CONTROL OF DIESEL EXHAUST EMISSIONS

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ABSTRACT

The operation of diesel engines releases both gaseous and particulate pollutants into the atmosphere. The control of these emissions is necessary to ensure a healthful work environment. Several components of the gaseous fraction of the emissions can be toxic, asphyxiating, or strongly irritating at low concentrations. Of all the pollutants in diesel exhaust, the particulate matter ranks among the most important to control. Diesel particulate matter is entirely respirable and contains adsorbed substances, some of which are known carcinogens.

This paper reviews conventional work practices and devices used to control diesel exhaust emissions and new control techniques being tested by the Bureau of Mines. New exhaust control techniques and devices may be necessary to meet future diesel particulate matter emission standards in underground coal mines. The development of future exhaust control devices is discussed in the context of ongoing industry/government cooperative research projects for Part 36 permissible equipment. Discussions of control devices include the waterbath and dry-type exhaust conditioners, conventional and developmental oxidation catalytic converters, ceramic-element and other particulate filters, and combinations of devices.

INTRODUCTION

The National Institute for Occupational Safety and Health recently declared that whole diesel exhaust should be regarded as a potential occupational carcinogen and that reductions in exposure would reduce the health risk. Diesel particulate matter emissions are of special concern because they are respirable in size and contain adsorbed hydrocarbons, some of which are known carcinogens (Anon., 1988). This fact was recognized by the Mine Safety and Health Administration's (MSHA) Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines which recommended that MSHA establish a diesel particulate matter exposure limit (Anon., 1988a). For the mining industry to comply with this and other health and safety standards, it is expected that new exhaust control technology will be required. The objective of the Bureau of Mines diesel research program is to develop and test new exhaust controls which will enable continued use of diesel power without compromising health or safety.

CONTROL OF DIESEL EXHAUST EMISSIONS

The Bureau began investigating the composition of diesel exhaust and the variables affecting composition in 1937. These studies recognized the hazards of using diesel equipment in confined spaces and pointed out the need to adequately ventilate mines and tunnels to avoid excessive exposure to asphyxiant gases such as carbon monoxide (CO). Research has continued, and the practical application of results has led to improved work practices.

Important Work Practices

Ventilation is necessary to dilute and purge exhaust emissions, as well as to replace oxygen consumed in the combustion process. Ventilation can generally reduce exhaust pollutants to acceptable levels under most circumstances.

Engine selection is important because diesel engine design and emission characteristics vary widely. The indirect injection (combustion chamber) engine is one of the lowest emission mobile power sources commercially available. This has long been recognized in the underground mining industry.

Engine deration lowers emissions by limiting the maximum fuel injection rate setting, thus ensuring excess oxygen for complete fuel combustion. This reduces emissions but also reduces power.

Engine maintenance keeps the balance between performance, durability, and emissions. Deviation from proper servicing methods and intervals will result in poor performance, higher emissions, and increased engine wear. Maintenance information in the service manual should be strictly followed by trained mechanics.

Table I shows the effects of engine faults on hydrocarbons (HC), CO, oxides of nitrogen (NO_x), and diesel particulate matter (DPM) emissions, with the increase above baseline given in percent. These faults are maintenance related and effectively change the engine's fuel-air ratio. For convenience, the percentage increases are given in groups, i.e., <50, 50 to 200, and >200. In general, engine faults increase pollutant concentrations in the exhaust. The level of emission caused by a pair of faults occurring individually, is not as severe as the level when the same faults are combined (Waytulonis, 1985).

Table I. Effects of Engine Faults on Exhaust Composition, Increase Above Baseline. Percent

