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MINING ENVIRONMENTS, VENTILATION, RADIATION, DUSTS AND DIESEL EMISSIONS

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ABSTRACT

Minimizing the risk to a worker from their work environment has a high priority. Canadian mines have a very good record of concern for the mining environment, namely, the ventilation and exposure to hazardous elements therein: respirable dust, ionizing radiation, and noxious gases. For the most part, the occurrence of pollutants is unavoidable; dust comes from the mining process, airborne radiation is a natural occurrence and gases result from diesel equipment and blasting.

CANMET's Mining Research Laboratories at Elliot Lake and Bells Corners have, with the cooperation of the mining industry, contributed to improving environmental conditions underground. The collaborative research spans from: a) the long-term $1 m + projects that are run by a task force encompassing 30 interested parties from government down to small mining companies; to b) small short-term low budget investigations just between a laboratory and a single mine.

Specific mention is given to collaborative work on: i) evaluating mine ventilation efficiency with tracer gases; ii) optimization of ventilation with real-time monitoring and controlled recirculation; iii) assessment of respirable dust and radiation control techniques; iv) diesel emission abatement with ceramic filters; and v) the control of sulphide dust explosions and resulting sulphur dioxide production.

Key words: Mine ventilation; Mine environment.

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INTRODUCTION

The dangers from contamination of the mine environment and of poor ventilation were common knowledge even in Roman times. Pliny (23-79 AD) records black damp (an excess of carbon dioxide and nitrogen) as the first known danger. He wrote: "In deep wells the occurrence of sulphurata and of aluminosa vapour is fatal to diggers" (1). Since that time, ventilation has been recognized as a prerequisite of underground mining. Ventilation is necessary to supply oxygen, and acts as both a diluent and removal medium for a wide spectrum of pollutants. Generally, these pollutants include: gases, dust, heat (or lack of it) and humidity. In respect of the dust and gases, radioactive elements and carcinogenicity add further concern. Pliny also describes early ventilation problems and control, "... the air itself becomes noxious with depth, which can be remedied by constantly shaking linen cloths, thus setting the air in motion." (Figure 1). The benefits of a two entry system for removing pollutants were also known at these times.

By the time of Agricola's extensive record of metal mining and metallurgy, De Re Metallica, 1556 (1), the methods of mine environmental control through ventilation had advanced greatly. The simplest were natural ventilation techniques that included wind catchers, Figure 2. State-of-the-art methods employed were a diverse array of mechanical means, forerunners of modern day fans, which were either run by hand, treadmill, wind or water. Both types of ventilation were still used predominantly to dispel black damp. Around this time a fire damp (methane) danger was also recognized with possibly one of the first recorded fatalities from an ignition occurring in 1621 (2).

In contrast to the blame being put on demons, as was the belief in the Middle Ages, today's mine reflects an understanding of the 'cause and effect' of contaminating the mine environment. Dust is liberated through rock breakage and attrition. Gases result from the strata, blasting, combustion and breathing. Heat is an attribute of the climate and supplied from the strata, machinery and both heaters and air conditioners.

Canadian mines have put a high priority on the health and safety of their work force and are recognized for it worldwide. This achievement is a result of constant efforts by the mining companies, research establishments, and both legislative and advisory bodies to reduce a worker's exposure to potential working hazards and dangerous substances.

CANMET, through its Mining Research Laboratories (MRL), is aiding the industry to maintain its reputable position for health and safety. The Elliot Lake Laboratory provides the industry with extensive services for the evaluation of dust, radiation and ventilation in underground mines. The Bells Corners Laboratory supplies the expertise for diesel emission assessment and sulphide dust explosion control measures. MRL also has unique calibration and testing facilities for dust, radiation and diesel emission monitors.

MINE VENTILATION

Regardless of pollutant type and control strategy employed, a pollutant free mine environment is impossible. The adequacy of mine ventilation and its deployment predominantly determine the final concentration and effective removal of any fugitive pollutant.

The mechanisms for provision of mine ventilation are well known and need no mention here. A better understanding of mine air distribution, its improvement and control started with the introduction of simulators in the 1960s. Since then, the advent of computers has made mine ventilation simulation programs commonplace. A ventilation engineer can now model a whole mine on a micro-computer (e.g., PC/XT) and test future planning, fan failure or some other exercise in a matter of minutes.

Typically, mine ventilation simulations deal with the air as an incompressible medium and assume plug-flow. The former has been corrected through such adaptations as CANMET's deep mine simulation (DMVNET) which was developed at the University of British Columbia (UBC) to account for density changes (3). These simulators are acceptable provided only quantitative information of solely air quantities is required. In certain situations more quantitative information of the air flow is desired. For example, turbulence of the air and pollutant dispersal rates become important for real-time simulations of the spread of contaminants from fires and explosions. Also, even after a pollutant control method has been optimized, it can still be important to know how quickly any fugitive pollutant is removed or diluted.

