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REPORT OF INVESTIGATIONS/1989

Control of Diesel Particulate Matter in Underground Coal Mines

By W. F. Watts, Jr., K. J. Baumgard, B. K. Cantrell, and K. L. Rubow

BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	m^3/min	cubic meter per minute
cm	centimeter	mg/m^3	milligram per cubic meter
cm^2	square centimeter	min	minute
g	gram	μm	micrometer
h	hour	N·m	Newton meter
h/d	hour per day	Pa/h	pascal per hour
in	inch	pct	percent
kW	kilowatt	rpm	revolution per minute
kPa	kilopascal	s	second
L/min	liter per minute		

CONTROL OF DIESEL PARTICULATE MATTER IN UNDERGROUND COAL MINES

By W. F. Watts, Jr.,[1] K. J. Baumgard,[2] B. K. Cantrell,[3] and K. L. Rubow[4]

ABSTRACT

The U.S. Bureau of Mines has conducted research on methods to reduce and to measure diesel particulate matter (DPM) aerosols in underground coal mines. One objective of this report is to present findings from an investigation of the DPM reductions obtained by an engine-mounted integrated control system consisting of a dry system (DS) and a diesel particulate filter (DPF). Another objective is to present results from the use of a size selective personal sampler to measure DPM concentrations in an underground coal mine.

Bureau laboratory tests of the integrated dry system and diesel particulate filter (DS-DPF) have shown that DPM emissions can be reduced up to 97 pct with little change in gaseous emission concentrations. The DS-DPF is undergoing certification tests conducted by the Mine Safety and Health Administration (MSHA). Subsequent to passing all safety requirements, it will be tested in an underground coal mine.

A baseline survey of DPM concentrations and aerosol size distributions in a cooperating mine was completed in August 1988. A prototype DPM personal sampler was tested during this survey. Based on results from this test, an improved unit has been developed. This unit is scheduled for extensive field testing by MSHA in 1989.

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INTRODUCTION

A miner working in an underground mine with diesel equipment is exposed to a wide array of pollutants in the diesel exhaust. These include CO, CO_2, NO, NO_2, SO_2, DPM, and a variety of hydrocarbon (HC) compounds. A quantitative definition of the health risk resulting from these exposures remains elusive, but during the past several years progress has been made in defining the problem. Results from epidemiological, animal inhalation, and in vitro studies have provided sufficient data for the National Institute of Occupational Safety and Health (NIOSH) to classify diesel exhaust as a potential human carcinogen. There is still uncertainty about the magnitude of the health risk and about the maximum level of exposure that should be established for DPM.

HEALTH CONCERNS

Diesel exhaust contains noxious gases and DPM. A partial list of the more common exhaust components and the underground mine air quality standards are shown in table 1.

Table 1.–Common pollutants[1] found in diesel exhaust and standards used in underground coal and noncoal mines, parts per million

Pollutant	Noncoal		Coal	
	FSEL	STEL	FSEL	STEL
CO	50	400	50	400
CO_2	5,000	15,000	5,000	30,000
NO	25	37.5	25	NAp
NO_2	NAp	5	3	5
SO_2	5	20	2	5

FSEL Full-shift exposure limit.
STEL Short-term exposure limit.
NAp Not applicable.
[1]DPM is also a pollutant, but no standards for exposure have been established at this time.

DPM is of particular concern because it is almost entirely respirable in size, with more than 90 pct of the particles by mass, having a mass median diameter (MMD) less than 1.0 μm. This means that the particles can penetrate to the deepest regions of the lungs and, if retained, cause or contribute to the development of obstructive or restrictive lung disease. Of even greater concern is the ability of DPM to adsorb other chemical substances such as mutagenic polynuclear aromatic HC's, and gases such as SO_2 and NO_2, and acids such as H_2SO_4 and HNO_3. DPM acts as a carrier to bring these substances into the lungs where they may leach to other regions of the body and cause problems (*1*).[5] Solvent extracts of DPM have repeatedly demonstrated the presence of mutagens (*2-4*).

Animal studies suggest chronic exposure to DPM can cause impaired pulmonary function, reduced growth rate, increased susceptibility to lung infections, and decreased clearance of lung particulate matter. Recent studies (*5-7*) have shown increased rates of cancer in exposed animals. The increased incidence of lung tumors has occurred when the animals have been exposed to at least 3.5 mg/m^3 of DPM in dilute diesel exhaust for at least 7 h/d, 5 days per week, for 30 months.

A recent epidemiological study (*8*) of deaths among U.S. railroad workers found that occupational exposure to diesel exhaust slightly increased the risk of lung cancer.

In response to these studies, NIOSH recently recommended (*9*) that "whole diesel exhaust be regarded as a 'potential occupational carcinogen,' as defined in the Cancer Policy of the Occupational Safety and Health Administration." NIOSH further stated that "though the excess risk of cancer in diesel-exhaust-exposed workers has not been quantitatively estimated, it is logical to assume that reduction in exposure to diesel exhaust in the workplace would reduce the excess risk." MSHA has also been directed by an advisory committee to establish a DPM standard and to establish regulations to minimize exposure to diesel pollutants in underground coal mines (*10*).

