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Comparison of use of booster fans in US Coal Mines to alternative approaches for maintaining ventilation

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ABSTRACT: A booster fan is an underground main fan which is installed in series with a main surface fan and used to boost the air pressure of the ventilation to overcome mine resistance. Currently booster fans are used in almost all major coal mining countries requiring this form of ventilating air motivation including the United Kingdom, Australia, South Africa, Poland and China. In the United States booster fans are prohibited in coal mines although they are used in many metal and non-metal mines. A hypothetical mine example has been used to examine alternatives for ventilating an underground US room and pillar coal mine system including use of a ventilation network incorporating booster fans. A feasibility study of the hypothetical situation has shown that current ventilation facilities are incapable of fulfilling mine air requirements in the future due to increased seam methane levels. A current ventilation network model has been projected to a mine five years plan. Network simulations of different ventilation options have been conducted in which varying methane levels occur at working faces. Several scenarios for improving the ventilation situation such as improving main surface fans, adding intake or exhaust shafts and utilizing booster fans have been examined. After taking into account the total capital and operating costs over five years the booster fan scenarios are recommended as being the best alternatives. The optimum option is a properly sized and installed booster fan system that can be used to create safe working conditions, maintain adequate air quantity with lowest cost, generate a reduction in energy consumption and decrease mine system air leakage.

1 Introduction

The total mine resistance substantially increases as an underground coal mine gets deeper and workings more extensive. The demand for fresh air at working faces forces engineers to redesign or upgrade the existing ventilation system (Wempen, Calizaya and Peterson, 2011). Several scenarios for improving a ventilation situation such as altering the main surface fans, adding intake shafts or exhaust shafts or installing booster fans to the system have been examined.

Booster fans are technically main fans which are installed underground to maintain the required airflow by overcoming the mine resistance. In the United States the usage of booster fans are permitted in metal mines however federal legislation prohibits their use in underground coal mines with the exception of anthracite mines (Title 30 Code of Federal Regulations 2010). Booster fans can reduce the pressure required from the main fan and decrease the system leakage and the total required air power (Martikainen and Taylor, 2010). The objective of this study is to find the optimum method for ventilating an underground U.S. coal mine. The optimal ventilation design is to determine the best combination of fans and regulators that will fulfill the airflow requirements in the mine and minimize the present value of the total cost. Both booster fans and regulators are used to control air distribution throughout the mine network. Regulators destroy energy (initially put into the mine ventilation system by fans) while booster fans add energy to the system; from an energy balance point of view airflow control through use of booster fans will be more efficient than use of regulators.

This paper presents seven different scenarios simulating the ventilation network of an underground coal mine in the U.S. The study started by expanding the model from the current workings to the mine's five years production plan. The airflow simulation has been conducted as well as contaminant simulation. In addition, the cost study has been done to determine the uneconomic and impractical scenarios especially regarding power consumption. Scenarios 4 and 6 can meet the required face airflows. However scenario 6, with the use of two booster fans, is recommended as being the best alternative in the five year plan after taking into account the total cost and the expected life of the new infrastructure.

2 General Information on the Mine

This underground coal mine uses the room and pillar method. The coal seam is horizontal with thickness of 1.8 m. Development mains are driven with eleven entries (four intakes, four returns and three neutral airways). Sub-mains are driven with two intakes, two returns and three neutral airways.

Currently the mine has five active working faces ventilated by a 670 kW axial fan using a pull exhausting system. The mine currently exhausts 230 m^3/s of air at static pressure of 1.95 kPa. The input power of 460 kW is required. A pressure and air quantity survey has been conducted to construct the base ventilation model. This has been expanded to the five years production plan using the current mine schedule approach as shown in Figure 1a and 1b. Figure 1b shows the schematic view of intake, exhaust and slope in more details.

Working Units #1 and #3 dump return air to Main West Return, Unit #2 and #4 dump air to Main East Return, and Unit #5 dumps air to Main North Return. Eventually Main East Return and Main West Return dump air to Main North Return which goes to the exhaust upcasting shaft.

