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In-Mine Evaluation of Catalyzed Diesel Particulate Filters at Two Underground Metal Mines

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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Rhea Lydia Graham, Director

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Metric Units

cm	centimeter	mg/min	milligram per minute
cm^3/min	cubic centimeter per minute	mg/(min•t)	milligram per minute per metric ton
h	hour	min	minute
Hz	hertz	mm	millimeter
kPa	kilopascal	pct	percent
kW	kilowatt	ppm	part per million
L	liter	rpm	revolution per minute
L/min	liter per minute	t	metric ton
m	meter	t/d	metric ton per day
m^3	cubic meter	wt pct	weight percent
m^3/min	cubic meter per minute	μm	micrometer
mg/m^3	milligram per cubic meter	°C	degree Celsius

U.S. Customary Units

ft	foot	in H_2O	inch of water
ft^3/min	cubic foot per minute	st	short ton
hp	horsepower	st/d	short ton per day
in	inch	yd^3	cubic yard

IN-MINE EVALUATION OF CATALYZED DIESEL PARTICULATE FILTERS AT TWO UNDERGROUND METAL MINES

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ABSTRACT

The U.S. Bureau of Mines evaluated the performance of a catalyzed diesel particulate filter (CDPF) and a CDPF combined with a diesel oxidation catalyst (DOC) at two metal mines. This report describes the results from the two field evaluations.

The CDPF-DOC was installed on a load-haul-dump (LHD) powered by a 175-kW, prechambered, turbocharged engine. This system reduced diesel particulate matter (DPM) concentrations by 71±28 pct, as determined by size-selective sampling with gravimetric analysis, and by 71±29 pct, as determined by respirable combustible dust (RCD) analysis at the vehicle operator's location.

The CDPF was installed on a diesel-hydraulic, roof-bolting jumbo, powered by a 172-kW engine. The CDPF reduced DPM concentrations by 72±21 pct, as determined by size-selective sampling with gravimetric analysis, and by 62±25 pct, as determined by RCD analysis at the vehicle operator's location. Underground evaluation was more difficult because of frequent movement by the roof-bolting jumbo, variation in daily workload, tremendous fluctuation in ventilation airflow rates, and use of a high sulfur diesel fuel, which promotes the formation of sulfate particles, decreases filtration efficiency, and hastens the deterioration of the catalyst.

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INTRODUCTION

The goal of the U.S. Bureau of Mines (USBM) diesel research program is to reduce exhaust emissions from diesel-powered equipment used in underground mines. Emphasis is placed upon reducing diesel particulate matter (DPM) emissions because DPM is respirable in size, carries adsorbed and condensed hydrocarbons (HC's), and is a potential carcinogen. Catalyzed diesel particulate filters (CDPF's) and CDPF's combined with diesel oxidation catalysts (DOC's) are used to reduce DPM and gaseous emissions underground. The USBM evaluated the performance of a CDPF alone and a CDPF combined with a DOC at two metal mines (mines Q and T) and in the laboratory. This report describes the results from the two field evaluations and summarizes the results of the laboratory evaluations. Data from the two field evaluations are also compared to DPM concentrations reported by the USBM and other investigators from studies conducted in coal mines. This comparison provides information on the range of DPM exposure in underground mines using diesel equipment with and without emission controls.

BACKGROUND

DESIGN AND OPERATION OF CDPF'S

CDPF's are used underground to filter DPM from diesel exhaust. They are used on nonpermissible mine production vehicles that have exhaust temperatures exceeding 400 °C for at least 25 pct of the duty cycle. These engines are frequently operated at high power, such as engines used in vehicles that climb a steep ramp many times each shift.

The CDPF has a catalyst-coated, porous, ceramic substrate with longitudinal channels enclosed in a steel housing (*1*).[8] The inlet end has every other channel plugged with ceramic material, while the adjacent channel is plugged at the outlet end. The exhaust gas enters a channel and is forced to pass through the porous channel walls where filtering takes place. The exhaust exits through adjacent channels. Previous laboratory studies have shown that CDPF's remove 63 to 95 pct of the DPM from the exhaust (*2-4*).

The CDPF is installed in the exhaust stream as close to the engine as possible. As DPM collects within and on the porous walls of the ceramic, the back pressure on the engine increases. When the temperature in the CDPF exceeds 400 °C, the DPM burns and the back pressure decreases. This self-cleaning process is called autoregeneration and takes about 15 to 20 min to complete (*5-6*). If the CDPF reaches regeneration temperature frequently during a vehicle's duty cycle, the engine back pressure will remain within acceptable limits. However, if the vehicle's duty cycle or the operating condition of the engine changes such that regeneration does not occur, or occurs less frequently, the CDPF may become overloaded with DPM. If the DPM burns too quickly and there is insufficient exhaust gas flow to dissipate the heat, thermal stress may crack the CDPF or excessive heat may melt the ceramic substrate. This is referred to as an "uncontrolled regeneration." A USBM laboratory investigation of uncontrolled regeneration (*7*) showed that exhaust temperatures can exceed 925 °C and carbon monoxide (CO) emissions can exceed 5,000 ppm. This study concluded that as long as the engine back pressure remained below the engine manufacturer's recommended limit, uncontrolled regeneration was unlikely to occur. The frequency of occurrence of uncontrolled regeneration in mining applications is not known.

The primary reason a catalyst is applied to the ceramic substrate is to lower the regeneration temperature. However, the catalyst also promotes the oxidation of CO, gaseous HC's, and a portion of the volatile HC associated with DPM. One study (*2*) of a CDPF on a mining engine reported decreases in CO emissions of 79 pct and HC emissions of 59 pct when the engine was operated in the laboratory under a duty cycle that simulated mining conditions.

The catalyst is applied on a wash coat, which improves performance by increasing the surface area of the substrate, enhancing catalyst binding (*8*), and strengthening the substrate (*9*). Catalysts are composed of either base or noble metals, and numerous manufacturers are developing new formulations for heavy-duty diesel engines. (The specific details of catalyst and wash coat formulations are proprietary.) A CDPF should only be used with fuel containing <0.05 wt pct to minimize the formation of sulfate particulates and poisoning of the catalyst.

DESIGN AND OPERATION OF DOC'S

DOC's are used to reduce emissions of CO and HC, but they may also reduce DPM emissions. The DOC has a catalyst-coated ceramic or metallic substrate enclosed in a steel housing. Channels run the length of the substrate, but unlike the CDPF, no channels are blocked. Gases

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

flow through the channels and react with the catalyst. Depending on the type of engine, exhaust temperature, and catalyst formulation, DOC's oxidize 30 to 80 pct of the HC and 30 to 90 pct of the CO present (*10*). DOC's have little effect on the portion of DPM composed of elemental carbon, but DPM emissions are reduced because DOC's promote the oxidation of gaseous HC's before they adsorb or condense on the particulate to form the soluble organic fraction (*11*). Engine tests have shown DPM reductions of 30 to 50 pct (*10*). Because DOC's are most effective at higher exhaust temperatures, they are installed as close to the exhaust manifold as possible. The higher exhaust temperatures also help prevent DPM buildup on the substrate that will decrease its effectiveness.

