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COMPREHENSIVE PRESSURE QUANTITY SURVEY FOR INVESTIGATING THE EFFECTS OF BOOSTER FANS IN A TRONA MINE

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ABSTRACT

The ventilation survey was conducted in an underground longwall trona mine. The mine is relatively shallow and categorized as a gassy mine. The ventilation system consists of nine shafts (three intakes and six exhausts). Three surface based axial fans ventilate the mine configured in a blowing arrangement. Following the ventilation survey airflow quantity, frictional pressure losses and air psychrometric characteristics have been quantified. An accurate resistance survey has been conducted to calculate the pressure drop with regard to moving cages and skips in the shafts. This paper discusses the benefits of utilizing high accuracy digital pressure transducers and psychrometers in a "leapfrogging" survey to gather data needed to build the computer ventilation model. Two underground booster fans with VFD are currently idle but available at the mine. The ventilation model has been used to determine the optimal booster fan locations to decrease the overall operating cost by reducing the load carried by the main fans. A leakage study has been conducted to evaluate the effects on the system of additional pressure from a booster fan. The study finally prepares a future ventilation model for the next fifteen years of mine operation and investigates the effect of proposed scenarios.

BACKGROUND STATEMENT

FMC's Westvaco mine, Green River, Wyoming, is the world's largest underground trona mine and producer of soda ash. The mine hoists 4.5 million tons of trona to the nearby plant where it is refined in one of eight processing plants. The mine is relatively shallow and categorized as a gassy mine (MSHA Class III). Currently the mine is being ventilated with about 500m^3/s. The air is forced into the mine by three shafts each fitted with a vane axial Jeffrey 8 HU-117 (2 stage Aerodyne) surface fan. There are six exhaust shafts.

INTRODUCTION

The mine has two active continuous miners and one longwall sections. The room and pillar panels are being driven by bore miner continuous miner machines and are comprised of four rooms with adjoining crosscuts. An internal air requirement of 8 m^3/s has been determined for each room which gives a combined requirement of 20m^3/s at the bore miner panel regulator. The amount of 50 m^3/s is also required for the longwall (LW) face, measured at 110 shield on the face, to dilute methane and keep the concentration below 1.0% (Mine Health and Safety Administration (MSHA) Title 30 Code) regulation. A total of 95 m^3/s is required to maintain ventilation for active faces.

The air at the south of the mine is being exhausted from Number 9, 6 and 4 Shafts. Number 4 Shaft does not play an important role due to its long distance (9 km) from active mining sections. During the Pressure Quantity survey (PQ) it was found that 108 m^3/s is being drawn from 592 S district S to Numbers 6 and 4 upcasting Shafts (55 m^3/s west regulator and 30 m^3/s at the east regulator).

An approach to increase the pressure upstream of the bore miner section in 592 S needs to be found. Different scenarios have been investigated to find an economic alternative which fulfills minimum requirements.

VENTILATION SURVEYS

State-of-the-art Paroscientific 765-16B digital pressure transducers have been used to measure absolute pressure at each station. Digital instruments have been used to measure air thermal properties. A Davis anemometer has been used to measure air velocities. The trailing-hose method has been used to measure the frictional pressure in the returns.

During the pressure survey the leapfrog method was selected where both sets of instruments were taken underground and read simultaneously at adjacent stations. Both pressure instruments have been adjusted to the same reading at each station, and with simultaneous readings with the aid of synchronized watches, the effect of atmospheric pressure changes is eliminated. Since readings at each station are also duplicated, the results are likely to be more accurate. A total of 85 ventilation stations have been used for measurements throughout the mine.

Figure 1. Present Ventilation Network.

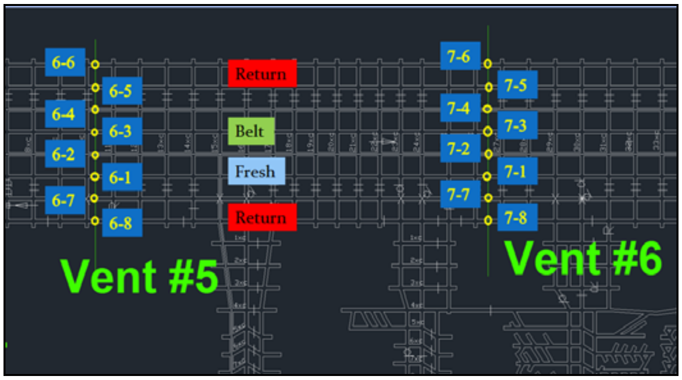

Figure 2. Example of Ventilation Stations.

A comprehensive PQ survey has been conducted across all airways in the "Mains" including "Belt Air", "Returns" and "Main Roads". For safety purposes the belt air has not been measured with the belt running (figure 2). The Paroscientific pressure transducers and digital psychrometers are not rated "permissible" for use in gassy atmospheres and so not used in the returns. For this reason absolute pressure was measured in fresh air. Frictional pressure was calculated by subtracting pressure drop from absolute pressure. The psychrometric properties of wet and dry bulb temperatures have been measured with sling psychrometers.