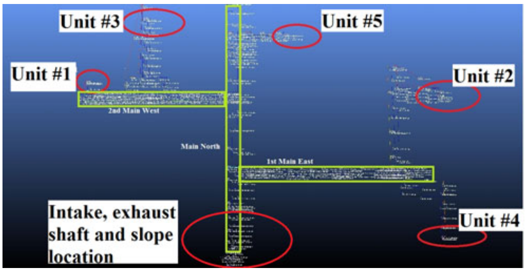

Figure 1a Ventsim Visual Schematic view of Mine Ventilation Model

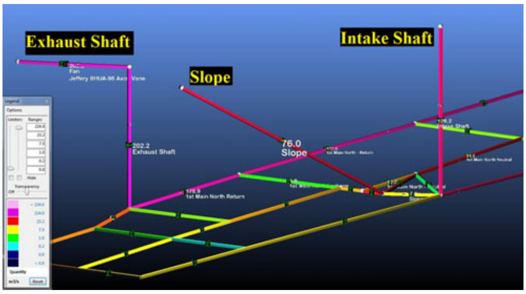

Figure 1b View of Ventilation Infrastructure

3 Issues with Booster Fans

Boosters can overcome some major ventilation problems and provide extremely important advantages. It should be recognised that boosters have a number of disadvantages particularly in the coal mine environment.

Sometime into the ventilation life of a mine it is quite common that the duty point of the surface fan lies near the unstable portion of its characteristic. If the ventilation requirements are cannot satisfy, the following factors must then be examined.

1. Whether the fan performance, particularly its pressure capability can be increased and if so, what power increase would result. A completely new primary fan may be necessary.
2. The feasibility of an additional ventilation shaft or additional underground airways may have to be considered.

Either alternative is likely to involve considerable capital expenditure and/or may be impracticable. Under such circumstances, it is very likely that a booster fan would be a viable cost-effective solution. The key factor, which is not always apparent to the mine operators, is that the artificial restrictions or regulators in the ventilation system increase the pressure necessary to generate the total flow (Gillies. S 2010).

4 Study Assumptions

The original five year plan and seven different alternative hypothetical scenarios have been simulated to determine the optimal option which offers the lowest total cost (capital cost plus operating cost) as well as providing required airflows at working faces. In this hypothetical exercise higher coal seam methane contents (1 m^3 CH_4/t and 2 m^3 CH_4/t) are presumed to be encountered in mining coal seams in five years. Options examined consideration of the cases where more ventilation is made available underground from alternatives of:

i. The driving of more intake or return shafts,
ii. The use of various surface main fan combinations
iii. The use of various booster fan combinations.

Financial simulation modeling has estimated optimum ventilation infrastructure size by considering mining costs as well as the life of mine ventilation operating costs. These simulations can, for instance, help to optimize airway sizes and save substantial money over the life of a mine. This approach optimizes the size of the development airways to maximize cost savings in ventilation while minimizing mining costs. Increasing airway size is the easiest way to reduce frictional pressure losses and decrease ventilation costs in a mine. However it causes additional mining capital costs and this is further exacerbated by "time value of money" considerations. Operating costs include electricity, maintenance and installation charges over five years discounted at 10% to the Present Value. Another factor to consider is the length of the time that the airway is required to carry air.

Methane dilution calculations have been undertaken. These are based on a minimum peak required of 15m^3/s of fresh air at each of the working faces. A methane source has been added at each of the five working faces.

The Safe Scenario: A liberation rate of 2.0 m^3 CH_4/t from broken coal with mining rate of 345t/hr (265m^3 coal/hr) at density 1.3 t/m^3 has been used. An airflow rate of greater than 15m^3/s across a working face is deemed to be required to give CH_4 concentrations of less than 1.0% in face air. The steady state contaminant simulation has been performed based on the requirement of an allowable peak concentration of methane at each individual working face. The spread of methane concentrations in downstream airways is identified.

The Very Safe Scenario: A liberation rate of 1.0m^3 CH_4/t from broken coal with mining rate of 345t/hr (265m^3 coal/hr) at density 1.3t/m^3 has been maintained. The airflow rate of greater than 15m^3/s is deemed to be required to give CH_4 concentrations of less than 0.5% in face air. The simulation has been performed by adding 0.5%

methane to each individual faces and tracking the spread of the contaminant. The results show the concentrations of the methane in the network which emphasizes that the predicted concentration in all network airways is lower than 0.5%.