Catalysts used on DOC's are dispersed on an aluminum oxide or silicon dioxide wash coat and are typically platinum or palladium based. Numerous catalyst manufacturers are attempting to optimize the proper combination of substrate, wash coat, and catalyst to maximize reductions in emissions and to ensure long life (*10*).

PREVIOUS IN-MINE EVALUATIONS OF CDPF'S

Previous in-mine evaluations of CDPF's have shown mixed results. A study of 18 CDPF's in Canadian underground mines reported that 8 were removed after an average of 1,704 h of operation because of failure to regenerate, physical deterioration, production of unusual odors, or other reasons. The remaining 10 CDPF's were still operable and had accumulated an average of 1,984 h of operation with 1 CDPF operating for over 4,000 h at the time of the report (*12*). However, similar problems of inadequate regeneration that led to plugging of CDPF's and unusual odors that concerned some vehicle operators were also reported for the filters that remained in service.

As a result of a trial of uncatalyzed DPF's and CDPF's on load-haul-dumps (LHD's), front-end loaders, and bulldozers at a Canadian mine, it was concluded that DPF's and CDPF's can be used successfully underground if vehicles are screened to ensure proper function. DPF's and CDPF's were reported to decrease vehicle maintenance costs by reducing the frequency of vehicle removal from service because of exhaust smoke (*13*). Maintenance personnel frequently use smoke characteristics as an indicator of engine problems, and the use of a CDPF may mask engine problems associated with smoke production. Therefore, this may lead to higher engine maintenance costs over the long term.

Another study (*14*) reported that an uncatalyzed DPF operated for about 5,000 h on an LHD in an underground mine. When the DPF was removed and analyzed, no cracking or melting of the substrate was observed. However, significant ash accumulation was apparent. Ash accumulation corresponded to an increase in back pressure from 2.5 to 4.0 kPa (10 to 16 in H_2O).

DURABILITY AND PERFORMANCE EVALUATIONS

The two metal mines involved in the field study also participated in CDPF (mine T) and CDPF-DOC (mine Q) durability and performance studies (*15-16*). In these studies, control devices were performance tested in the laboratory and then installed on LHD's at the respective mines. At periodic intervals, the control devices were removed from the vehicles and returned to the laboratory for repeat testing to determine whether the regeneration temperature, collection efficiency, and CO and HC removal efficiency changed with use.

At mine Q, the CDPF-DOC, manufactured by Diesel Controls Ltd., was installed on a Dale B. Elphinstone Pty. Ltd. R1500 LHD with a 5.7 m^3 (7.5 yd^3) bucket, powered by a Caterpillar, Inc. 3306, prechambered, turbocharged, aftercooled diesel engine rated at 175 kW at 36.6 Hz (2,200 rpm). The CDPF-DOC was installed on this vehicle during the in-mine evaluation. The LHD's duty cycle was (1) loading ore into its bucket from a drawpoint, (2) hauling the load 13 to 48 m (42 to 157 ft), (3) dumping it down an orepass, and (4) returning unloaded to the drawpoint. The vehicle hauled 35 to 50 loads per hour, depending on the haul distance (*16*). An exhaust temperature trace obtained prior to the installation of the CDPF-DOC showed that the exhaust temperature exceeded 450 °C most of the time.

The CDPF-DOC had substrates that were housed in one steel canister because of limited space on the vehicle. The CDPF had a ceramic substrate with a cell density of 15.5 cells per square centimeter (100 cells per square inch). The substrate was 38.1 cm (15 in) in length and had a diameter of 38.1 cm (15 in). A base metal catalyst was applied to the CDPF to reduce its regeneration temperature. The DOC had a metallic substrate that was 21.7 cm (8.5 in) in diameter, 10.0 cm (3.9 in) long, and a cell density of 31 cells per square centimeter (200 cells per square inch). The DOC used a noble metal catalyst to reduce CO and HC. The DOC was placed inside the outlet cone downstream from the CDPF to prevent fouling with DPM.

The CDPF-DOC was installed downstream of the turbocharger. It was mounted vertically in the existing exhaust compartment of the LHD, replacing a muffler-catalytic converter assembly of a smaller size. The clearance between the CDPF-DOC and compartment walls was about 15 mm (0.6 in). The muffler compartment was not high enough to accommodate the CDPF-DOC, so the upper cone of the unit protruded outside the compartment. A protective metal shield was installed to prevent contact with the hot surface.

The CDPF-DOC was removed from the LHD and evaluated in the laboratory after operating for 308 and 1,200 h. After 308 h of operation, laboratory testing revealed its particulate collection efficiency varied from 41.0 to 93.5 pct, depending on engine operating condition. Its regeneration temperature was about 415 °C. It reduced HC emissions by 43.1 to 97.6 pct and CO by 8.5 to 95.0 pct, depending on engine mode. When the system was tested in the laboratory after operating for 1,200 h on the vehicle, no significant change in performance was observed (*16*).

At mine T (*15*), a CDPF, manufactured by Engelhard, Inc., was installed on a 3.8 m^3 (5 yd^3) LHD powered by a Deutz Corp. F10L413 FW engine rated at 172.3 kW (231 hp) at 38.3 Hz (2,300 rpm). This CDPF was similar to the CDPF installed on a roof-bolting jumbo during the in-mine evaluation. The duty cycle of this LHD consisted of loading trucks rather than tramming to the orepass. Typically, the LHD made four passes in the muck pile to load one truck, then either idled while waiting for another truck or shut down while the operator drove the truck to the orepass. Temperature traces of the LHD's exhaust obtained prior to installation of the CDPF indicated that exhaust temperatures periodically exceeded 400 °C and were sufficient to initiate regeneration, but may not have been sustained long enough to ensure complete regeneration.

The CDPF had a ceramic substrate composed of Corning, Inc.'s EX-66 cordierite material, which has a mean pore size of 35 μm and 15.5 cells per square centimeter (100 cells per square inch), and an advertised, uncatalyzed collection efficiency of 65 to 70 pct (*17*). The ceramic substrate was 38.1 cm (15 in) in length, had a diameter of 38.1 cm (15 in), and was mounted in a steel canister. The application of the wash coat and catalyst may increase the collection efficiency by decreasing porosity and promoting oxidation of the soluble organic fraction of the trapped particulate.

