KOCSIS, C.K., HALL, R., and HARDCASTLE, S.G. The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system. *Application of Computers and Operations Research in the Minerals Industries*, South African Institute of Mining and Metallurgy, 2003.

The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system

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In Canada's metal mines, ventilation, which requires electricity to operate the fans and fossil fuel for heating, accounts for a significant portion of the overall mine's underground power consumption. Mine ventilation systems are usually designed near the end of the mine design process and often designed for the 'worst-case-scenario' with respect to ventilation demand. In Canada's metal mines this is commonly dictated by either diesel equipment usage or heat management considerations. Once designed, mine ventilation systems tend to operate at this peak level throughout the operating life of the mine. This is despite there being significant periods when this quantity is not required this is done mainly due to lack of appropriate ventilation controls. Consequently, such systems are inefficient and wasteful and this must be changed if mining operations are to remain competitive while meeting increasingly more stringent regulations of underground environmental conditions.

The advances in computing power and modelling software now make it possible to design, model and schedule a mine from opening to closure. The tools used for this include several disparate types of software. A developing trend is to design and plan the mine using orebody modelling software, followed by using discrete event simulation to predict production and evaluate various operating scenarios. It seems that again ventilation design is not being integrated into this process. Although, several modelling packages exist for ventilation design, little work has been done on integrating ventilation modelling into the overall life cycle plan of the mine. This paper will present a discussion of the work where the authors are attempting to integrate discrete event simulation for mine planning with ventilation modelling to predict the ventilation requirements for the operating life of the mine.

Introduction

In recent years environmental standards in mines have been raised substantially. Although threshold limits are based on workers safety and tolerance, increasing concern is being expressed for standards of human comfort as well. Worker productivity and job satisfaction correlate closely with the environmental quality. Furthermore, forecasts of significant increase in energy prices and new commitments with regard to reductions in greenhouse gas (GHG) emissions, are forcing mining operations to develop new concepts and design tools and incorporate latest mining technologies in order to lower production costs while meeting commitments regarding GHG emissions.

The introduction of intelligent systems to underground mining can provide a significant improvement in the performance of the mine when compared with conventional mining. Canada's metal mines, similar to those in other developed countries are increasing their level of equipment automation. This push for the development of robotic mining equipment has been exemplified by the Mining Automation Program (MAP) formed in 1996. This was an international collaboration between Inco Limited, Sandvik Tamrock, Dyno Nobel and CANMET, the mining research sector of Natural Resources Canada.

The MAP has shown that Telemining™ is achievable and consequently with its introduction, mine ventilation systems would have to be designed accordingly. Investigations have shown that the overall air volumes required under the Telemining™ conditions are less than those required in a conventional mine, however, because of the need to control the heat generated during the tele-remote and automated processes, the air volumes are still significant. Despite this, Telemining™ has the potential to reduce the number of pieces of mining equipment and hence the required air volumes[1].

Although today's technology has significantly improved, environmental challenges underground still abound. Not only do rock pressures rise inexorably with depth, but temperatures also, with subsequent deterioration of the underground climate. At great depths, ventilation requirements and costs will eventually climb to unsustainable levels. To maintain adequate underground climatic conditions, ventilation at great depth may have to be supplemented by cooling systems. At depth, although the heat generated from strata, auto-compression and mining machinery may impose the ultimate limit, the underground climate has other detrimental conditions to consider, such as gases and dust. As mines expand in size, the increasing depth, complexity and mechanization, demands on the ventilation and air conditioning system to maintain more stringent standards of environmental quality, likewise will rise. Fortunately, advances in science, technology and new design concepts tend to give solutions to worsening hazards underground[4].

The development of mine ventilation systems based upon a new design concept by means of production process and mine ventilation simulators would allow the mining engineering team to better understand the interactions between the mine support infrastructures and all variables that make up the complex process of mining. Ventilation systems developed according to a new design criterion would be based upon a 'life-cycle' ventilation demand schedule generated from a mining process simulator (e.g. AutoMod™ simulator) for the operating life of the mine. Based upon the 'life-cycle' airflow demand schedule, the ventilation system could then be modelled and developed using a ventilation simulation software package.

