Studying intake airway pressurization by ventilation modeling and leakage evaluation

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Abstract

Utilization of belt air in underground coal mines has been discussed extensively during the last decade. The Final Report of the Technical Study Panel on the Utilization of Belt Air and the Composition and Fire Retardant Properties of Belt Materials in Underground Coal Mining formed by the Mine Improvement and New Emergency Response (MINER) Act of 2006 recommends research on leakage, use of booster fans, and escapeway safety. This paper discusses the role of ventilation modeling in evaluating primary escapeway pressurization in a three-entry development system to improve emergency escape in a coal mine using belt air. The intake entry of the National Institute for Occupational Safety and Health (NIOSH) Bruceton Experimental Mine was pressurized using a 1.1-m (42-in.) diameter, 37 kW (50 hp) fan. The work details air movement in the simulated three-entry system and the resulting leakage patterns. Three mine ventilation software packages were compared to analyze their performance in predicting the airflows and leakage conditions with different fan settings. NIOSH researchers found that the measurement results correlated well with the results of modeling.

Key words: Ventilation, Coal, Modeling and simulation

Introduction

The MINER Act of 2006 (Public Law 109-236) established a technical study panel on the utilization of belt air and the composition of fire retardant properties of belt materials in underground coal mines. The report, published by the panel in 2007 (Mutmansky et al., 2007), included recommendations to conduct research on improving escapeway design in various ventilation situations, reducing air leakage through ventilation controls and use of booster fans in underground coal mining operations. This research primarily studies ventilation in intake airways that are adjacent to belt entries and provide intake air to the working section. The purpose of the research is to assure that workers can safely use the intake airway to escape a section in the event of a fire or other emergency in which hazardous contaminants are produced in the belt entry. The panel recommended that research utilizing ventilation modeling, engineering design and risk analysis be performed.

Leakage through stoppings from the belt entry to the intake escapeway endangers escaping miners. Escapeway safety can be improved by pressurizing the intake entry to prevent influx of contaminants from the belt entry. MSHA shares the panel's view that the primary escapeway should have a higher pressure than the belt entry (*Federal Register*, 2008).

The objective of this research is to evaluate the role of ventilation modeling as a tool for planning the pressurization of an intake entry. Ventilation models created with different software packages are compared to define their feasibility for planning, as well as their ability to predict the leakage and airflow directions in the intake and belt entries. Different intake airway pressurization scenarios are modeled and the performance of three software packages is evaluated based on the comparison of measurement and modeling results.

Test site

General. The National Institute of Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory Experimental Mine was used to evaluate pressurization of an intake entry in a three-entry system and provide data for validating simulation models. The experimental mine is part of a complex of mines used to support research for the development and evaluation of new health and safety interventions for mine workers (NIOSH, 2008). The Experimental Mine consists of multiple drift entries and cross cuts driven approximately 430 m (1,400 ft) into the Pittsburgh coal seam (Fig. 1). The cross-sectional area of the entries is roughly 2 m (7ft) high and 3 m (10 ft) wide.

The 'main entry' of the mine was used as an intake, the 'air course' was defined as a belt entry and the 'east air course' acted as an exhaust. These definitions were made for simulation and comparison purposes. The air course does not have a belt installed. The east and west entries on the sides are separated from the main entries with bulkheads. The mine is ventilated with one exhausting main fan, which circulates approximately 14 m^3/s (30,000 cfm) of air through the mine when operating on its highest setting. The main fan is located on top of a shaft at the end of the east air course, as shown in Fig. 1.

Fan setup. The intake entry was pressurized for leakage testing using a 1.1-m (42-in.) diameter, 37-kW (50-hp) fan shown in Fig. 2. The maximum theoretical airflow based on the fan curve is 26.4 m^3/s (56,000 cfm). In practice, this airflow can't be reached due to pressure limitations.