Cage Shock Loss

The cage movement creates shock losses in the shafts. There are two possible ways of calculating resistance that correspond to shock loss. If the cage does not fill the compartment, the force of the air can be calculated on the cage area, and it can be applied in the ventilation simulation program "Ventsim" as a fixed pressure in the shaft airway. An approach using Ventsim is to place an orifice in the airway with an area size equal to the surrounding gap around the cage if the cage is almost the full size of the compartment and acts as a plunger.

In the FMC mine case, the cage does not fill the cross sectional area. The construction of the cage allows the air to pass through. Screen type metal pieces have been welded to cover the top and the bottom of the cage. When the cage is moving up or downwards in the shaft the air can pass around and across the cage. The pressure drop across the cage has been measured by putting one digital transducer on the bottom of the cage and the other on the top. The airflow measurements have been taken in five different cross sections from top of the cage.

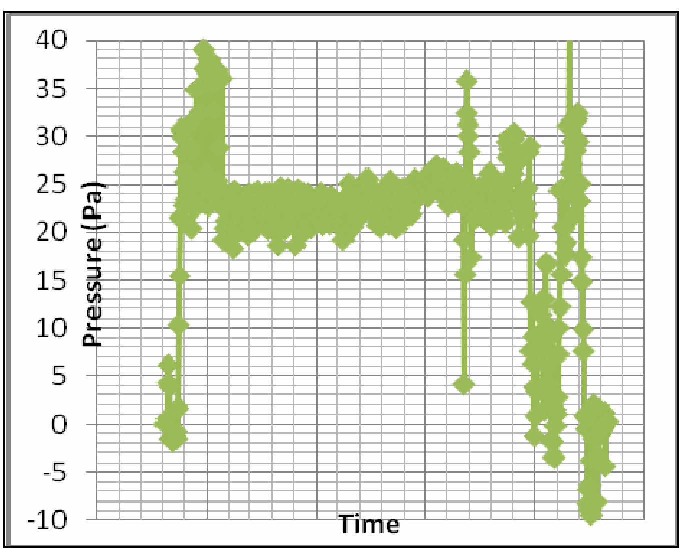

Figure 4. Shaft Cross Sectional Top View.

In order to take the measurements, the cage was stopped about 150 m below the collar. The pressure readings during the survey has been plotted and the average pressure drop across the cage has been determined to be 25 Pa. Figure 4 is the plotted pressure readings. The airflow readings were compared against the weekly ventilation report to ensure that the airflow readings are accurate. The airflow and pressure results have been used to calculate resistance by using the $\Delta p=RQ^2$ equation. The cage calculated resistance is 0.0245 Ns^2m^{-8}.

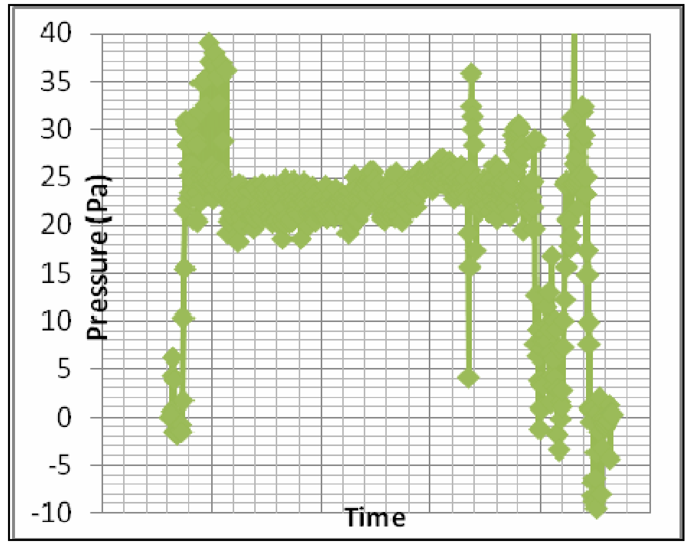

Figure 4. Shaft Cross Sectional Top View

Surface fan curves

The fan manufacturer's characteristic curves have been used for simulation purposes (Figure 5). Both Numbers 5 and 8 Shafts fans are operating on the same blade setting (4B-4S) and 7 Shaft fan is set on 2B-2S. All the fans have been turned off (one at a time) and inspected to determine the current blade setting. In order to use the manufacturer's curves all the blades (leading and trailing edges) have been inspected in regard to corrosion to make sure that the blades are able to deliver an adequate amount of air and the fans will operate on the curves.