Mine ventiliation systems for automated mining conditions

The Telemining™ technology

The purpose of Telemining™ is the application of remote sensing, control and the limited automation of mining equipment and systems, to mineral ores at a profit. The main technical elements of the Telemining™ technology are[2]:

- Advanced underground mobile computer networks
- Underground positioning and navigation systems
- Mining process monitoring and control software systems
- Mining methods designed specifically for Telemining™
- Advanced mining equipment.

Advanced underground mobile computer networks form the foundation of the Telemining™ technology. The underground mine may be connected via telecommunication systems to surface control rooms so development and production processes can be operated from surface. To apply mobile robotics to mining, accurate positioning systems are an absolute necessity. Today, underground positioning systems have sufficient accuracy to locate the mobile equipment in real-time at the tolerances necessary for mining processes. Practical uses of such systems include machine set-up, hole location and remote topographic mapping. The systems that have been developed function similar to Global Positioning Systems. Units can be mounted on all types of mining machines so surface operators can position the equipment without going underground and without conventional surveying[2].

Mine planning, simulation and process control systems using the foundations of telecommunications, positioning and navigation are the next logical step in applying advanced manufacturing systems to underground mining. Linking engineering directly to operations is the key to the successful application of tele-remote mining[2].

Cost savings offered by the Telemining™ technology

The Mining Automation Project (MAP) an international research collaboration between Inco Limited, Sandvik Tamrock, Dyno Nobel and CANMET has shown that ventilation will still be required in an automated mine, and the volumes required are significantly greater than those required to maintain suitable oxygen levels for diesel equipment. The primary controlling factor in an automated mine will be the need to remove heat from the machinery, and for this ventilation is probably the most effective means.

Due to the effects of auto-compression when air descends into a mine, and increasing strata heat with depth, the air volumes required are of comparable order to those supplied for conventional mines. Hence, the general design of ventilation systems will not change, i.e. shafts and raises will still be required. However, the Telemining™ technology does offer the following savings[3]:

- The temperature design criteria throughout would be 40°C dry bulb for equipment as opposed to the order of 28°C wet bulb for humans, (this latter wet-bulb would correspond to a 35°C temperature in a 60% relative humidity environment which is typical of metal mines)
- At shallow depths, a tele-remote operation can require up to 75% less air than the current diesel exhaust design standards
- With the removal of humans, controlled recirculation of air would be more acceptable
- Controlled recirculation has the benefit of reducing the amount of air brought underground, this fact alone is significant as this is often the most expensive part of the ventilation system
- At depth, controlled recirculation can be combined with refrigeration to avoid increasing the mine intake airflow
- At shallow depth or where refrigeration is applied, natural or convection ventilation may be possible in local vertical circuits
- Tele-remote mining has the potential to reduce the number of vehicles underground and hence the required volume
- Automation would readily facilitate the optimization of auxiliary ventilation, so permitting 'ventilation-on-demand' as opposed to the full-out norm. In combination, these potential savings could be considerable.

Ventilation system design with controlled recirculation

Despite the heat studies showing that comparable ventilation volumes are required at the mining machine, this does not mean that that volume has to come from surface. The only prerequisite of the air being supplied to the machines is that it has the ability to cool as it has also been shown that only a fraction of this volume is required to maintain oxygen levels. Therefore, there is the potential to continually use the air that is underground as long as it can cool. This re-use of air is called recirculation and is commonly employed in buildings. In mines, where it is deliberately employed, the principle is referred to as controlled recirculation. This form of ventilation is ideally suited to the automated mine and can even take advantage of the drilling machines creating a local hot 'micro-climate'[3].

For example, shallow depths, despite the drill creating a local temperature of 40°C, after the machine's removal, the airflow cools as heat is rejected to the strata. Consequently, it has regained some of its cooling potential and can be re-used, however it will not be as cold as the natural intake air. Therefore with recirculation, the required face volumes, upon mixing fresh and recycled air, will be greater than previously calculated. Despite this, the principle still has advantages as one of the major costs in mine ventilation is delivering the air underground. For example rather than supply 100% of the required air from surface, it could be possible to[3]:

- Firstly reduce the mine intake flow by as much as 40%
- Then double the face flow, through recirculation, to 120% of the original non-recirculating system to provide the same cooling effect.