DPM CONTROL IN UNDERGROUND MINES

The Bureau has tested various types of emission controls to reduce DPM concentrations at the tailpipe. These controls include catalyzed and uncatalyzed DPF's, fuel additives, water scrubbers, and catalytic converters. The most promising device to control DPM was determined to be the DPF. Research by the Bureau (*11*) and others (*12-14*) has shown that the DPF has a particle collection efficiency from 85 to 95 pct. The DPF is currently being evaluated in Canada on equipment used in underground, nongassy, noncoal mines (*15*).

The DPF is placed in the exhaust stream as close as possible to the exhaust manifold. When the DPF is sufficiently loaded with DPM, and the engine is operated so that the exhaust temperature is about 510° C, the collected DPM ignites and burns in a process called regeneration. The DPF will not completely regenerate unless the vehicle has a period (10-15 min) of sustained high exhaust temperature. Regeneration may be assisted by elevating the exhaust temperature with an onboard heater, exhaust gas restriction, intake restriction, or by lowering the regeneration temperature by using fuel additives or a catalyzed DPF. Alternatively, the DPF can be regenerated off board the vehicle using a remote heating device. DPF's are designed to require regeneration after an 8-h work-shift, but the actual length of service is dependent upon the duty cycle and other factors (*11*).

There may be a problem under some operating conditions with controlling the rate of DPM burnoff. Uncontrolled regeneration may result in cracking or melting of the ceramic substrate causing unsafe operating conditions. During uncontrolled regeneration, high DPF surface and

[5]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

exhaust temperatures and high CO emissions result. However, if engine back pressure is kept below the recommended maximum, uncontrolled regeneration is not likely to occur (*11*).

In order to permit DPF's to be used safely in coal and gassy metal and nonmetal mines, an integrated control system was developed and is being tested by the Bureau with cooperation from the mining industry (*16*). A comprehensive approach was adopted to evaluate the integrated system. The approach includes laboratory tests of the individual components and combined system to determine safety and control effectiveness, certification testing by MSHA to permit use of the system in underground coal mines on face haulage equipment, field trials to determine performance and durability, and postlaboratory testing to determine the effects of in-use conditions on performance. One objective of this report is to present results from the Bureau's laboratory tests of the integrated control system.

This system combines a DS, which replaces the water scrubber, with a DPF to simultaneously control fire and explosion hazards and reduce DPM emissions (*17*). A key feature is the placement of the DPF downstream of the DS so that only cool exhaust passes through the DPF, thus the potential for uncontrolled DPF regeneration is eliminated. However, the DPF must be regenerated off board the vehicle because exhaust passing through the DPF is limited to temperatures below 150° C by the DS.

SIZE SELECTIVE DPM MEASUREMENT

Another objective is to present results from the use of a size selective personal sampler to measure DPM concentrations in an underground coal mine. Size selective aerosol sampling can be used to separate submicrometer DPM from mechanically generated mineral aerosols, which are predominantly supermicrometer (>1 μm) in size. It has been shown in the laboratory (*18*) and in underground field tests (*18-22*) that inertial impaction can be used to separate these two fractions, and provide estimates of DPM concentrations that are accurate within 10 pct. Based on the success of this method, a simple two-stage sampler with size separation at 0.8 μm is being developed by the University of Minnesota and the Bureau (*21*) for routine monitoring of DPM in coal mines. This sampler will allow personal exposure to DPM to be determined. Size selective sampling will also allow the performance of the DS-DPF emission control technology to be evaluated during underground field tests scheduled for 1989.

LABORATORY TESTS FOR EVALUATING DS-DPF

All engine tests were conducted in the Diesel Engine Research Laboratory at the Bureau's Twin Cities Research Center, which was described in detail in reference 11. A Caterpillar[6] 3306 naturally aspirated, prechamber diesel engine rated at 112 kW at 2,200 rpm was used for all tests. The engine intake air was controlled to Society of Automotive Engineers (*23*) standard conditions of 100 kPa and 25° C using an O_2 control system described previously (*24*).

The engine was coupled to an eddy-current dynamometer and controlled by a computer that regulated engine speed and load to within 1 rpm and 1.4 N·m torque. The computer also recorded various parameters such as speed, load, fuel rate, temperatures, pressures, and gas emissions. Figure 1 shows a schematic diagram of the engine test cell along with the placement of various sensors.

A schematic of the engine and DS-DPF are shown in figure 2. The DS consists of (1) a lube oil reduction device designed to remove oil particulate, which forms hard deposits on the cooling fins; (2) a fin and tube heat exchanger, which uses the engine's coolant to dissipate the exhaust heat; and (3) a parallel-plate flame trap to ensure no flames pass to the atmosphere if an engine backfire should occur.

The exhaust gas exits the DS and passes through the DPF, which consists of Corning EX 47 ceramic material that has a mean pore size of 12 μm, porosity of 50 pct, and 15 cells per square centimeter (*13*). The 38- by 36-cm cylindrical substrate can accommodate volume flow rates up to 29 m^3/min and can collect approximately 240 g of DPM before regeneration is required. During laboratory tests, regeneration was accomplished off board the engine using a portable diesel-fueled burner. Regeneration was accomplished in about 15 min.