The fan is equipped with a variable frequency drive for easy control of the flow. Three fan settings were used in testing, high, medium and low. The measured flows for these settings were 24 m^3/s (52,000 cfm), 16 m^3/s (33,000 cfm) and 12 m^3/s

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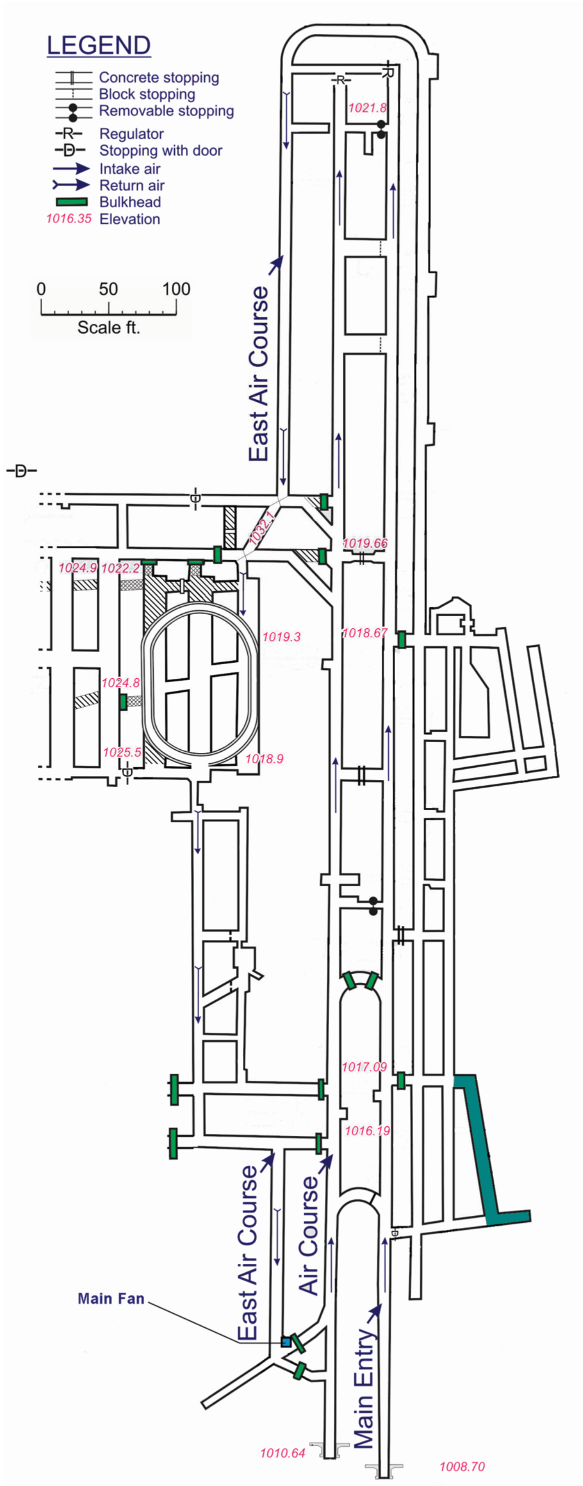

Figure 1 — Map of the Pittsburgh Research Lab Bruceton Experimental Mine.

Figure 2 — Fan at the installation location.

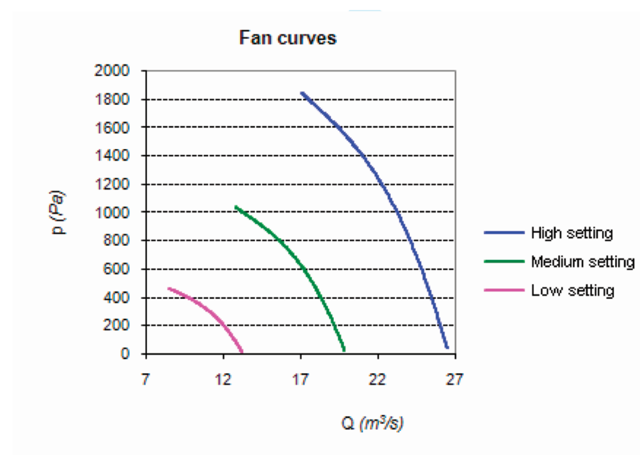

Figure 3 — Fan curves for the free-standing fan.