This potential for controlled recirculation has distinct financial advantages. For example, assuming only a 20% reduction in intake flow, and that the recirculation system is small, in a given ventilation system the power requirement could drop by 50%. In deep mines, controlled recirculation has potential when combined with refrigeration. In this instance, it could be more economical to refrigerate the air being re-used rather than bringing the air from surface[3].

However, there is a limit to how much recirculation can be employed. To compensate for a reduction in the mine's intake flow, there is a disproportionate increase in flow within the recirculation zone. At some point this need to increase the recirculation flow will result in the recirculation system being more expensive to operate than the original conventional flow through ventilation system.

Mine ventilation systems developed according to conventional design criteria

The enhanced power and reduced costs of microcomputers led to the evolution of self-contained software packages that allowed very easy interaction between the user and the computer. These self-contained software packages incorporated the use of graphics, which, for the first time allowed ventilation engineers to conduct multiple planning exercises on large ventilation networks. Personal computers together with readily available ventilation software packages led to a revolution in the methodologies, speed and accuracy of mine ventilation system design[5].

The primary purpose of a mine ventilation simulator is to predict the airflow distribution and pressure differentials throughout the network and produce numerical results that approximate those that would be given by a real system. There are three major considerations that govern the accuracy of a mine ventilation simulator as follows[5]:

- The accuracy with which an individual process is represented by its corresponding equation (e.g. RQ^2)
- The precision of the data used to characterize the ventilation model (e.g. measured airway resistances, differential pressures, geometrical elements of airways), and
- The accuracy of the numerical procedure to converge to a solution.

The structure of a mine ventilation system developed and analysed according to current design criteria using a ventilation simulator is shown in Figure 1[6].

Information required to develop the model of the ventilation system usually includes:

- Numerical data needed to define each airway (branch) of the ventilation system. Each branch entry requires specific 'junction' numbers, which can be defined as XYZ co-ordinates
- A schematic representation of the ventilation system, which consists of junctions and delineating branches in a closed circuit. Each branch will represent a single airway, a group of airways, or leakage paths that can be combined into a single equivalent path
- Data defining the locations and characteristics of mechanical ventilation devices (e.g. fans, doors, regulators, bulkheads). The fan data consist of location, characteristic curve, arrangement (i.e. series/parallel), type and initial estimated operating points
- Descriptive data for both user preferences and model documentation.

After the 'model development' phase, the current airflow requirements for major levels (i.e. active developments and production stopes) and mucking horizons are evaluated. The basic stipulation in determining the airflow requirements in mines where diesels are used is that there should be sufficient airflow to dilute exhaust gases and particulates to below their threshold limit values. The criterion that is most widely used to estimate the airflow needed to dilute the diesel exhaust gases is based on the rated output power of the diesel equipment, involved in the mining process. This is typically 0.063 m^3/s for each 1 kW (100 cfm/bhp) of rated diesel power. The ventilation system is then solved and balanced by means of ventilation network simulation techniques.

At this point, if airflow distribution requirements in the ventilation system have been satisfied, optimization exercises may follow the analysis of the newly solved and balanced ventilation system. Based upon the total underground power consumption and the ventilation system's operating cost, an optimized model of the base case scenario ventilation system can then be determined by means of a mine ventilation simulator. The air volumes delivered during development and production processes in order to maintain the diesel exhaust components below their threshold limit values (TLVs) can also be evaluated by means of climatic simulators, which are able to simulate and evaluate the underground climate during both development and production processes as a function of the mining depth (geothermal gradient) and specific rock thermal properties.

If the underground climatic conditions are inappropriate, the airflow requirements at development and production phases will be determined based upon the 'heat management' design criteria rather than the 'diesel engine usage' design criteria. Further to this, the ventilation system will be solved, balanced and optimized according to new airflow requirement conditions.

Mine ventilation system design by means of ventilation and mine process simulators

Mine process simulators

Competition in the computer industry has led to technological breakthroughs that are allowing hardware and software companies to continually produce better products. As a result the number of businesses using simulation tools is rapidly increasing. Presently, because of advances in software products, many organizations are incorporating simulation techniques in their daily operations on a regular basis[7].