To provide better quantitative information on the mine environment, CANMET is promoting the use of real-time monitors for all pollutants. These can provide maximum, average and minimum concentrations in association with time and duration of specific polluting events. When one considers the major efforts and steps that have already been taken to reduce pollutant concentrations, this information is important when trying to further isolate the remaining major contributor of an individual pollutant.

TRACER GASES

In association with the real-time monitoring of pollutants, CANMET is developing the usage of tracer gas techniques for determining the effectiveness of all or part of a ventilation system. Many of these techniques were developed at CANMET's Cape Breton Coal Research Laboratory, and have since been adopted within MRL. Tracer gases can be used as easily as an anemometer to determine bulk airflow. They can also supply a variety of other qualitative information that may be required for pollutant prediction models and better understanding of pollutant control. Tracer gases such as sulphur hexafluoride (SF_6) and Freons can be released under controlled conditions into the general airstream and collected downstream for gas chromatographic analysis.

Depending on the design of the release, collection method, analysis instrumentation and airflow regime, tracers can supply information on the following: the quickest and slowest air routes as well as the average route, times associated with these including the average residence time and total clearance time, the volume of the air path, air distribution between paths, the presence of leakage paths and the efficiency of the ventilation. Tracer gases may also be used as a surrogate for a pollutant to simulate its flow, dilution or removal within the ventilation system.

An example of a tracer gas application is shown in Figure 3, which depicts an enclosed heap leaching stope and muckpile. In this instance, tracer gas was necessary to determine the efficiency of a sub-muckpile aeration system that was used for oxidation of the ore (4).

CANMET presently employs some of the best field and laboratory tracer gas chromatographic units in the world for airflow analysis and measurement. Worthy of note are: i) the field portable rapid sequential gas analyzer for SF_6 which is capable of analysis every 10-12 seconds (5); and ii) a laboratory unit that can analyze for three tracer gases simultaneously (6). In most instances CANMET's mine ventilation analyses are used in conjunction with contaminant investigations. These may be used for evaluation or control studies for dust, radiation or diesel pollutants.

CONTROL AND MEASUREMENT OF DUST AND RADIATION

Dust sources are found at all stages of mineral extraction. Dust is produced at the initial drilling and blasting stage, continues to be produced through mucking, transportation and ore transfers, and is also a product of secondary breakage such as crushing. Radiation sources relate to two primary groups. First, there are those associated with the short-lived decay products of radon and thoron which readily attach to sub-micron airborne particles. Second, there are the long-lived radioisotopes of the uranium decay series. Radon and thoron gases diffuse from uranium minerals either in muckpiles or the solid rock mass. As they are readily soluble in water, mine-water can subsequently be an emanation source. Long-lived products are mainly a concern of uranium mines where they are associated with airborne dust.

Both respirable dust and radiation require similar control methods as listed in Table 1. For dust an important and common control technique is suppression at source through wetting with water. This can be very effective for discrete sources such as during drilling. Extended sources such as conveyors and tramming are harder to control. Once the dust becomes airborne, segregation or cleaning of the contaminated air has to be considered. Generally, the success of a dust control strategy depends on how well it is adapted to the mining operation. It is always important to consider the type of dust and its size to optimize the control, and then, once a system is in place, to maintain it as one would production machinery.

Radioactive respirable dust may be captured and controlled in the same manner as ordinary respirable dust. In certain situations electrostatic deposition and plate-out can be effective, however, the most common control of radiation in mines is through dilution with massive amounts of air.

COOPERATIVE EFFORTS FOR DUST AND RADIATION CONTROL

Collaborative work between the mining industry and MRL has been geared to the short-term needs of industry. The following are specific examples of this work performed by the Elliot Lake Laboratory.

Evaluation of a Wet Dust Collector at an Underground Crusher Station (7,8)

A uranium mine replaced a bag-type filtration system with a wet dust collector and MRL performed a before and after investigation to evaluate the new system. The bag system was inadequate and prone to problems. The presence of diesel soot caused the bags to clog rapidly and then hindered their regeneration through shaking because of the soot's sticky nature.

Although the replacement wet collector theoretically has a lower dust removal efficiency than a bag system, because of its implementation with better contaminated air control the respirable silica concentration was reduced by 70-80% for workplaces in the crusher area. In association with this, long-lived radioactive dust similarly decreased 70%, but short-lived elements were only marginally reduced by 10%.

Evaluation of Electrostatic Water Sprays (9,10)

Airborne particles, for the most part, are bearers of a significant number of elementary electrical charges. In recognition of this attribute, various methods, including charged water sprays, are being promoted to accelerate dust removal or precipitation. The configuration of sprays tested succeeded in reducing both respirable and long-lived radioactive dust by up to 40% at low air velocities, and then decreased with increasing air velocity.