(26,000 cfm). The fan curve information showing all speed adjustments is presented in Fig. 3.

The fan was sized so that it could be installed freestanding close to the portal to provide a positive pressurization of the entire intake entry. Air recirculation around the fan was expected due to the lack of enclosure and a 1.1-m- (3.6-ft-) diameter regulator located at the end of the intake entry. Similar pressurization of the intake entry would have resulted from the installation of a smaller fan in a bulkhead. Bulkhead construction was not feasible in the Experimental Mine at this location, due to access requirements inby the fan.

The intake entry is separated from the other entries by stoppings and bulkheads. In the 430-m (1,400-ft) entry, the velocity pressure produced by the fan transforms into static pressure.

Data acquisition

Ventilation survey. Prior to the fan installation, a ventilation survey was performed in the mine to define the airflows. The cross-sectional areas were measured throughout the mine for planning purposes by taking three vertical and horizontal measurements. Several air velocity measurements were taken and the roughness of the walls was evaluated to estimate friction factors. Airflow directions and pressures were measured with the main fan only to evaluate leakage in the baseline operation situation.

Airflow study. Davis vane anemometers were used to measure air velocities at the locations A through G shown on Fig. 4. Green arrows are used in the figure to determine airflow direction in the intake, blue arrows in the belt entry and red arrows in the exhaust.

Airflow measurements at each sampling location were made during each of four fan states, with only the main fan operating and with the freestanding fan operating at three flow rates. Each air velocity measurement result was an average of two

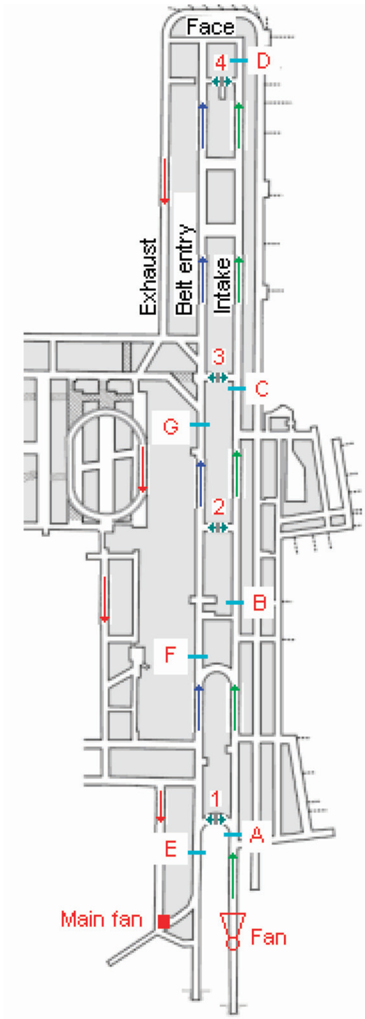

Figure 4—Air velocity and leakage measurement locations.

one-minute traverse readings and the cross-sectional areas were measured with high accuracy. A grid of 0.3 m (1 ft) was used for cross-sectional area measurements. Air velocity readings were taken simultaneously in the two entries to minimize the effect of the changing surface conditions and to ensure accurate results that can be used to compare the simulation models.

Leakage study. Leakage between the intake and belt entries was minimal due to thick, gunite-coated, concrete block stoppings constructed between the entries. Three 10-cm (4-in.) diameter pipes running through the stoppings (Locations 1, 2 and 4) were opened to act as leakage points (Fig. 4). The leakage point at Location 3 was an open 0.5 m^2 (5.4 ft^2) square hole in the stopping.

Plastic tubing was extended through the three metal pipes and one hole. These tubes were used for measuring pressure differentials across the stoppings. Numbers from 1 to 4 and two-headed arrows are used to identify the leakage locations.

Pressure differentials were measured with a DP-Calc micromanometer, with an accuracy of ±1% of the reading or ±1 Pa (0.004 in wg) and a resolution of 0.1 Pa (0.0004 in wg). At each location the measurements were averaged over 15 seconds. Airflow direction at each leakage location was confirmed using a smoke tube.

