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Xintan CHANG Jerry C. TIEN

Shugang LI Jun DENG

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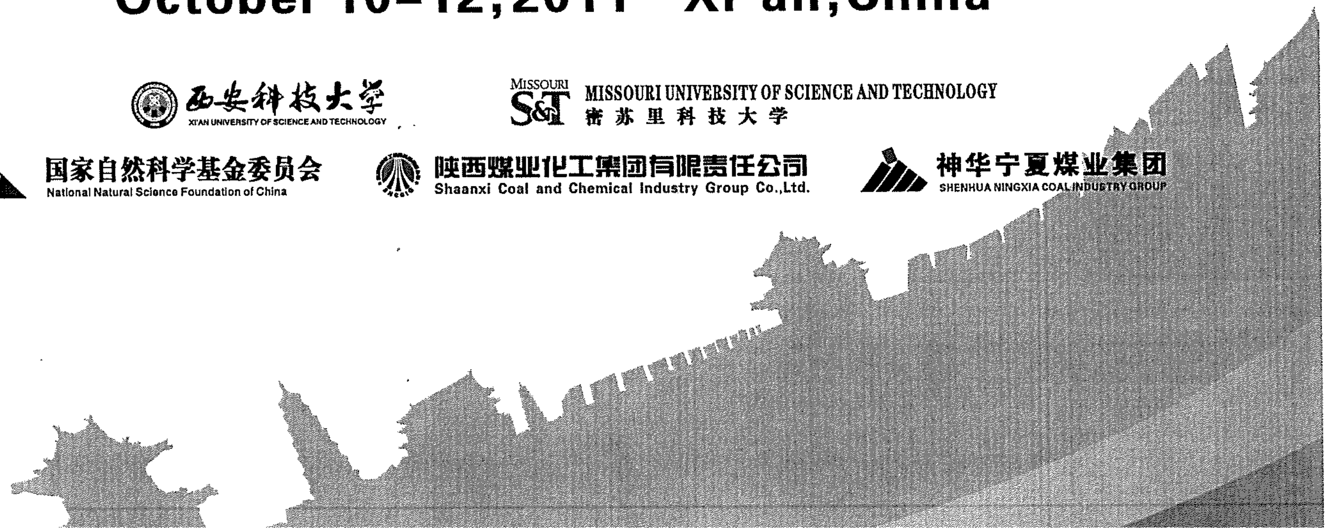

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Ⅱ. SPONTANEOUS COMBUSTION, FIRE AND EXPLOSION

Use of Booster Fans in Underground Coal Mining to Advantage*

A. Habibi[1], A. D. S. Gillies[2]

(1. Graduate Student; 2. Union Pacific Rocky Mountain Energy Mining Professor,
Department of Mining and Nuclear Engineering, University of Missouri Science
and Technology, Rolla MO 65409-0450, USA)

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 several major coal mining countries including the United Kingdom, Australia, Poland and China. In the United States booster fans are prohibited in coal mines although they are used in several metal and non-metal mines. A study has been undertaken to examine alternatives for ventilating an underground room and pillar coal mine system. A feasibility study of a 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 prepared and projected to a mine five years plan. "Ventsim visual" software simulations of different possible ventilation options have been conducted in which varying methane levels are found at working faces. The software can also undertake financial simulations and project present value total costs for the options under study. Several scenarios for improving the ventilation situation such as improving main surface fans, adding intake shafts, adding exhaust shafts and utilizing booster fans have been examined. After taking into account the total capital and operating costs for the five years mine plan the booster fan scenarios are recommended as being the best alternatives for further serious consideration by the mine. The optimum option is a properly sized and installed booster fan system that can be used to create safe work conditions, maintain adequate air quantity with lowest cost, generate a reduction in energy consumption and decrease mine system air leakage.

Keywords booster fan; mine ventilation; optimization design; ventsim simulation

Introduction

Booster fans are technically main fans which are installed underground to maintain required airflow by overcoming the mine resistance. In the United States the use of booster fans is permitted in metal and nonmetal mines however legislation prohibits their use in underground coal mines with the exception of anthracite mines (Title 30 Code of Federal Regulations 2010). The

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demand for fresh air at working faces leads engineers to design or upgrade the existing ventilation system (Wempen and others, 2011). Booster fans can reduce the pressure of the main fan and decrease the system leakage and total required air power (Martikainen et al 2010). The objective of this study is to find the optimum method for ventilating an underground US 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 operating cost (Calizaya and McPherson 1987). 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.

