conclusions

The goal to validate the use of Ventgraph for modelling M/NM mine fires has been met by verifying that fire contaminants and disruption to the Sunshine Mine ventilation system were modelled to a degree of accuracy that lends confidence to the software and method in this particular case. Fire modelling was especially challenging in an application that included considerable natural ventilation effects and complex underground booster fan pressures and recirculation. These issues cause an increase in complexity over previously modelled coal mine validations, lending credibility to the results. Additional work should be done to further investigate the use of Ventgraph in M/NM applications. The ability to assign fire locations and vary their intensity, along with changing the characteristics of ventilation structures and mine fan operation in real-time, proved to be an excellent tool to study mine fires in M/NM mines.

More work needs to be done to understand the Ventgraph system of Mine Fire Intensity Levels. The arbitrary levels from 0 to 10 are expedient, but they make it difficult to design and implement modelling of fires and determine what heat levels actually correspond to those values. A more detailed user manual would also help define the actual heat values derived from the Mine Fire Intensity Levels and length of fire input values. Modellers also need to be aware that not all fires produce CO and hydrogen in the default ratio of 10:1, and modellers must obtain accurate estimates of the type of fire envisioned.

Ventgraph modelling of the early stages of the Sunshine Mine fire shows that the fire produced CO levels in the fire zone of around 16,000 ppm. Ventilation dilution reduced that to approximately 4,000 ppm at the exhaust fan, comparing closely with USBM measurements. The model's CO levels in the working areas corroborated the toxic effects described in the investigation reports.

In Ventgraph, the 3400 level booster fan airflows after the 910R bulkhead failure did not correspond to USBM contractor model results. Ventgraph model airflow was lower, possibly due to buoyancy effects from the fire acting against and restricting airflow from booster fans from the 3400 Level down to 3700 Level. The Ventgraph simulation may actually be closer to reality, as the USBM researchers did not incorporate fire dynamics into the network simulation.

The Mine Safety and Health Act of 1977 required remote control of main fans and a separate fresh air supply to underground hoisting chambers, which might have made a great difference in the number of survivors at Sunshine Mine. Realistically, turning off mine fans is a difficult decision and, in most cases, leaving the fans running is the best option. Turning the booster fans off at 12:30 p.m. as discussed by Mine Supervisors underground would have greatly reduced CO contamination for miners escaping and for those trapped in lower levels. Unfortunately, there was insufficient time to save those in the area of the mine hoist who already had been exposed to high CO concentrations. Turning off the booster fans might have also aided rescuers' access to 10 SH.

Ventgraph allows engineers and safety professionals to model an operation after performing a risk analysis of mine fire sources. Once identified, risks can be simulated to observe the flow paths of the contaminants and the effects on the ventilation system. Exposures for evacuating miners may be determined and evacuation routes planned. "What if" scenarios to improve escape opportunities or to contain the fire may be examined. Fire fighting and mine rescue plans may be deployed to take advantage of this knowledge. Mine ventilation plans can be expanded to include these exercises.

Advances in mine ventilation modelling such as Ventgraph have provided tools to greatly enhance the mine ventilation engineer's ability to effectively plan for and provide support during mine fires. Should a fire situation arise, an updated ventilation model for that mine can be used to simulate fire and ventilation changes. This could provide valuable information to mine engineers, management, and regulatory authorities to make better informed decisions during the event.

Disclaimer

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