Fault description	HC	CO	NO_x	DPM[1]
Intake restriction:				
25 in H_2O	<50	<50	<50	<50
50 in H_2O	<50	<50	<50	50-200
Exhaust restriction:				
3 in Hg	<50	<50	<50	<50
6 in Hg	<50	<50	<50	<50
Timing advance:[2]				
Minus 4°	>200	50-200	<50	>200
Plus 4°	50-200	<50	<50	<50
Plus 8°	50-200	<50	50-200	<50
Overfueling:				
10%	<50	50-200	<50	50-200
20%	<50	>200	<50	50-200
Combined faults:				
25 in H_2O intake restriction, minus 4° timing advance	50-200	<50	<50	50-200
50 in H_2O intake restriction, minus 4° timing advance	>200	50-200	<50	>200
25 in H_2O intake restriction, 10% overfueling	<50	50-200	<50	50-200
50 in H_2O in take restriction, 20% overfueling	<50	>200	<50	>200
10% overfueling and plus 4° timing advance	<50	50-200	<50	50-200
20% overfueling and plus 8° timing advance	<50	50-200	<50	>200
3 in Hg exhaust restriction and 10% overfueling	<50	50-200	<50	>200
6 in Hg exhaust restriction and 20% overfueling	<50	>200	<50	>200

[1]DPM production at most severe engine operating mode.
[2]Deviation from manufacturer's specification.

Fuel composition affects diesel emissions. Generally, increased cetane number and volatility (as indicated by the 90 pct distillation temperature) reduces CO and smoke. The most important fuel properties for low particulate emissions are the aromatic hydrocarbon and sulfur content. Reducing the aromatic content would reduce hydrocarbon emissions and the carbonaceous fraction of particulate emissions. Reducing fuel sulfur would reduce sulfur dioxide emissions and the sulfate fraction of exhaust particulate matter. This has the added benefit of reducing corrosive wear and would extend engine life. Low sulfur fuel is not widely available, but availability may increase in the future due to legislative actions taken by the Environmental Protection Agency to reduce particulate emissions on over-the-road diesels. Table II is a list of optimum property limits for good quality diesel fuel.

Table II. Optimum Property Limits for Good Quality Diesel Fuel.

Property	Limit
Cetane number	> 48
Aromatics	< 20 pct
90 pct distillation temperature	< 320° C
Sulfur	< 0.10 pct by mass

Fuel additives, such as barium- and calcium-based compounds, can be effective in small quantities in reducing smoke opacity. Bureau research has found that although smoke opacity can be reduced, total particulate emissions are frequently increased because carbonaceous particles are replaced with oxides and sulfates of barium and calcium (Zeller, 1987; 1990).

Keeping the engine clean and cool is essential. Dirt is very detrimental to engines. The diesel requires large volumes of air to function and regular maintenance of the engine's air induction system is necessary for peak performance and low emissions. One of the most common causes of excessive exhaust particulates and CO is intake air restriction caused by dust-saturated air cleaners, see Table I.

Overheating is a frequent cause of premature engine failures. Lubrication oil of the correct viscosity must be kept at the proper level and all radiators or heat exchangers must be kept free of accumulated dirt and open to circulating air.

Idling engines for long periods wastes fuel, overcools the engine which hastens wear, and pollutes the air. Engines should be shut down if idling is expected to exceed 5 minutes.

Lugging or operating the engine at high load and low speed significantly increases CO and particulate emissions, and engine temperature. Operators should shift gears to run the engine at a higher rotational speed, or lessen the load, rather than lug the engine.

Overpowering caused by fuel system tampering should not be tolerated. Changing the calibration of the fuel pump or installing larger capacity injectors results in greater pollutant production and possible engine damage, see Table I.

Watch for black smoke because in a confined environment it is a dangerous condition due to the accompanying high CO and respirable particulates. Machines emitting black smoke should be taken out of service (Waytulonis, 1987).

Current Exhaust Aftertreatment

The following exhaust aftertreatments are currently used to reduce, modify or disperse exhaust emissions:

Tailpipe location is a straightforward technique to avoid exposure of miners to raw exhaust by dispersing it immediately upon exiting the tailpipe. This can be accomplished by directing the exhaust-gas into the moving air from the radiator fan. Another dispersion technique in dead-end headings can take advantage of the exhaust's natural buoyancy. By directing the exhaust upward and to the rear at about a 20 to 30 degree angle to horizontal, operator exposure to exhaust can be reduced.

Additionally, a fume diluter can be connected to the tailpipe to dilute and direct exhaust away from the operator. This device emits a jet of cool diluted exhaust at high velocity and promotes mixing with surrounding air.

Waterbath exhaust conditioners, used on Part 36 (permissible) equipment, are intended to provide cooling and protection from flames, sparks, or backfires from reaching gassy atmospheres. They are sometimes referred to as "water scrubbers" due to their removal of some particulates and sulfates. Exhaust conditioners must be regularly flushed and replenished with water to perform these functions.

