Organization, objectives and achievements of a three-government collaborative program on diesel emissions reduction research and development

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ABSTRACT

The historical development of the collaboration among three funding agencies: the United States Bureau of Mines (USBM), the Canada Centre for Mineral and Energy Technology (CANMET), and the Ontario Ministry of Labour (MOL), and numerous private sector contractors, is briefly discussed in this paper. Each government agency has had a diesel-related program in place for some time in recognition of the need to better understand the impact of diesel emissions on the underground worker. Official collaboration began on December 1, 1981 with the signing of a Memorandum of Understanding by all three governments. The program officially ends in June 9 of 1987, the termination date given in that document.

The result of this Memorandum was the formation of the "Collaborative Diesel Research Advisory Panel" (CDRAP), which undertook the resolution of a number of issues including: (1) the use of a criterion by which to evaluate the comprehensive toxicity of the major components of diesel exhaust, and the consequent provision of a tool for ventilation prescription and engineering economic studies, (2) research and development to produce add-on exhaust hardware and study of other techniques to reduce emissions from diesel engines, (3) development of the means of measuring the impact of such devices on the underground environment for the benefit of regulatory agencies and mine operators, and finally, (4) synthesis of the principles learned into an overall strategy by which to improve mine environments, reduce ventilation costs, increase productivity and improve safety underground, depending on the circumstances of each case.

These matters are elaborated in general in this paper, amplified in the other five papers of this series, and further detailed in the reprinted papers and annotated bibliography of this compendium.

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INTRODUCTION

Diesel-powered machines were gradually introduced into underground mines in Europe in the 1940s to improve some aspects of coal mining operations. Their introduction into North American mines began in earnest in the 1950's. By the early 1960s, many North American non-coal mines were employing diesel machinery, but their use in coal mines remained limited.

The general perception has been that untethered diesel machines provide flexibility which in turn fosters improved operating efficiency and increased productivity. This perception persists to date, but not without voices that question this viewpoint when the entire mining system is considered. There is also a current view that a combination of fixed and flexible machines may prove to be a better system for some mining operations.

To cope with the increasing use of diesel machines, regulatory agencies in the major mining nations undertook R&D for the development of standards for the use of such machines underground. Notable among these efforts was the work of John C. Holtz et al. at the United States Bureau of Mines (USBM) in Pittsburgh. This work was well-defined by 1960 in (1), providing supporting data for the ventilation provisions of the several USBM-fostered standards for diesel application in several types of mines (2).

The energy crisis of the Mid-1970s caused the Western nations to review the use of the entire spectrum of petroleum-based products. The high thermal efficiency of diesel engines suggested an increase in their use relative to others in all applications, in turn raising the fear that a many-fold increase in urban air-borne particulate matter could result, potentially producing a severe health impact.

These circumstances stimulated renewed interest on the part of government regulatory authorities in North America, and was the catalyst for the R&D collaboration of three mining-oriented agencies: the United States Bureau of Mines, the Ministry of Labour (MOL) of the Province of Ontario, and the Canada Centre for Mineral and Energy Technology (CANMET).

INITIATION OF THE THREE-GOVERNMENT COLLABORATION

In an effort to protect the health of mine workers in Canada's heavily dieselized mining industry (27% of the free world's estimated 15 000 machines), a comprehensive plan for diesel-related health and safety R&D was formulated during 1977 (3). This timing coincided with the availability of Canadian Government funding as a direct result of the energy crisis. The plan confirmed two initiatives taken the year before and placed them into a continuing program which suggested the need for inter-government collaboration. These two initiatives were: (a) the formulation of a comprehensive criterion for evaluating the combined impact of the several toxic constituents of diesel exhaust leading to the Air Quality Index expression described below, and (b) the determination of the performance of the then-current water scrubbers and catalytic purifiers.

Because two thirds (i.e., 2700 machines) of the Canadian underground diesel machine fleet were in the jurisdiction of the province of Ontario, there was likewise considerable concern on the part of that provincial government, sensitive to the mounting criticism of the use of diesels by the miners themselves.

Consequently, because of these concerns, because the mining sector makes a substantial contribution to Canada's overall economy, and because much of the mining industry was dieselized, the perception grew in Canada that the time was right to launch a major study.

The U.S. Bureau of Mines' original initiatives in this field were described above. In addition to those strong beginnings, efforts on the part of the Bureau resulted in the achievement of a significant milestone in January of 1973. This milestone, the Pittsburgh Symposium (4) on the use of diesel-powered equipment in underground mining, along with a number of other important matters relating to this evolving study, are described by Schnakenberg (5). That reference describes the cooperation of the U.S. Bureau of Mines and its sister agencies: the Mining Enforcement and Safety Administration, now called the Mining Safety and Health Administration (MSHA), the National Institute of Safety and Health (NIOSH), and also the American Conference of Governmental Industrial Hygienists (ACGIH), for the period from 1973 to 1978. That cooperation fostered the evolution of the view that further research into diesel exhaust control and health impact studies were necessary.