5 Simulation Alternatives

5.1 Scenario 1

The simulation has been conducted based on the expanded model and current ventilation infrastructure for the next five years. Typical resistance values for the mine were used in the projected model.

It was determined that unit #1 and #3 are the furthest sections and due to the distance and airways resistance, the available airflow at working faces is less than the minimum required. Unit #4 also does not have the minimum required airflow. Quantity across the #2 and #5 faces is marginal at best. According to the results, the current surface fan infrastructure is not capable of ventilating the mine and meeting methane requirements.

Table 1 shows the simulation results. Scenarios #2 to #7 are based on ventilation changes from this expanded five years plan model. The operating cost

The input power (fan air power) has been calculated on Fan Total Pressure and represents the power the fan motor is applying to the fan blades to generate the pressure and flow through the fan.

The annual operating cost is derived from the power cost set in the Setting Menus for a fan operating at this duty point continuously for a full year (Ventsim Visual, 2012).

Table 1. Scenario 1 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	205.4 m^3/s
Intake Shaft	121.4 m^3/s
Slope	74.3 m^3/s
Unit#1	8.9 m^3/s
Unit#2	13.4 m^3/s
Unit#3	7.9 m^3/s
Unit#4	6.2 m^3/s
Unit#5	13.2 m^3/s
Input Power	792 kW
Annual Operating Cost, $	693,270

5.2 Scenario 2

This scenario has an intake shaft added in 1st Main East. The simulation adjusts the flow through the airway based on the resistance of each airway size. The required shaft diameter can be determined from the mining costs and the required airflow. The schematic view of the shaft and the simulation results can be found in table 2.

Table 2. Scenario 2 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	206.1 m^3/s
Intake Shaft	73 m^3/s
Slope	38.1 m^3/s
Intake Shaft #2	95 m^3/s
Unit#1	6.7 m^3/s
Unit#2	15.8 m^3/s
Unit#3	6.3 m^3/s
Unit#4	15.0 m^3/s
Unit#5	14.4 m^3/s
Input Power	813.4 kW
Annual Operating Cost, $	712,511
Capital Cost, $	1,464,000

The main fan operates at static pressure of 0.22 kPa and exhausts 206.1 m^3/s of air. Under this simulation the full quantity of air is unaltered and the minimum air requirement in the eastern part of the mine (Units 2 and 4) has been met. However not enough air reaches the other three faces.

Financial simulation estimates optimum ventilation infrastructure size, by considering mining costs as well as life of mine ventilation operating costs. This simulation can help optimize airway sizes and save substantial money over the life of a mine. Increasing airway size is the easiest way to reduce frictional pressure losses and decrease ventilation costs in a mine. Increasing airway size however creates additional mining costs, and this is further exacerbated by the 'time value of money' which dictates that a dollar saved in mining costs now is worth more than a dollar saved in ventilation costs in the future. Another factor to consider is how long the airway is required to carry air, which affects how much ventilation cost can be saved in the future. Ventsim Visual financial simulator takes all this into account and simulates up to 10 different airways sizes for an airway or group of airways. The simulator reports the effect on mining cost and ventilation costs as the Net Present Value (NPV) cost adjusted overall cost (Ventsim Visual, 2012).

The study has optimized the size of the shaft development airways, to maximize cost savings in ventilation, while minimizing mining costs. Increasing airway size is the easiest way to reduce frictional pressure losses and decrease ventilation costs in a mine.

However it creates additional mining cost and this is further exacerbated by the "time value of money" which dictates that a dollar saved in mining costs now is worth more than a dollar saved in ventilation costs in the future. It was found that the optimum diameter of intake shaft is 2.8 m.