DIESEL EMISSION CONTROL AND REDUCTION TECHNOLOGY

The Canadian Explosive Atmospheres Laboratory (CEAL) is responsible for the testing of diesel engines. This includes the development of evaluation techniques used in the laboratory and in the field (11).

Diesel machinery has been extensively used in non-coal mines globally since the 1950s. The Canadian mining industry is heavily dieselized (12) with 3,000 to 4,000 units underground (in comparison the U.S.A. has 5,000 units). The two safety concerns for such vehicles are the explosion hazard and ventilation contamination from their exhaust. Canada included explosion-proof diesel machines in the list of certifiable equipment for coal mines in 1970.

HEALTH CONSIDERATIONS AND THE AIR QUALITY INDEX

In recent years, the health implications of exposure to diesel exhaust have come to the forefront. Mining standards already prescribe both the volume of fresh air required to dilute exhaust contaminants to an acceptable level in underground environments, and the maximum contaminant concentrations of the raw exhaust.

Table 2 lists the major contaminants and the dangers they pose. In recognition of these dangers and the popularity of diesels, CEAL has concentrated their research in two areas. First, towards the reduction of diesel emissions and/or toxicity; and second, the development of a yard-stick for the assessment of dieselized mine environments and control measures employed.

Early investigations at CEAL demonstrated that engine adjustments could make significant changes to the production of individual exhaust contaminants. These can be both positive and negative. For example, retarding the fuel injection timing generally causes soot (Respirable Combustible Dust, RCD) and the nitrous oxides to decrease, carbon monoxide to increase and sulphur dioxide to remain unchanged (13).

As any adjustment to a diesel engine can produce a unique set of exhaust contaminant concentrations, it has been necessary to develop a method of evaluating the overall toxicity of that exhaust. In 1978, medical specialists supplied the Air Quality Index (AQI) (14) which mathematically equates the five toxic exhaust components with their respective limit values as follows:

$$AQI = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + 1.5 \left| \frac{SO_2}{3} + \frac{RCD}{2} \right| + 1.2 \left| \frac{NO_2}{3} + \frac{RCD}{2} \right|$$

The suggested maximum for the AQI to avoid tissue damage or diminution of respiratory function is 3.

Table 3 details the average exposure from 3 metal mines of an LHD operator with no emission control device on the machine and using 0.2% sulphur content fuel (15). Listed are the five toxic elements, their compound AQI, their relative contribution to the AQI, and an order of concern for control purposes. The AQI is very close to its suggested limit value of 3. Examination of the equation shows RCD/soot to be heavily weighted, occurring three times, and in this example contributing 57% of the AQI value. This weighting reflects RCD or soot's ability to cause tissue damage when in conjunction with the acid gases, and its potential carcinogenicity. The second major contributor to the AQI is SO_2. Its rank can be reduced with low sulphur (<0.1%) fuels.

CONTROL TECHNOLOGY AND THE CERAMIC FILTER

As RCD is the major toxic contributor to the AQI, it has also been the main target for reduction or removal from diesel exhaust. CANMET pioneered early work on soot filtration systems through the optimization of 'baffle' water scrubber design, development of the venturi scrubber, and ultimately participated in the implementation of a ceramic element filter.

The ceramic element was originally developed by Corning Glass. Its adaptation to mining diesel engines was sponsored through the collaboration of the U.S. Bureau of Mines, the Ministry of Labour of Ontario, CANMET, and some 27 others: manufacturers, mine operators, research agencies and regulatory authorities.

Figure 4 details the ceramic element, and Figure 5 illustrates the filtration principle. Soot is filtered out as the exhaust gases are forced through the porous ceramic membrane walls of the unit. Direct flow through the unit is impossible as every other channel is plugged at one end and the adjacent channels plugged at the other. Some of the performance characteristics of a simple ceramic filter installation are given in Table 4 (the diesel unit is assumed to be working sufficiently hard to cause combustion of trapped soot and on-going regeneration of the filter).

This type of operation has been demonstrated by CANMET in association with Engine Control Systems (ECS), the supplier, at Cominco's Sullivan Mine, INCO's Little Stobie Mine, and Noranda's Brunswick Mine (16). Depending on the engine type and the diesel unit's duty cycle, certain units are unable to create autoregeneration. In such instances the addition of catalysts can reduce the required soot burn-off temperature.

The use of ceramic diesel particulate filters has also yielded other benefits detailed in Table 5. As a consequence of such benefits detailed in Tables 4 and 5, some companies are considering the implementation of the filters on all heavy duty vehicles.