At the ACGIH November 1978 Industrial Hygiene Symposium the CANMET Air Quality Index approach, formulated by I.W. French and A. Mildon (6) and discussed in the next section, was first presented, the initial results of the Bureau's environment monitoring efforts performed by Michigan Technological University were described, and the MSHA/NIOSH silica/diesel exhaust study was presented.

All these important developments preceded an informal discussion between representatives from Canada and the United States at the 1979 International Conference of Safety in Mines Research Institutes, which proposed a joint research program for the development of hardware to substantially reduce diesel emissions, as well as the continued development of environmental assessment techniques. Similar discussions at the 1980 American Mining Congress reinforced the need for a joint R&D program. These discussions were followed by a meeting in 1980 of three funding agencies in Pittsburgh: USBM, MOL, and CANMET, along with a major contractor, the Ontario Research Foundation (ORF). The purpose of the meeting was to report the status of diesel emissions R&D and to lay plans for formal collaboration. Such a cooperative program was instituted by the signing of a Memorandum of Understanding during December of 1981, and the Collaborative Diesel Research Advisory Panel (CDRAP) was formed.

Among the first matters undertaken was the installation of an advanced engine test facility at the Ontario Research Foundation, with major support from the Ontario Ministry of Labour. This facility featured: (1) computer-controlled dynamometers to simulate vehicle duty cycles, (2) a dilution tunnel sampling system to cope with dynamic sampling of particulate matter, (3) sophisticated analytical equipment necessary for monitoring the several gaseous, liquid and solid constituents in diesel exhaust, and (4) development of Ames mutagenic assessment capacity to flag potential occurrence of carcinogens.

The Panel has subsequently been the vehicle for the sharing of R&D results not only among the funding agencies, but also among the several contractors and contributing private sector manufacturers, equipment users, and regulatory agencies. The Panel has also been the vehicle for consultation on the directions that future R&D should take to achieve the four main objectives listed in the abstract. The minutes of the Panel meetings have been widely distributed throughout the mining community to inform all concerned of the activities and progress.

The highlights of the achievement of these objectives are described briefly in the remainder of this paper, and in greater detail in the following five papers of this compendium.

SELECTION OF THE MEASURE OF PROGRESS

Diesel emissions contain a number of constituents which are toxic to those exposed to high enough concentrations for long enough periods of time. Discovering the safe levels and periods of exposure is a process, and perceptions as to appropriate values of these parameters change as experience and understanding grow.

Of the many constituents in diesel exhaust, six are the cause of varying degrees of concern: carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), sulphur dioxide (SO_2), aldehydes and soot. Table 1 indicates their general order of present concern from least to greatest and the reduction in the general magnitudes of these tail-pipe levels over time (for the higher range of levels for full load/speed conditions). These reductions are due to the developments in two-stage combustion or indirect injection of fuel (IDI) relative to direct injection (DI) over the last 20 years. Finally, the table gives the dilution ratios necessary to reduce these tail-pipe levels to the ACGIH TLVs or other appropriate levels.

Table 1 - Undiluted contaminant levels in diesel exhaust at full load/speed engine operation

Constituent	Units	Prior generation engine levels (DI)	Present generation engine levels (IDI)	TLV or other limit	Present dilution ratio required
CO	ppm	2000	300	50	6
NO_2	ppm	-	48	3	16
NO	ppm	1500	700	25	28
SO_2*	ppm	80	80	2***	40
soot	mg/m^3	1000	75	1.5**	50
EQI	-	-	232	3**	77

*0.20% sulphur in the fuel.

**proposed in (6).

***note that the TLV for SO_2 remains 3 ppm when used in the EQI expression defined below.

CO, formerly of great concern, now has become much less of a concern relative to other constituents as our knowledge of their health effects has increased: NO_2 is generally not a controlling constituent, although concentrations tend to rise at lower loads; NO produces moderate concern; SO_2 has perhaps become the individual gas of greatest concern because its TLV has recently been reduced to 2 ppm - if the fuel sulphur is below 0.2%, it is of less concern; the aldehydes are generally kept below their TLVs when the other constituents are controlled; and soot would appear to require the greatest fresh air dilution given a limit value of 1.5 mg/m^3.