The CDPF was removed from the LHD and tested in the USBM's diesel emissions laboratory after 839, 1,584, and 2,881 h of in-mine service. Briefly, testing showed that the regeneration temperature of the CDPF increased from 405 to 450 °C after 839 and 2,881 h of operation, respectively. The CDPF reduced CO emissions from 21 to 65 pct and HC emissions from 5 to 90 pct after 839 h, depending on the engine mode. The CDPF was still effective at lowering CO and HC emissions after 1,584 and 2,881 h, and in most instances, the emissions reductions were within 20 pct of the reductions measured after 839 h. DPM collection efficiency decreased when measured after 1,584 h of operation and again after 2,881 h, suggesting damage to the substrate. Collection efficiency after 2,881 h ranged from 28 to 82 pct. The CDPF was no longer used after 2,881 h because of the lower collection efficiency and higher regeneration temperature.

IN-MINE EVALUATIONS

MINE DESCRIPTIONS

Mine Q is an underground panel-caving molybdenum mine located in Colorado. Diesel-powered, rubber-tired equipment is used for all development and primary production operations. The mine produces 34,013 t/d (37,500 st/d) from two production levels. Caved ore is loaded with LHD's from drawpoints on either side of a production drift and trammed to orepasses located alongside the drift every 97 m (320 ft). The orepasses transfer the ore to the haulage level, where an electric train is loaded for hauling the ore to the mill. Ventilation is provided by raises from intake and exhaust ventilation drifts. The orepasses act as exhaust raises in each production drift. The mine uses DOC's on all diesel equipment to reduce CO and gaseous HC emissions. Analysis of diesel fuel samples showed that the mine was using a low sulfur diesel fuel containing 0.024 wt pct S.

Mine T was an underground gold producer located in central Washington State. The mine used rubber-tired diesel equipment and produced approximately 966 t/d (1,065 st/d). The mine closed in March 1995. Mining was conducted by underhand bench and fill, a variation of longhole open stoping with backfilling. Ore from the development headings and the nominal 15-m (50-ft) high stopes was mucked with LHD's and loaded into 23.6-t (26-st) trucks for haulage to the orepass, which fed the underground crushing and hoisting system. The mine was ventilated by approximately 14,150 m^3/min (500,000 ft^3/min) of air.

In September 1987, this mine became the first in the United States to install a CDPF and continued to use CDPF's to reduce DPM emissions from underground diesel equipment until closure. The mine also installed CDPF's on one roof-bolting jumbo, one road grader, five 23.6-t (26-st) trucks, two 3.8-m^3 (5-yd^3) LHD's, two 4.6-m^3 (6-yd^3) LHD's, and one 6.1-m^3 (8-yd^3) LHD. CDPF's were tried, unsuccessfully, on a diesel farm tractor used for personal transportation. Two separate diesel fuel analyses, conducted before and after the in-mine study, showed that the mine was using a high sulfur diesel fuel containing 0.41 and 0.47 wt pct S. Fuel with such high sulfur content is not recommended for use with catalyzed emission-control devices because of catalyst poisoning and the formation of sulfate particles.

AEROSOL MEASUREMENT AND ANALYSIS

Three methods were used to measure DPM and respirable dust concentrations in mines Q and T. Two methods used size-selective sampling by inertial impaction to measure the respirable and <0.8-μm fractions of the mine aerosol. In the third method, respirable dust samples were also collected and burned to determine the respirable combustible dust (RCD) portion of the aerosol (*18*). These methods are described briefly below.

It was shown in the laboratory (*19*) and in underground mines (*20-22*) that size-selective separation of sampled aerosol at a nominal aerodynamic diameter of 0.8 ± 0.1 µm by inertial impaction, followed by gravimetric analysis, can be used to separate and sample DPM and mineral dust aerosol fractions and provide estimates of DPM concentrations. In-mine evaluations of this sampling technique indicate that DPM estimates are accurate to within 25 pct, 95 pct of the time, for concentration levels above the estimated limit of detection of 0.3 mg/m^3 (*23*). Below this level, indications are that the 95-pct confidence interval can exceed 60 pct because of interferences caused by submicrometer mineral dust and background atmospheric aerosol.

This information was used to develop the first of the size-selective samplers used in the field evaluations, the personal diesel exhaust aerosol sampler (PDEAS). This sampler is described in detail elsewhere (*24-25*). It has three stages and employs inertial impaction for separating and collecting the diesel and mineral dust fractions of the sampled respirable aerosol. The first stage is an inertial preclassifier, a 10-mm Dorr-Oliver cyclone that separates and collects the larger, nonrespirable aerosol. The second stage is a four-nozzle impactor with a sharp 50-pct cut point of 0.8-µm aerodynamic diameter at the design flow rate of 2.0 L/min. Most aerosol particles larger than 0.8 µm are deposited on an impaction substrate in this stage. The third stage is a filter that collects the remaining aerosol of <0.8-µm aerodynamic diameter, and the weight gain of this filter provides an estimate of DPM. For the experiments reported here, the sampler operated at a flow rate of 1.7 L/min, which is compatible with both the personal sampler pump and the 10-mm cyclone. At this flow rate, the sampler provides size separation at 0.87 µm, well within the performance range of 0.8 ± 0.1 µm. In each mine, the PDEAS's were deployed upwind and downwind of the Elphinstone LHD in mine Q or the roof-bolting jumbo in mine T and on the vehicles near the operator's location.

The second size-selective aerosol sampler used in the field evaluations is the micro-orifice uniform deposit impactor (MOUDI) samplers (*26*). The MOUDI is a multistage inertial impactor that can separate aerosol particles by size from 0.1 to 18 µm. Gravimetric analyses of MOUDI-derived size distributions provided accurate estimates of DPM for particles with aerodynamic diameter sizes in the range of <0.1 to 0.8 µm and respirable dust concentrations for sizes in the range of <0.1 to 10 µm. These concentrations were used to evaluate the performance of the PDEAS. MOUDI's were located at three stationary sampling points, upwind and downwind of the vehicles and at the mine portal.

RCD is composed of DPM that includes the soluble organic fraction and combustible material not associated with diesel exhaust, such as drill oil mist and lube, hydraulic or fuel oils evaporated from hot surfaces (*27*). Studies done in Canadian noncoal mines have shown that the nondiesel fraction of RCD varies between 10 and 50 pct, averaging about 33 pct. The Canadian researchers provide limited data to show that the nondiesel fraction is composed of drill oil mist, lube oil leakage on hot surface, and other nonexhaust emissions. Based on this evidence, the Canadian researchers use an empirical correction factor of 0.67 to determine the amount of DPM in the RCD fraction (*28*). This correction factor was not applied to data collected during this field study because no ancillary measurements were made to determine the nondiesel fraction of RCD.