After passage through the DPF, approximately 3 pct by mass of the exhaust was diverted into the primary dilution system illustrated in figure 1. The dilute sample was obtained by placing a 2.54-cm-diameter sample line between the exhaust pipe and a 15-cm dilution tunnel. A 1.04-cm orifice was placed in this line, and the pressure drop and temperature were measured so that the actual exhaust flow rate could be calculated. The dilution airflow was determined by measuring the pressure drop and temperature across a laminar flow element. These flows were corrected to standard conditions and the dilution ratios determined. Dilution ratios, which were around 25:1, were verified by measuring oxides of nitrogen (NO_x) concentrations in the raw and diluted exhaust and determining the ratio.

Particle mass measurements were obtained using a high-volume sampler, which collected DPM on 20- by 25-cm Pallflex TX40HI20-WW glass fiber filters. All mass measurements made after the DPF required prolonged sampling times of 2 to 6 h, thus fewer replicates were possible. Exhaust gas emissions were measured using Beckman model 864 nondispersive, infrared analyzers for CO and CO_2, a Beckman model 955 chemiluminescence

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

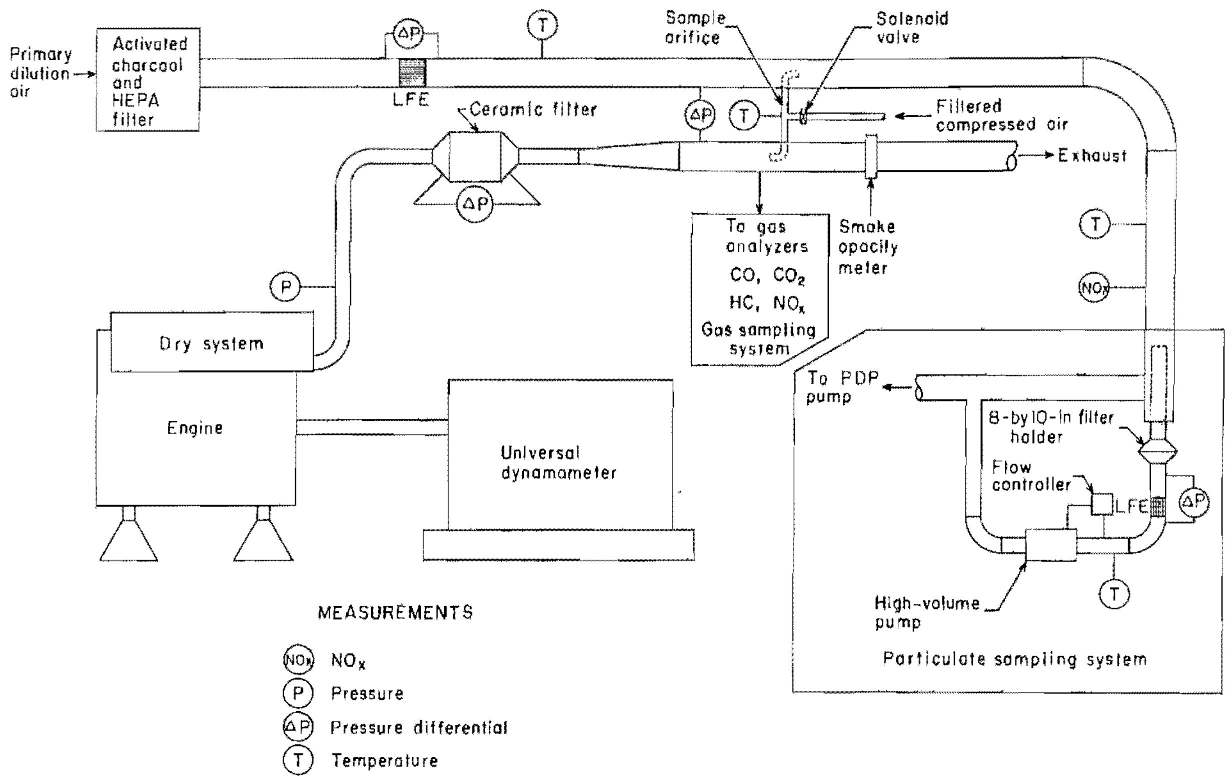

Figure 1.-Schematic diagram of engine test facility.