Diesel soot is visible and has always been perceived as objectionable, and possibly noxious by miners. However, widespread concern for its relative effect on health has been clearly expressed only in the last decade. The Environmental Protection Agency (EPA) in the United States and the Canadian Environment Department both anticipate similar substantial reductions in soot emissions from surface diesels by 1991 relative to the present to neutralize the health consequences. Recent studies indicate that, while coal dust exposure was characterized by normally activated alveolar macrophages (as would be expected as a result of the invasion of a hostile particulate) the appearance of the microphage population on exposure to diesel soot suggested poisoning with consequent degradation in function (7). I.W. French and Associates, contractors to CANMET, after studying 1500 citations in the literature in 1978 (6), concluded that diesel soot was the most potentially hazardous component in diesel exhaust, suggesting an emphasis with respect to its control.

In general, when engine adjustments such as injection timing are made, the relative proportions of these various constituents change. Changes in these constituents due to malfunction, wear and maladjustment have been addressed in detail by Waytulonis (8) in a major effort performed on behalf of the U.S. Bureau of Mines Twin Cities Research Center in Minneapolis. Sometimes these changes compensate - as one constituent increases another decreases. Further, derating an engine, i.e., reducing the maximum fuel rate, can reduce the soot emissions to below the 'smoke point', perhaps interchanging the governing constituents in the exhaust. Finally, addition of emission control devices can greatly alter the relative constituent concentrations.

These facts present all segments of the mining industry with a dilemma: by what criterion should adequacy of ventilation, i.e., air quality, be assessed? Such a criterion would ideally: (a) take into account the changing nature of the constituents, (b) assess comprehensively the toxicity of the exhaust constituents of major concern, (c) give credit for any air quality improvements allowing engineering economic tradeoffs to be made, and (d) allow regulatory agencies to prescribe ventilation consistent with items (a), (b), and (c), and permit compliance measurements to be made.

At a meeting of the participants in Pittsburgh in 1980, the above aspects were considered and it was decided that the Health Effects Index (HEI), then renamed the Air Quality Index (AQI), was the best criterion in existence by which to accomplish the above objectives and particularly to measure the progress of control technology developments on the reduction of overall diesel emissions.

At the same meeting, CDRAP decided to use the reduced emissions IDI Deutz engines* for application of emission control equipment because of their widespread use by the U.S. and Canadian mining industries. Although some R&D had already been carried out on the F8L714 engine, particularly the successful water-in-fuel emulsion work to reduce soot and NO, the 413FW series was chosen because of its introduction in 1976 to ultimately replace the 714 version. Unfortunately, the water in fuel emulsion system did not prove to be effective when applied to the new 413FW series.

Except for minor and beneficial changes, the relative concentration of the components of diesel exhaust are unaffected by dilution. Therefore, the French-Mildon criterion, intended for the evaluation of the diluted or ambient air, and known as the Ventilation Index, the Health Effects Index or preferably the AQI, can be used to evaluate the potential toxicity of undiluted diesel exhaust. When used for this purpose it is referred to as the Exhaust Quality Index (EQI). The French-Mildon literature study recommended a maximum value for the AQI of 3, above which some control measure was suggested. The mathematical expression recommended was:

$$\text{EQI or AQI} = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + \frac{H_2SO_4}{1} + 1.5\left[\frac{SO_2}{3} + \frac{RCD}{2}\right] + 1.2\left[\frac{NO_2}{3} + \frac{RCD}{2}\right]$$

where the ppm concentration for each gas is divided by its ACGIH TLV at the time of the formulation of the expression, and RCD is Respirable Combustible Dust having a limit of 2 mg/m^3. In addition, it should be pointed out that no constituent should be permitted to rise above its own individual limit, and that the sum of the gaseous terms (CO, NO, and NO_2 relative to their respective TLVs) should be less than 1.

A minimum ventilation dilution ratio then can be calculated from EQI/AQI_{max} = EQI/3, and the minimum ventilation prescription equation is:

ventilation rate = undiluted dry exhaust gas rate x EQI/3

Assuming sulphur in the fuel to be 0.20%, and applying the above maximum values for the various constituents, produces typically an EQI value of 232, which when divided by AQI_{max} = 3, yields a dilution ratio of 77. Therefore, the comprehensive EQI value, if employed, will govern ventilation prescription in most circumstances, rather than any of the individual constituents as indicated in Table 1.

There is a further development of this criterion which separates the gas effects from the RCD effects by the formulation of two independent expressions each with its own limit. The reader is referred to (9) for further elaboration. For the purposes of control technology performance assessment however, CDRAP has continued to use the above single equation for consistency as both equation systems give virtually identical results from the standpoint of fresh air dilution ratio.