During the field evaluations, the RCD samplers were interspersed with PDEAS samplers upwind, on the Elphinstone LHD or roof-bolting jumbo and downwind of the vehicles. The RCD dust samples were collected using preweighed, 25-mm silver membrane filters after passage through a 10-mm cyclone at a flow rate of 1.7 L/min. These samples were conditioned, reweighed, combusted at 500 °C for 3 h, and reweighed to determine the mass of ash remaining on the filter. RCD was determined by determining the total respirable dust mass, subtracting the mass of ash, and correcting the result for the average mass lost by several filter blanks during ashing.[9]

Figure 1 is a schematic diagram of the underground sampling locations in mine Q. PDEAS and RCD samples were collected over a 2-week period at each of the three locations: upwind, on-board the vehicle, and downwind. MOUDI samples were collected at the two stationary locations and at the mine portal. During the first week, the Elphinstone vehicle was equipped with the CDPF-DOC. The system was removed and replaced by the DOC normally used on the vehicle over the middle weekend. Samples were collected for 2 days during the second week. Sampling times varied, but sampling typically commenced underground at the start of production and stopped near the end of the workshift. The portal MOUDI ran unattended during the entire workshift.

Sampling at mine T was similar except that the roof-bolting jumbo, shown in figure 2, moved from one location in the mine to another on four of the five sampling days. This caused the relocation of the sampling equipment. Figure 3 shows one of the upwind sampling locations at mine T. The RCD and PDEAS samplers are located on the left side of figure 3 and the MOUDI is on the right side. Two high-volume samplers are located in the center of the figure.

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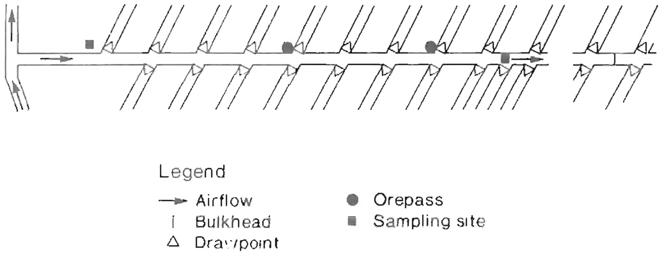
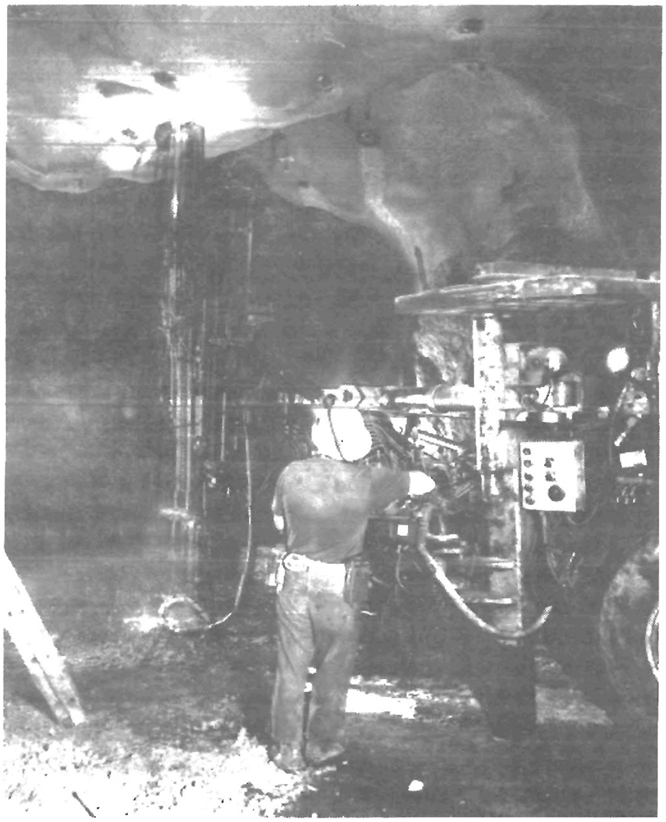
[9] RCD analysis was conducted courtesy of M. K. Gangal at the Mining Research Laboratories, Canada Centre for Mineral and Energy Technology, Ottawa, Ontario.

Figure 1



Sampling locations at mine Q.

Figure 2



Roof-bolting jumbo installing roof bolts at mine T.

Figure 3

Upwind sampling location at mine T.

GASEOUS MEASUREMENT AND ANALYSIS

Measurements of the CO, CO_2 (carbon dioxide), NO (nitric oxide), and NO_2 (nitrogen dioxide) concentrations were made at each mine. To measure CO and CO_2, mine air was pumped into a 22-L, five-layer bag at approximately 50 cm^3/min using a Dupont Co. P-125 pump. The CO and CO_2 concentrations were analyzed at the end of the sampling period using an Ecolyzer 2600 CO instrument and a Fuji ZFP5 CO_2 instrument. NO_2 and NO were sampled using Palmes (*29*) passive samplers or diffusion tubes (*30*). Samplers for CO, CO_2, NO, and NO_2 were collocated with the aerosol samplers at the three locations.

VENTILATION AND PRODUCTION MEASUREMENTS

Ventilation measurements were conducted at all the sampling stations using a vane anemometer. For mine Q, the variance in this number was <10 pct. For mine T, ventilation quantities changed by a factor of 10 during the study. As a result, significant error was introduced into the calculation of diesel exhaust aerosol reduction because of the CDPF. Vertical stratification was shown to exist in mine T.[10] This stratification affected measurements at the downwind site and may have caused major differences in the calculated control efficiency between the downwind and vehicle locations. These data suggest that the high airflows kept the exhaust stream stratified in the upper half of the drift, allowing minimal mixing. The instrument suite was located near the floor of the drift and thus did not have the opportunity to collect aerosol from a well-mixed exhaust stream.

Production estimates were made for mine Q using the number of LHD buckets loaded during the sampling periods. The LHD operated almost continuously through the entire shift. At mine T, the number of roof bolts installed was used as the measure of the amount of work done. The roof-bolting jumbo operated continuously but not always for the entire shift.

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[10] Stratification measurements were conducted by J. M. Mutmansky at The Pennsylvania State University, University Park, PA. This investigation was funded under a grant from the USBM's Generic Mineral Technology Center for Respirable Dust, University Park, PA.

IN-MINE SAMPLING RESULTS

AIR QUALITY MEASUREMENTS

Respirable dust, DPM, and RCD concentrations are shown in tables 1 and 2. These data are not normalized to account for day-to-day differences in ventilation airflow, ore tonnage hauled at mine Q, or the number of roof bolts driven at mine T. The RCD data shown in tables 1 and 2 do not reflect the empirical correction factor used in Canada. The uncorrected raw data are a measure of mine air quality with and without the control devices installed. Tables 1 and 2 show the total number of samples collected over several days either with or without control devices in place. The standard deviation includes the variation between samplers and the variation between days.