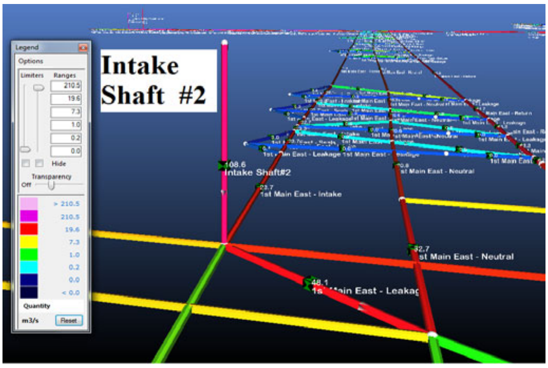

Figure 2. Ventsim visual schematic view of intake shaft #2

5.3 Scenario 3

Two intake shafts were added to the model in order to supply the required air at faces. Intake shaft #2 has been added to 1st Main East and Intake shaft #3 is added to 2nd Main West.

The total exhausted air quantity has not been increased. An optimized diameter of 2.4m has been selected based on the lowest excavation cost. Table 3 shows the predicted results.

This scenario almost meets the minimum requirements for all units; however, the air quantity at unit #3 which is the furthest face from both faces has not been reached. Moreover, the shaft excavation operation is a time and cost consuming exercise which causes this scenario to have a high capital cost.

The advantage of sinking two small diameter intake shafts is that the fresh air will travel a shorter distance compared to the air provided from main intake shaft and slope.

Table 3 Scenario 3 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	202.2 m^3/s
Intake Shaft	43.2 m^3/s
Slope	24.6 m^3/s
Intake Shaft #2	74.5 m^3/s
Intake Shaft #3	59.9 m^3/s
Unit#1	15.1 m^3/s
Unit#2	15.2 m^3/s
Unit#3	12.4 m^3/s
Unit#4	15.3 m^3/s
Unit#5	15.4 m^3/s
Input Power	811 kW
Annual Operating Cost, $	710,407
Capital Cost, $	3,150,000

5.4 Scenario 4

Exhaust Shaft #2 has been added to the base case in 1st Main East Return. A fan similar to the main fan is added to the network and the optimal diameter of 4.2m is selected. Ventsim simulator also designs optimum ventilation infrastructure size by considering mining costs as well as life of mine ventilation operating costs. This function can help optimize airway sizes and save substantial money over the life of a mine.

Table 4 Scenario 4 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	165.4 m^3/s
Intake Shaft	260.1 m^3/s
Slope	96.5 m^3/s
Exhaust Shaft #2	200.2 m^3/s
Unit#1	17.4 m^3/s
Unit#2	18.3 m^3/s
Unit#3	15.2 m^3/s
Unit#4	16.0 m^3/s
Unit#5	17.4 m^3/s
Input Power	1624.3 kW
Annual Operating Cost, $	1,420,279
Capital Cost, $	2,665,000

The simulation results in table 4 show that this alternative fulfills the air requirements at working faces. However the operating cost is increased dramatically. The capital cost is also increased since sinking a permanent ventilation shaft and purchase and installation of a second surface fan is an expensive process.

5.5 Scenario 5

A second surface exhaust fan #2 (similar to a Jeffery 8HUA-96 Axial Vane) has been added in parallel (Fig 3) to the original Main fan. The air simulation was successful but with warning that “the lack of airflow rate causes the fans to be stalled”. One of the fans is exhausting 123.1 m^3/s at static pressure of 0.33 kPa and the second is exhausting 129.9 m^3/s at the same static pressure

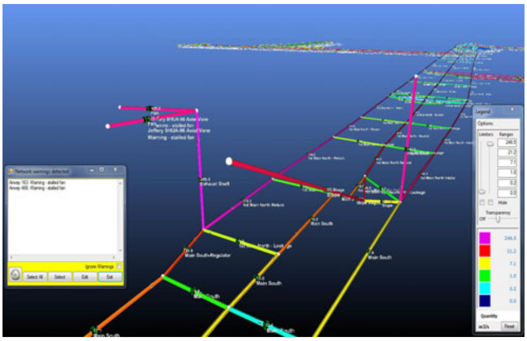

Figure 3. Ventsim Visual Schematic view of Exhaust Shaft #2

The operating points drops off the curve (Fig 4). The network efficiency is estimated at 57.4%. The network efficiency is largely influenced by the configuration of fans throughout a network. The network efficiency is the ratio of theoretical to installed power. The efficiency will decrease as more fans are required to boost airflow through the mine. This scenario does not meet the requirements at any of the working faces.