*Reference to specific brands, equipment or trade names in this paper is made to facilitate understanding and does not imply endorsement by the government agencies.

It should also be noted that the use of AQI = 3 in the single equation relation generally increases the prescribed ventilation rate for untreated exhaust only slightly relative to the use of the U.S. criterion: NO_x (as equivalent NO_2) divided by a limit of 12.5, as prescribed in Part 36 (2).

Therefore, with respect to the objectives stated above, this criterion takes into account the changing relationship of the constituents and assesses their overall effects. With respect to giving credit for air quality improvements, the addition of a device that is 90% efficient in reducing particulate emissions, reduces the EQI by say 30 to 50% depending on the circumstances as is evident from inspection of the AQI expression. Therefore, a balance can be struck between realizing a total benefit in improved air quality from the use of such a device and maintaining ventilation as before on the one hand, and by realizing an economic benefit on the other hand by reducing ventilation to the appropriate level determined by the maximum limit of the AQI or of the individual constituents. Likewise, the buying of low sulphur fuel will have an effect which is easily assessed, etc.

Further, technology has been evolving as described below, which permits the underground ambient assessment of these major constituents using time-weight-average field measurement devices permitting calculation of the AQI levels. This in turn permits operators or regulatory authorities to evaluate the on-site performance of engines, and/or treatment devices or systems, in order to assure adequate levels of ventilation in a given circumstance. Thus all four requirements by which to evaluate progress listed (a) to (d) on page 4 above, are addressed by the use of such a criterion.

In addition to applying this AQI criterion for equipment performance determination, CDRAP has applied an additional assay - the Ames test. The mutagenic activity, as determined by the use of the Ames microbial assay, has demonstrated a high positive correlation with a number of other tests (in-vitro and in-vivo) of mutagenicity and carcinogenicity for the soluble fraction of diesel particulate (10). Thus the Ames assay provides an inexpensive, convenient and relevant means of comparing diesel-derived contaminants from engine to engine and/or among treatment devices, permitting engineering judgements to be made regarding which R&D avenues to pursue, emphasize or discard.

DEVELOPMENT OF EXHAUST TREATMENT DEVICES

Exhaust treatment devices such as those developed in connection with the CDRAP program, can be applied to diesel emissions reduction in all types of underground workings: coal mines, other types of gassy mines, metal mines, and all other non-gassy types of underground workings. In the case of gassy mines, further developments to reduce the fire and explosion hazards are required. Traditionally, water scrubbing equipment has been employed in gassy mines to assist in avoiding this hazard. A decade ago, however, they were common in metal mines. In this connection, the original 1977 CANMET contract with the Ontario Research Foundation described in (11), detailed, evidently for the first time in the published literature, the performances of two then-current water scrubbers, and a once-through catalytic purifier all employed in metal mines. The scrubbers removed a respectable 40 to 65% of the sulphur oxides (SO_2 and SO_3 - an important point to note in view of the recent TLV reduction for SO_2 from 3 to 2), but only 30% or so of the soot. The catalytic purifier reduced 90% of the CO to carbon dioxide (CO_2), but converted significant amounts of the SO_2 to SO_3 and NO to NO_2 (SO_3 and NO_2 are the more toxic forms). These early results suggested that there was room for improvement, particularly in the capture of soot. Consequently, control technology development work was begun.

As part of this development program, a CANMET Research Agreement with the University of Waterloo was implemented to study materials by which soot could be filtered from diesel exhaust. This study continued for 3 years (1977-79), and showed that six materials were potential candidates. The USBM and CANMET studied the two most promising materials by the building, and in-house testing, of prototype systems with modest success.

At this point, the Corning Glass Works representatives approached CANMET and the USBM to assess the potential of the ceramic wall-flow filter element as an underground diesel emission control system. Initial trials were successful. As the unit appeared to offer considerable advantages in terms of bulk, maintenance and regeneration potential, further development of the Waterloo materials was suspended.

These initial studies have subsequently led to the study by CDRAP of the following array of emissions reduction equipment options:

1. (a) a simple optimized baffle-type water scrubber design, and
   (b) a high efficiency venturi-type water scrubbing system.