Table 1.—Mine Q mean concentrations and standard deviations derived from measurements using RCD and PDEAS methods

	Sampling location		
	Upwind	Vehicle	Downwind
CDPF-DOC INSTALLED—3 DAYS			
RCD sampler:			
Number of samples	6	6	6
Concentration, mg/m³:			
RD mean	0.22	0.72	0.79
RD SD	0.11	0.04	0.07
RCD mean	0.21	0.38	0.43
RCD SD	0.09	0.12	0.08
RCD, pct	94	53	54
PDEAS:			
Number of samples	7	9	6
Concentration, mg/m³:			
RD mean	0.30	0.72	0.79
RD SD	0.06	0.09	0.12
DPM mean	0.11	0.20	0.26
DPM SD	0.02	0.05	0.02
DPM, pct	36	28	33
CDPF-DOC REMOVED—2 DAYS			
RCD sampler:			
Number of samples	4	4	4
Concentration, mg/m³:			
RD mean	0.21	1.04	1.16
RD SD	0.05	0.18	0.10
RCD mean	0.20	0.78	0.83
RCD SD	0.05	0.11	0.05
RCD, pct	98	75	72
PDEAS:			
Number of samples	4	5	6
Concentration, mg/m³:			
RD mean	0.30	0.87	1.20
RD SD	0.06	0.24	0.23
DPM mean	0.08	0.42	0.51
DPM SD	0.04	0.07	0.02
DPM, pct	26	48	42

RD Respirable dust.
SD Standard deviation.

Table 2.—Mine T mean concentrations and standard deviations derived from measurements using RCD and PDEAS methods

	Sampling location		
	Upwind	Vehicle	Downwind
CDPF INSTALLED—3 DAYS			
RCD sampler:			
Number of samples	6	6	6
Concentration, mg/m³:			
RD mean	0.28	0.50	0.56
RD SD	0.13	0.23	0.18
RCD mean	0.17	0.23	0.24
RCD SD	0.04	0.09	0.07
RCD, pct	65	52	44
PDEAS:			
Number of samples	4	6	5
Concentration, mg/m³:			
RD mean	0.25	0.41	0.40
RD SD	0.13	0.10	0.08
DPM mean	0.10	0.19	0.22
DPM SD	0.05	0.07	0.06
DPM, pct	37	45	56
CDPF REMOVED—2 DAYS			
RCD sampler:			
Number of samples	6	6	6
Concentration, mg/m³:			
RD mean	0.49	0.61	0.55
RD SD	0.29	0.10	0.31
RCD mean	0.25	0.31	0.29
RCD SD	0.19	0.07	0.19
RCD, pct	46	51	50
PDEAS:			
Number of samples	5	6	5
Concentration, mg/m³:			
RD mean	0.44	0.54	0.52
RD SD	0.30	0.10	0.33
DPM mean	0.24	0.36	0.32
DPM SD	0.18	0.01	0.20
DPM, pct	49	68	62

RD Respirable dust.
SD Standard deviation.

Table 1 shows the results for respirable dust and DPM obtained by the two methods in mine Q with and without the CDPF-DOC installed. Without the CDPF-DOC installed, the RCD sampler measured a range of mean respirable dust concentrations from 0.21 to 1.16 mg/m³ and the PDEAS measured 0.30 to 1.20 mg/m³. Without the CDPF-DOC installed, the RCD sampler measured mean RCD concentrations ranging from 0.20 to 0.83 mg/m³ and the PDEAS measured DPM ranging from 0.08 to 0.51 mg/m³. The RCD samples provided higher estimates of DPM than the PDEAS samples. Installation of the

CDPF-DOC reduced concentrations of RCD and DPM at the vehicle and downwind locations. These reductions are discussed in the section "Control Efficiency Determination."

Measurements made at mine T with and without the CDPF installed are summarized in table 2. Without the CDPF installed the RCD sampler measured a range of mean respirable dust concentrations from 0.49 to 0.61 mg/m³ and the PDEAS measured 0.44 to 0.54 mg/m³. Without the CDPF installed the RCD sampler measured mean RCD concentrations ranging from 0.25 to 0.31 mg/m³, and the PDEAS measured DPM ranging from 0.24 to 0.36 mg/m³. Installation of the CDPF-DOC reduced concentrations of RCD and DPM at the at the vehicle and downwind locations. These reductions are discussed in detail later.

The concentrations measured at mine T are lower than those at mine Q, and there is more scatter in these data, as indicated by the higher standard deviations. The sampling conditions at mine T were not optimal. On the first day of sampling, the upwind sampling site was located on the level below the downwind sampling site. As a result, the data from this day was not used in the control efficiency determination. For the remainder of the tests, the roof-bolting jumbo moved every day, forcing a relocation of the sampling equipment. The ventilation air quantity at these locations ranged from 1,606 to 4,828 m³/min, and the higher airflows contributed to the stratification of diesel aerosol.

CONTROL EFFICIENCY DETERMINATION

Average diesel aerosol concentrations measured with the RCD and PDEAS samplers were used to determine the rate of diesel aerosol generation per unit measure of production with and without the diesel exhaust control in place. The control efficiencies for the CDPF-DOC and CDPF, shown in tables 3 and 4 for mines Q and T, respectively, were determined from the reduction in the generation rate values corrected for material entering the section in the ventilation air with use of the control. The equation used to calculate the percentage reductions (Δ) is:

$$\Delta = 100\left(1 - \frac{R_w}{R_{w/o}}\right),$$

where R_w, $R_{w/o}$ = intake corrected average diesel aerosol generation rates per unit production measured with and without the control device in place, respectively.

R_w and $R_{w/o}$ are calculated using:

$$R = \frac{VC_m - VC_i}{P},$$

where R = intake corrected rate per unit production,

V = average section ventilation air quantity,

C_m = average diesel aerosol concentration measured at sampling site, either on or downwind of vehicle,

C_i = average aerosol concentration measured in section intake,

and P = section's production of ore in metric tons or number of roof bolts installed.

C_m and C_i are given in tables 1 and 2.

Table 3.—Reduction of diesel aerosol in mine Q using CDPF-DOC

	Sampling location	
	Vehicle	Downwind
RCD		
With CDPF-DOC installed:		
Ventilation, m³/min	1,865 ± 356	NAp
Production, t	2,130 ± 477	NAp
Rate,[1] mg/(min•t) of ore hauled	0.149	0.193
With CDPF-DOC removed:		
Ventilation, m³/min	1,999 ± 240	NAp
Production, t	2,295 ± 89	NAp
Rate,[1] mg/(min•t) of ore hauled	0.505	0.549
Reduction (Δ), pct	71 ± 28	65±22
PDEAS		
With CDPF-DOC installed:		
Ventilation, m³/min	1,865 ± 356	NAp
Production, t	2,130 ± 477	NAp
Rate,[1] mg/(min•t) of ore hauled	0.087	0.140
With CDPF-DOC removed:		
Ventilation, m³/min	1,999 ± 240	NAp
Production, t	2,295 ± 89	NAp
Rate,[1] mg/(min•t) of ore hauled	0.296	0.374
Reduction (Δ), pct	71 ± 29	63±24

NAp Not applicable.