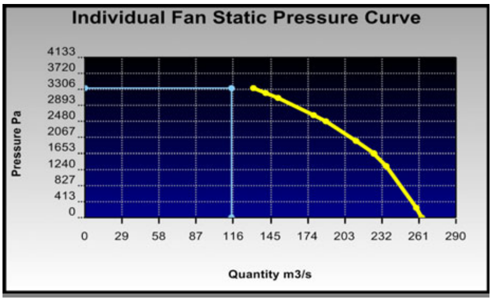

Figure 4. Stalled fans characteristics curve and operating point

Table 5 Scenario 5 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	253 m^3/s
Intake Shaft	162 m^3/s
Slope	91 m^3/s
Exhaust Fan #1	123.1 m^3/s
Exhaust Fan #2	129.9 m^3/s
Unit#1	9.2 m^3/s
Unit#2	10.5 m^3/s
Unit#3	9.4 m^3/s
Unit#4	4.4 m^3/s
Unit#5	13.1 m^3/s
Input Power	1402.4 kW
Annual Operating Cost, $	1,228,476
Capital Cost, $	490,000

Although in this scenario two surface fans are working in parallel the total amount of exhausted air is not significantly changed. Based on the fan laws, total air quantity should increase. The reason for this incident could be the high resistance which occurred because of the distance to the workings and also limited diameter of the exhaust shaft. In this scenario the capital cost consists of the cost of purchasing the second surface fan and mechanical and civil works that are needed.

5.6 Scenario 6

Since the current surface main fan by itself is physically incapable of meeting the airflow requirements two booster fans have been added to the network to add in series air pressure to overcome resistance. Booster fans could be installed in the main airways or in a split of the main airways. Booster fan #1 has been added to the 1st Main East Return and Booster fan #2 has been added to 2nd Main West Return. Figs 5 and 6 show the fan characteristics curves. Figure 7 shows the locations of booster fans in the network. This scenario meets the required airflow at working faces with relatively low additional capital cost. Table 6 shows the simulation results.

Table 6. Scenario 6 predicted airflows on working faces

Locations	Predicted Values
Exhaust Shaft	204.4 m^3/s
Intake Shaft	148.6 m^3/s
Slope	55.8 m^3/s
Booster fan #1	77.1 m^3/s
Booster fan #2	55.3 m^3/s
Unit#1	17.2 m^3/s
Unit#2	15.0 m^3/s
Unit#3	15.3 m^3/s
Unit#4	15.0 m^3/s
Unit#5	15.0 m^3/s
Input Power	915.7 kW
Annual Operating Cost, $	802,120
Capital Cost, $	310,000

Booster fan installation may require the development of a bypass drift, widening of an existing drift, installation of airlock doors, and miscellaneous civil constructions. The next task is fan testing and commissioning. Testing involves checking the fan for stability, and running it initially at no load with the airlock doors open and then at full load with the doors closed (Calizaya, Stephens and Gillies, 2010).

Inappropriate booster fan selection or installation introduces potential hazards including an increased likelihood of mine fires or recirculation of contaminants. Addition of bulkheads and changing regulators downstream of the booster fans may be required to adjust the resistances of branches to control air distribution. Most changes need to be done in 2nd Main west, 1st Main East and the intersection of Main North Vs 2nd Main.