Oxidation catalytic converters, used on non-permissible equipment, oxidize some exhaust constituents and render them less toxic. Figure 1 shows a typical installation of a catalytic converter on a non-permissible load-haul-dump mining machine. The effectiveness of catalytic converters is dependent on their operating temperature, fuel quality, and catalyst formulation and configuration. As shown in Table III, the positive effects of conventional catalysts are to reduce CO, HC, and aldehydes (associated with odor). Negative effects are their tendency to increase nitrogen dioxide emissions, and, depending on the fuel sulfur content, promote the conversion of sulfur to sulfur oxides and sulfuric acid.

Table III. Effects of Current Commercial Oxidation Catalytic Converters on Some Exhaust Constituents

Constituent	Percent Change
Carbon Monoxide	- 40 to - 90
Hydrocarbons	- 2 to - 70
Aldehydes	up to - 55
Nitrogen Dioxide	up to + 25
Sulfate	+ 10 to > 1000

The use of conventional catalytic converters is generally not recommended unless they are used on machines that operate under a sustained moderate to heavy-duty cycle; i.e., with exhaust temperatures 200° C or greater, and with low sulfur fuel (McClure, 1988).

Future-Exhaust Aftertreatment

Diesel research projects are underway in an effort to reduce exhaust pollutants to levels lower than conventional techniques can achieve. Emphasis is on reduction of particulate matter emissions.

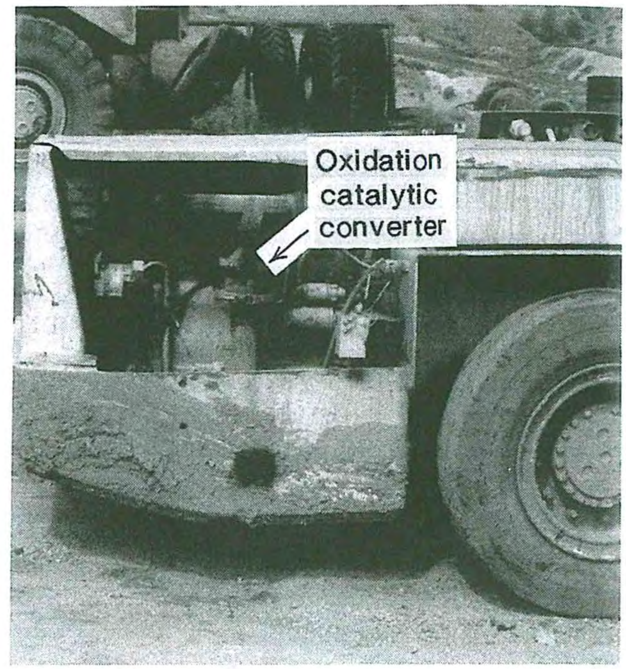

Figure 1. Typical Installation of an Oxidation Catalytic Converter on a Non-Permissible Load-Haul-Dump Mining Machine

Diesel-exhaust particulate matter is composed of three primary constituents: a carbonaceous fraction, a soluble organic fraction (SOF), and oxides (primarily oxides of sulfur). The formation of carbon particles is inherent in the combustion process and they form the nucleus upon which the SOF condenses. The SOF is important because this fraction contains organic hydrocarbons that are a suspected health threat (Anon., 1988). The oxides of sulfur originate from the sulfur contained in the diesel fuel. No single control method is effective in removing all three constituents, however, methods are being pursued to reduce them individually.

The wall-flow (ceramic) diesel-particulate filter is a square cell shaped honeycomb with parallel channels running the length of the unit. The body of the structure is a porous cordierite which has the necessary mechanical strength, chemical resistance, thermal fracture resistance, and melt resistance to survive effectively in the hostile environment of diesel engine exhaust.

Ceramic wall-flow filters are being used on selected heavy-duty diesel vehicles in noncoal mines (Dainty, 1988) and figure 2 shows a typical installation on a non-permissible mining machine. Bureau research is ongoing to expand the use of the wall-flow particulate filter to coal mine equipment (Watts, 1989).