[1] Generation rate of diesel exhaust aerosol per unit measure of production.

The mean reduction in the diesel aerosol generation rate per unit production noted in table 3 due to the CDPF-DOC for mine Q is approximately 70 pct. This is very close to the filter efficiency of the ceramic substrate before the wash coat is applied and is probably to be expected of a filter that is used hard and for which the regeneration process is effective. During the course of the study, a small leak was observed at the junction of the exhaust pipe and CDPF-DOC. This leak could decrease the CDPF-DOC filtration efficiency by a small percentage. For each emission reduction estimate, the standard deviation is ≤33 pct of the calculated mean value.

Reductions in DPM measured for mine T are less certain. The location of the roof-bolting jumbo changed daily, which changed the sampling geometry for the section. This problem was so pronounced for the first day of sampling when the roof-bolting jumbo and sampling stations were on different levels that only the last 4 days were used to calculate the averages shown in table 2.

Stratification was evident at the downwind sampling site. This and the nearly tenfold change in ventilation from the time when the CDPF assembly was in place until it was removed complicated the sampling situation and may account for the apparent discrepancy between the reductions determined for the vehicle and the downwind fixed site. This is reflected in the large standard deviations associated with the results, which are up to 67 pct of the calculated mean downwind reduction.

Figures 4 and 5 show the size distribution of mine aerosol produced by the test vehicle for mines Q and T, respectively, with and without the control device. These figures are based on data collected from the MOUDI's located at the upwind and downwind sites. They illustrate the control effectiveness of the emission-control devices in removing DPM from the mine atmosphere. On the basis of these measurements, 72 pct of the DPM was removed from mine Q and 37 pct was removed from mine T. These results confirm both the RCD and PDEAS measurements made at the downwind locations.

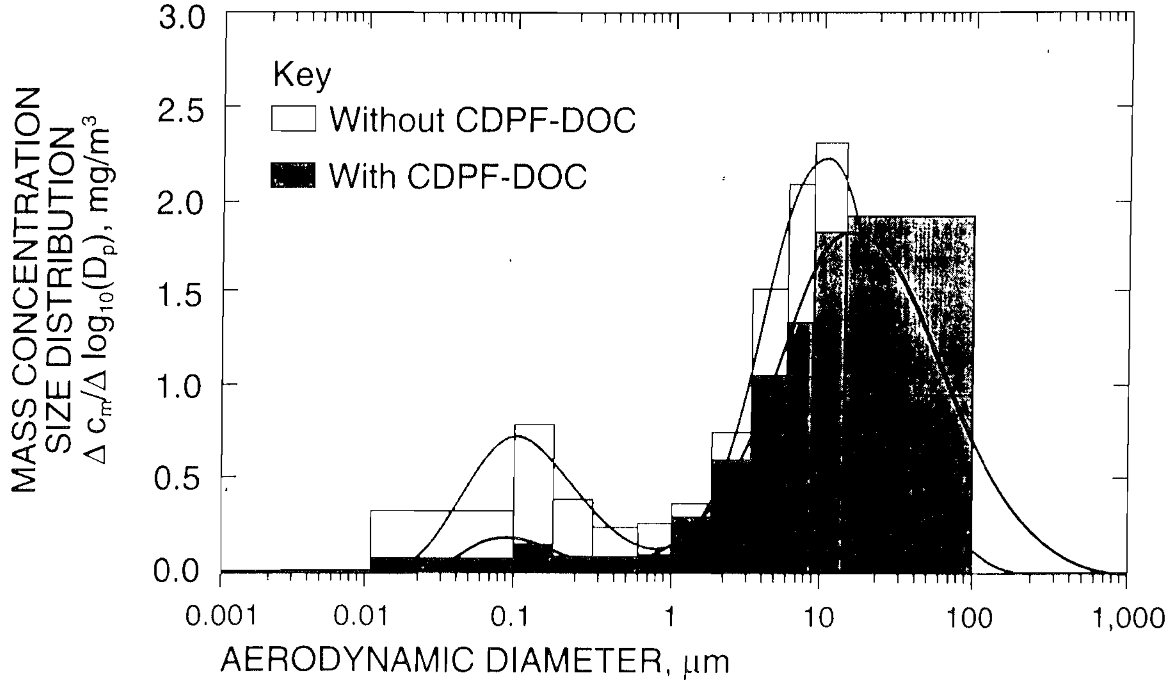
Table 4.—Reduction of diesel aerosol in mine T using CDPF

	Sampling location	
	Vehicle	Downwind
RCD		
With CDPF installed:		
Ventilation, m^3/min	1,606 ± 88	NAp
Production, bolts	47 ± 10	NAp
Rate,[1] mg/min per bolt installed	2.04	2.38
With CDPF removed:		
Ventilation, m^3/min	4,828 ± 401	NAp
Production, bolts	54 ± 2	NAp
Rate,[1] mg/min per bolt installed	5.36	3.58
Reduction (Δ), pct	62 ± 25	33 ± 22
PDEAS		
With CDPF installed:		
Ventilation, m^3/min	1,606 ± 88	NAp
Production, bolts	47 ± 10	NAp
Rate,[1] mg/min per bolt installed	3.06	4.09
With CDPF removed:		
Ventilation, m^3/min	4,828 ± 401	NAp
Production, bolts	54 ± 2	NAp
Rate,[1] mg/min per bolt installed	10.72	7.15
Reduction (Δ), pct	72 ± 21	42 ± 13

NAp Not applicable.

