An Integrated Approach to Control Diesel Particulate Matter In Underground Coal Mines

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ABSTRACT

Diesel engines were introduced in European, Asian, and Australian coal mines nearly fifty years ago and more recently in U.S. coal mines. Their use minimizes the risks of mine fires and gas explosions associated with trolley wire haulage. While there is no epidemiological evidence that properly diluted diesel exhaust creates any health hazard, some concern persists about the long-term effects of inhaling diesel particulate matter. Existing control technology has been able to dilute all gaseous components of diesel exhaust to safe levels. Because there is no medically established threshold limit value for diesel particulate matter in U.S. coal mines, it was deemed appropriate to investigate the levels that can be achieved by adopting an integrated approach to diesel particulate matter control and using state-of-the-art technology. Technologically achievable control of diesel particulate matter concentrations in mine air can provide a basis for the use of diesel in mines until an in-mine standard based on scientific epidemiological studies can be derived.

KEYWORDS

Diesel Exhaust, Diesel Particulate Matter, Fuel Additive Properties, Catalytic Converter.

INTRODUCTION

Coal is the most abundant and economical fossil fuel resource in the world today. Over the past 200 years, it has played an increasingly vital role in the growth and stability of the world economy. In the USA, coal provides about 56 percent of all electrical energy generated and 32 percent of all energy consumed. Total proven reserves of coal exceed one trillion metric tons and indicated reserves of coal are estimated at 24 trillion metric tons (Kuuskraa, 1992). Sixty countries around the world mine about 5,000 million metric tons of coal annually and, at this rate, coal is likely to remain a dominant source of energy throughout the next century.

During the past 30 years, the U.S. coal industry and particularly underground coal mining have gone through some major changes. Some of these changes are obvious by now, but others are in the making. They are as follows:

1. Restructuring of the mines (fewer but larger coal mines).
2. A productivity of 70-80 tons/manshift versus 20-30 tons/manshift.
3. Longwall mining versus room and pillar mining for improved safety and productivity.
4. Three-entry longwall developments versus 4-6 entry development sections.
5. Diesel personnel and material transport versus trolley wire equipment.
6. Belts for coal transport versus mine cars and locomotives.
7. Mine slopes versus vertical hoists.
8. Trained and skilled personnel versus on-the-job training.
9. Zero accident goals versus fewer accidents than the previous year.

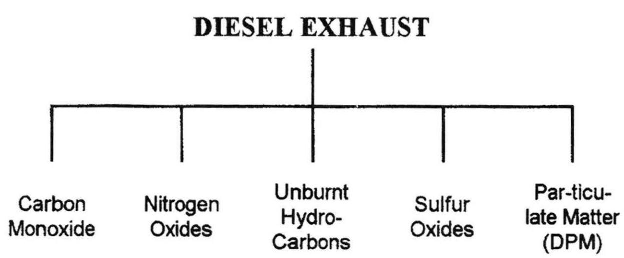
The use of diesel equipment in coal mines is questioned based on the suspicion that exposure to diesel exhaust may affect the health of miners. Diesel engines were introduced in U.S. underground coal mines nearly 30 years ago, and their numbers have steadily increased to approximately 3000 at present. Safety and productivity advantages are the driving forces for the popularity of diesel engines. Diesel equipment improves safety by eliminating shock, fire, and explosion hazards from trolley wires and electrical cabled equipment.

An additional safety advantage of diesel equipment use is improved ventilation in the face area. Currently, the belt-entry is isolated from intake air in many mines, and the trolley wire entry is regulated for air velocity at 250 ft/minute. The latter restriction is imposed to safeguard against rapid spreading of fire in the trolley wire entry, but all such restrictions can be eliminated with the use of diesel equipment, and air quantities at the face can be maximized to improve safety and health of miners.

Diesel exhaust contains some substances that can be poentially harmful to human health at high exposure levels. However, the toxicological effects of any substance are functions of the dose and duration of exposure. For example, carbon monoxide is a deadly substance in very high conentrations. The American Conference of Governmental Industrial Hygienists (ACGIH) has set a threshold limit value for it at 50 ppm. This means it can be inhaled at this concentration for eight hours a day, five days a week over the lifetime of a worker without harmful effects. Similarly, if all components of the diesel exhaust are diluted to their respective threshold limit values, diesel exhaust does not constitute a hazard to human health.