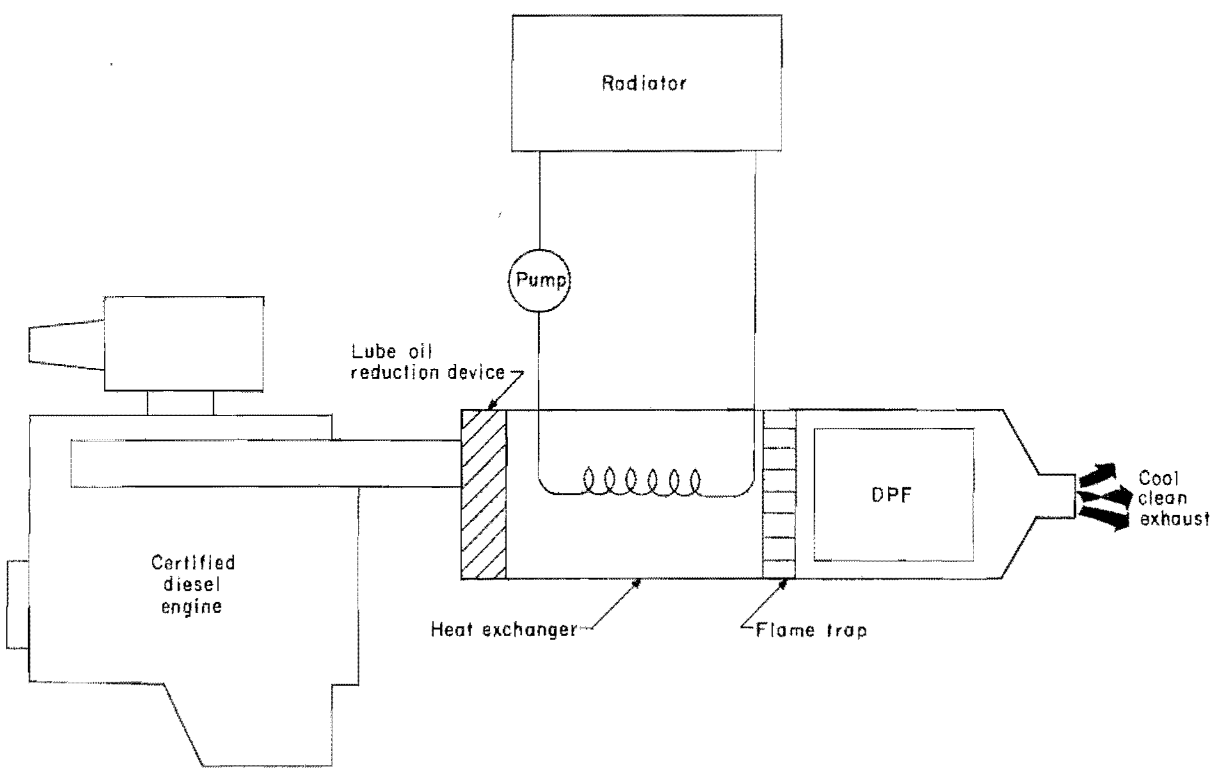

Figure 2.-Engine and DS-DPF.

analyzer for NO_x, a Beckman model 402 heated flame ionization analyzer for HC's, and a Beckman model OM-11 oxygen analyzer for O_2.

Size distributions were obtained by passing aerosol samples withdrawn from the primary dilution tunnel just below the NO_x probe (fig. 1) through a micro-orifice uniform deposit impactor (MOUDI). The MSP Corp. model 100 MOUDI is a 10-stage inertial impactor that classifies the particles by their aerodynamic diameter (*20*). The cutpoints for the 10 stages of the MOUDI are 15.0, 10.0, 5.6, 3.2, 1.78, 1.0, 0.56, 0.32, 0.178, and 0.10 μm.

PROCEDURES

A new 112-kW, prechamber, naturally aspirated Caterpillar 3306 engine was broken in by operating the engine for about 100 h at various speeds and loads over a specific break-in cycle. In order to fully understand the effect the DS-DPF has on diesel emissions, the experimental protocol was divided into four tasks or test configurations (table 2).

Table 2.–Tasks for evaluating DS-DPF

Task	Description	Designation
1 . . .	Test with no controls	Baseline.
2 . . .	Test with DPF using hot exhaust . .	DPF.
3 . . .	Test with dry system only	DS.
4 . . .	Test with dry system and DPF	ICS.

During each task, the engine was operated at both steady-state and transient conditions. The two steady-state modes produced the extremes in types of DPM emitted from a properly maintained engine. Mode 1 was rated speed, 50 pct load; mode 2 was peak torque speed, 100 pct load. Mode 1 has exhaust temperatures around 260° C and a high soluble organic fraction, while mode 2 has exhaust temperatures around 540° C and DPM with a high carbon fraction.

The majority of tests conducted for each task were transient tests using a research duty cycle developed by the Bureau to represent many of the conditions the vehicle experiences in the mine. One cycle has a duration of 8 min and consists of 13 modes, varying in time between 25 and 55 s. An actual time trace of speed and load is shown in figure 3.

During baseline testing, the duty cycle was repeated three times and data were collected on cycles 2 and 3 to complete one test. This test was repeated 16 times. When the DPF was tested the cycle was repeated 21 times in order to obtain sufficient mass on the 20- by 25-cm collection filter. This test was repeated twice for each mode. The durability tests consisted of operating the engine over the research duty cycle in 2-h increments and collecting data over the last three cycles. After every 8 h, the flame trap was removed and steam cleaned. This enabled a data point to be obtained every 2 h. A total of 32 h was accumulated on the system. The DS-DPF was evaluated under the same conditions for an additional 22 h for a total of 54 h of durability tests.