Table 6 summarizes the installation of ceramic particulate filters presently on mining equipment either in Canada under PILP (Private Industry and Laboratory Program) funding or internationally. The installations are further categorized by vehicle type.

Where ceramic filters are used extensively, the improvement in air quality could be such that working areas have reduced ventilation requirements, and this could in turn reflect in lower operating costs.

AIR QUALITY MONITORING

Through the emission control studies and the AQI concept, various monitoring requirements have been identified. First, the importance of RCD or soot measurement has been emphasized. Second, Michigan Technological University (MTU) demonstrated that each of the major pollutants and the AQI in dieselized mines were related functions of the carbon dioxide (CO_2) concentration for the operation of a single machine.

The concept of using CO_2 as a surrogate arose from MTU's findings and has important benefits: a) it removes the sophisticated and costly measurement of all elements in the AQI equation that are not normally performed; b) CO_2 can be measured both cheaply and reliably; c) simplification of required monitoring readily allows uncomplicated environmental control to ensure a vehicle's compliance.

The possibilities of extending CO_2 usage as a surrogate in automated mine ventilation monitoring and control is presently under investigation. Although it may reduce the requirement for all the gaseous measurements in the AQI, other factors may dictate the monitoring of soot and both SO_2 and NO_2 gases. It is possible that soot may be the object of special concern because of its toxicity. SO_2 and NO_2 are becoming increasingly important as their limiting concentration values have been reducing in recent years. SO_2 monitoring is also a concern in sulphide ore bearing mines where sulphide dust explosions may occur.

SULPHIDE ORE DUST EXPLOSION CONTROL

The occurrence of sulphide dust explosions following blasting operations in sulphide ores has been known since 1924 (17). That year had the first recorded fatalities, and to date a total of 12 fatalities and 13 injuries have been documented in Canada, the U.S.A. and Sweden. The most recent fatality in Canada was at the Geco Mine, 1985 (18). Sulphide dust explosions have the potential to be as catastrophic as those of coal dust, however, their effect has been limited by their occurrence after blasts which are initiated only during shift change.

The 1985 fatality lead to the formation of a Dust Explosion Control Group with representation from the U.S. Bureau of Mines, CANMET, 15 mines, 5 universities, 2 mining associations, 2 explosive manufacturers, 1 inspectorate, and 3 other interested parties. The mandate of this group is to coordinate and direct research into controlling sulphide dust explosions. Participants in British Columbia include Westmin and UBC.

DUST EXPLOSIONS (19)

In a sulphide dust explosion, sulphide ore dust (pyrite among others) provides the fuel, air supplies oxygen, and blasting supplies the ignition source. Pyrite (FeS_2) is consumed through one of the following reactions to form magnetite (Fe_3O_4) and hematite (Fe_2O_3):

$$3\ FeS_2 + 8\ O_2 \rightarrow Fe_3O_4 + 6\ SO_2 + 2370\ kJ/mol$$

$$4\ FeS_2 + 11\ O_2 \rightarrow 2\ Fe_2O_3 + 8\ SO_2 + 3310\ kJ/mol.$$

For either reaction to take place the pyrite must be suspended in the air. In a pyrite dust explosion's reaction, the explosion has not been the cause of injuries and fatalities as it occurs at blasting times, but rather they are from the toxic by-product sulphur dioxide (SO_2) gas. The minimization, dilution and/or removal of SO_2 is the prime environmental concern in sulphide dust explosions.

The potential danger from SO_2 is shown in the analysis within Table 7. Because of the phenomenal SO_2 production, one can readily understand why large parts of mines can become contaminated, and why such explosions should be combatted. The Fox Mine provides an example, "the explosion caused 4-5 stope to upcast to the surface through the shaft and drill holes. The SO_2 polluted air in the head frame and shifter's offices, where the crews had taken refuge from the stope blast, and forced crews outside to the machine shop. The slow wind present that evening drifted the SO_2 laden air into the machine shop and the concentration plant and these places in turn had to be evacuated." (17). Also the fatalities and injuries relating to SO_2 exposure at the Geco Mine, 1985, were sustained 2.25 km from the stope explosion (18).

Even in the absence of personnel, the SO_2 production is very undesirable and costly. At Westmin's H-W mine, corrosive gases leaving the mine after blasts have damaged the exhaust fan system, and contributed to the corrosion of an underground trolley line, chute doors and Swellex stabilizers (20).

RESEARCH OF CONTROL METHODS

Many mines avoid the danger of personal injury or fatalities from SO_2 exposure after a blast by removing the workforce until that area has been tested. Such a procedure is costly to production and may not be foolproof in such incidents as those at Fox, Geco and H-W mines.