Ventilation modeling

Modeling software. Three different software packages referred to as Program A, Program B and Program C, were used in ventilation modeling. The input parameters required in these software packages differed from each other, so differences were expected in the results as well.

Two of the software packages, Programs A and B, were based on incompressible flow and did not take into account thermodynamic behavior. One of the software packages, Program C, takes into account thermodynamics and compressibility of airflow.

Four scenarios were simulated with all three programs. The first scenario was the basic network model with main fan only, the other scenarios were fan on the low, medium and high settings, respectively.

Baseline model. The basic network model was created based on the information gathered by a ventilation survey prior to the installation of the freestanding fan. This model, created by Program A and validated by the measurement data, was used to size the fan.

The challenges of the modeling included varying weather conditions affecting airflows in the mine and immeasurable changes in pressures due to the small size of the mine at the baseline situation. The Experimental Mine has three surface connections and due to the size of the mine the surface conditions affect the conditions underground, especially close to the portals. All tests were performed when the weather was rather stable, with little temperature or wind variation. Also, the measurements were taken simultaneously in the intake and belt entries to minimize effects of weather changes. The temperature data was included in the input of Program C. Improved pressure analysis was achieved by acquiring a more accurate measurement instrument that was used throughout the rest of the study.

Modeling expectations. Pressurizing the intake was expected to result in increased airflow between the entries, as there was originally very little difference in the pressures of the simulated belt and intake entries. The air velocity in the intake and belt entries at the time of the ventilation survey was around 1 m/s (200 fpm). The fan was sized to provide approximately 2 m/s (400 fpm) for the simulated intake and 0.5 m/s (100 fpm) for the simulated belt entry. The simulations showed that these values would result in pressurization of the intake all the way up to the simulated face. If the air velocity in the intake would have been above 2.5 m/s (500 fpm), the airflow direction in the belt entry would have changed based on modeling results. The minimum accepted air velocity in the belt entry is currently 0.5 m/s (100 fpm), according to regulation.

Results

Leakage study. As previously noted, with only the main fan operating, the air velocities are very close in the two entries. The freestanding fan increased the air velocity in the intake as expected. In the belt entry the air velocity decreased. The lowest air velocities were measured in the belt entry with the fan on high. The opposite was true for the intake. The expected values in both the intake and belt entries agreed quite well with the measured values of 1.9 m/s (370 fpm) and 0.6 m/s (120 fpm) when the fan was on the high setting. The airflows calculated based on the measurement results are presented in Table 1.

For the baseline condition, flow at all leakage locations was toward the intake, but the measured pressure differentials were small, ranging from 3.6 Pa (0.014 in wg) to 9.1 Pa (0.037 in wg). This shows that the barometric pressures in the entries were almost identical without the effect of the freestanding fan.

Using the low setting of the fan resulted in leakage towards the belt entry in Locations 1 through 3, and leakage towards the intake in Location 4. The medium and high settings pressurized the intake enough to cause the air to flow from intake to the belt entry in all four measurement locations. The smoke tube confirmed the airflow directions shown by the pressure readings. The measured pressure differentials and leakage directions are shown in Table 2.

Table 1 — Calculated airflows with and without the freestanding fan.

	Airflow (m^3/s)			
Location	Main fan only	Fan low	Fan medium	Fan high
A	7.3	8.6	10.9	11.8
B	7.5	8.9	9.9	11.7
C	7.9	9.4	10.0	11.8
D	7.5	8.0	8.5	10.1
E	6.4	5.8	4.9	3.9
F	6.3	5.3	4.6	3.5
G	5.7	4.9	4.4	3.4

Comparison of mine data and computer simulation data. The results of the modeling were compared with the four airflow measurements made in the intake and the three made in the belt entry. The compared model values and measurement values are referred to as value pairs.

The baseline models created by Programs A, B and C correlated well with the measured and calculated values. A comparison of the measurement information and network model values is shown in Table 3. Most of the model values are within 5% of the airflow values calculated from the measurement results. All three programs gave their best performance with the baseline.