Table 1 shows the major components of diesel exhaust. Threshold limit values (TLVs) for all gaseous components of diesel exhaust have been established by the ACGIH and are incorporated into Federal Mine Safety and Health Administration (MSHA) regulations. Such incorporations are done only after careful examination of their technical and economic feasibility. Many field studies confirm that meeting these TLVs for gaseous components of diesel exhaust has not been a problem in coal or other mines (Johnson, 1980; Reinbold, 1981).

Table 1. Major components of diesel engine exhaust.

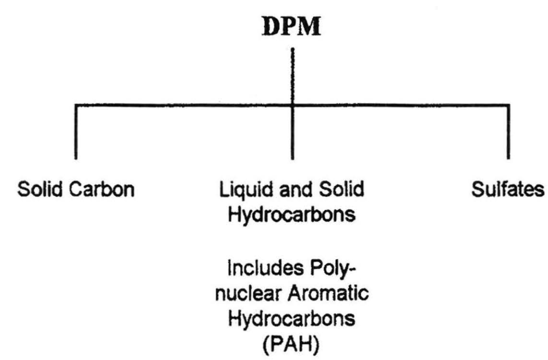


MSHA has not established a TLV for diesel particulate matter (DPM) yet, although ACGIH has recommended a TLV of 0.15 mg/m^3. The National Institute of Occupational Safety and Health (NIOSH) has identified DPM as a potential human carcinogen, but in-mine experience over the past fifty years does not provide any epidemiological evidence for such risks. A recent study in Australian coal mines, many of which are partially dieselized, determined that the standardized mortality ratio (SMR) for lung cancer in a large cohort of miners was only 78 percent of that in the general population (Christie et al., 1995). A parallel study in highly dieselized German potash mines (with no confounders, such as, silica, radon, arsenic, etc.) found similar results for the incidence of lung cancer (Säverin and Dahmann, 1999). Thus, DPM at prevailing concentration levels, does not appear to create any additional health risks. Apart from the lack of substantial epidemiological data, another difficulty in establishing any in-mine personal exposure limit (PEL) in the coal mines is the lack of instruments that can accurately measure the DPM concentrations. Previous experience with the coal mine dust PEL also dictates that any PEL for DPM must be based on gravimetric measurements.

In non-coal mines, the combustible fraction of respirable dust can provide a good measure of DPM, but this obviously will not work in mines where combustible minerals are being mined. The elemental carbon technique that differentiates between the fractions of elemental and organic carbons in coal dust and DPM cannot be utilized universally because neither the composition of the coal mine dust nor that of DPM is always the same. Many other techniques, such as carbon isotope ratio analysis, Raman spectroscopy, and electron spin resonance, also suffer from a similar shortcoming. The size cut-off-based instruments measure everything in mine air below a certain size (0.8 or 1.0 µm). This can be a useful instrument if there was a TLV for all submicron dust particles in the mine atmosphere but is useless if it is used to measure DPM only.

Table 2 shows the major components of DPM. It is generally believed that the polynuclear hydrocarbons attached to solid carbon particles are the potential carcinogens in DPM, but their TLVs are yet to be established. Under these circumstances, the most prudent option is to minimize the concentration of DPM in mine air using state-of-the-art technology and introduce diesel engines in all underground coal mines to improve safety by removing ignition, fire, explosion, and tripping hazards related to the use of trolley wire and other electrical equipment. The intent of this paper is to take an integrated approach to determine a practically achievable DPM concentration level in underground coal mines.

Table 2. Major components of diesel particulate matter.



AN INTEGRATED APPROACH

An integrated approach to control DPM in mine air consists of the following:

- **Reduce DPM generation**
  1. Clean engines.
  2. Clean fuel.
- **Collect generated DPM**
  3. A catalytic converter on each unit of diesel equipment.
  4. If needed, soot filters on engines working in face areas and large engines working outby.
- **Dilute DPM**
  5. Adequate ventilation for all approved engines based on DPM emissions.
- **Monitor DPM emissions and maintain equipment**
  6. Routine engine performance monitoring.
  7. Proper maintenance.
  8. Adequate training for safe operations and maintenance.

Clean Engines

The amount of DPM emitted in grams per brake horsepower is known as the "specific DPM emission" for the engine and is a measure of "clean engines." Tables 3 and 4 list MSHA approved clean engines that are used in underground coal mines. The specific DPM emissions for all approved engines range from 0.19 to 0.3 g/bhp-hr. While efforts to reduce this specific emission for larger engines for highway use are in progress, it is unlikely that a small market, such as the underground coal mines, will ever generate such an effort. Electronic injection and turbo-charging of engines are known to reduce DPM emissions, but making these devices permissible for underground mine use is a daunting task.