The major benefits of utilizing computer simulation techniques go beyond just providing a look into the future. These advantages are mentioned by many authors (Banks, Carson, Nelson, and Nicol (2000); Law and Kelton (2000); and Schrieber (1991)), and include the following[7]:

- *Making correct choices*—Dynamic simulation techniques allow the user to test every aspect of a proposed change or different process scenarios without

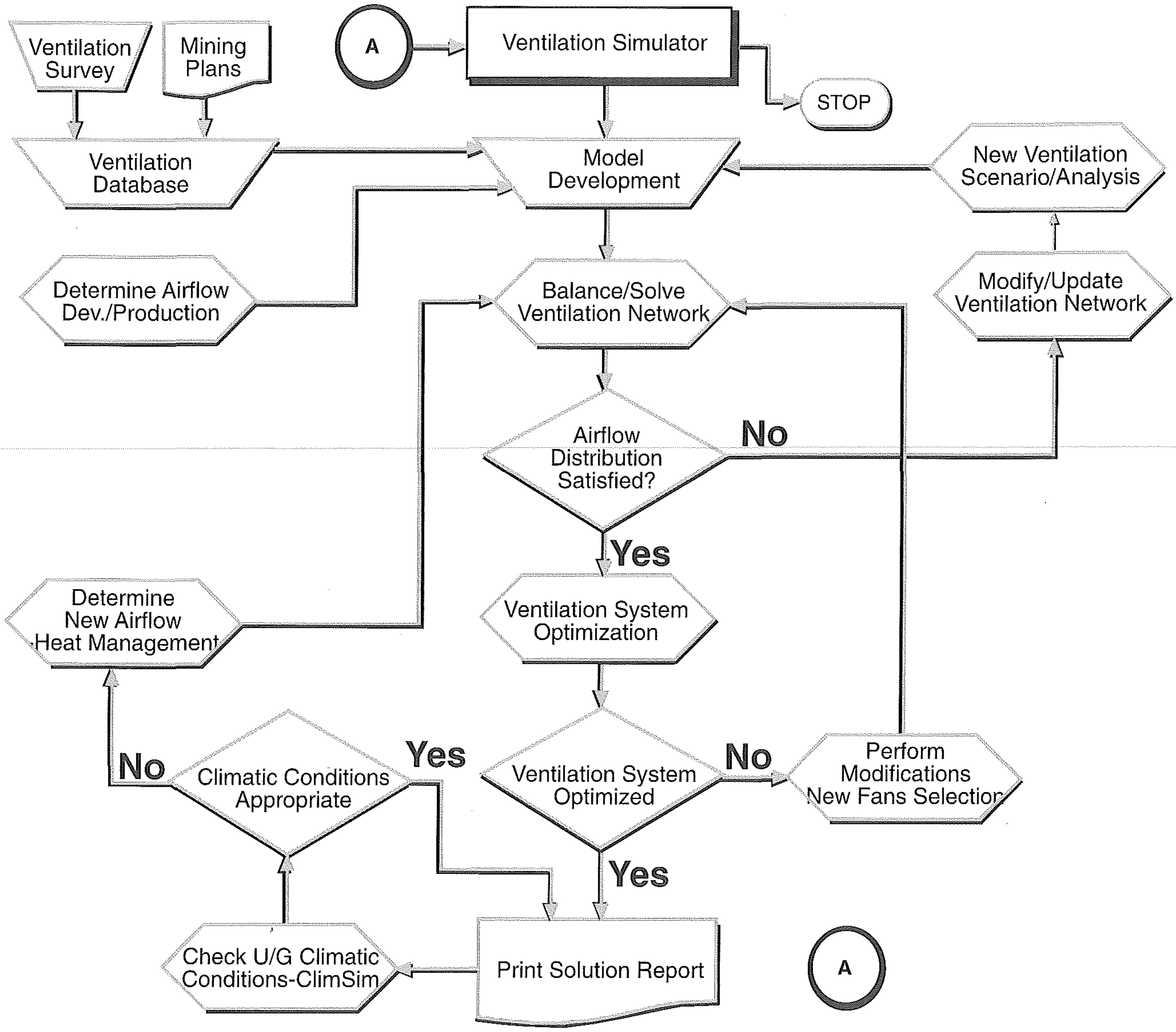

Figure 1. Mine ventilation system developed upon the conventional design criteria[6]

committing any resources to its development. This is quite critical, because once components of the overall system have been purchased and installed, later changes and corrections to the system can be extremely expensive. Dynamic simulation exercises allow the user to test design scenarios without acquiring resources[7].