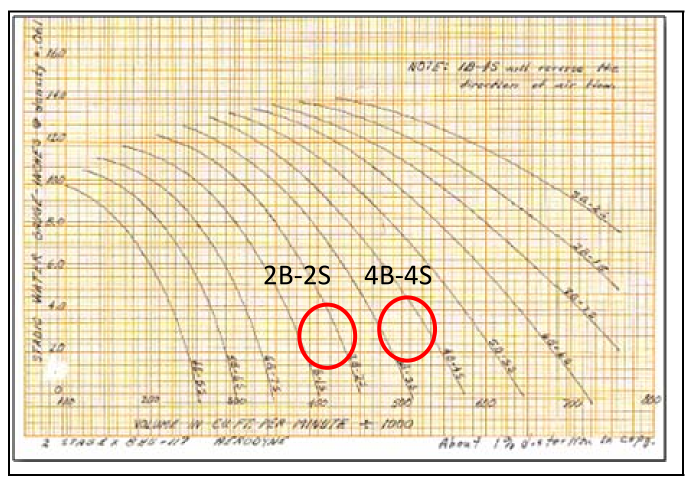

Figure 5. Main Fans Characteristics Curves.

Data Analysis

The pressure, density, k frictional value and airflow resistance for every station has been determined. The psychrometric properties (such as humidity, vapor pressure, dew point, saturation vapor pressure) have been measured and calculated. The results were then used to calculate the average corrected density with respect to local elevation, temperature and barometric pressure. Table 1 shows the final k value results for different airways.

Table 1. Example PQ Survey Results.

Drift	Air Type	K (SI)	K (PU)
3 Main E	Fresh	0.00437	23.58
	Fresh	0.00627	33.82
	Belt	0.00962	51.87
	Fresh	0.00589	31.74
592 S	Fresh	0.00453	24.44
	Fresh	0.00424	22.87
	Return	0.01221	65.82
	Return	0.00978	52.74
493	Fresh	0.00720	38.84
	Return	0.00895	48.25
TailGate	Return	0.00945	55
Longwall	Face	0.00957	56
Overcast	Return	0.01118	60.29

MODEL CALIBRATION

Heat Simulation Studies

The ventilation simulation model has been built from the mine's existing AutoCAD model. The model consists of 26,725 airways with total length of 983 km. A temperature survey was conducted and results have been analyzed. The mine's pump stations were identified as the highest heat source category (Table 2). The assumption of 80% motor efficiency was used for power calculations. Most of the pumps are not running continuously; therefore the heat input numbers have been slightly lowered.

Table 2. Pump Stations Power Usage.

Pump Station	Power (kW)	Heat (MJ/hr)
5 Shaft	895	3,220
578	75	268
349	522	1,878
Bypass	261	939
3 NE	261	939
2 NW	112	402
7 Shaft	186	671
3 Shaft	298	1,074
311	93	335
8 Shaft	75	268
473	75	268
LW 4 Panel	30	107
LW pump	75	268
3 ME	75	268
1 NE	22	80
Total	3,054	10,986

Virgin Rock Temperature (VRT)

Some Environment and Rock Thermal Properties are set down in Table 3. The increase in the VRT of strata (unaffected by underground activities) with respect to depth is known as the geothermal gradient. It is the linear increase in depth for each unit increase in temperature. The geothermal gradient varies according to the local rock's thermal conductivity and the depth of the earth's crust in the area (Duckworth 2011). In order to evaluate strata heat flow in subsurface environments it is vital that the geothermal gradient is determined.

Data on the natural rock temperature at a known elevation is required to measure VRT. At FMC mine a 6 m long, 40 mm diameter hole was drilled by a jumbo rock drill. Location wise, the hole was drilled into the fresh air course close to the face (23m outby the last open cross cut). Two thermocouples were inserted into the hole immediately after the hole was drilled. One thermocouple was placed at the hole's bottom-end (6m from the hole collar) and the other was placed 3m from the collar (Figure 6).

The hole was sealed from the atmosphere with urethane foam to avoid fresh air affecting the results. Every effort was made to insert the probe into the hole as soon as possible after drilling. The probes were connected to a laptop and readings were logged for four full shifts. The rock temperature values started dropping shortly after the probes were inserted into the hole.

Table 3. Environment and Rock Thermal Properties.

	Value	Unit
Surface Air Density	0.98	kg/m^3
Geothermal Gradient	1.1	°C/30m
Rock Density	2130	kg/m^3
Rock Specific Heat	1256	J/kg°C
Trona Thermal Conductivity	0.43	W/m/°C
Rock Thermal Diffusivity	0.162	---
Surface Barometric Pressure	81.3	kPa
Surface Rock Temperature	13.4	°C
Surface Wet bulb Temperature	12	°C
Surface Dry Bulb Temperature	28.1	°C
Virgin Rock Temperature	25	°C

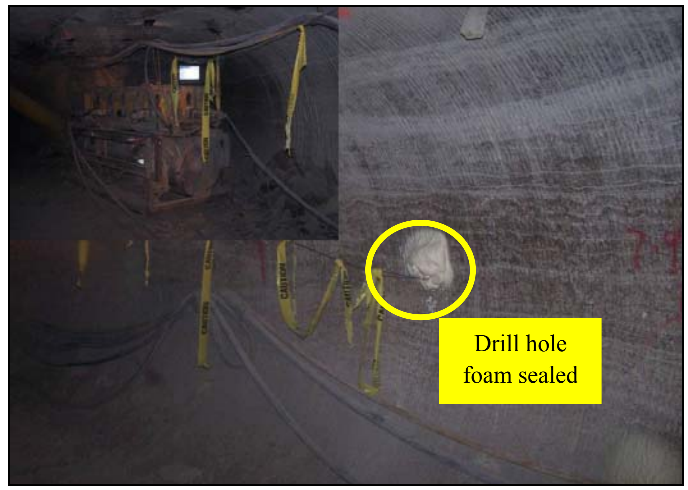

Figure 6. Virgin rock temperature experiment.