Ceramic wall-flow filters are 80 to 95 pct efficient in removing particulate mass from the exhaust. The successful application of diesel-particulate filters (DPF) in underground coal mines depends on their ability to store the collected soot over a useful operating period without creating excessive backpressure or surface and exhaust temperatures which could jeopardize mine safety. Heavy-duty vehicles that consistently generate exhaust temperatures 500° C or higher, are the first candidates for DPF technology. Vehicles with moderate or light-duty cycles will require a method to supply heat to burn-off the soot (regenerate the filter). Methods to elevate the exhaust temperature include use of an onboard heater, exhaust gas restriction, intake air restriction, or catalytic fuel additives. Regeneration can also be assisted by using a catalyst coating on the ceramic substrate which lowers to the regeneration temperature to about 400 to 420° C.

Controlling the rate of particulate burn-off in the filter can be a problem under some operating conditions. It can result in cracking or melting of the ceramic substrate causing unsafe operating conditions. During uncontrolled regeneration, high filter surface and exhaust temperatures, and high CO emissions result. However, if engine backpressure is kept below the recommended maximum, uncontrolled regeneration is not likely. It is therefore necessary to mount a backpressure sensor upstream of the filter to signal excess exhaust backpressure and remedial action.

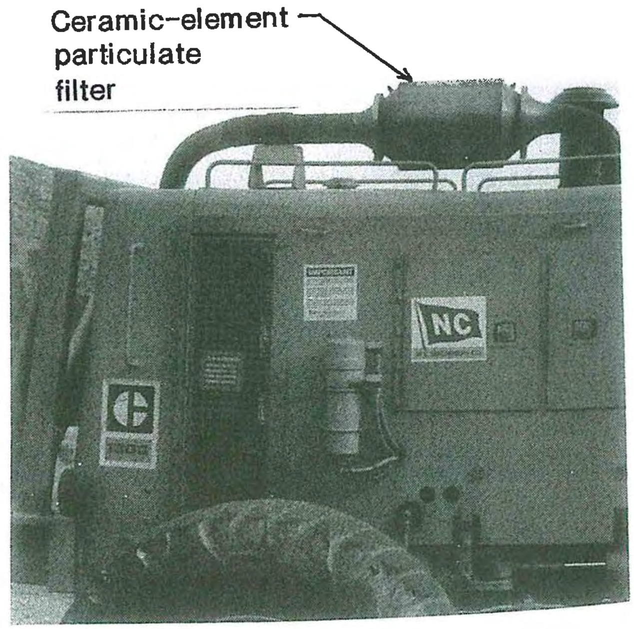

Figure 2. Typical Installation of a Wall-Flow (Ceramic-Element) Particulate Filter on a Non-Permissible Mining Machine

The (ceramic) fiber-coil particulate filter consists of a bundle of sheet metal support tubes with one end closed, around which threads of ceramic fibers are wound crosswise. The threads are made of endless, highly heat-resistant ceramic fibers which are twisted together. The preferable materials are silicon dioxide or aluminum silicon oxide. The exhaust gas flows from the outside through the windings into the support tubes, thereby depositing particulate matter on the fibers. (Hardenberg, 1987).

The advantage of the fiber coil over the wall-flow particulate filter is that it is relatively insensitive to thermal and mechanical stress. Importantly, an electric heating element can be integrated into the fiber mat and used to induce regeneration, thus greatly reducing the chance of uncontrolled regeneration. The disadvantages when compared to the wall-flow filter are lower soot loading capacity and efficiency (approximately 70 pct). Because this technology has very recently become available for exploitation, the Bureau plans to evaluate it for applications in mining.

Pleated-(fiber) element particulate filters are very similar to the pleated element intake air filters used on diesel engines. The fiber media can be treated paper or synthetic material, and is disposable.

Tests of a pleated-filter media have recently been completed in cooperation with the Donaldson Co. and Utah Fuel Co. The exhaust systems of four diesel machines were modified with the addition of the pleated-element particulate filters. Figure 3 shows this disposable particulate filter installed downstream of the waterbath exhaust conditioner on a Jeffrey 4114 Ramcar. Installation at this location is intended to negate any effects of the filter on the machine's MSHA-approved permissibility system.