2. several ceramic wall-flow diesel particulate filter options (DPFs):

   (a) simple DPFs for high exhaust gas temperature levels fostering unassisted soot auto-regeneration (combustion), resulting in acceptable equilibrium backpressures,
   (b) the use of fuel additives in conjunction with the above DPF unit, significantly depressing the soot auto-ignition temperature and further widening the filter applicability or further ensuring untended, passive auto-regeneration of the filter,
   (c) the use of noble catalyst-impregnated DPFs further depressing the soot auto-ignition temperature relative to (b), useful particularly for low sulphur fuels. Recent preliminary work indicates negligible conversion of SO_2 to SO_3 for one noble catalyst formulation, perhaps eliminating this concern when fuels with moderate fuel sulphur levels are employed,
   (d) the use of non-noble catalyst formulations which, it is hoped will demonstrate helpful soot ignition temperature depression and similar insensitivity to fuel sulphur levels,
   (e) the use of combinations of the above, such as applications of the simple DPF unit at non-auto-regenerating exhaust temperature levels, thus requiring some means of out-of-service regeneration such as is possible with the addition of auxiliary heat [for example, the face heater described in (12)],

3. a wire mesh catalytic trap oxidizer (CTO) filter unit (13),

4. exhaust gas recirculation (EGR) for NO control in connection with DPF use (14),

5. water-in-fuel emulsions for NO and soot control (15), and

6. emissions effects of varying types of fuels and emulsions (16).

The following sections describe highlights of the first two development thrusts. For the remainder, the attention of the reader is directed to the references indicated at the end of each item.

WATER SCRUBBING SYSTEMS

In-house CANMET assessment of commercial water scrubber performance over several years indicated a variation from 10 to nearly 50% removal of soot. Further, scrubbers built to some non-Canadian specifications were often either heavy or costly to import or both. Because of this fact, the Beaver Construction Group approached CANMET in 1981 to design and test a series of simple, low-cost, baffle-type, flameproof water scrubbers. These were to be used to drive the development heading to the Donkin-Morien seam of the Cape Breton Development Company in Cape Breton, Nova Scotia.

The outcome was that design principles were established and two scrubber sizes were drawn, built and tested by Beaver, Hovey and Associates (1979), and CANMET in collaboration. Careful use of a water separation criterion resulted in a 40 to 49% (maximum) soot removal efficiency, plus other beneficial effects including the absorption of some of the acid gases. The performance matched or exceeded the best of available scrubbers at reduced cost. Such performance may represent a limit for basic uncomplicated designs.

In 1981 CANMET scientists realized that momentum-transfer, and consequent impact of soot particles with water droplets in a water-injected venturi throat inserted into an exhaust system, could be optimized for soot capture using a mathematical model. This resulted in the design, manufacture and testing of a venturi system mounted in the exhaust system of a Deutz F6L 912W engine. This unit captured 70% of the soot, some of the sulphur oxides, and 19% of the NO_2, utilizing a backpressure of 10 kPa. Such a performance reduces the EQI by a substantial 50 to 60% depending on the backpressure, suggesting beneficial application to coal mine vehicles where the prescribed airborne soot plus coal dust levels are difficult to attain, and in non-coal mines where humidity is not a problem.

These water scrubbing developments are amplified in paper 2 of this series.

CERAMIC FILTER SYSTEMS

The filtering element in such filters is a porous ceramic material, the configuration of which is shown in (17) - see paper 3 of this series, and in (18,19). The porosity can be varied so that the degree of soot trapping can be tailored to the need and coupled with tradeoffs in size and shape, filtering surface area, and soot-free backpressure, etc.

The rapid optimization of the ceramic element size to the gas rates of six and eight cylinder Deutz engines, for a nominal trapping efficiency of 90%, led quickly to several development directions including underground tests described in (20) - see paper 4 of this series, and to the option definition process of the above list. These option developments are described briefly as follows.

In essence the successful application of ceramic filters depends on the capability of the filter to handle the collected soot: (1) over a useful operating period, and (2) in such a manner that the backpressure buildup does not jeopardize engine warranty or mine safety. Thus methods for promoting and enhancing the handling/disposing of the collected soot, were held in high priority by the CDRAP and investigated. The method appropriate for the ceramic DPF is the combustion of the collected soot while it remains in the DPF. The most advantageous circumstances would be to have the collected soot burn off as collected, a so-called auto-regeneration.

Auto-regeneration of soot results from the inter-related effects of several parameters including the amount of carbon deposited on the filter surfaces and in the pores, the oxygen content of the exhaust gases passing through the ceramic element, and perhaps most important, the temperature of the exhaust gases. Cyclic dynamometer tests at ORF, simulating Load-Haul-Dump (LHD) machine operation, have approximately defined the average values of some of these parameters as reported in Table 2.