The energy absorbed by the rock during drilling was considered enough to significantly raise the temperature of the rock mass. The test was conducted in early August when the surface temperature was 30°C. The results show the test ambient air temperature is higher than the VRT temperature. In other words, the air loses temperature while it is traveling underground. The ambient temperature was determined to be 26°C.

Natural Ventilation Pressure (NVP)

The natural ventilation pressure and compressibility of the air were taken into account in simulations. A simulation was conducted for a case where all the surface fans were off. The results were compared against the experiment that was carried out during a mine-idle shift with fans off. The simulation and experimental data are shown in Table 4. The surface dry bulb temperature was 4.4°C.

Table 4. NVP Ventsim Simulation Results vs Experimental Results.

Shaft	Ventsim Simulation Results		Experimental Results
	Air Direction	Quantity (m^3/s)	
1 Shaft	Down cast	1.9	Down cast
2 Shaft	Down cast	12.6	Down cast
3 Shaft	Down cast	15.8	Down cast
4 Shaft	Down cast	29.2	Up cast
5 Shaft	Up cast	19.8	Up cast
6 Shaft	Down cast	15.5	Down cast
7 Shaft	Up cast	18.3	Up cast
8 Shaft	Up cast	21.5	Up cast
9 Shaft	Down cast	3.8	Down cast

IDENTIFIED IMPROVEMENTS FROM MODEL

A number of scenarios were examined to identify how mine ventilation could be improved.

Scenario 1. 5 Shaft fan Off, Booster fan Added

The objective of this scenario is to ventilate the entire mine using 7 and 8 Shaft surface fans. The 7 Shaft blade setting is on 2B-2S and 8 on Shaft 4B-4S. This scenario investigates the possibility of ventilating the longwall, development panels and pump stations with two fans. For this purpose, the mine has been divided in two regions (Figure 7).

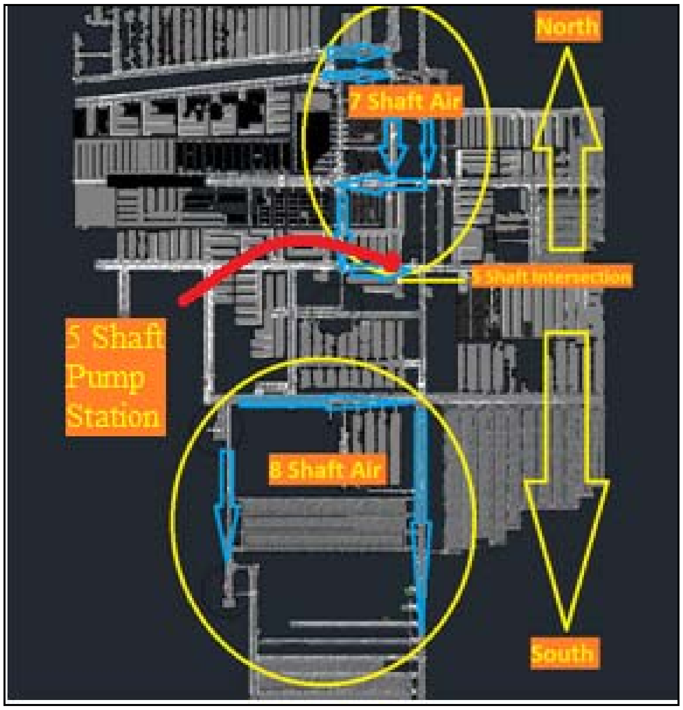

Figure 7. Schematic View of Divided Regions.

Ventilating the 5 Shaft pump station is crucial since it generates a significant amount of heat. Heat transfer of all kind has to be considered. The heat conduction in between roof layers (the pump station roof, consists of trona and shale) may affect the roof condition and interrupt the solution mining. The heat convection needs to be considered to keep the pump station temperature at a reasonable constant temperature.

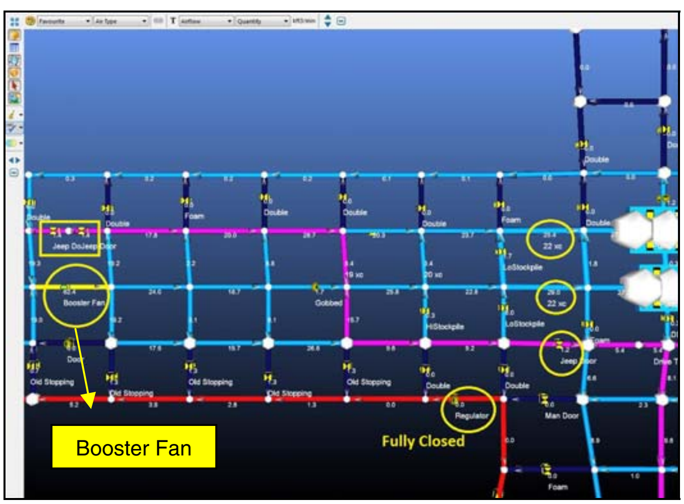

Figure 8. Additional Booster fan in Fresh Air.