The paper presents a number of different scenarios by simulating the ventilation network of a US underground coal mine. Different approaches examined have involved improvements to the main surface fans, adding intake, or exhaust shafts or adding booster fans to the system. A current ventilation network model of a hypothetical mine has been prepared and projected to a mine five years plan. Seven "Ventsim Visual" software simulations of different possible ventilation options have been conducted. The project was initiated by expanding the model from the current workings to the mine's five years production plan. Airflow and contaminant simulation have been undertaken. In addition a cost study has determined the uneconomic and impractical scenarios in regard to power consumption. Scenarios 4 and 6 can meet the required face airflows however after taking into account total cost and expected life of the new infrastructure scenario 6 with the use of two booster fans is recommended as being the best alternative in the five year plan.

1 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 pullsystem. 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 five years production plan using the current mine schedule approach as seen in Fig. 1. Working Units #1 and #3 dump return air to Main West Return, Unit #2 and #4 dump air to Main East Return. Unit #5 dumps air to Main North Return. Main East Return and Main West Return then dump air to Main North Return which goes to the exhaust upcasting shaft.

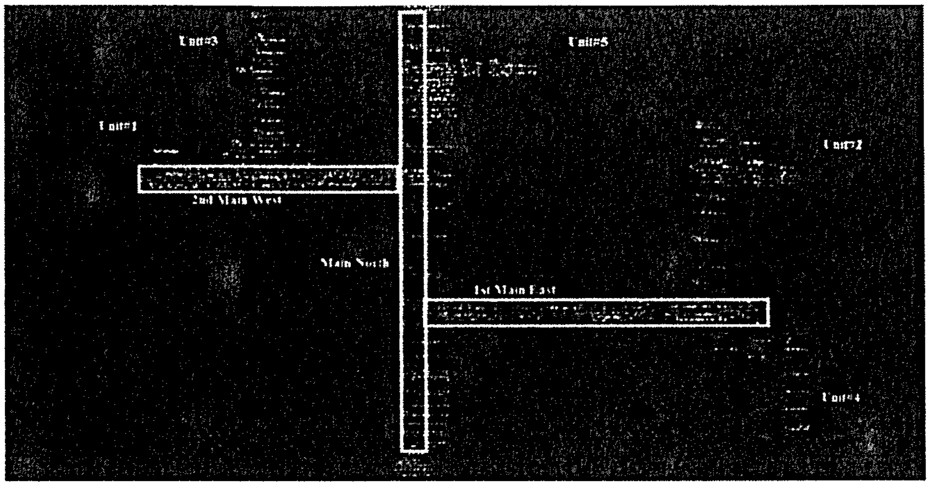


Fig. 1 Ventsim visual schematic view of mine ventilation model

2 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 provides required airflows at working faces. In this hypothetical exercise higher coal seam methane contents (either $1m^3CH_4/t$ or $2m^3CH_4/t$) are presumed to be being encountered in extraction in five years. Options examined look at cases where more ventilation is made available underground from alternatives of: a) The driving of more intake or return shafts; b) The use of various surface main fan combinations; c) The use of various booster fan combinations.

Financial simulation modeling estimates optimum ventilation infrastructure size by considering mining costs as well as 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 how long the airway is required to carry air.

Methane dilution calculations have been undertaken. These are based on a minimum of $15m^3/s$ of fresh air being required at each of the working faces.

The Safe Scenario: A liberation rate of $2.0m^3CH_4/t$ from broken coal. The mining rate of 345t/hr ($265m^3$ coal/hr) at density $1.3t/m^3$ has been used. An airflow rate of greater than $15m^3/s$ 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 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. The 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%.

3 Simulation Alternatives

3.1 Scenario one

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

Table 1 Scenario 1 predicted airflows on working faces

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

It was determined that unit #1 and #3 are the furthest distant sections and so due to airways resistance available airflow at their working faces is less than the minimum required. Unit #4 also does not have the minimum required airflow also. From these tests it is concluded that current surface fan infrastructure is not capable of ventilating the mine in 5 years. Table 1 shows the simulation results. Scenarios #2 to #7 are based on ventilation changes from this expanded five years plan model.