Table 2 - Ceramic filter regeneration threshold parameters

Option		Unassisted filter	Additive assisted	Noble catalyst assisted
minimum average load	(%)	77	54	48
CO_2/O_2 concentrations	(%)	8.0/9.7	6.0/12.2	5.4/13.0
fuel/air ratio	(-)	0.037	0.028	0.025
average exhaust	(°C)	427	365	349
temperature	(°F)	800	690	660

The application of these three regenerating options of Table 2 to specific types of vehicles powered by conventional four-stroke engines, appears initially to be a question of exhaust gas temperature characteristic determination. Such tests have been completed in the field at INCO Limited (21). These confirm the above LHD dynamometer results for the unassisted auto-regenerating filter from the standpoints of average exhaust temperature and also confirmation of the necessity of temperature excursions in excess of the 500°C (932°F) soot ignition temperature for sufficient periods to initiate combustion.

There have been examples of runaway regeneration which have resulted in damage, i.e., melting through or channelling of the ceramic matrix of the filter, the metal can remaining unaffected (22). This appears to have resulted when excessive amounts of soot are deposited in the filter and ultimately subjected to sufficient oxygen and temperature to produce continuous high intensity combustion. The result is that soot removal virtually ceases and filter pressure drop decreases to a lower value with little immediate safety hazard.

The INCO experience (21), indicates that high exhaust gas temperature operation, which fosters continuous regeneration, maintains the backpressure at an acceptable equilibrium limit of 4 kPa (20 in H_2O) for a Deutz F8L 714 engine. Under these conditions the filter neither self-destructs nor results in apparent significant thermal overstressing for periods up to 1830 h of operation. The key to safe operation seems to be the limiting of the amount of soot in the filter. To limit the amount of combustible material, and thus foster filter integrity, it is prudent to mount a backpressure sensor before the filter and arrange for a signal to illuminate a dash light when the backpressure is constantly in excess of a given upper limit, say 7.5 kPa (30 in H_2O). Unreported in-house CANMET experiments using a Deutz F6L 912W engine in connection with electric face heater development studies, showed that soot ignition did not occur when a filter loaded to a 5 kPa backpressure level was heat-soaked at high exhaust temperature (but below the soot ignition temperature) and suddenly exposed to the high oxygen concentration associated with low speed idle conditions. It should also be noted that the use of additives or catalysts depresses the soot ignition temperature significantly, appreciably reducing the likelihood of soot accumulation. While it appears that the type of operation described above results in safety thus far, safety research is currently continuing at the Twin Cities Research Center of the United States Bureau of Mines.

In addition to safety considerations, extensive studies of exhaust treatment devices have been made both in the laboratory and in the field to indirectly gauge the health effects of diesel pollutants. These studies have been in the form of polynuclear aromatic hydrocarbon (PAHs or PNAs) analyses to determine the levels of known carcinogens, and Ames mutagenic assessments, to flag their apparent collective carcinogenic potential relative to presently applied technologies. This latter aspect is detailed in (10) - see paper 5 of this series, which indicates that a significant reduction in Ames mutagenicity levels occurs as a result of the use of novel emission control options such as those developed in connection with the CDRAP program.

As a result of this multi-facetted examination of these filtration systems, it is estimated that they can be applied to most LHD machines and a portion of haulage trucks (say a total of 50% of the underground fleet), thus coping with by far the greater part of diesel vehicle soot contributions to underground environment contamination. Other applications would require periodic induced regeneration, either off or on the vehicle, prompted by a panel-mounted warning light, indicating backpressure buildup due to soot deposition.

DEVELOPMENT OF FIELD ENVIRONMENT ASSESSMENT TECHNIQUES

The U.S. Bureau of Mines has had an on-going environmental assessment program in place for some time, involving study of such concepts as: (a) tube bundle continuous monitoring (23), (b) in-mine array of sensors relaying signals to the surface, (c) a Mine Air Quality Laboratory (MAQL) for in-mine deployment where possible (24) and (25) - see paper 6 in this volume, and (d) a portable analysis equipment array carried into the mine to monitor environmental contaminants in order to provide both time-weighted-average (TWA) and instantaneous levels of five contaminants (26).

While each of these can be related to mine diesel technology, the latter two have been of most assistance to the CDRAP diesel program. The MAQL has been and continues to be employed by Michigan Technological University (MTU) under contract to the Bureau of Mines to evaluate some of the options listed above. Among these are the catalyst and fuel additive filter options installed in a Wagner Mining Equipment Company Scooptram. The venturi water scrubbing system, and some ceramic filter options are being evaluated in the same facility employing an LHD machine furnished by the Jarvis Clark Company Limited supported by the Mining Industry Research Organization of Canada (MIROC).