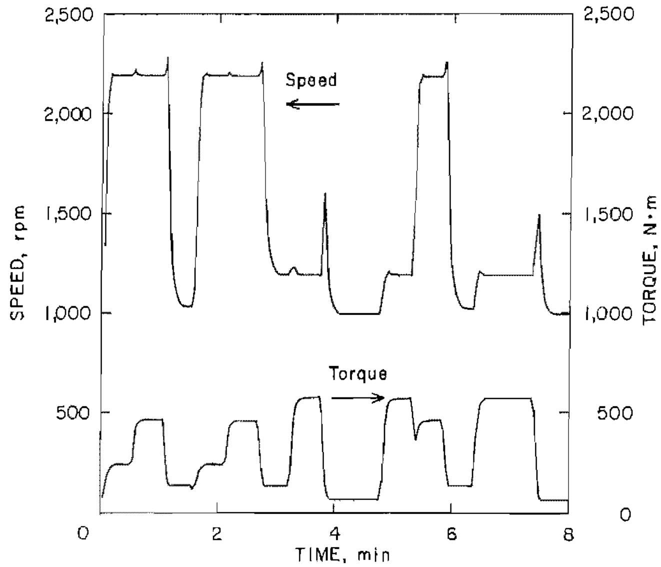

Figure 3.–Time trace of research transient cycle.

RESULTS

DPM

Table 3 shows the total DPM concentrations for the four different test configurations (table 2). The exhaust concentration after the DS-DPF varied from 2.2 to 3.8 mg/m³. In a mine, the exhaust is typically diluted by a factor of 200 and therefore, the in-mine dust concentrations from the controlled diesel vehicle would be around 0.01 mg/m³ (*25*). The average mass collection efficiency was 93 pct for the DPF, 45 pct for the DS, and 97 pct for the DS-DPF.

Table 3.–Effect of exhaust controls on DPM concentration and DPM bound volatile concentration, milligrams per cubic meter

Test condition	Baseline	DPF	DS	ICS
DPM CONCENTRATION				
Transient test . . .	86	9.8	49	2.2
Steady state:				
Mode 1	144	13.5	73	3.8
Mode 2	133	8.1	76	2.2
DPM BOUND VOLATILE CONCENTRATION				
Transient test . . .	10.6	4.4	4.0	NA
Steady state:				
Mode 1	17.0	6.9	2.2	2.2
Mode 2	7.1	3.7	NA	1.9

DPF Diesel particulate filter.
DS Dry system.
ICS Integrated control system (DS-DPF).
NA Not available.

Table 3 also shows the DPM bound volatile concentrations for each of the four test configurations. The volatile portion, measured by vacuum sublimation, is important because this is where much of the mutagenic material is found. The average volatile collection efficiencies are 55 pct for the DPF, 74 pct for the DS, and 80 pct for the DS-DPF. The DS and DS-DPF have higher removal efficiencies than the DPF alone because the process of cooling the exhaust forces a larger percentage of volatiles to condense or adsorb onto the carbon particles before the carbon particles are collected.

Data from the MOUDI are shown in table 4. MOUDI samples were collected at each of the four test conditions and the masses for each stage were summed before analyzing the data because of the small amount of mass collected on each stage. This averages the weighing errors. The upper two stages from the MOUDI (cut size 15.0 and 10.0 µm) were not used in the analysis because particles of this size are typically those that have become reentrained from the exhaust pipe wall and cause random noise in the data analysis.

Baseline data measured by the MOUDI indicated 84 pct by mass was submicrometer, which is typical of uncontrolled diesel exhaust (*13*). The percent of submicrometer DPM measured after the controls varied from 62 to 71 pct. The nuclei mode (particles less than 0.056-µm diameter) appeared when the DPF only was evaluated. This agrees with previously published results (*13, 26*), which identified very fine particles being formed downstream of the DPF during certain engine operating conditions. The fine mode MMD was fairly constant for all conditions varying from 0.11- to 0.16-µm diameter, while the coarse mode varied from 1.4 to 5.3 µm. The coarse mode data after the DPF consist mainly of particles that have become reentrained from the exhaust pipe and dilution tunnel walls causing considerable noise in the coarse mode size distribution parameters. This sampling artifact occurs at all conditions, but is magnified after the DPF because of the long sampling times required to obtain sufficient mass for weighing.

It was expected that the size distribution of the particles after the DS would increase in size over time because DPM deposits on the cooling fins and agglomerates, and eventually these deposits break off and become reentrained in the exhaust stream. However, this reentrainment was not evident from the data. The DS was operated for 32 h, and during this time the collection efficiency was very constant at 42 pct and the size distributions did not change significantly. This indicates that diesel particles are difficult to remove in the DS and will require some sort of cleaning system to periodically clean the cooling fins.

Back Pressure

The major problem with the DS was excessive back pressure. The maximum observed back pressure during the transient cycle after 54 h of operation was 16.9 kPa with the DS-DPF in place. The initial back pressure was about 9.9 kPa, which exceeds the manufacturer's recommended maximum back pressure of 8.0 kPa. Back pressure steadily increased during the test period. After every 8 h of operation, the flame trap and/or DPF was removed and cleaned. (The DPF was added to the DS after 32 h of operation.) The rate of pressure buildup was 75 Pa/h across the DS and 124 Pa/h across the DPF, which gave a total buildup rate of 199 Pa/h for the DS-DPF. The manufacturer was notified of these results and is considering alternatives to alleviate this problem.