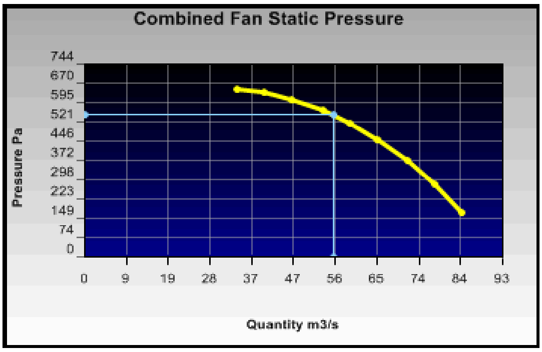

Fig 6 Booster fan #2 characteristics curve, 1st main east

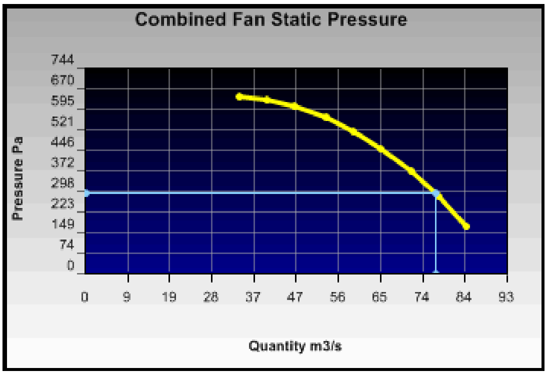

Fig 6 Booster fan #1 characteristics curve, 2nd main west

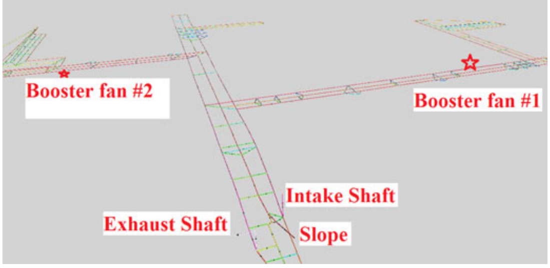

Figure 7 Booster fans locations

In this scenario the capital cost is the cost of purchasing and installing two booster fans in determined sections. The capital cost of $105,000 for each fan has been assumed. This cost includes the cost of motor and other fan accessories. The installation cost has been assumed to be 50% of the fan cost.

5.7 Scenario 7

One booster fan added to Main North Return to increase air pressure and reduced overall power costs. Although the capital cost is lower than some other scenarios, the booster fan could not meet the required airflow at the working faces. The booster fan exhausts 177m^3/s at static pressure of 0.61 kPa with efficiency of 68%. Table 7 shows predicted values for this scenario. Figure 8 shows the location of booster fan in the network.

The air quantities at working faces do not meet the minimum requirement. The amount of air has been adjusted by adding the regulators to the network. However the average amount of fresh air at working faces is 11.5 m^3/s.

The capital cost in this scenario is the cost of purchasing one booster fan with all accessories of $340,000 plus installation fee $150,000.

Table 7 Scenario 7 predicted airflows on working faces

Locations	**Predicted Values**
Exhaust Shaft	208.2 m^3/s
Intake Shaft	130.6 m^3/s
Slope	77.6 m^3/s
Booster fan	177 m^3/s
Unit#1	12.2 m^3/s
Unit#2	11.5 m^3/s
Unit#3	11.4 m^3/s
Unit#4	11 m^3/s
Unit#5	11.8 m^3/s
Input Power	977.8 kW
Annual Operating Cost, $	856,578
Capital Cost, $	490,000

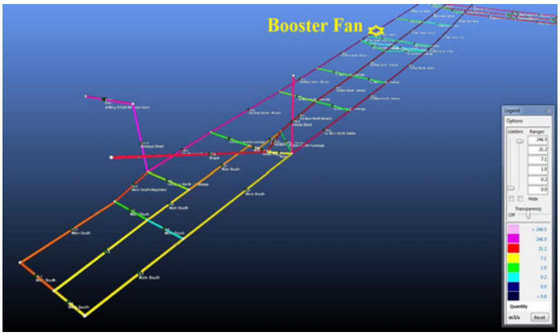

Figure 8 Boster fan location in scenario 7

6 Contaminant Simulation

The seven scenarios show that following the addition of either 1% or 0.5% methane to each working face, the average of methane across all five faces and consequently throughout the mine network is respectively less than these figures. This is because the simulation optimizes for one critical face minimum quantity and consequently other faces receive more than the minimum air, a situation that is rarely a problem.

The CH_4 concentration has been diluted through leakage as air is lost through stopping leakages. The study aims to undertake a technical and cost comparison of ventilation of a typical (although artificial) model of a modern Room and Pillar mine layout.