Research into control rather than avoidance is being conducted at a number of mines. Some of this work is in part funded through CANMET contracts. For example, Noranda Technology is studying the amount of SO_2 and dust produced during blasts as well as methods of making the explosion inert.

The work by Westmin and UBC at the H-W mine included part of Noranda's contract. The results of various preventive methods tested at H-W mine, Table 8, show both lime and water stemming and water atomization as effective techniques (20). Other areas of research include non-incendiary explosives development (21,22) and the use of slurries.

In association with the field research, CANMET has set up a dust explosion testing facility for the evaluation of dust/air mixtures. This facility is capable of determining such fundamental information as: the maximum explosion pressure, the maximum rate of change of pressure, the minimum explosible concentration, the minimum spark energy, the minimum ignition temperature for the explosion, and the shape of particles both before and after the explosion.

To date, the facility has tested 28 different sulphide ore samples from 11 mines (23). Results tend to indicate that a minimum of 26% sulphur content is required for an explodible mixture, but the explosive power is not a function of sulphur alone. Also, all sulphide mineral samples do not react in the same way. Of decreasing explosive strength are the explosions of pyrite, pyrrhotite and chalcopyrite, all of which produce the oxide, SO_2. Galena is also capable of causing powerful explosions and blast damage, but it reacts to form only the sulphate, whereas it has been impossible to explode sphalerite under test conditions.

THE FUTURE OF MINE VENTILATION

Understanding of the mine environment, the requirement for ventilation and understanding of pollutant generation and control have all greatly improved since the flapping linen cloth, wind catchers and rudimentary fans. They have now developed into a complicated science.

With today's capacity to monitor the diverse array of mining pollutants on a real-time basis, the Canadian mining industry should be looking towards optimizing the use of mine ventilation through its strict control. Canadian mines typically operate where winter temperatures are below freezing, which can necessitate heating of the air with annual costs of up to $2,000 for every m^3/s of mine intake air (24). Such costs are in addition to those of mechanically supplying the ventilation. In the present economic climate of increasing energy costs, compounded with low mineral prices, the industry must identify possible energy cost savings. Ventilation and its heating are considerable consumers of energy, but there exist today five possible methods of heat recovery and/or ventilation optimization. These are, heat transfer/exchange from exhaust to intake, waste heat reclamation from mine machinery, ice stopes, fuel conversion and the controlled recirculation of exhaust air into the intake (25).

CONTROLLED RECIRCULATION OF MINE AIR

Recirculation of ventilation is not a new concept designed for mine ventilation. Recirculation is extensively used in modern buildings to conserve heat or to sustain cooling, and results in energy savings. In mining, concern has to be given to specific pollutants that it would be undesirable to recirculate. These would include products of combustion, both acidic and explosive gases and air containing any other excessive pollutant concentration. Present day technology can monitor such pollutants and control the degree or existence of recirculation. This technology has already been proven and recirculation has been adopted in South Africa, Great Britain and Australia. Trials have also been performed in the U.S.A. and here in Canada. CANMET has funded investigations by UBC in Manitoba and Saskatchewan mines (25-27). All the Canadian investigations have shown significant potential of reducing winter heating costs without jeopardizing the environment.

MINE ENVIRONMENTAL MONITORING

Where recirculation is employed it will be necessary to include some degree of continuous mine environmental monitoring, alarm and control system. These would combine to form a safety system to protect against the re-introduction of excessive contamination and also facilitate the stopping of recirculation.

Regardless of whether recirculation is being used, the introduction of mine environmental monitoring allows for optimized usage of the air supplied. This is achieved through judiciously employing the air entering the mine, and hence, controlling costs.

CANMET has been pursuing a long-term strategy related to introducing mine environmental monitoring (28), and ultimately an automated mine air quality control system. Wherever possible this has been done with the support and cooperation of the mining industry. Elements of that strategy have been highlighted throughout this report. They include:

1. The development of both dust and gas control strategies and reduction equipment;
2. Assessment surveys of mine air quality and developments of 1) above;
3. The advancement of monitoring equipment and methodology development;
4. Usage of continuous, computerized mine air monitoring.

CONCLUSION

It is hoped that through continued full cooperation between mining companies, support industries, universities and both provincial and federal organizations and government bodies, that the underground environment will continue to improve.

CANMET, through its Mining Research Laboratories is committed to a partnership in research with the British Columbian mining industry as with the rest of the Canadian mining industry.

The benefits of collaborative research have been evident for diesel emission reduction. Sulphide dust explosion control research has the same potential. These are examples of how, together, the Canadian mining industry and CANMET can keep the world's respect of our research in the areas of health and safety.