- *Exploring possibilities*—One of the greatest advantages of using simulation techniques is that once a valid simulation model has been developed, the engineering team can explore and evaluate new operating procedures, or methods without the expense and disruption of experimenting within the real system. Modifications can be incorporated into the model, and the user can evaluate and observe the effects of those changes on the simulated model rather than on the real system[7].
- *Diagnosis of problems*—Today's underground metal mines, are extremely complex operations. Therefore, it can be said that during the mining processes it is nearly impossible to consider all the interactions that are taking place in a given moment. Simulation techniques could allow the engineering team to better understand interactions between support infrastructures and all the variables that make up the complex mining process. Diagnosing problems and gaining insight into the importance of all of the system components and variables increases the understanding of their effects on the performance of the overall system especially at the mine design phase[7].
- *Preparing for change*—Due to its dynamic nature an underground mining operation may suffer significant changes during its operating life as new production areas open and old production stopes close. Answering the 'what if?' questions is extremely useful for both new mine design and redesign phases. The model can usually be taken beyond the CAD layouts by using the animation features offered by many simulation packages. Animation allows the engineering team to 'see' the mining process from various angles and levels of magnification during the operating life of the mine. Animation features also allow the engineering team to detect possible design flaws within the system that may

appear credible when seen on paper or in 2D-CAD layouts[7].

Life-cycle ventilation system demand schedule developed by means of mine process simulators

It has often been the case that types and sizes of mining equipment, ground control considerations and underground haulage systems have dictated the layout of the mine without taking the demand of ventilation into account. Another frequent related problem is a ventilation infrastructure that was adequate for an initial layout (e.g. mining at shallow depth) but lacks the flexibility to handle fluctuating market demands or varying production rates during the operating life of the mine. The results of inadequate ventilation system design will result in high costs of reconstruction, poor environmental conditions and as a result potential tragic consequences for the health and safety of the workforce. It is therefore, most important to integrate the ventilation system design with production objectives and overall mine design during the early stages of planning a new mine or other surface facility.

Today, mine ventilation simulators developed specifically for personal computers, integrating true 3D graphical interfaces with the mine ventilation simulator, coupled with extremely powerful mine process simulators provide excellent opportunities for the mine ventilation engineers in analysing, developing and optimizing mine ventilation systems.

The development and application of specialized software packages, which are able to incorporate the mine design elements and specific constrains associated with a particular operation would allow the development of a dynamic model for various mining operations by means of a production process simulator (i.e. AutoMod™). Further to this, by means of dynamic simulation exercises, and output data of AutoMod™ model 'runs' would facilitate the development of the 'life-cycle' ventilation demand schedule according to design elements such as mining method(s), mine sequencing, mining depth, hoisting/haulage systems, equipment utilization and estimated market demands[6].

Mine ventilation systems—The new design concept

Based upon the 'life-cycle' ventilation demand schedule, the ventilation system will be designed by means of a mine ventilation simulator. Such a ventilation system will be able to accommodate all major development and production process changes during its operating life. The structure of this new design concept[6] is shown in Figure 2.

Figure 2, also shows that mine ventilation systems designed according to this new design criterion would readily facilitate development of auxiliary ventilation systems based upon the 'ventilation-on-demand' technology. Such auxiliary ventilation systems would further reduce the power consumption underground and consequently the overall ventilation system's operating cost.