The reduction of exhaust particulate matter resulting from the use of the pleated media was measured using size-selective sampling instrumentation. Preliminary analysis of the test data from the ventilation return indicate that diesel-generated submicron aerosol was reduced an average of 95 ± 4 pct over a 1-week period. Average filter life was 1 shift and cost is about $50 each. Although the pleated media has been shown to be highly effective in reducing diesel exhaust particulate matter, further development and tests are expected to identify filter media that is nearly as efficient and longer lasting.

The dry exhaust conditioning system may be a low-maintenance alternative for waterbath exhaust conditioners and development is ongoing. The dry-type exhaust conditioner dissipates waste heat from the exhaust with a closed-circuit heat exchanger, and a mechanical flame arrester is used. This concept does not require direct contact between the exhaust gas and water, thus it has the potential for controlling fire hazards and requiring less maintenance than waterbath conditioners (Bickel, 1987).

Integrated control systems with ceramic particulate filters must meet Part 36

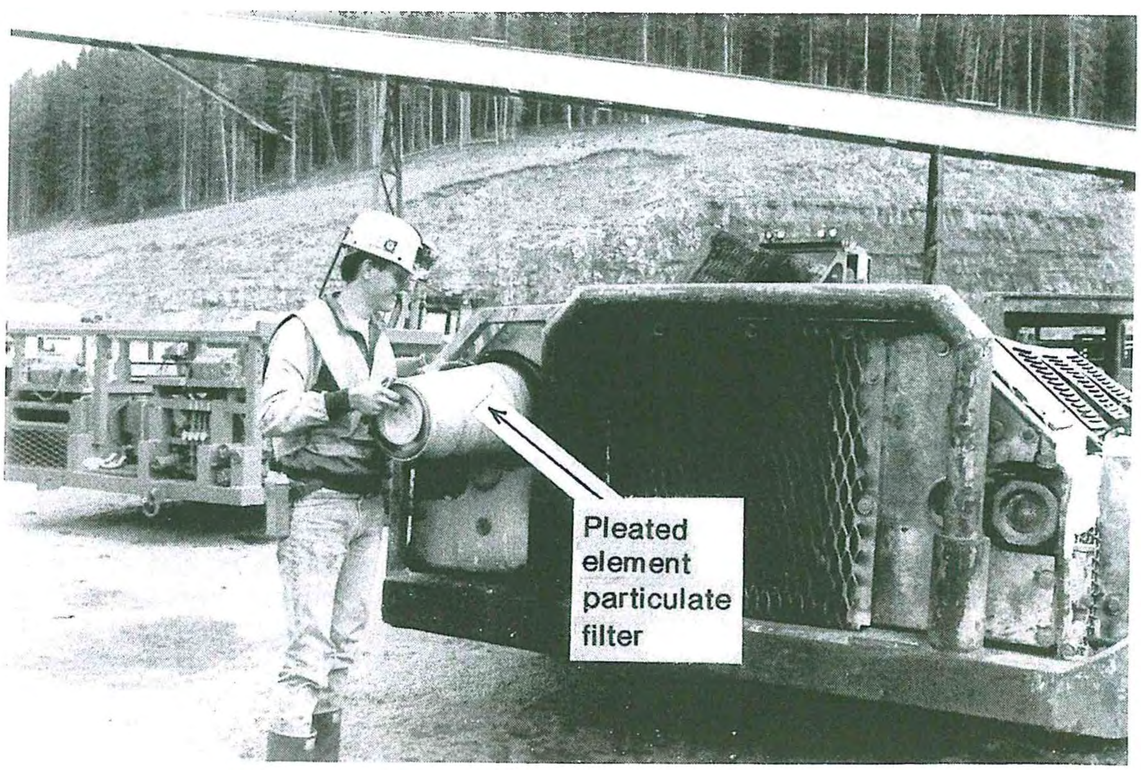

Figure 3. Prototype Installation of the Pleated-Element Particulate Filter on a Permissible Coal Hauler

surface temperature requirements (150° C) and the consequences of a potentially uncontrolled regeneration must be contained. Two types of integrated control systems for coal mines are being jointly developed by the Bureau and the mining industry. These are a combination of the: 1) wall-flow ceramic filter and conventional waterbath and 2) wall-flow ceramic filter and dry exhaust conditioning system.