Table 3. MSHA Approved permissible diesel engines.

Engine Type	Horsepower	Specific DPM Emission (g/bhp-hr)
Cat 3306 PCNA	150	0.306
Cat 3304 PCNA	100	0.297
Deutz MWM 916-6	94	0.271

Table 4. MSHA approved non-permissible (outby) diesel engines.

Engine Type	Horsepower	Specific DPM
Cat 3306 PCNA	150	0.261
Cat 3304 PCNA	100	0.255
Deutz MWM 916-6	94	0.208
Deutz F4L1011F	59	0.187
Deutz F3L1011F	44	0.193

Clean Fuel

Clean diesel fuels, such as ASTM defined D2 fuel, have a sulfur content less than 500 ppm (.05%), aromatic contents less than 35%, and a cetane number of 40 to 48. Since sulfates typically constitute 50% of DPM by weight, reducing the sulfur content of diesel fuel can significantly reduce the DPM emissions. Fuels with sulfur content of 210 ppm (.021 %) are available at competitive prices, but ultralow sulfur diesel fuels (sulfur = 0.4 to 5 ppm) cost nearly four times more than the regular D2 fuel. Moreover, ultralow sulfur fuels do not have enough lubricity and may curtail the engine life by damaging the valves. Adding lubricants to ultralow sulfur fuel will once again increase DPM emissions. Hence, there are practical limits to reducing the sulfur contents of diesel fuels.

Several fuel additives (Table 5) mixed with D2 fuel in different proportions have shown reductions in DPM emissions. A ten percent addition of diethylene glycol methyl ether (DGME) to D2 fuel appears to be the most viable (Hess, et al., 1998) at present. A detailed discussion of this subject is not possible here, but there certainly appears to be much room for further research in this area.

Catalytic Converter

A well-designed catalytic converter placed in the exhaust system next to the engine can drastically reduce all gaseous emissions including carbon monoxide, unburnt hydrocarbons, and soluble organic fractions (containing polynuclear aromatics). It is a compact, durable, reliable and a low-cost component. It should, therefore, be an integral part of all diesel engines approved for underground coal mines. Table 6 shows the characteristics of a well-designed catalytic converter.

Table 5. Properties of fuel additives for reducing DPM emissions.

FUEL ADDITIVE PROPERTIES				
Additive	**Suggested Blend Ratio (Additive/ Fuel)**	**Weight Percent Oxygen**	**Flash Point (°F)**	**DPM Reduction (Percent)**
Diethylene Glycol Methyl Ether	10/90	40.0	189	25.3
Liquid DME (L-DME) 96% 1,2-Dimethoxy-ethane 4% Dimeth-oxyethane	11/89	36.5	71*	32.8
Triethylene Glycol Dimethyl Ether (Triglyme)	11/89	36.0	185	12.1
Diethylene Glycol Dimethyl Ether (Diglyme)	11/89	35.8	156	19.3
1,2 Dimethoxy ethane (Glyme)	11/89	35.6	78*	17.5
Methyl Soyate	35/65	11.0	207	30.9

**These fuel additives have a flash point temperature lower than ASTM specification of 125° F.*

Table 6. Charateristics of a well-designed catalytic converter.

CO	Reduced by 80 to 95%
HC	Reduced by 85 to 90%
DPM	Reduced by 25 to 35%
Odor Control	Very Good
Influence on Engine	Low Pressure Drop; No Fuel Penalty
Reliability	Very Good
Durability	≥5000 Hrs.

Soot Filters

Heavy duty diesel engines working outby, and diesel equipment working inby where generally the ventilation air is not as plentiful, as it is outby, may need a soot filter to further control the DPM emissions. Soot filters may be broadly classified as either high temperature or low temperature filters. A comparison of two systems is shown in Table 7. A high temperature soot filter, consisting of a catalyzed ceramic body, is by far the most popular soot filter currently used in North American and Australian underground mines.

High temperature soot filters require that exhaust temperatures be maintained above 350°C for a short duration each shift for proper operation. They are ideally suited to heavy duty equipment but may not be able to regenerate if used on light duty outby units. Low temperature soot filters require a heat exchanger, which makes the system very large and expensive. Their use, therefore, is practically limited to only large, heavy duty diesel equipment. At present, there is no practical soot filter available for use on light-duty outby diesel equipment.

A relatively high pressure drop across both types of filters (typically 5-10 kPa) reduces fuel efficiency, but the additional emissions and cost do not preclude their use under proper conditions.