A leakage recirculation branch (Fig. 5) was added to every fan scenario to enable simulation of recirculation around the freestanding fan with each of the different settings. The resistance values of the recirculation branch ranged from 0.045 Nm^2/m^8 to 0.8 Nm^2/m^8 depending on the scenario. Measurements were taken at the fan outlet and 9 m (30 ft) downstream from the fan in order to define the amount of recirculation around the fan. The recirculation with the highest fan setting was about 50%, with the medium setting about 40% and the low setting only 25%. This information was used in modeling.

Concerning the other three fan scenarios, all programs showed more fluctuation compared with the baseline. The difference between the simulated and calculated values is shown in Tables 4-6 as a percentage. A negative value indicates that the simulated value was lower than the measured value.

For each fan scenario, Program A had four out of seven measured values within 5% of the calculated values and over 75% of compared values were within 10% overall. However, two of the simulated values were over 20% different from the calculated values.

Program B performed better with the low and medium fan settings ,where five out of seven sample locations had calculated values within 5% of simulated values. At the high fan setting, however, only three out of seven values were within 5% of each other. At the 10% comparison level, Program B showed a marked decrease in performance as the fan speed increased. There were seven out of seven, six out of seven and five out of seven value pairs within 10% of each other for the low, medium and high fan settings, respectively. For Program B, the only value pair not within 20% was found with the high fan setting.

Program C gave the same results as Program A for the low and medium fan settings, each with four out of seven value pairs being within 5%. At the high setting, the results were the same as with Program B, three out of seven within 5%. However, Program C had seven out of seven comparisons within 10% with the fan set on low (Table 4, Fig. 6) and five out of seven with the fan set on medium. On the high setting, Program C had six out of seven occasions when the calculated values were within 10% of the simulated values (Fig. 5, Table 6). Out of the three programs, Program C did not show any simulated values more than 20% different from the measurements. In fact, the

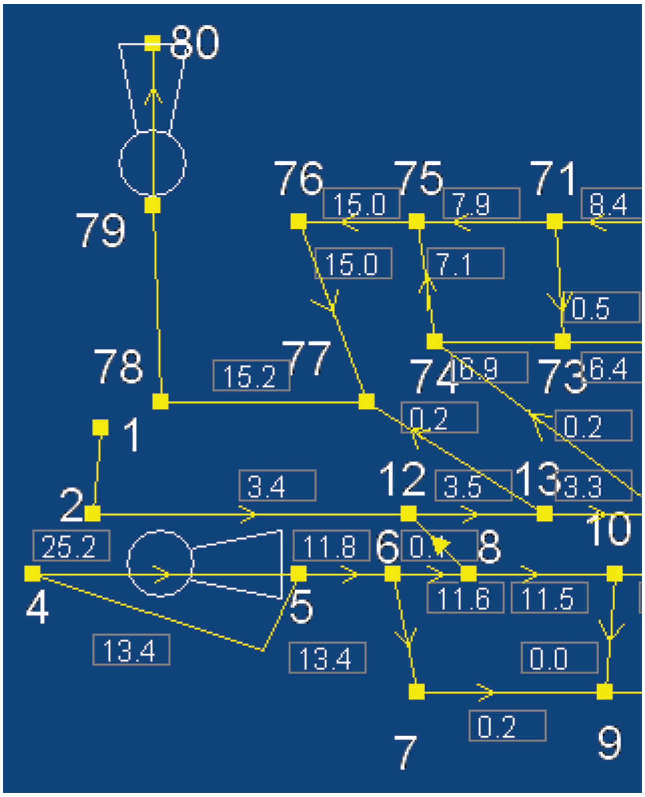

Figure 5 — A close-up of a ventilation network showing airflows, fans, recirculation branch and leakage Location 1.

Table 2 — Measured pressure differentials.

	Pressure differential (Pa)			
Point	Main fan only	Fan low	Fan medium	Fan high
1	3.6 to intake	11.5 to belt	47.9 to belt	98.4 to belt
2	3.6 to intake	12.5 to belt	46.6 to belt	91.8 to belt
3	4.9 to intake	6.5 to belt	43.1 to belt	92.3 to belt
4	9.1 to intake	8.5 to intake	36.7 to belt	78.1 to belt

Table 3 — Computer simulation comparison – baseline.