This work is performed in an underground experimental mine heading in Hancock, Michigan, designed to duplicate real world conditions for an LHD mucking cycle, while at the same time permitting careful control of all the experimental conditions relating to ventilation, multi-component sampling, analytical precision, and vehicle cycle repetition, so difficult to realize in the dynamics of an operating mine. Results of this option testing program are described in (25).

The portable analysis system has been developed by MTU and employed by an MTU team and/or a CANMET team for a number of mine environmental assessments including coal, salt, nickel, zinc and potash mines, to evaluate the impact of new diesel emissions reduction concepts on the environment and to evaluate the contaminant levels. Some aspects of four such studies are detailed in (20) - see paper 4 in this volume.

The result of applying these portable systems is the determination of the time-weighted-average values (TWAs) of CO_2, CO, NO and NO_2 gases (in % of ppm), plus the respirable combustible dust (RCD) in mg/m^3, for however many sampling stations are employed in a given investigation. These are the necessary values for characterizing the comprehensive toxicity of all the major components of diesel exhaust using the AQI described above, and relating such values to the CO_2 concentration. Instantaneous, real-time concentrations of the four gases are also determined at one sampling station for confirming comparisons to the TWA values, and for assisting in the definition of the variations of the machine operating cycle.

By such field measurements, comparative evaluation of the air quality can be made, with and without control devices for example. The studies reported in (20) indicate environmental improvements due to ceramic filter application of 35 to 65% relative to catalytic purifiers as measured by the AQI criterion.

There are several important generalizations which emerge from this detailed environmental assessment work, a summary of which follows:

1. Examination of voluminous constituent concentrations in the MAQL has led to the conclusion that the CO_2 concentration is a direct surrogate for all the other measured pollutants. This is most useful for an engineering approach to environmental control, which approach is described in relative detail by Schnakenberg (27) of the Pittsburgh Research Center, and Daniel (28) of the Washington D.C. Office of the Bureau of Mines, Department of the Interior.

2. TWA values of NO_x and NO_2 are presently determined by the easy in-mine deployment of Palmes diffusion-type samplers. These simple devices can, when care is exercised, produce an in-sample variation generally well within plus or minus 20% of the mean, and levels that compare well with integration of constituent concentrations derived from real-time traces generated by portable laboratory-type analyzers (20). The Palmes sampler approach is acceptable but it requires considerable pre-test preparation time and post-test analysis time plus some laboratory analytical equipment. TWA values of CO_2 and CO are determined by bag sampling and post-test analysis using the same type of portable laboratory zero/span analyzers, likewise involving some additional time before the answer emerges. Long-term stain tubes (CO_2, CO, NO_x, and NO_2), plus associated pumps, are now available to provide immediate answers at the end of the testing period without further effort. While pump failure and NO_2 sensitivity are present difficulties (20), it would appear that further development of long-term stain tubes will reduce the effort to make spot AQI and individual constituent assessments underground by an estimated 40% relative to the use of the present array of equipment.
3. Soot, assumed to comprise 75% of the RCD, is composed of solid carbon plus varying amounts of adsorbed hydrocarbons. The hydrocarbon fraction has been a source of difficulty in assessing the efficiency of ceramic filters in the underground environment. Dynamometer-derived efficiencies of the order of 90% were not confirmed by the results of a number of underground assessments which suggested a 40% or so level of filtration efficiency. MTU personnel were asked to look into this lack of agreement. Preliminary considerations, quoted from an MTU progress report showing that "half an ounce of oil (leakage) per hour could offset the test results and lower the MAQL (emissions) system efficiencies from 78% to 36% due to this additional particulate source", were confirmed in (25) - see paper 6 of this series. It appears that leakage of fuel, hydraulic oil, etc., onto hot surfaces, can add substantially to the air-borne contributors to the RCD measurement in addition to exhaust-generated soot; a point that must be kept in mind not only when field assessments are made, but also as a source of unwanted respirable particulate matter and hydrocarbon vapours even though the limits for the latter may be higher than that for suggested for soot.
4. Over reasonable periods of time assuming proper maintenance and small variations in the vehicle duty cycle, the components of diesel exhaust remain in relatively constant proportion with one another and CO_2. The AQI for such periods is therefore in relatively direct and constant proportion to the CO_2. Consequently, easy measurements of CO_2 can then provide quick estimates of the suitability of the ventilation keeping in mind the following proviso. Changes in emission levels due to engine wear, fuel system adjustments, malfunctions, etc., can change the relativity of the various constituent levels of CO_2. Thus, undiluted exhaust levels of the constituents and CO_2 should be monitored from

time to time to determine such changes, re-establish the appropriate dilution ratio and adjust the ventilation accordingly. In the short term, assuming no significant changes in engine emissions or ventilation rate and an AQI = 3, the easily-measured CO_2 control limit can be determined by using the ratio of the measured CO_2 and AQI values for the ambient environment. As long as the CO_2 remains at or below this control limit, the AQI can be assumed to be 3 or less. For example, during one filter evaluation described in (29), an AQI value of 0.51 and a CO_2 value of 0.05% were determined for the LHD operator's station. Because the AQI, of all of the possible limiting items, was closest to its limit of 3 (both the SO_2 and the NO concentrations were similarly close to their respective limits), the ventilation could theoretically be reduced by a factor of six, to produce a CO_2 value of 0.3% (i.e., 0.05 x 3.0/0.51), assuming that other difficulties would not result.