3.2 Scenario two

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

Air quantities	m^3/s
Exhaust Shaft	206. 1
Intake Shaft	73
Slope	38. 1
Intake Shaft #2	95
Unit#1	6. 7
Unit#2	15. 8
Unit#3	6. 3
Unit#4	15
Unit#5	14. 4
Input Power (kW)	813. 4
Operating Cost ($)	712,511

The main fan operates at static pressure of 2. 2 kPa and exhausts 206. 1 m^3/s of air. The total quantity of the air has not increased but an improved air distribution at the east part of the mine has been fulfilled.

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. 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. Thus it was found that the optimum diameter of the intake shaft is 2. 8 m.

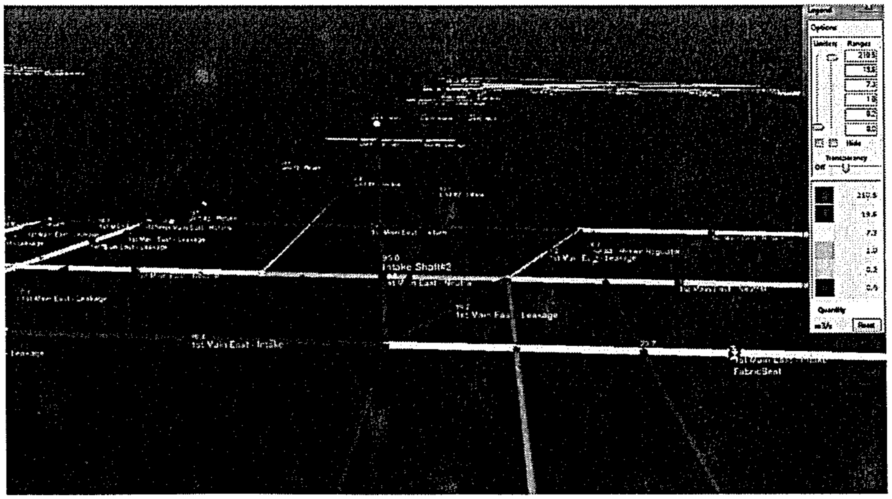


Fig. 3 Ventsim visual schematic view of intake shaft #2

3.3 Scenario 3

Two intake shafts were added to the model in order to supply the required air at faces. Intake shaft #1 has been added to 1st Main East and Intake shaft #2 added to 2nd Main West. The total exhausted air quantity has not been increased. An optimized diameter of 3.6m has been selected based on the lowest excavation cost. Table 3 shows the predicted results.

Table 3 Scenario 3 predicted airflows on working faces

Air quantities	m^3/s
Exhaust Shaft	202.2
Intake Shaft	43.2
Slope	24.6
Intake Shaft #2	74.5
Intake Shaft #3	59.9
Unit#1	15.1
Unit#2	15.2
Unit#3	12.4
Unit#4	15.3
Unit#5	15.4
Input Power (kW)	811
Operating Cost ($)	710,407

This scenario almost meets the minimum requirements for all units, however the required air quantity at unit #3 which is the furthest face 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.

3.4 Scenario 4

Exhaust Shaft #2 has been added to 1st Main East Return. A fan similar to the main fan added to the network and the optimal diameter of 4.2 is selected.

Table 4 Scenario 4 predicted airflows on working faces

Air quantities	m^3/s
Exhaust Shaft	165.4
Intake Shaft	260.1
Slope	96.5
Exhaust Shaft #2	200.2
Unit#1	17.4
Unit#2	18.3

续表

Air quantities	m³/s
Unit#3	15.2
Unit#4	16
Unit#5	17.4
Input Power (kW)	1624.3
Operating Cost ($)	1,420,279

The simulation results show in Table 4 that this alternative fulfills the air requirements at working faces. However the operating cost has increased dramatically. The capital cost has also increased since sinking a permanent ventilation shaft and purchasing and installing a second surface fan is expensive.