Table 4.–Laboratory MOUDI size distribution data for fine and coarse modes

	Baseline	DPF	DS	ICS
Samples combined for analysis	6	2	6	2
Concentration:				
Total . . . mg/m^3	54.5	8.2	44.7	0.7
Submicrometer . . . mg/m^3	46.0	5.1	31.3	0.5
Nuclei . . . mg/m^3	<0.000	2.98	<0.000	<0.000
Submicrometer portion . . . pct	84	62	70	71
Fine mode:				
Mass median diameter . . . µm	0.11	0.15	0.14	0.16
Geometric standard deviation	2.0	3.0	2.9	2.5
Coarse mode:				
Mass median diameter . . . µm	1.4	5.3	2.6	2.3
Geometric standard deviation	2.0	1.4	2.2	2.3

DPF Diesel particulate filter.
DS Dry system.
ICS Integrated control system (DS-DPF).

Exhaust Temperature

The DS-DPF was effective at cooling the exhaust to below the regulated temperature during the transient test (fig. 4). The upper curve is the exhaust temperature at the inlet to the DS and the lower curve is the temperature at the DPF outlet. The inlet to the DS had peaks around 425° C, but the outlet from the DPF was fairly constant at about 110° C. The DPF has a large thermal mass causing the outlet temperature to be fairly constant over the transient cycle. However, during one test, the engine was operated at rated speed and load for 30 min. Throughout this time the exhaust temperature steadily increased and after about 25 min exceeded the 150° C limit imposed by MSHA. To solve this problem, the manufacturer developed an automatic cleaning system that senses the exhaust temperature. If the temperature approaches 150° C, the system automatically injects water into the DS. As the water turns to steam, it expands causing some of the DPM from the cooling fins to be removed and the exhaust temperature quickly returns to about 110° C.

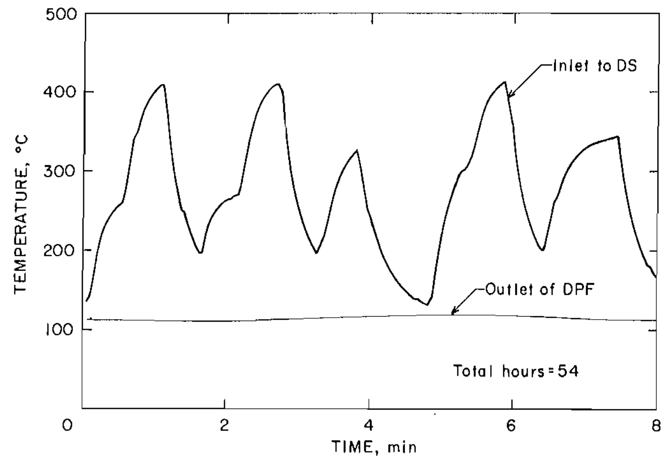

Figure 4.–Effect of DS-DPF on exhaust temperature.

FIELD STUDY FOR EVALUATING DS-DPF

An underground coal mine in Utah is cooperating as a field site for testing the DS-DPF on face haulage equipment. In August 1988, a team of scientists from the University of Minnesota, Michigan Technological University, and the Bureau spent 1 week at the mine gathering baseline environmental data. Prior to the trip, the Caterpillar 3306 engine used in the DS-DPF laboratory tests was installed in a Jeffrey 4114 RAMCAR designated by the mine as R-2. The DS-DPF will be installed on R-2 once certification is received from MSHA. A second field trip will be made to determine the effects of the DS-DPF on air quality. Finally, after the DS-DPF has been operating for several months, it will be removed and retested in the laboratory to determine if performance was affected by service in the mine.

EXPERIMENTAL PROCEDURES

Baseline size differentiated aerosol samples were collected using MOUDI's located at the mine portal, the intake to a room-and-pillar continuous miner section, and in a haulageway one crosscut downwind from the feeder breaker and belt. Three to four RAMCAR's operated per shift and the haulageway sampling site was located at the point where the RAMCAR's turned around to dump their loads. A dichotomous sampler was used to collect aerosol for the elemental analysis used in referee chemical mass balance (CMB) model calculations to be reported in a subsequent paper. The samplers and CMB analysis are described elsewhere (*18, 21*). The MOUDI's and dichotomous samplers were operated at a flow rate of 30 L/min.

Personal DPM samplers described elsewhere (*21*) were located at the intake and feeder breaker site, and personal samples were collected on RAMCAR operators and a Bureau scientist. High-volume samplers operated at 1.13 m^3/min with size selective heads were also located at the two stationary sampling points. The high-volume samplers were used to collect submicrometer aerosol for chemical characterization and biological analysis (Ames test). This work is being conducted by Michigan Technological University under sponsorship of NIOSH and will be reported upon in detail in a subsequent paper.

The majority of the area aerosol samples were collected periodically at the intake and haulage locations during each 10-h-work-shift. For the most part, these samples were collected only when coal was being mined. As a result these samples may not be representative of time-weighted average exposure for the work-shift. The personal DPM samplers placed on individuals were operated continuously.

FIELD TEST RESULTS

Average aerosol size distributions obtained from the MOUDI samples collected at the portal, intake, and haulageway are shown in figure 5. The plots are of the impactor defined, size interval concentrations plotted as the change in concentration and/or the change in log particle diameter. The scales increase from 0.4 mg/m^3 for the portal distribution to 2.0 mg/m^3 for the haulageway distribution. It is evident that the submicrometer aerosol concentration contributed by exhaust from diesel equipment increases from the portal to the haulageway site. It is also apparent that the haulageway size distribution is similar to the average haulageway size distributions obtained from three other dieselized coal mines (*21*) (fig. 6.)