The 'ventilation-on-demand' systems

In underground metal mines, auxiliary ventilation can be responsible for approximately 50% of the electrical energy consumed by the total mine ventilation system. This is considerable, and one of the major causes of this expense is that fans are often left running continuously at their

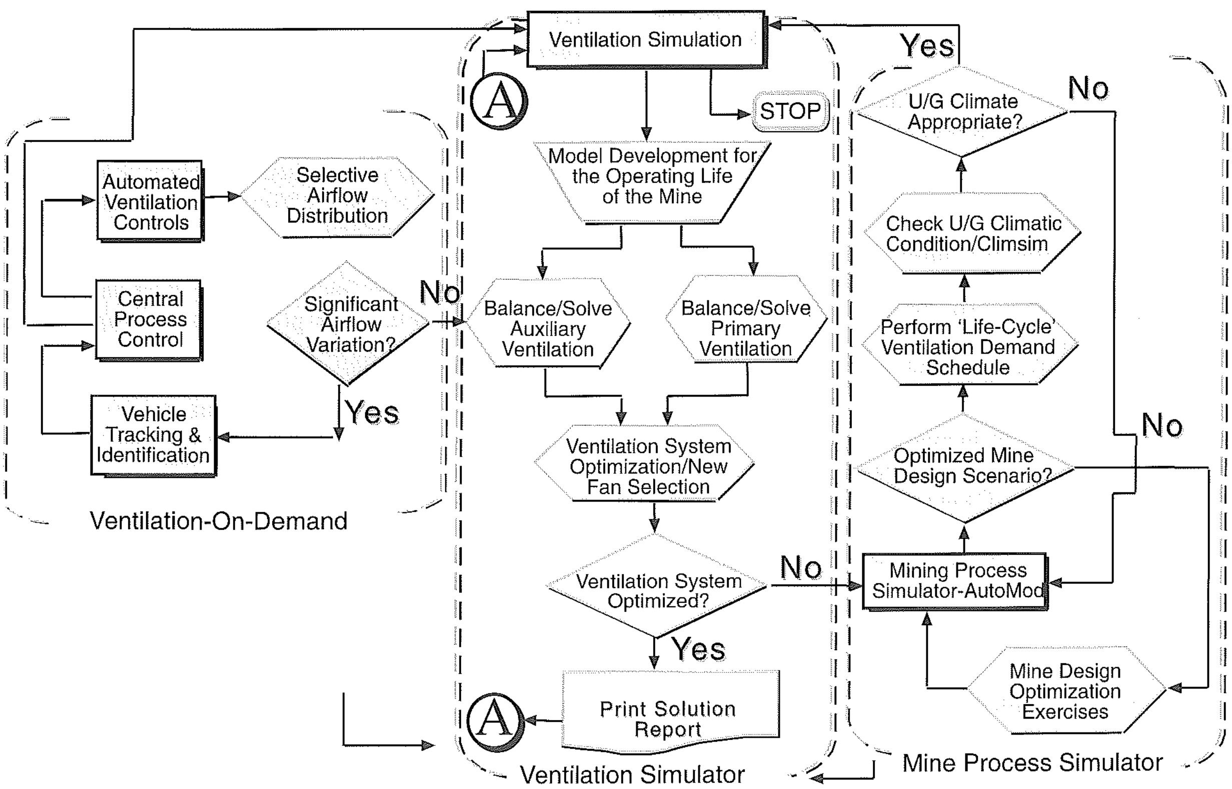

Figure 2. Ventilation system design based upon the 'Life-Cycle' airflow demand schedule[6]

maximum delivery due to lack of automated ventilation controls. However, in either conventional or potentially automated mines, the auxiliary ventilation system can easily be controlled such that it only operates when needed and the airflow is appropriately delivered according to the mining operation (e.g. drilling, blasting, mucking, shotcreting), namely the 'Ventilation-On-Demand' concept[8].

For example in a mine with 10 active development/production faces, if only 7 of them operate at any one time, there is an immediate 30% reduction in auxiliary fan power. Remembering the cubic relationship between the power consumption and airflow (Power ~ Flow[3]), even a small reduction of airflow in the auxiliary ventilation system has the potential to generate significant savings in operating cost. The ability to minimize the amount of air being delivered by auxiliary systems can have the added benefit of reducing the air demand on the total system[9].

The 'ventilation-on-demand' system will include the following primary data acquisition and process control elements[6] (See Figure 2).