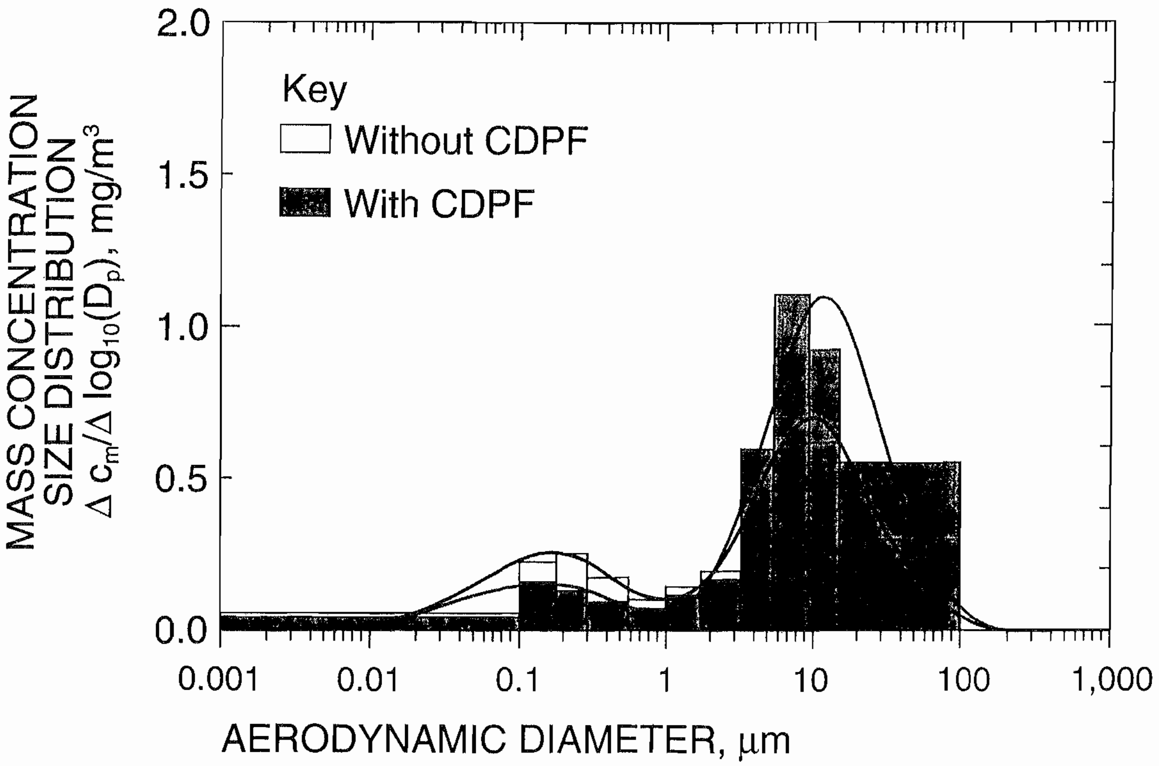
[1] Generation rate of diesel exhaust aerosol per unit measure of production.

Figure 4



MOUDI-derived mass size distributions of mine particulate aerosol containing diesel exhaust with and without CDPF-DOC installed at mine Q. (ΔC_m = differential mass concentration; D_p = particle size.)

Figure 5



MOUDI-derived mass size distributions of mine particulate aerosol containing diesel exhaust with and without CDPF installed at mine T. (ΔC_m = differential mass concentration; D_p = particle size.)

Average measurements for CO, CO_2, NO, and NO_2 made at mines Q and T are shown in table 5. Measurements were collected upwind, downwind, and on the Elphinstone LHD and roof-bolting jumbo. Data in table 3 are not normalized for changes in ventilation, production, or the number of roof bolts installed. All reported concentrations are well below regulated levels.

Table 5.—Gas concentration data from mines Q and T with and without emission-control devices installed

Sampling location	CO	CO_2	NO	NO_2	CO	CO_2	NO	NO_2
	CDPF-DOC removed				CDPF-DOC installed			
Mine Q:								
Upwind:								
Mean, ppm	0.50	0.05	0.32	0.04	0.50	0.06	0.57	0.03
SD, ppm	0.71	0.00	0.05	0.01	0.50	0.01	0.35	0.01
CV, pct	141	0	16	35	100	8	61	33
Vehicle:								
Mean, ppm	1.25	0.08	2.44	0.07	1.33	0.09	2.80	0.43
SD, ppm	1.06	0.00	0.40	0.02	0.58	0.01	0.90	0.15
CV, pct	85	2	17	33	43	8	32	35
Downwind:								
Mean, ppm	2.50	0.08	3.17	0.10	1.67	0.12	3.96	0.48
SD, ppm	0.71	0.03	0.45	0.01	0.58	0.01	0.26	0.09
CV, pct	28	45	14	14	35	8	7	18

See footnotes at end of table.

Table 5.—Gas concentration data from mines Q and T with and without emission-control devices installed—Continued

Sampling location	CO	CO_2	NO	NO_2	CO	CO_2	NO	NO_2
	CDPF removed				CDPF installed			
Mine T:								
Upwind:								
Mean, ppm	0.75	0.05	1.67	0.20	0.25	0.05	0.24	0.09
SD, ppm	0.35	0.01	1.90	0.09	0.35	0.00	0.08	0.07
CV, pct	47	28	113	47	141	0	33	79
Roof-bolting jumbo:								
Mean, ppm	1.00	0.06	2.88	0.25	2.00	0.15	9.42	0.84
SD, ppm	0.00	0.00	0.12	0.04	1.41	0.07	2.02	0.04
CV, pct	0	6	4	14	71	47	21	5
Downwind:								
Mean, ppm	1.00	0.05	2.42	0.15	3.00	0.17	8.65	0.64
SD, ppm	0.00	0.01	1.61	0.01	1.41	0.08	3.22	0.23
CV, pct	0	20	67	9	47	47	37	37

CV Coefficient of variation.
SD Standard deviation.

DISCUSSION

Averaging the reduction efficiencies shown in table 3 gives a mean reduction efficiency of the CDPF-DOC at mine Q of 67±26 pct. This reduction is close to the amount expected. The reduction efficiency of the CDPF at mine T varied considerably from the vehicle to the downwind locations. The mean reduction on the vehicle was 67±23 pct while the mean reduction at the downwind site was 38±18 pct. The evaluation at mine T was hindered by highly variable ventilation, aerosol stratification, sampling locations that moved daily, fluctuation in the amount of work performed by the roof-bolting jumbo, and the use of high sulfur fuel. The test conditions at mine T, especially at the downwind site, make results of the evaluation less certain.

RCD and PDEAS data collected at the two mines can be used to estimate mine worker exposure to DPM with and without control devices installed. At mine Q, DPM exposure estimates at the vehicle and downwind sites ranged from 0.42 to 0.83 mg/m^3 without the CDPF-DOC installed and from 0.20 to 0.43 mg/m^3 with the CDPF-DOC installed. At mine T, exposures were lower, ranging from 0.29 to 0.36 mg/m^3 without the CDPF installed to 0.19 to 0.24 mg/m^3 with the CDPF installed at the vehicle and downwind sampling sites.

The mean DPM concentrations determined at the two metal mines using the <0.8-μm fraction as the measure of DPM are quite similar to PDEAS data collected in underground coal mines using diesel coal haulage equipment with and without disposable diesel exhaust filters (DDEF's). Briefly, the DDEF is a paper filter capable of withstanding temperatures <100 °C. It is placed in the exhaust stream following the water scrubber. A water scrubber is used to remove flame and sparks and to cool the exhaust on permissible equipment in underground coal mines. Caterpillar or Motoren-Werke Mannheim indirect injection engines, in the 56- to 112-kW range, were used in these coal haulage vehicles. DDEF control efficiency evaluations were conducted using the same instrumentation and methods as described above, except that RCD samples were not collected. Complete details of the coal mine studies are reported elsewhere (*30-31*).