DPM CONTROL STRATEGY

The control strategy for all gaseous species of diesel exhaust is quite simple. MSHA carries out a laboratory test, using an ISO 8-mode duty cycle, on each approved engine to determine the emission rates of carbon monoxide, nitrogen oxides, etc. MSHA then specifies a given quantity of ventilation air (popularly known as the "nameplate air") that will dilute the gasses to their corresponding threshold limit values. Compliance with the law is easily verified in underground mines by direct measurement of these gaseous emissions in the mine air.

As mentioned earlier, in spite of an ongoing effort for the past several years, no instrument is yet available that can directly measure the DPM concentration in mine air. The measurement of DPM emissions, therefore, must be quantitatively done outside the mine in a laboratory under controlled conditions. An adequate quantity of ventilation air must be assigned to each approved diesel engine to reach a technically achievable DPM concentration level in the mine air. The "nameplate air" for diesel equipment will most likely be based on DPM emissions in the future. Considering the available diesel engines, fuels, mine ventilation air, and the state-of-the-art DPM control technologies, it appears feasible to achieve a laboratory DPM standard of 0.5 mg/m^3 at present. The following strategy is proposed to achieve this standard for all approved diesel engines used in underground coal mines.

Table 7. Comparison of low and high temperature filters.

Characteristics	Low Temperature Filters	High Temperature Filters
Heat Exchanger	Yes	No
Cost	$30-45,000	$3-5,000
Size	Very Large	Small and Compact
Maintenance Needed	8 Hours	2000 Hours
Collection Efficiency (in conjunction with a catalytic converter)	70 to 90%	70 to 90%

1. Use engines with a specific DPM emission of less than 0.3 g/bhp-hr.

2. Use ASTM D2 fuel with a sulfur content of equal to or less than 500 ppm.

3. All MSHA-approved diesel engines for underground coal mine use will incorporate a catalytic convertor that will remove at least 25% of DPM by weight.

4. All inby equipment and heavy duty equipment working outby will also have a soot filter capable of removing at least 70% of DPM. The efficiency calculation must be done on mass basis with actual diesel emissions from the engines. An ISO 8 mode test will be used to determine the average bare engine emissions and average DPM emissions with the after-treatment devices in use.

5. Adequate ventilation will be specified by MSHA for each diesel engine "as configured" such that the diluted DPM concentration will not exceed 0.5 mg/m^3. "As configured" clearly defines the type of engine, fuel selected, the type of catalytic converter, and the soot filter, if any.

6. For multiple diesel engines working inby and heavy duty engines working outby in one air split, ventilation air calculations will be done as follows:

   Apply 100:75:50 rule for multiple engines working in an air split; i.e., the ventilation air required for the first unit is the MSHA specified nameplate air (for DPM); 75% of this ventilation air is needed for the second unit and 50% of the nameplate air is needed for the third and each additional unit.

The above strategy provides a vehicle for uniform control of diesel exhaust emissions in underground coal mines regardless of the variety of engines, fuels, and after-treatment devices used. It makes sure that the DPM concentration in coal mine air cannot exceed 0.5 mg/m^3, even under the worst circumstances, as long as the minimum required ventilation air is available and net engine emissions are not allowed to deteriorate. Using the above strategy, we can use diesel equipment in U.S. underground coal mines to enhance safety and productivity.

BUILT-IN SAFETY FACTORS

The laboratory-based DPM standard of 0.5 mg/m^3 is based on two very conservative assumptions. They are:

(1) All engines work continuously, i.e., 8 hrs/shift, and

(2) All engines are stationary.

In fact, almost all diesel units are mobile and do not work continuously. For these two reasons, the actual ambient mi ne air DPM concentration will be considerably less than the laboratory standard of 0.5 mg/m^3. In addition, the 100:75:50 rule for ventilation air calculations provides more air than what is needed under actual working conditions. The ventilation air calculations also do not allow for any decay of DPM in mines; however, it is visually obvious in any non-coal mine that DPM does get deposited in mine airways on all exposed surfaces. Thus, the above strategy for DPM control has four built-in safety factors to ensure that ambient mine air DPM concentration will be considerably less than the laboratory-based value of 0.5 mg/m^3. Each of the safety factors will now be examined in somewhat greater detail.

Duty Cycle

A recent time study (McDonald, 1998) over a 7-day period in a large dieselized coal mine determined that:

a) All light duty engines work for only 36 percent of the time on any given day or shift; i.e., 2 hrs., 53 min/8-hr shift.
(b) All heavy duty engines work for only 64% of the time on any given day or shift; i.e., 5 hrs. and 7 min/8-hr. shift.