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Table 1 - Control techniques for dust and radiation

Ventilation

Mechanical filtration and scrubbing

Electrostatic precipitation and deposition

Air curtains

Deposition by sedimentation or plate-out

Wetting (dust only)

Sealants (radioactive gases only)

Table 2 - Dangers of toxic contaminant excessive exposure

Contaminant	Danger
Carbon monoxide	Affinity to haemoglobin
Nitric oxide	Acidic reaction in lung and oedema
Nitrogen dioxide	As nitric oxide
Sulphur dioxide	Irritant and asphyxiant
Respirable combustible dust/soot	Carcinogen

Table 3 - LHD operator exposure to toxic diesel exhaust contaminants

Contaminant	Ave. LHD Conc.	AQI %	Order of Concern
Respirable combustible dust (RCD)/soot	0.85 mg/m^3	57	2
Sulphur dioxide (SO_2	1.19 ppm	22	3
Nitrogen dioxide (NO_2)	0.80 ppm	11	4
Nitric oxide (NO)	5.68 ppm	8	5
Carbon monoxide (CO)	2.65 ppm	2	6
Air quality index (AQI) (Suggested limit 3.0)	2.80		

Table 4 - Standard ceramic filter performance data

Soot retention	90%
Soot regeneration data ave. minimum cycle temp.	427 C
Minimum ignition excursion	500 C
Carbon monoxide	Slight increase
Other AQI gases	Negligible change
Exhaust back pressure (clean)	2.5 kPa
Equilibrium back pressure during autoregeneration	5.0 kPa
Maximum filter life	4,000 hrs +
U/G vehicle suitability	25%

Table 5 - Benefits of ceramic filters

The ceramic filter provides a higher air quality underground.

The filter removes engine smoke, improving visibility with its subsequent safety and production implications.

Smoke removal can also eliminate nuisance maintenance. One mine estimates potential savings of $400 k/y with mine wide filter usage.

The filter reduced diesel smell which is subjectively felt to be an improvement.

The filter also acts as a muffler.

Table 6 - Diesel particulate filter mine installations as of April 1989, (courtesy ECS)

Vehicle Type	Canadian (PILP)	International
LHD	14	11
Teletrams	6	20
Dozers and tractors	3	11
Loaders		3
Bolter		2
Boom truck	1	
TOTAL	24	47

(PILP participants: Noranda (Brunswick), INCO, Falconbridge, Kidd Creek, Rio Algom and Denison).

Table 7 - SO_2 production from a sulphide ore dust explosion

Pyrite source:

0.1 mm thick dust layer on stope roof and walls
stope dimensions 25 m x 25 m x 50 m

SO_2 production:
(Assumes complete reaction and standard temp. and press.)

volume produced 800 m^3
stope concentration 2.6% in air

SO_2 concentration equivalents:

5,000 times greater than TLV
10,000 km of 4 m x 4 m roadway at TLV.

Table 8 - Tests of sulphide dust explosion preventive methods (20)

Mining Method	No. of Holes and Depth	Control Methods	Sulphide Ignition
Room and pillar	25 @ 3 m	WW, WA, WS	No
Misfire	14 @ 2 m	-	Yes
Room and pillar	45 @ 4 m	LD, WW	Yes
Room and pillar	42 @ 2 m	WW, WA	No
9 hole burn cut	9 @ 2 m	LS	No
9 hole burn cut	9 @ 2 m	WW, WS	No
Cut and fill	43 @ 4 m	LD, WA, WW	No
Room and pillar	42 @ 4 m	LD, WW	Yes

Key: WW - Washing; WA - Water atomization; WS - Water stemming;
LD - Lime detonated; LS - Lime stemming.