The effect of adding a booster fan to handle the heat issue was investigated. This was accomplished by setting a fixed pressure in two different locations for the purpose of increasing the volume flow rate through the 5 Shaft pump station. The booster fan has been added in fresh air (figure 8). In this case the additional 80 Pa pressure (as fix pressure in Ventsim Visual model) will increase the volume flow rate in the pump station.

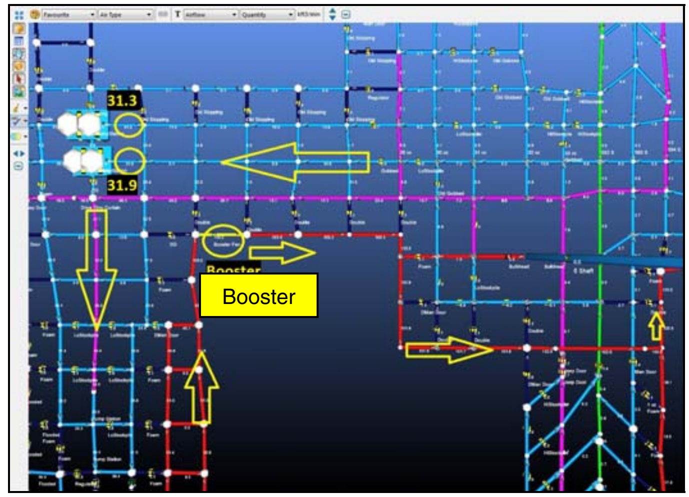

Figure 9. Scenario 1, Booster fan installation in Return.

In a second case the booster fan has been added in the sump return (figure 9). Minimum air requirement in both scenarios was met. In this case the air would not be exhausted from 5 Shaft. Instead it will be dumped to the return using the existing overcast. The second case would require a bigger booster fan to push 50m^3/s at 0.6 kPa of total pressure.

Scenario 2. Redirecting Main Shop Air

Currently, the Main Shop air (approximately 50m^3/s) is being exhausted to 6 Shaft passing through three existing regulators. This air is not exposed to any source of contaminants in the shop and can be used for ventilation purposes. Figure 8 shows the changes that need to be done to add up to 70% of shop air quantity flow back to the system. Table 5 shows the Ventsim simulation results.

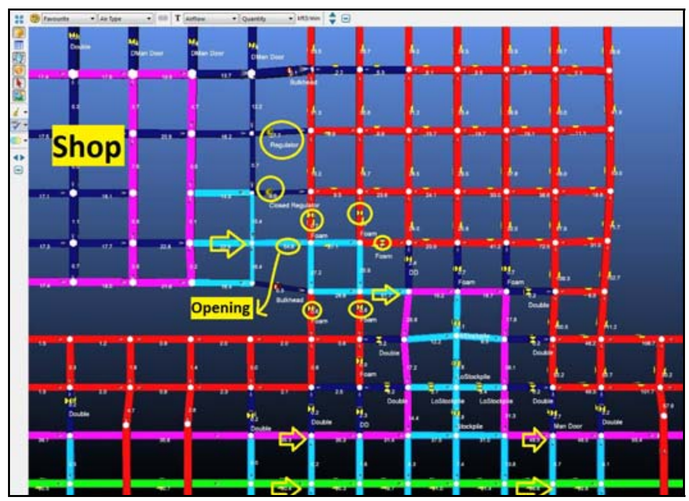

Figure 10. Scenario 2, Rerouting the Shop Air.

Table 5. Scenario 2 Ventsim Workshop Simulation Results.

Location	Present Model Q (m^3/s)	Scenario 2 Q (m^3/s)
Fresh Air, 592 S, 133 xc	96.7	101.7
10 HG	6.5	7.1
9 HG	2.4	2.8
8 HG	11.0	13.7
Set-up Room (Regulator)	9.9	9.6
LW	42.1	41.5
9 Shaft	94.6	98.1

Scenario 3. Booster Fan Installation in Main Return

As mentioned before, the differential pressure between development panels and 6 Shaft is relatively small owing to long distances. This scenario investigates the effect of adding a booster fan to the main return. The additional pressure from the booster fan may increase the leakage in the adjacent outby and inby stopping lines and also that may cause recirculation as noted in the work done by Gillies, 2010.

In this scenario the booster fan has been added in series with the main fans at 592 S (589 S drift). Figure 11 shows the location of the proposed booster fan. The mine operation already owns the recommended booster fan as a spare. Figure 12 shows the booster fan operating point. For simulation purposes, blade setting #6 has been selected and inputted into the simulation software. A Variable Frequency Drive (VFD) has been used to reduce the fan speed to 90% rpm. This is the highest blade setting and could draw up to 160m^3/s of air. The main task for this booster fan is to increase the differential pressure and draw the air into the panels; in other words, the booster fan ventilates the panels and 9 Shaft is used to ventilate the LW. The results are shown in Table 6.