	Program A		Program B		Program C	
Location	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)
A	7.5	2.3	7.62	3.8	7.7	4.8
B	7.5	0.4	7.58	1.5	7.5	0.4
C	7.5	-4.7	7.59	-3.4	7.5	-4.7
D	7.6	1.8	7.79	4.2	7.8	4.3
E	6.6	2.7	6.55	1.9	6.3	-1.9
F	6.3	-0.2	6.19	-2.0	5.9	-7.0
G	6.2	7.4	6.21	7.6	5.8	1.0

Table 4 — Computer simulation comparison – fan on low setting.

	Program A		Program B		Program C	
Location	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)
A	8.9	3.7	8.95	4.2	8.9	3.7
B	8.6	-3.5	8.67	-2.7	8.8	-1.2
C	8.5	-11.0	8.60	-9.7	8.7	-8.5
D	6.3	-27.1	7.93	-1.0	8.1	1.1
E	5.6	-3.7	5.53	-5.0	5.3	-9.6
F	5.3	-0.1	5.24	-1.2	5.0	-6.1
G	5.4	10.0	5.33	8.8	5.0	2.8

Table 5 — Computer simulation comparison – fan on medium setting.

	Program A		Program B		Program C	
Location	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)
A	10.8	-0.7	10.41	-4.5	10.5	-3.6
B	10.4	4.7	10.02	1.1	10.2	2.8
C	10.4	3.6	9.89	-1.4	10.2	1.7
D	7.1	-19.2	8.45	-0.1	8.7	2.7
E	4.4	-11.0	4.37	-11.8	4.3	-13.6
F	4.3	-6.0	4.26	-7.0	4.0	-14.0
G	4.4	0.5	4.35	-0.7	4.1	-6.8

Table 6 — Computer simulation comparison – fan on high setting.

	Program A		Program B		Program C	
Location	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)	Airflow (m³/s)	Difference (%)
A	11.7	-1.2	11.92	0.6	11.6	-2.1
B	11.3	-3.8	11.45	-2.4	11.3	-3.8
C	11.2	-5.5	11.23	-5.2	11.2	-5.5
D	8.2	-22.6	9.14	-10.0	9.3	-8.1
E	3.7	-6.4	3.24	-21.5	3.5	-12.5
F	3.5	-1.0	3.25	-8.8	3.3	-7.2
G	3.5	3.5	3.38	0.1	3.5	3.5

greatest difference was found on the medium fan setting and was only 14.0%. These results showed that Program C was more consistent than the other programs.

Even if Program A did not perform as well as Program B in giving comparison values with the fan scenarios, it gave a good estimate of the functionality of the fan in installation planning. The air velocity values aimed for were realized quite well with the high setting of the fan (Table 1).

Discussion

The freestanding fan increased the total airflow, changed the pressure balance of the entries and changed the direction of the leakage flows towards the belt entry in every leakage location with the medium and high fan settings. The pressure