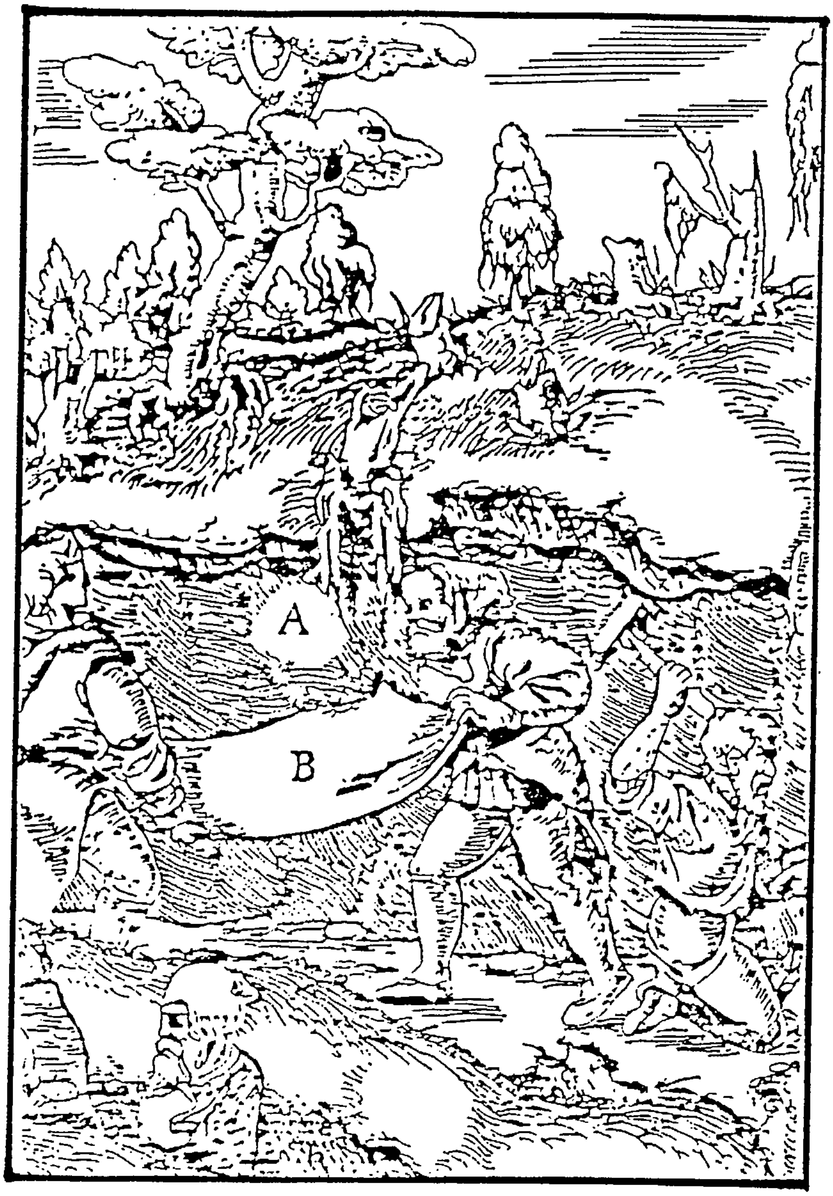

Figure 1. Roman Method Of Mine Ventilation [From Agricola (1)]
Key : A - Tunnel, B - Linen Cloth.

Figure 2. Natural Ventilation Methods For Mines [From Agricola (1)]
Key: A - Sills, B - Pointed Stakes, C - Cross Beams,
D - Upright Planks, E - Hollows, F - Winds,
G - Covering Disc, H - Shafts, I - Machine Without
a Covering.