Both systems incorporate a water jacket on the filter to limit surface temperatures but use different devices to lower the exhaust temperature and control flames and sparks. The approach to these developments includes laboratory tests of the individual components and combined system to determine effectiveness, approval testing by MSHA to Part 36 requirements, in-mine trials to determine performance and durability, and laboratory retesting to determine the effects of in-use conditions on performance and durability.

The first system, shown in figure 4, uses a conventional waterbath exhaust conditioner downstream of the ceramic filter. Two prototype water-jacketed wall-flow filters were built by Engine Control Systems, Ltd., but both filters did not function due to design deficiencies. Once a working water-jacketed filter is demonstrated, it will be installed on a Jeffrey 4114 Ramcar and evaluated in-service in an underground coal mine in Utah. In high-altitude applications such as this, achieving adequate oxygen concentration and temperature of the exhaust will be critical for filter regeneration.

In the second system, the waterbath is substituted with a dry exhaust conditioning system. Bureau laboratory tests of an early prototype (built by Engine Control Systems, Ltd.), showed that particulate emissions can be reduced up to 97 pct with little change in gaseous emissions (Waytulonis, 1988). Two problems encountered during these tests were that the backpressure and exhaust temperature limits were exceeded when the engine was operated at rated speed and load. This was a result of excess accumulation of soot within the heat exchanger. Additionally, the system did not pass MSHA spark trapping tests (Watts, 1989).

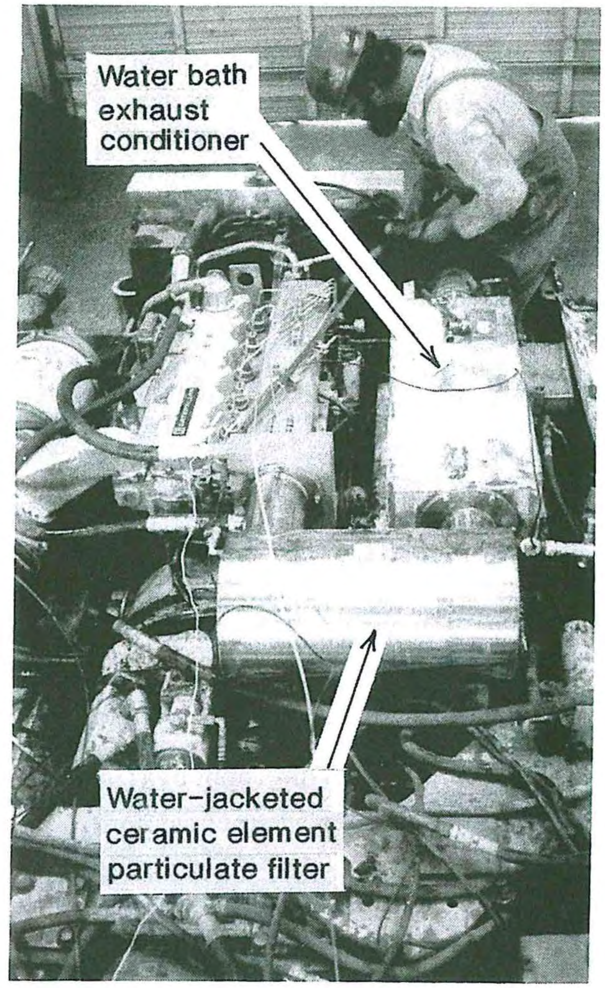

Figure 4. Prototype of the Integrated Wall-Flow (Ceramic-Element) Particulate Filter with Waterbath Exhaust Conditioner on a Permissible Coal Hauler

Developmental oxidation catalytic converters using new catalyst formulations that may not have the negative effects of current catalysts are being tested in cooperation with the Engelhard Corporation. New formulations are being evaluated for their ability to reduce the SOF of particulate emissions, and to oxidize CO and HC to carbon dioxide and water vapor. The catalysts are foreseen to be used as stand-alone exhaust purifying devices when used with low sulfur fuel. Additionally, when impregnated on a ceramic particulate filter, the catalyst will tend to burn off the collected soot at a lower temperature, promoting continuous filtration without supplemental cleaning.

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