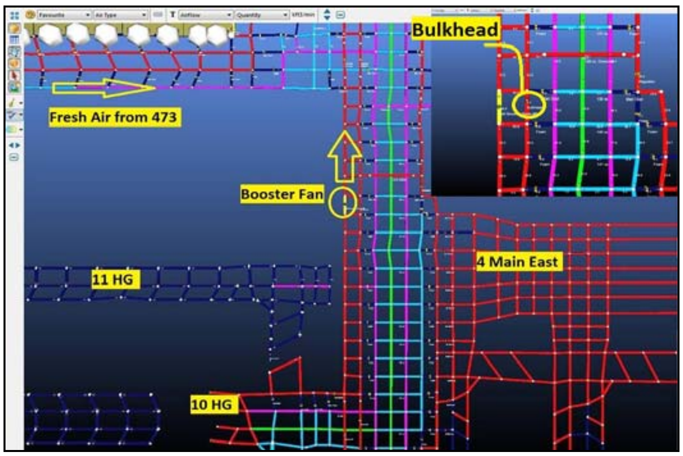

Figure 11. Scenario 3, The Location of Booster Fan in the Return Airway.

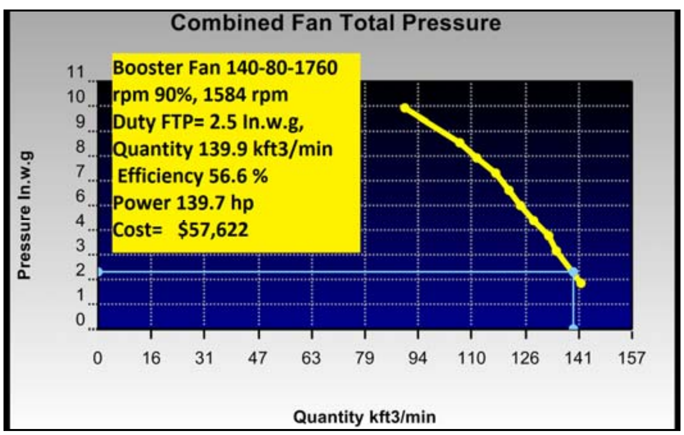

Figure 12. Scenario 3, Booster Fan Characteristics Curve.

Table 6. Scenario 3,Ventsim Simulation Results.

Location	Present Model Q (m^3/s)	Scenario 3 Q (m^3/s)
Fresh Air, 592 S, 133 xc	96.7	119.4
10 HG	6.5	26.5
9 HG	2.4	8.5
8 HG	11.0	24.0
Set-up Room (Regulator)	9.9	9.0
LW	42.1	38.7
9 Shaft	94.6	93.8

Scenario 4. Reducing Main Fan RPM to 85%

This scenario investigates the practicality of reducing operating costs by installing VFD units on the surface-based fans. Currently, the surface fans are operating at 100% design speed (710 rpm, at 60 Hz). The PQ results show that 5 and 8 Shaft fans are working to overcome their opposing pressures and push more air. This increases the power consumption and operating cost for both.

There are a number of advantages realized with installation of VFD's on surface fans:

1. Reducing the fan speed by adjusting the frequency lowers wear on fan parts.
2. Reducing the operating cost by reducing the speed in off-shift/maintenance).
3. Increases safety by being more flexible in case of emergency. For example increasing the 8 Shaft speed to ventilate the 5 Shaft pump station in case of losing 5 Shaft fan.
4. Capacity to over speed the motors.
5. Set the blades on high setting and slow it down to reduce the operating cost. In this case the fan is capable of pushing more air by increasing the frequency at any time.

In this scenario all the fans were operated at 85percent speed (600 rpm). The simulation results are shown in Table 7. There are numerous alternatives such as over speeding one fan and slowing down the other with higher blade setting. Followings are the simulation results when the fans rpm are set at 85%. The Ventsim simulation results show that annual operating cost could be significantly reduced.

Table 7. Scenario 4. Vetsim Visual Results, 600 rpm.

Fan	Quantity (m^3/s)	
	Present	Simulated
8 Shaft	206.2	186.0
5 Shaft	210.8	177.7
7 Shaft	166.0	139.6
Total	583.0	

Scenario 5. Additional Fresh Airways

In this scenario additional fresh air has been used to maintain ventilation in development panels. In order to reduce the amount of labor work and capital cost, the 134 crosscut (in 590 S drift) has been chosen as the starting point for the additional fresh airway (Figure 13). The estimated capital cost for pushing back the line of stopping was determined to be $35,000. This change increases the incoming volume flow rate to south by 20m3/s.