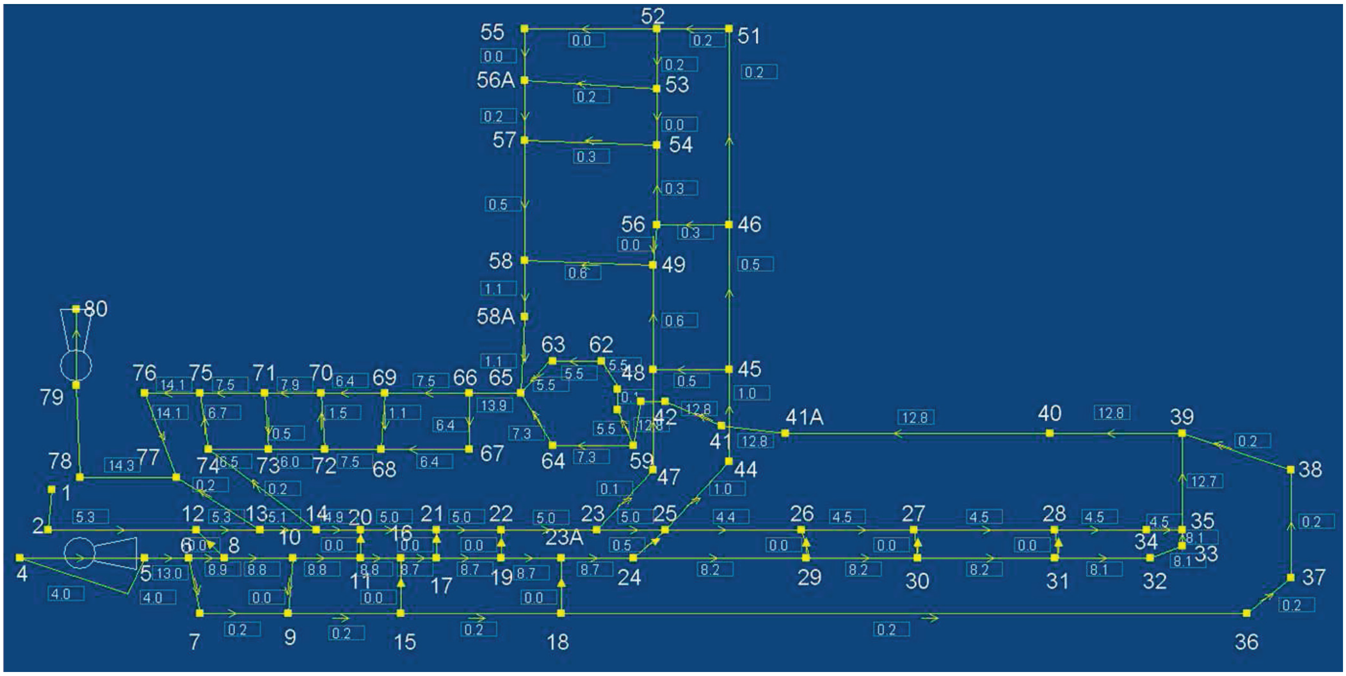

Figure 6 — An example of the mine ventilation network with fan on low, Program C.

differentials of up to almost 100 Pa (0.4 in. wg) with the high setting of the fan resulted in a properly pressurized escapeway, with no risk of contaminant leakage from the belt entry.

Intake entry pressurization as described in this paper can be achieved in an operational mine to improve escapeway safety. A main fan or a freestanding fan can be used to pressurize the intake entry, depending on where the use of one is applicable. Future research will include feasibility evaluation for installing a pressurizing fan for emergency use only.

Buoyancy induced by fire affects airflows and may change leakage directions. Evaluation of buoyancy effects would require a fire simulation. This would be beneficial in defining the pressurization requirements of an intake in an operational mine.

Conclusions

The fan operation was well predicted by the simulations prior to installation. The air velocities in the entries, as well as leakage directions, changed as expected based on the simulation results.

Ventilation modeling with three different simulation software packages provided similar results in the case of the baseline model. The programs performed well at the baseline, giving results within 5% of the airflows observed in the mine. The other fan scenarios were further from the measurement results, but still most simulated values fell within 10%.

All three software packages were able to predict the pressurization of the intake entry with a reasonably good accuracy. In this case, a small mine, in which surface conditions affect the conditions inside the mine, was analyzed. Program C, with the thermodynamic input, was considered to have performed best, as its results were the most consistent with the calculated values.

The software packages mostly underestimated the airflow in comparison with the measured values in the fan scenarios. This is an advantage, as slightly higher pressurization than planned was acquired in this application and might act as a safety factor in future ventilation planning exercises.

Based on the underground study and modeling, it can be concluded that ventilation modeling software can be used as a tool for planning to study intake airway pressurization and leakage directions with good accuracy. In the future, a larger network with more complicated structures will be modeled and optimal locations for underground fans will be sought. Also, pressure differentials and contamination outby the fan will be studied in the larger network.

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Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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