- Vehicle Identification and Tracking System (VITS), which could operate under the mine's Leaky Feeder System or a dedicated hard wire system. The vehicle tracking and identification system would track and identify the mining equipment entering the active development/production area of the mine and send the information to Central Data Acquisition and Process Control System (CDPC).
- The Central Data Acquisition and Process Control System (CDPC) will selectively determine the appropriate amount of airflow according to the mining operation (e.g. drilling) and as a function of the mining depth (geothermal gradient).
- The Central Data Acquisition and Process Control System (CDPC) will then deliver the appropriate amount of airflow through the use of Automated Ventilation Controls (AVC).
- The Automated Ventilation Controls (AVC) would consist of variable speed auxiliary fans and automatically controlled ventilation doors and regulators operating under the CDPC System.
- A Mine Ventilation Simulator and climatic monitoring units should continually monitor the underground climatic conditions (e.g. dry bulb/wet bulb temperature, relative humidity) of the primary and auxiliary ventilation system.

Discussion

The forecasts of significant increase in energy prices and commitments with regard to reductions in greenhouse gas emissions, are forcing the Canadian mining operations to develop new design tools and incorporate new mining technologies in order to lower production costs while meeting commitments regarding GHG emissions Furthermore, many of the Canadian mining operations are relatively mature and become deeper while increasing production rates in order to achieve economies of scale.

With the advent of bulk mining methods the size of underground equipment has gradually increased in order to meet production demands. Due to greater amounts of heat generated by large electrical and diesel equipment and significant levels of heat transferred from the strata as a result of increasing depth, the amount of airflow throughout the primary and auxiliary ventilation systems and consequently the ventilation system operating cost has significantly increased. The size of the excavations required to accommodate larger mining equipment has also meant that the development and ground control related costs have also increased.

In mine ventilation, there is a cubic relationship between the supplied air power and the airflow (Power ≈ Flow[3]). As a result, even small reductions of airflow in the primary and auxiliary ventilation systems have the potential to generate significant savings in operating costs. For example, computer simulation exercises have been performed using the ventilation model of a medium-depth metal mine from the Sudbury Basin. Computer simulation results show that a 19% reduction in the mine's total intake airflow, could represent as much as 50% reduction in the ventilation system's operating cost. This example shows the importance of airflow management underground and its potential for significant savings in ventilation operating costs.

In underground metal mines, Telemining™, which includes the tele-remote operation of mobile development and production equipment from surface, will change the mine design criteria including its support infrastructure such as the ventilation system. With the removal of machine operators to surface control rooms, conventional ventilation systems designed to dilute and remove pollutants can become redundant. Depending on the ultimate need for ventilation, its cost in automated mines with tele-remote equipment operated from surface will be lower than the cost of ventilation in conventional mines. These cost savings, which could be significant, would not only come from the ability to reduce the amount of ventilation in the mine, but also through the capacity to automate its distribution.

The introduction of intelligent systems to underground mining can provide a significant improvement in the performance of a mine when compared with conventional mining techniques. The major benefits provided by the Telemining™ technology are as follows:

- Increased workplace safety through the relocation of workforce to safe and secure surface control rooms
- Increased worker efficiency with the removal of machine operators travel time to underground workplaces
- Increased safety and reduced production delays such as re-entry delays for ground control operations (e.g. shotcreting) after blasting
- Reduced production costs as a result of accelerated mining cycles, increased equipment utilization, and hence fewer pieces of equipment, reduced maintenance, improved safety and quality control.

The integration of mine process simulators and mine ventilation software packages to develop life-cycle ventilation systems would allow the mine ventilation engineers to better understand the interaction between the mine support infrastructures such as the ventilation system and all the variables that make up the complex process of mining. Mine ventilation systems designed based upon this new design criterion can provide the following benefits:

- Efficient primary and secondary ventilation system adjustable to variable production rates and able to meet the mine's dynamic nature and fluctuating market demands

- Integration of the mine ventilation system design with production objectives and the overall mine design process during the early stages of planning a new subsurface operation
- Facilitate the implementation of the ventilation-on-demand system, a continuously variable and interactive system incorporating new and innovative technologies such as Vehicle Identification and Tracking System and Automated Ventilation Controls operating under the Central Data Acquisition and Process Control System
- Minimize power consumption underground, lower production costs and implicitly greenhouse gas emissions.

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