Therefore, suitably accurate measurement techniques are available to assess all the constituents normally necessary for environmental assessment. While some aspects of these techniques presently require time and capital, developments in the near future should minimize both of these aspects. Once such measurements are made, they will facilitate the making of engineering judgements regarding ventilation acceptability by virtue of the direct relationship of easily-measured CO_2 with each of the toxic constituents and/or the AQI, ratioing each to its respective limit and keeping in mind the assumptions stated.

CONCLUSIONS

RETROSPECT AND PROSPECT

It has been estimated that there are some 5000 to 6000 diesel vehicles in the underground mining fleet in all types of mines in the U.S.A. Similarly, there are between 3000 and 4000 such vehicles in underground service in Canadian mines (30). In very approximate terms, this means that the North American mining industry has a substantial capital investment of between 0.5 and 0.75 billion dollars directly in such equipment, to say nothing of the indirectly related investments. This substantial sum suggests on the one hand, that such equipment might have a minimum life to say 10 years perhaps longer before writeoff. At such a time it would be replaced when and if superior, proven technologies emerge that can be applied. Therefore the application of the control technology produced by this program would appear to be suitable for a commensurate period of time. It is likely on the other hand, that a residual number of diesel vehicles will always be required for some mining tasks, by virtue of their flexibility of operation. Therefore, emissions technology may have a considerable lifetime of applicability in excess of the 10-year period.

It would also appear that sharper definition of the health effects of diesel emissions, as well as the development of reduced emissions technologies, can reduce the legitimate fears and lessen the perception on the part of some members of the mining community, of the necessity of discarding diesel equipment technology, making it more feasible to extend the lifetime at least to the point of investment recovery and perhaps longer.

SPECIFIC OUTCOMES

There is a view expressed in connection with the listing of technologies necessary to meet the 1991 EPA soot standards for surface diesels vehicles, that engine development has already contributed the maximum possible to the reduction of emission levels with no significant engineering breakthrough in sight. Therefore, it is assumed that major reductions can only come from exhaust treatment, fuel alterations, etc. To this end the CDRAP collaborators have advanced two water scrubbing systems (venturi and baffle types) suitable particularly for coal mines, to the demonstration and application stages, respectively. In addition, mainly for non-gassy mines, six ceramic filter options including EGR, have been studied as listed above. These are variously applicable depending on the circumstances. Extended field durability tests of approximately 1830 h in service, suggest that filtration is a strong option with which to either reduce the toxicity of the environment or reduce costly ventilation, or to strike a compromise, depending on the stance taken by the appropriate regulatory authority. It is estimated that these filter options are applicable to up to 50% of the underground diesel fleet of which the contribution to the underground contaminants is thought to be 70% of the total.

The AQI/EQI concept, while not presently promulgated as a standard, does provide a means of assessing the comprehensive toxicity of emissions. Use of the AQI as a ventilation criterion generally only slightly increases the ventilation prescription resulting from use of the NO_x/12.5 criterion. In general, the order of ventilation-governing items is: (1) the AQI, (2) soot concentration, and (3) SO_2. In cases where the fuel sulphur exceeds 0.3%, SO_2 may be the governing constituent.

Therefore, use of the EQI/AQI concept and the principle that CO_2 concentration is an easily-measured surrogate for the AQI or each contaminating constituent, rationalizes choice of engine, treatment option selection, ventilation system and mine design, and makes possible the ultimate closing of the loop, i.e., the establishment of automated control of ventilation and related systems, based on continuous sensing of CO_2 or the individual contaminants and the ventilation parameters in order to effect considerable operating cost reductions.

THE POWER OF COLLABORATION

The willing cooperation of the various segments of the mining community in North America has resulted in the numerous significant developments described above. The large number (approximately 31) of collaborating organizations attests to the power that has been brought to bear on the emissions problem by this active cooperation of all parties, public and private, participating in the CDRAP programs. Gratitude for these efforts is extended to all the participants in the acknowledgement section of this compendium.

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