3.5 Scenario 5

A second surface exhaust fan #2 (similar to a Jeffery 8HUA-96 Axial Vane) has been added in parallel (Fig. 4). The air simulation ran but with warning "the lack of airflow rate causes the fans to be stalled". One of fan is exhausting 123.1 m^3/s at static pressure of 3.3 kPa and the later is exhausting 129.9 m^3/s at the same static pressure. The operating points drops off the curve (Fig. 5). The network efficiency is estimated 57.4%. This scenario does not meet the requirements at working faces.

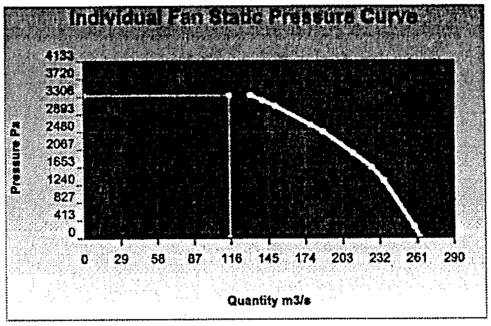
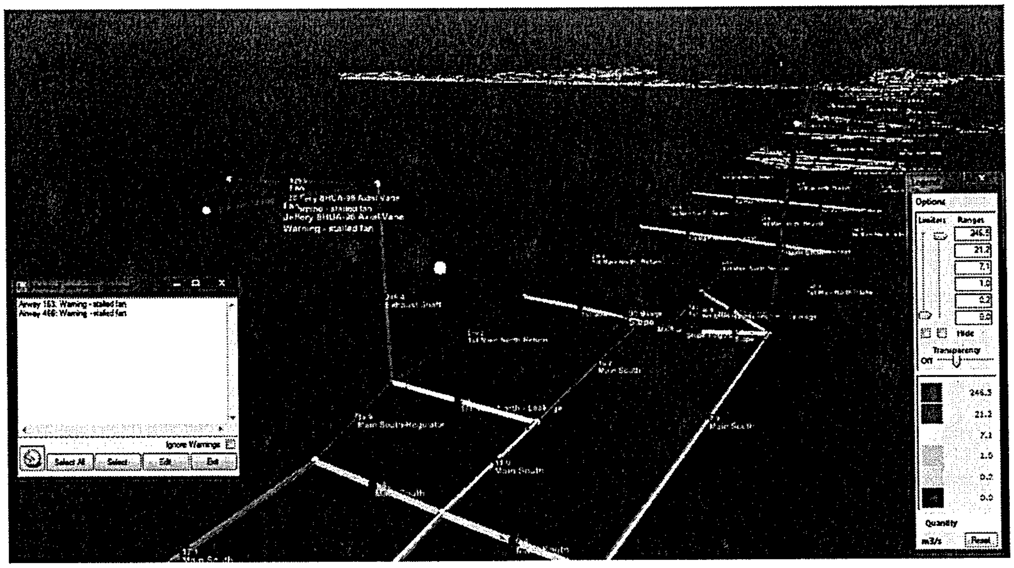


Fig. 5 Stalled fans characteristics curve and operating point



Airway 153: Warning - stalled fan
Airway 466: Warning - stalled fan

Fig. 4 Ventsim visual schematic view of exhaust shaft #2

Table 5 Scenario 5 predicted airflows on working faces

Air quantities	m^3/s
Exhaust Shaft	253
Intake Shaft	162
Slope	91
Exhaust Shaft #2	123.1
Exhaust Shaft #3	129.9
Unit#1	9.2
Unit#2	10.5
Unit#3	9.4
Unit#4	4.4
Unit#5	13.1
Input Power (kW)	1402.4
Operating Cost ($)	1,228,476

Although in this scenario two surface fans are working in parallel the total amount of exhausted air has not significantly changed. Base on the fan laws, total air quantity should increase. An explanation for this is the high resistance which occurs because of distance to the workings and also the exhaust shaft low diameter.

3.6 Scenario 6

Table 6 Scenario 6 predicted airflows on working faces

Air quantities	m^3/s
Exhaust Shaft	104.4
Intake Shaft	148.6
Slope	55.8
Booster fan #1	77.1
Booster fan #2	55.3
Unit#1	17.2
Unit#2	15
Unit#3	15.3
Unit#4	14.9
Unit#5	14.8
Input Power (kW)	915.7
Operating Cost ($)	802,120

Since the current surface main fan alone is physically incapable of meeting airflow requirements two booster fans have been added to the network to add air pressure to overcome resistance. Booster fans could be installed in the main airways or in a split off the main airways. Booster fan #1 has been added to the 1st Main East Return and Booster fan #2 to 2nd Main West

Return. Figs. 6 and 7 show the fan characteristics curves. This scenario meets the required airflow at working faces with relatively low additional capital cost. Table 6 shows the simulation results.