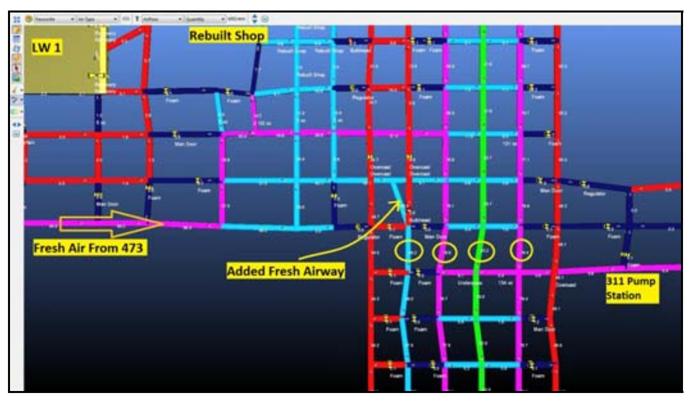

Figure 13. Scenario 5, Vetsim Visual Schematic View, Additional Fresh Airways.

Scenario 6. Sinking Ventilation Raise

In this hypothetical scenario, the possibility of sinking a ventilation raise was investigated. The ventilation raise was located in the southern part of the mine to create adequate differential pressure to exhaust 90 to 52m^3/s of air. This scenario allows use of a ventilation raise to exhaust air that ventilates the bore miner sections. The LW air will remain being directed to 9 Shaft. Figure 14 shows the location of ventilation raise.

The mining cost is assumed to be $600/m for fully reinforced concrete ventilation raise (Anon, 2009). Ventsim optimization program was used to determine the raise diameter. It was determined that a 2m diameter ventilation raise will reduce the frictional pressure loss. This pressure will draw up to 20m^3/s of air to surface. It is important to note this amount can be increased if the main return airways are blocked. The ventilation raise adds the additional frictional pressure to the network to help 4 and 6 Shafts. The mining cost for sinking this shaft will be approximately $3,000,000 (Mining cost services 2010, InfoMine 2009).

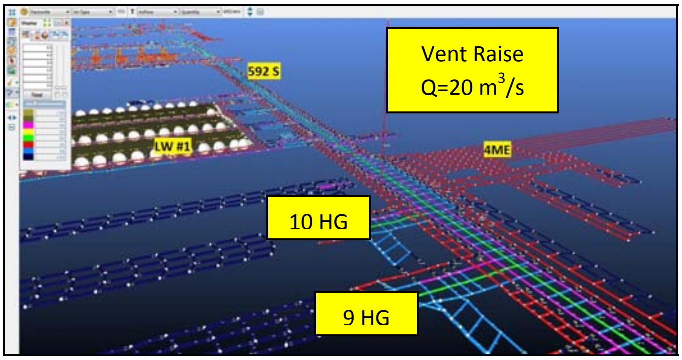

Figure 14. Scenarios 6, Ventilation raise location.

The simulation result shows the ventilation raise increase airflow quantity and is capable of ventilating all development panels. The slight increase in the raise diameter (2.6m) will increase the airflow quantity up to 26m^3/s. It will also increase the mining cost. The ventilation raise is going to be used for ventilating the panels and 9 Shaft will ventilate the LW and Set-up room. The 5 Shaft blades setting can be lowed to 2B – 2S to reduce the operating cost. Table 8 shows the simulation results.

Table 8. Scenario 6. Ventsim Visual Simulated Results.

Location	Present Model Q (m^3/s)	Scenario 6 Q (m^3/s)
Fresh Air, 592 S, 133 xc	108.9	118.0
10 HG	3.5	3.7
9 HG	3.3	20.8
8 HG	23.5	20.9
Set-up Room	11.3	11.8
LW	43.9	42.1
Total Panel Return (149 xc)	30.7	47.7
Ventilation Raise	-----	17.9

Scenario 7. Booster Fan in Fresh Airway

In this scenario a booster fan has been placed in the fresh airway. The demand for fresh air at working faces forces engineers to redesign or upgrade the existing ventilation system (Wempen, 2011). The goal is to deliver more air from 8 Shaft to 592 S Dev and reduce the pressure at the three way intersection. Figure15 shows the location of the booster fan.

This scenario barely meets the minimum defined air requirement in bore miner sections. The operating cost is significantly reduced.

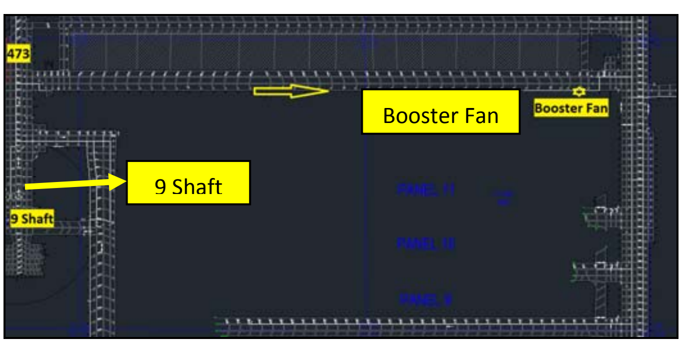

Figure 15. Scenario 7, Booster Fan in Fresh Air.