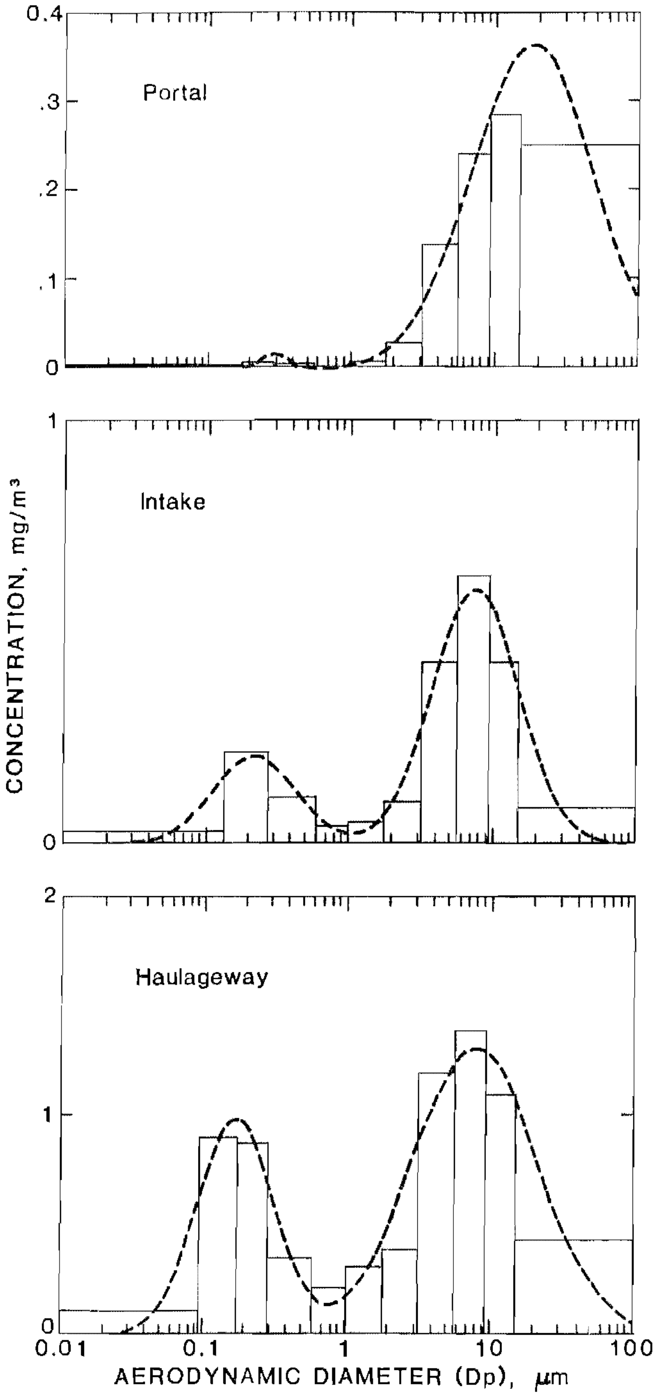

Figure 5.–Aerosol size distributions obtained from MOUDI's located at portal, intake, and haulageway. Dashed line represents mean distribution.

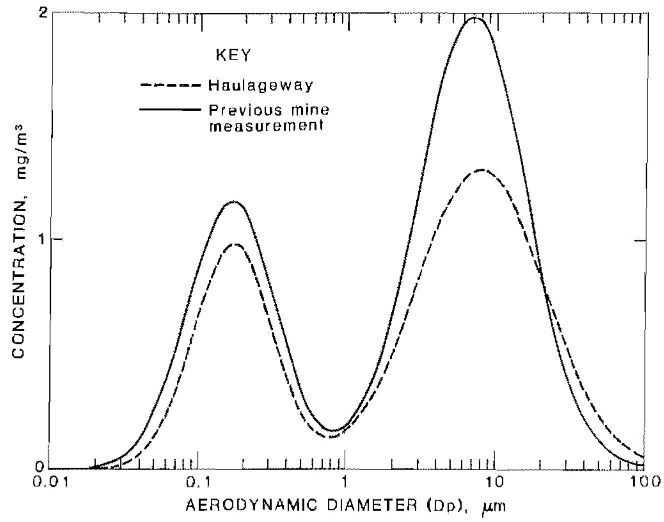

Figure 6.–Comparison of MOUDI size distribution obtained from haulageway with average size distribution from previous mine tests.

These distributions exhibit maxima or modes occurring in the submicrometer (fine fraction) and supermicrometer (coarse fraction). Each mode can be identified with the aerosol contributed by a primary aerosol source, diesel exhaust aerosol for the fine submicrometer mode and mineral dust for the coarse particle mode. Treating each mode as a source connected entity permits the determination of diesel aerosol concentrations in the mine.

Table 5 shows the modal parameters (the MMD, geometric standard deviation (GSD), and mass concentrations) for the coarse and fine fractions as well as the average respirable dust concentration at the three sampling locations.