Data from other mines also confirm the above duty cycles. The non-continuous duty cycles will clearly result in an eight-hour average DPM exposure lower than 0.5 mg/m^3.

Effective Ventilation

The DPM concentration in the mine air is likely to be further reduced by the mobility of the diesel equipment; i.e., by the effective ventilation. Effective ventilation is a term used to calculate diesel exhaust dilution for a mobile unit (Holtz, 1968 and Thakur, 1974) and is defined as:

Effective Ventilation = (V±U) x A

where V is the diesel equipment velocity in ft/min
U is the ventilation air velocity in ft/min, and
A is the roadway cross-section in ft^2

To illustrate the point, let us assume a diesel unit is traveling in an airway of 100 sq. ft cross-section with a velocity of 10 miles per hr (880 ft/m). The ventilation air quantity is 30,000 cfm, hence the air velocity is 300 ft/min. The effective ventilation responsible for diluting DPM is (880 ±300) x 100 or 58,800 to 118,000 cfm, depending on the direction of engine movement. Since the air quantity actually responsible for diluting the diesel emissions is much larger than 30,000 cfm, the laboratory-based DPM level of 0.5 mg/m^3 is again reduced to lower levels.

Adequacy of Ventilation for Multiple Units

The additional air requirement for multiple units working in a single air split under actual mining conditions was analyzed earlier (Thakur, 1974). Ventilation air requirements for three units working in one air split are shown below.

No. Of Engines	Air Quantity Needed (Percentage of Nameplate Air)	Air Quantity Proposed (Percentage of Nameplate Air)
1	100	100
2	130	175
3	160	225

The additional air will further reduce the laboratory-based DPM concentrations of 0.5 mg/m^3.

Agglomeration and Deposition of DPM

The mine air is much cooler than the diesel exhaust. The hot exhaust is cooled by mine air and diesel particles begin to agglomerate. The agglomerated particles are collected and deposited in the mine by (a) sedimentation, (b) impaction, and (c) brownian motion created by both thermophoresis and diffusophoresis. The visual evidence for such deposition is quite apparent in non-coal mines. No scientific study is known that quantifies the deposition efficiency of DPM in mines, but it appears to be significant.

The combined impact of these four built-in safety factors is that a laboratory-based DPM standard of 0.5 mg/m^3 translates into a much lower mine air DPM concentration.

MAINTAINING LABORATORY STANDARDS

Two factors that may mitigate any proposed laboratory standard are as follows:

(1) Poor maintenance and
(2) Age of the engines

Maintenance

It is obvious to anyone working in dieselized mines that a poorly maintained engine can aggravate the DPM levels in mine air. This can be avoided by preventive, routine maintenance of the entire diesel fleet. Such maintenance must be carried out by trained personnel on a periodic basis. Daily checking of gaseous emissions (e.g., carbon monoxide) should be done to confirm the condition of diesel engines. Ambient air quality examination can also provide a warning that one or more engines are not working properly. Mine personnel should be properly trained in performance monitoring.

Age of Engines

Unmaintained or poorly maintained diesel engines do show an increase in DPM emissions with age. However, a properly maintained diesel engine (including the changing of injectors if needed) should not have any deterioration in DPM emissions during its tenure in the mine. Routine maintenance as recommended by manufacturers should be carried out only by trained personnel.

CONCLUSIONS

The main conclusions of this paper are as follows.

1. Available data strongly support the use of diesel equipment underground in coal mines for improved safety and productivity. Trolley wire haulage and other electric hazards could be avoided by using properly designed diesel equipment.
2. Nearly 50 years of historical experience provides no

evidence that operating diesel equipment in underground coal mines subjects mine workers to health risks, such as lung cancer.

3. All diesel engines for underground coal mines must be tested "as configured" using ISO 8-mode test in a certified laboratory and a "nameplate ventilation" should be specified to dilute the DPM to 0.5 mg/m^3.
4. A catalytic converter must be an integral part of all approved diesel engines.
5. If needed, a properly designed soot filter should be used on all inby and heavy-duty outby equipment.
6. Built in safety factors, such as duty cycles, effective ventilation and the decay of DPM in mine airways indicate that actual mine air DPM concentration will be much less than 0.5 mg/m^3. However, research must continue to develop an instrument for direct gravimetric DPM measurement in mine air.
7. Periodic performance tests by properly trained operators and routine maintenance by trained personnel must be carried out to ensure that approved diesel equipment continues to meet the laboratory standard of 0.5 mg/m^3.

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