Scenario 8. Future Plan

Currently mining is occurring in Panel 7. The mine is expecting to finish the block holding panels 8, 9, 10 and 11 by 2018. These panels are located on the west of 592 South development. The future development plan calls for a mainline development (299 West Development) which will support mining until 2023 (Figure 16).

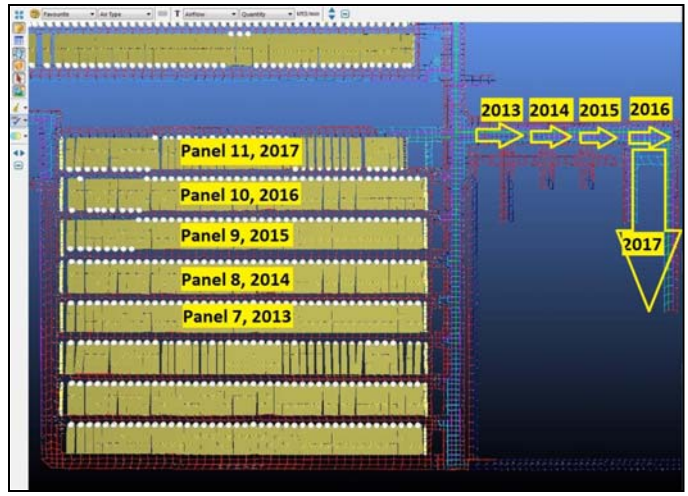

Figure 16. Scenario 7, Booster Fan in Fresh Air.

The airflow quantity in bore miner sections is increased. Table 9 shows the simulation results. No other major changes have been made in preparing this simulation. In summary, the airflow quantity in development panels increases with LW panels moving to north with a shorter distance to 9 Shaft. In addition this also justifies the increasing in development panel airflow since the distance to 6 Shaft is also reduced. Both LW and Development panels are at their closest distance to 5 and 8 Shafts.

Table 9. Scenario 8. Future Plan, Simulated Ventsim Results.

Location	Present Model Q (m^3/s)	Future Plan 2017 Q (m^3/s)
Fresh Air, 592 S, 133 cross cut	108.9	108.6
Active Bore Miner #1	7.6	20.4
Active Bore Miner #2	23.5	21.8
Set-up Room	11.3	-----
LW	43.9	49.7
Total Panel Return to North	30.7	44.7

CONCLUSION

The current ventilation model of the mine was built and projected to the mine's fifteen year plan. A feasibility review has been completed on alternatives available to improve working ventilation as production moves into new parts of the mine lease. The scenarios examined alternatives utilizing additional infrastructure such as main ventilation shafts and fans or underground booster fans.

The following is a review of the various scenario simulations;

1. Scenario 1. In this scenario the mine is divided into two regions. 7 Shaft has been used to ventilate the North. A booster fan has been used to draw 7 Shaft air to the South to ventilate 5 Shaft Pump Station. However with current ventilation network, 8 Shaft fan is not capable of fulfilling minimum air requirements. Since all mining operations and active panels are located in south.

2. Scenario 2. The main shop air is reintroduced to 3 Main East. This air does not become contaminated and continues on to extraction areas. The capital cost for this scenario is low and would increase the air flow in 592 S.

3. Scenario 3. A booster has been added to the main return. This scenario reduces the operating cost by ventilating the

LW and panels using 8 Shaft fan and one booster fan. It was determined that the booster fan pressure will overcome the 9 Shaft pressure. The requirement of $25m^3/s$ for each active panel is easily fulfilled by using a booster fan. In this case the total fresh air entering the LW is $60m^3/s$. With the failure to meet the minimum requirement at the LW without utilizing 5 Shaft fan, the lower blade setting (1B – 1S, 2B – 2S, 3B – 3S) for 5 Shaft fan was tried. In all cases, the minimum airflow requirement was almost fulfilled. The operating cost for this scenario is low since FMC owns the permissible booster fan required for this scenario. The State approval is needed prior to installation.

4. Scenario 4. The main fans' speeds were reduced by 85%. The operating cost significantly dropped while maintaining the minimum requirement. The capital cost for this scenario is high. The FMC is considering executing this scenario since it a great energy saving opportunity with large rate of return.

5. Scenario 5. Additional fresh airway has been added to the main. This airway increases the amount of fresh airway going south. The scenario

6. Scenario 6. A ventilation raise was sunk to reduce the frictional pressure. The capital cost is high. Therefore it is not cost effective and not recommended and is not of mine interest.

7. Scenario 7. A single booster fan has been added in series carrying fresh airway. The airflow in key stations is marginal.

Finally, it can be seen that scenarios 2, 3, 4 and 5 can meet required face airflows. The company is considering stepping forward with Scenarios 2 and 5 in near future due to their low capital costs. Scenario 3 completely fulfills the requirements. However State approval is required. Scenario 4 meets required face airflows but the capital cost is over $1.5 million. For this reason the company is conducting further studies. Scenarios 4 and 3 are recommended as being the best alternative for serious consideration to meet the mine ventilation requirements in the fifteen year plan.

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