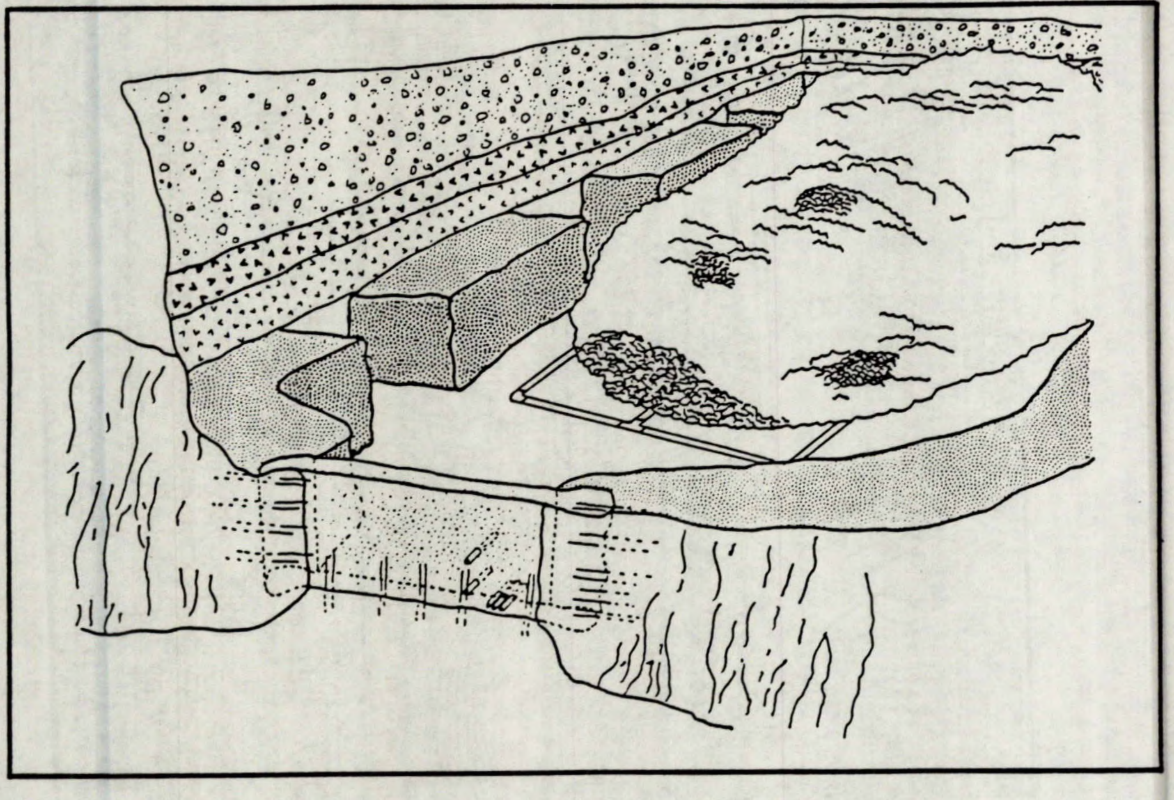

Figure 3. Typical Flood Leaching Stope Evaluated with Tracer Gas.

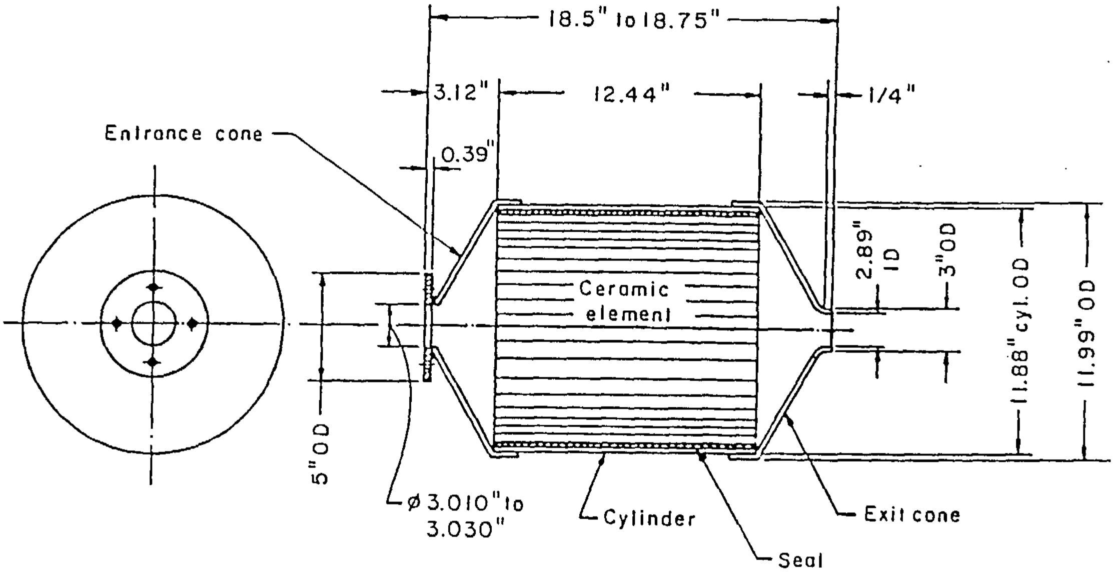

Figure 4. Engineering Sections Of The Diesel Particulate Ceramic Filter.

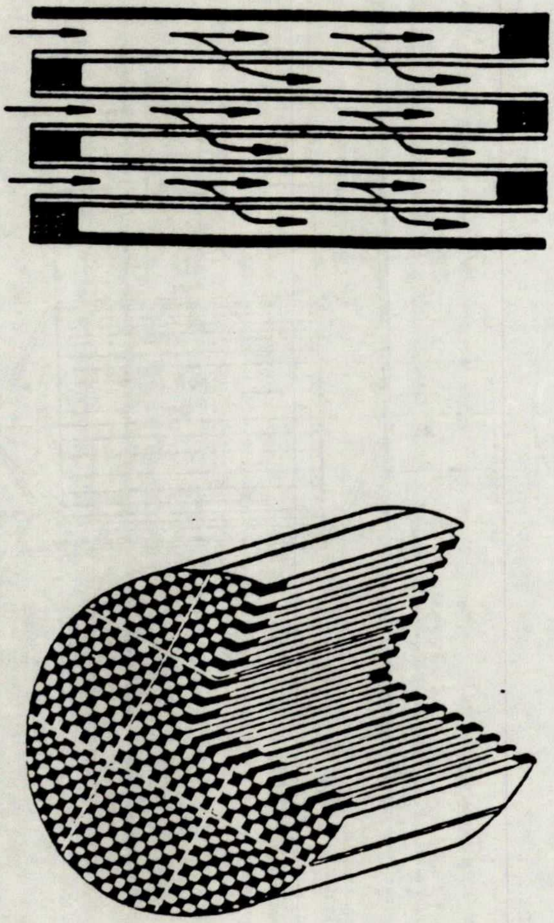

Figure 5. The Diesel Particulate Ceramic Filter Trap.