Table 6 compares PDEAS data collected at nine mines, five of which used an emission-control device. The reductions in DPM achieved by the use of the CDPF-DOC and CDPF at mines Q and T are less than the 70- to 90-pct reductions achieved by the use of a DDEF at coal mines M, R, and S (*31*). At the present time, DDEF's are not used in dieselized coal haulage vehicles without water scrubbers, but the advent of dry-type heat exchangers may allow the use of DDEF's in a wide array of coal and noncoal diesel vehicles in the near future (*32*).

Mean DPM concentrations at the nine mines ranged from 0.32 to 1.74 mg/m^3 with a median value of 0.74 mg/m^3 when no emission-control device was used and ranged from 0.12 to 0.28 mg/m^3 with a median of 0.23 mg/m^3 when an emission-control device was installed. Where measured, the concentrations of the common gases found in diesel exhaust were well below regulated levels at these mines. The use of emission-control devices reduced DPM exposure.

Other investigators have used size-selective sampling methods to quantify submicrometer aerosol concentrations in diesel-equipped coal mines. McCawley and Cocalis (*33*) reported concentrations of <1 μm aerosol from two underground coal mines using diesel-face haulage equipment. Measurements were made using a single-stage, single-jet

Table 6.—Comparison of DPM concentrations[1] at downwind sampling site at nine mines with and without emission-control devices installed

	Without control			With control		
	Number of samples	Concentration, mg/m^3		Number of samples	Concentration, mg/m^3	
		Mean	SD		Mean	SD
Coal mine:						
I	7	0.94	0.23	0	NAp	NAp
J	7	1.01	0.21	0	NAp	NAp
K	8	0.67	0.11	0	NAp	NAp
L	10	0.74	0.27	0	NAp	NAp
M	2	0.50	0.02	7	0.12	0.02
R[2]	39	0.83	0.17	56	0.28	0.07
S[2]	29	1.74	0.48	41	0.23	0.05
Metal mine:						
Q	6	0.51	0.02	6	0.26	0.02
T	5	0.32	0.20	5	0.22	0.06

NAp Not applicable.
SD Standard deviation.
[1] Measured using the personal diesel exhaust sampler.
[2] Samples collected on the vehicle.

impaction preseparator (*34*), a standard 10-mm nylon cyclone and cassette operated at an increased flow rate, and the Graseby Anderson 298 cascade impactor. Mean submicrometer aerosol concentrations ranged from 0.1 mg/m^3 at the intake to 0.8 mg/m^3 at the continuous miner for mines Q and T. Mean NO and NO_2 concentrations were also reported for the two mines, and the concentrations were well below regulated levels.

Haney (*35*) conducted tests of a single-jet impactor at five underground coal mines using diesel equipment. Miner exposure to DPM ranged from 0.18 to 1.00 mg/m^3, and area samples collected in haulageways agreed within 0.12 mg/m^3 of section worker exposure. At three mines, the single-jet impactor and PDEAS were used together at a sampling location. More than 60 paired data points were obtained, and respirable aerosol measurements agreed within 25 pct and DPM measurements agreed within 0.06 mg/m^3 of each other.

All of the DPM measurements made in coal and noncoal mines suggest that DPM contributes 40 to 60 pct of the respirable dust in areas of underground coal and noncoal mines where diesel haulage equipment is used without emission-control devices.

CONCLUSIONS AND RECOMMENDATIONS

The performance of two CDPF's at two underground metal mines (mines Q and T) was evaluated. The first test evaluated a CDPF followed by a DOC, while the second test evaluated a CDPF only. The CDPF-DOC was installed on an Elphinstone LHD powered by a Caterpillar 3306 prechambered, turbocharged engine at mine Q. Tests of this system in the laboratory yielded DPM collection efficiencies ranging from 41.0 to 93.5 pct. During in-mine tests, this system reduced DPM concentrations at the LHD by 71±29 pct, as determined by the concentration of <0.8-µm aerosol sampling with gravimetric analysis, and by 71±28 pct, as determined by RCD analysis.

The CDPF was installed on a Tamrock Oy diesel-hydraulic, roof-bolting jumbo, powered by a Deutz F6L912W engine at mine T. A similar CDPF evaluated in the laboratory reduced DPM emissions from 28 to 92 pct after 2,881 h of in-mine use. The CDPF evaluated underground reduced DPM concentrations at the roof-bolting jumbo location by an estimated 72±21 pct, as determined by the concentration of <0.8-µm aerosol sampling with gravimetric analysis, and by 62±25 pct, as determined by RCD analysis. In-mine measurements at this mine were more difficult, primarily because the roof-bolting jumbo moved almost daily, forcing the relocation of the sampling stations. Ventilation airflow rates varied by a factor of 10, aerosol was stratified at the downwind location, the number of roof bolts installed varied by nearly a factor of 3, and the mine used a high sulfur diesel fuel, which promotes the formation of sulfate particles as well as the deterioration of the catalyst.

Mean DPM concentrations at the operator's location or downwind site at mines Q and T ranged from 0.29 to 0.83 mg/m^3 with a median value of 0.39 mg/m^3 when no emission-control device was used and from 0.19 to 0.43 mg/m^3 with a median of 0.24 mg/m^3 when an emission-control device was installed. Where measured, the concentrations of the common gases found in diesel exhaust were well below regulated levels at these mines. The use of emission-control devices can reduce DPM exposure.

CDPF-DOC's and CDPF's are used to reduce DPM, CO, and HC emissions. These devices are used successfully on vehicles that have consistently heavy-duty cycles generating exhaust temperatures of 400 °C for 25 pct of the time. To ensure proper performance, the following recommendations are made:

1. Use a fuel with a sulfur content of 0.05 wt pct or below to minimize the production of sulfates and the risk of catalyst poisoning.
2. Before installation of the control devices, perform vehicle screening to determine if the exhaust temperature exceeds 400 °C for at least 25 pct of the time. Temperatures should be measured at the point where the control device is to be installed and under typical in-use conditions. If the vehicle's duty cycle changes, or if there is a change in engine condition after the control device is installed, the exhaust temperature should be remeasured to ensure proper regeneration.
3. Install the control devices as close to the exhaust manifold as possible to minimize the loss of exhaust heat. Minimize the number of pipe bends and length of exhaust pipe to reduce back pressure, and consider insulating the exhaust pipe and CDPF to minimize heat loss.
4. Install a back pressure gauge in the cab to alert the operator of excessive back pressure due to incomplete or faulty regeneration. CDPF's and CDPF-DOC's should be removed and cleaned if engine back pressure exceeds recommended levels. Consult with the CDPF supplier for the recommended cleaning procedures.
5. Periodically inspect and maintain all control device hardware to ensure proper function.
6. Instruct vehicle operators and mechanics on the control device functions and the steps to be taken to ensure maximum performance of the equipment.

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