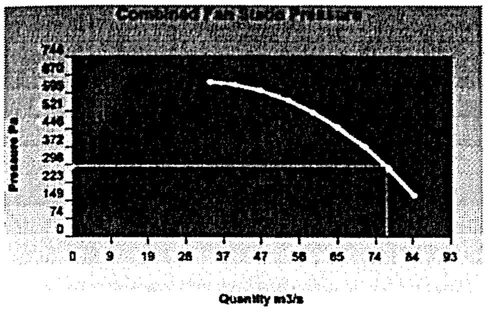


Fig. 6 Booster fan #1 characteristics curve, 2nd main west

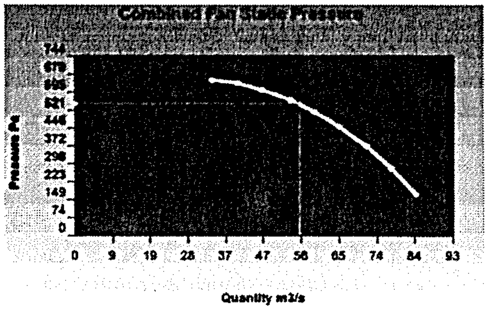


Fig. 7 Booster fan #2 characteristics curve, 1st main east

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 first 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 recirculation. 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.

3.7 Scenario 7

One booster fan was added to Main North Return to increase air pressure and reduced overall power costs. Although 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 0.61 kPa with 68% efficiency as shown in Table 7.

Table 7 Scenario 7 predicted airflows on working faces

Air quantities	m^3/s
Exhaust Shaft	208.2
Intake Shaft	130.6
Slope	77.6
Booster fan	177
Unit#1	122
Unit#2	11.5
Unit#3	11.4

续表

Air quantities	m^3/s
Unit#4	11
Unit#5	11.8
Input Power (kW)	977.8
Operating Cost ($)	856,578

4 Contaminant Simulation

The seven scenarios show that with addition of either 1% or 0.5% methane to each working face the average of methane across all five faces examined, 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 travels past leaking air control devices.

5 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 seams 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 thecurrent intake and return shafts and maintaining airflow to them will be difficult unless additional infrastructure is installed. Table 8 is a review of the research on the various scenario simulations.

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	One Intake shaft added	0.61	0.32	210.6	3,564,215	468,355	3,984,319
3	Two Intake Shafts added	0.71	0.36	210.1	3,500,695	1,158,093	4,658,788
4	One Exhaust Shaft added	0.61	0.33	361.9	7,030,455	1,731,050	8,761,965
5	Double Exhaust Fans Added	0.67	0.35	245.1	6,213,190	620,000	6,833,190

续表

#	Model	Average CH_4 level *		Mine Air Quantity m^3/s	Operating Cost** $	Capital Cost*** $	Total Cost $
		1%	0.5%				
6	Add Two Booster Fans Alternative	0.65	0.35	204.3	4,875,095	220,000	5,095,095
7	Add one Booster Fan	0.7	0.36	217	4,282,870	225,000	4,648,575

Note: * 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 and installation costs over 5 years discounted at 10%.

*** Capital Cost: Excavating and fan purchasing charges included.

(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. The exhausted airflow increased but the airflow on two faces is marginal. There are drawbacks.

(4) All airflow from working faces needs to travel a long distance in return airways to be exhausted through the single main fan.

(5) Mining areas may have a relatively short life before the additional shafts' locations are by passed or are no longer in useful positions.

(6) Scenario #4 fulfills the airflow requirements at working faces but the total cost is very high.

(7) A second exhaust fan has been added to the current surface infrastructure. The required airflow has not been achieved; moreover the shaft could not handle the increased airflow which caused the second fan to stall.

(8) 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.

(9) 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 the study is scenarios 4 and 6 can meet required face airflows. However scenario 4 has a total Present Worth cost of almost $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 further serious consideration to meet the mine ventilation requirements in the five year plan.

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