Table 5.–DPM size distribution data obtained underground

Location and fraction	Diameter, µm MMD	Diameter, µm GSD	Conc, mg/m³
Portal:			
Fine	0.30	1.20	<0.01
Coarse	18.12	2.62	.37
Respirable[1] . .	NAp	NAp	.03
Intake:			
Fine	.22	1.98	.15
Coarse	7.47	1.99	.44
Respirable[1] . .	NAp	NAp	.23
Haulageway:			
Fine	.17	1.86	.66
Coarse	7.81	2.72	1.42
Respirable[1] . .	NAp	NAp	.99

GSD Geometric standard deviations.
MMD Mass median diameter.
NAp Not applicable.
Conc Concentration.
[1]Average.

Several trends are apparent from data presented in table 5. The fine aerosol MMD decreases as the sampler is moved closer to the source, which suggests that the MMD of the fine fraction is related to the age of the aerosol. DPM aerosol at the haulageway site was freshly generated. The other apparent trend is that the fine fraction accounts for about 66 pct of the respirable fraction mass concentration at the intake and haulageway site, but a far smaller percentage in the portal sample where there was little or no diesel activity. The fine aerosol fraction at the portal (i.e., the mine intake air) contributes less than 6 pct to the fine fraction observed at the intake and less than 1.5 pct of that found in the haulageway, thereby indicating that the fine aerosol fraction is almost exclusively due to mine activity.

Results obtained from the personal DPM samplers are shown in table 6. A total of 26 samples were collected, but only 19 provided meaningful results because of severe overloading of the upper stage. Owing to the overloading problem, samplers located in dusty areas were operated for less than a full shift. The five samples collected on the Bureau scientist were collected consecutively over an entire shift. During this shift an effort was made to spend time in each area of the section to simulate the activity of supervisory personnel. These areas included the intake, kitchen, haulageway, and face. All of the exposures are below the 2.0 mg/m^3 respirable coal mine dust standard used by MSHA to regulate dust levels in coal mines. For each of the four locations in table 6, the mean fine aerosol concentration, assumed to be DPM, accounted for 59 (intake), 62 (haulageway), 62 (RAMCAR), and 47 (Bureau employee) pct of the mean respirable aerosol concentration. The mean fine aerosol concentration ranged from 0.25 to 0.94 mg/m^3.

Table 6.–Results from personal DPM samplers

Location	Samples	Sampling time, min	Concentration, mg/m^3					
			Fine		Coarse		Respirable	
			MM	SD	MM	SD	MM	SD
Intake	4	1,774	0.25	0.19	0.17	0.01	0.42	0.28
Haulageway	7	1,074	.94	.25	.57	.34	1.51	.48
RAMCAR	3	519	.90	.50	.56	.15	1.46	.48
Bureau employee ..	5	486	.66	.30	.74	.40	1.40	.62

SD Standard deviations.
MM Mass mean.

CONCLUSIONS

Bureau laboratory tests of the engine-mounted DS-DPF, designed to reduce DPM and to control temperatures, flames, and sparks, showed that DPM emissions can be reduced by 97±1 pct with little change in gaseous emissions concentrations. Two problems were encountered during tests of the DS-DPF. The manufacturer's recommended back pressure was exceeded and the exhaust temperature exceeded the regulated level when the engine was operated at rated speed and load. The manufacturer was advised of these problems and is considering alternative remedies. The DS-DPF must pass all certification tests conducted by MSHA prior to being tested on face haulage equipment in an underground coal mine.

A prototype personal DPM sampler was tested in an underground, dieselized coal mine. The sampler has three stages and employs inertial impaction for particle separation. The primary limitations on a personal DPM sampler based on size selective sampling are DPM aerosol loss from the sample, contamination by coarse particle mode aerosol, and resolution of the gravimetric analysis performed on the sample. Of secondary importance is the presence of background aerosol in the sample. The primary problem encountered during this field study was coarse particle contamination caused by overloading of the upper stage. A modified sampler, which utilizes a Dorr-Oliver cyclone, has been designed and is scheduled for extensive testing by MSHA.

For each of the four locations sampled the mean fine aerosol concentration, assumed to be DPM, accounted for 59 (intake), 62 (haulageway), 62 (RAMCAR), and 47 (Bureau employee) pct of the mean respirable aerosol concentration. The mean fine aerosol concentration ranged from 0.25 to 0.94 mg/m^3. At this mine and at these locations DPM contributed more than half of the respirable aerosol in the mine.

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APPENDIX.–ABBREVIATIONS AND SYMBOLS USED IN THIS REPORT

This listing does not include unit of measure abbreviations, which are listed after the table contents, or abbreviations that are used in the tables.

CMB	chemical mass balance
CO	carbon monoxide
CO_2	carbon dioxide
D_p	aerodynamic diameter
DPF	diesel particulate filter
DPM	diesel particulate matter
DS	dry system
DS-DPF	integrated dry system and diesel particulate filter
GSD	geometric standard deviation
HC	hydrocarbon
HEPA	high efficiency particulate air filter
HNO_3	nitric acid
H_2SO_4	sulfuric acid
LFE	laminar flow element
MMD	mass median diameter
MOUDI	micro-orifice uniform deposit impactor
MSHA	Mine Safety and Health Administration
NIOSH	National Institutes of Occupational Safety and Health
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	oxides of nitrogen
PDP	positive displacement pump
O_2	oxygen
SO_2	sulfur dioxide

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