Table 8 Contaminant and Airflow Simulation Results

#	Model	Average CH_4 level*		Mine Air Quantity m^3/s	Operating Cost**\$	Capital Cost***\$	Total Cost \$
		1%	**0.5%**				
1	5 Years Plan with Current Approach	0.63	0.32	205.4	693,270	-----	3,466,350
2	Add one Intake shaft added	0.61	0.32	210.6	3,564,215	1,464,000	5,028,215
3	Add Two Intake Shafts	0.71	0.36	210.1	3,500,695	3,150,000	6,650,695
4	Add one Exhaust Shaft	0.61	0.33	361.9	7,030,455	2,665,000	9,695,455
5	Add additional Exhaust Fan	0.67	0.35	245.1	6,213,190	490,000	6,703,190
6	Add Two Booster Fans	0.65	0.35	204.3	4,875,095	310,000	5,185,095
7	Add one Booster Fans	0.7	0.36	217	4,282,870	510,000	4,792,870

*The steady state contaminant simulation has been performed based on the requirement of an allowable concentration of methane at each individual working face to identify the path and spread concentration of methane from contaminant source.

** Operating cost: present value of electricity, maintenance costs over 5 years discounted at 10%.

*** Capital Cost: Excavating and fan purchasing and installation fee charges included

7 Capital Cost study

To determine the economic viability of a proposed mine, estimated costs and anticipated values have been compared. Costs are categorized as either capital or operating. Operating costs are those that can be directly expensed against revenues as they accrue and include funds that an organization spends operating the equipment and paying wages and salaries. Capital costs are those that cannot be fully expensed in the year incurred and include items such as infrastructure, excavating cost, working capital and purchasing equipment (SME Handbook, 2011).

7.1 Capital Cost of Shaft

The cost of shaft sinking depends on the method adopted, cross-sectional area of the shaft and the support lining method. It has been assumed in this exercise that the shaft is excavated by raise boring. This cost includes a fixed cost for mobilizing the raise boring equipment (SME Handbook, 2011). In this research the sinking costs of a circular concreted shaft with diameters of 2.2, 2.8 and 4.2m have been assumed to be \$9760/m, 10500/m and \$14500/m respectively (InfoMine, 2009).

7.2 Capital Cost of Fans

The capital costs for an underground booster fan(s) have been assumed to be \$105,000 (including motor and fan accessories) each for scenario 6 and \$340,000 each for scenario 7. The installation fee has been assumed to be 50 percent of total material fee (Gamble, personal correspondence, 2012, InfoMine 2010b).

8 Conclusion

The current ventilation model of the mine was projected to the mine five years plan. A feasibility review has been completed of alternatives available to improve workings ventilation as production moves into parts of the mine lease with higher methane contents. The scenarios examined alternatives that utilize additional infrastructure such as main ventilation shafts and fans or underground booster fans. Based on the five year plan model, unit #1 and #3 are the furthest sections in the main west area from the current intake and return shafts and maintaining airflow to them will be difficult unless additional infrastructure is installed.

The following is a review of the research on the various scenario simulations;

1. Scenario #1 expanded the network with the current infrastructure for the next five years and it was determined that due to distance and airway resistance available airflow at working faces is less than the minimum required.
2. Intake shaft #2 has been added to the 1st Main East. Although this alternative maintains the required airflow for Units #2 and Unit #4, the lack of airflow at other faces is obvious.
3. Intake shafts #2 and #3 were added to 1st Main East and 2nd Main West respectively. The exhausted airflow increased but the airflow on three faces is marginal and there are drawbacks. All airflow from working faces needs to travel a long distance in return airways to be exhausted through the single main fan. Mining areas may have a relatively short life before the additional shafts' locations are bypassed or are no longer in useful positions.
4. Scenario #4 fulfills the airflow requirements at working faces but the total cost is very high.

5. In scenario 5 a second exhaust fan has been added to the current surface infrastructure. The required airflow is not achieved; moreover the shaft could not handle the increased airflow which caused the second fan to stall.
6. Two booster fans were modeled in 1st Main East Return and 2nd Main West Return in Scenario #6. Scenario 6 meets required face airflows and total cost is a little more than $5 million.
7. A single booster fan has been added in series in Main North Return in Scenario 7. The airflow on the two faces is marginal.

The conclusion to this study is that scenarios 4 and 6 can meet required face airflows. However scenario 4 has a total Present Worth cost of over $9 million. Scenario 6 meets required face airflows and total cost is a little more than $5 million. For this reason Scenario 6 is recommended as being the best alternative for serious consideration to meet the mine ventilation requirements in the five year plan.

9 Acknowledgement

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