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Evaluation of a Catalyzed Ceramic Diesel Particulate Filter and Catalytic Converter on an Underground Mine Vehicle

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ABSTRACT

The U.S. Bureau of Mines (USBM) and Diesel Controls Limited are evaluating a new diesel emission control system on an underground mine vehicle. The system is a catalyzed ceramic wall-flow diesel particulate filter (CDPF) combined with an oxidation catalytic converter (OCC). It is the first installation in the U.S. of a CDPF on a mining vehicle with a turbocharged engine at a high altitude mine, and the first installation of both a CDPF and an OCC on a mine vehicle.

This paper describes the design and installation of the system on the load-haul-dump (LHD) vehicle. The results of screening tests conducted by the USBM are also given. The screening tests were conducted to determine if the device's particulate collection efficiency, regeneration temperature, and effect on gaseous hydrocarbon (HC) and carbon monoxide (CO) emissions changed over the period it was being used.

The system was removed from the LHD and evaluated in the laboratory after operating for 308 and 1200 hours. After 308 hours of operation, laboratory testing revealed its particulate collection efficiency varied from 41.0 to 93.5 percent, depending on engine operating conditions. Its regeneration temperature was about 415° C. It reduced HC emissions by up to 97.6 percent, and CO by up to 95.0 percent. When tested in the laboratory after operating for 1200 hours on the vehicle, no significant change in performance was observed.

INTRODUCTION

Diesel-powered mining equipment offers a number of advantages over other types of materials handling equipment. Its mobility, versatility, and ruggedness make it adaptable to many different mining methods. Since the development of the articulated body, 4-wheel-drive load-haul-dump (LHD) in 1962, the use of diesel equipment has become widespread in underground mines.

In 1988, the National Institute for Occupational Safety and Health recommended that whole diesel exhaust be regarded as a "potential occupational carcinogen" (*1*).* The Mine Safety and Health Administration (MSHA), the regulatory agency responsible for overseeing mines in the U.S., has proposed new standards for the use of diesel equipment in underground coal mines, and is expected to recommend an exposure limit for diesel particulate matter (DPM) (*2*).

DPM is respirable and is composed of nonvolatile carbon with adsorbed or condensed compounds. These include potentially mutagenic or carcinogenic compounds, such as polynuclear aromatic hydrocarbons and sulfates. Typical mean concentrations of DPM in mines range from 0.2 to 1.0 mg/m^3(*3,4*). The USBM, in cooperation with mining companies and equipment manufacturers, is investigating a variety of emission controls for reducing miner exposure to DPM.

The objective of this paper is to present results from an ongoing evaluation of a catalyzed diesel particulate filter (CDPF) and oxidation catalytic converter (OCC) combined into one exhaust system. The CDPF and OCC were combined into one system to obtain significant reductions in DPM, carbon monoxide (CO) and gaseous hydrocarbon (HC) emissions. A noble metal catalyst was applied to the CDPF to reduce its regeneration temperature, and a precious metal catalyst was used on the OCC because of its efficiency in reducing CO and HC. The system was installed on an LHD and removed twice for evaluation in the laboratory.

DESIGN AND OPERATION OF CDPFs - CDPFs are used to filter DPM from diesel exhaust. The CDPF has a catalyst-coated, porous, ceramic substrate enclosed in a steel housing with channels running the length of the substrate (*5*). 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 wall, where filtering takes place. The exhaust exits through an adjacent channel. CDPFs remove 63 to 95 percent of the DPM from the exhaust (*6-8*).

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 engine backpressure increases. When the correct conditions are achieved, the DPM burns and the backpressure decreases. This self-cleaning process is

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

called regeneration. Typically, regeneration will occur when the temperature in the CDPF exceeds 400° C for an extended period of time (*9-10*). Because CDPFs rely on exhaust heat for regeneration, they are most often used on nonpermissible mine production vehicles that have exhaust temperatures exceeding 400° C for at least 25 percent of the duty cycle. These vehicles operate frequently at high power. If the CDPF reaches regeneration temperature often enough during a vehicle's duty cycle, the engine backpressure will remain within acceptable limits. However, if the vehicle's duty cycle or condition of the engine changes, such that regeneration does not occur, or occurs less frequently, the CDPF may become heavily loaded with DPM. An uncontrolled regeneration can occur when regeneration is initiated in a heavily loaded CDPF. If the DPM burns too quickly, the heat will not dissipate fast enough, causing thermal stresses that may crack or melt the ceramic substrate. A laboratory investigation of uncontrolled regeneration (*11*) showed exhaust temperatures exceeding 925° C, and CO emissions exceeding 5000 ppm, and concluded that as long as engine backpressure remained below the engine manufacturer's recommended limit, uncontrolled regeneration was unlikely to occur.

The primary reason to apply a catalyst to the ceramic substrate is to lower the regeneration temperature, but some catalysts will also reduce CO and HC emissions. The catalyst may be applied directly to the ceramic substrate, or on a washcoat. The washcoat improves performance by increasing the surface area of the substrate, and improves catalyst binding (*12*). The strength of the substrate may also be enhanced by the washcoat (*13*). The catalyst formulations may be either a base-metal or a noble-metal; new formulations are under development. One study (*6*) reported a decrease in CO emissions of 79 percent and HC emissions of 59 percent using a CDPF with a precious metal catalyst on a mining engine, when tested over a transient engine cycle. A fuel containing less than 0.05 percent sulfur should be used with a CDPF to minimize the formation of sulfate particulates.

DESIGN AND OPERATION OF OCCS - OCCs are used to reduce emissions of CO and HC, but they may also reduce DPM emissions. The OCC 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 flow through the channels and react with the catalyst. Depending on the type of engine, exhaust temperature, and catalyst formulation, OCCs oxidize 30 to 80 percent of the HC and 30 to 90 percent of the CO present (*14*). OCCs have little effect on carbon particulate, but DPM emissions are reduced because OCCs promote the oxidation of the soluble organic fraction of the DPM. Engine tests have shown DPM reductions of 30 to 50 percent (*14*). Because OCCs 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 OCCs are typically platinum or palladium-based, and dispersed on an aluminum oxide or silicon dioxide washcoat. Research is focusing on optimizing the proper combination of substrate, washcoat and catalyst (*14*).

PREVIOUS IN-MINE EVALUATIONS OF CDPFs - Previous evaluations of CDPFs used in underground mines have shown mixed results. A study of 18 CDPFs in Canadian mines reported that 8 were removed after an average of 1704 hours of operation because of failure to regenerate, physical deterioration, production of unusual odors, or other reasons. The remaining 10 CDPFs were still operable and had accumulated an average of 1984 hours of operation with one CDPF operating for over 4000 hours at the time of the report (*15*). However, similar problems of inadequate regeneration which leads to plugging of CDPFs, and unusual odors that concerned some vehicle operators were also reported for the filters which remained in service.

Another study evaluated two CDPFs that were used on two vehicles in two mines. The CDPFs were periodically removed from service and evaluated in the laboratory. The collection efficiency of one of the CDPFs decreased at five of six engine modes, and its regeneration temperature increased from 405° C to 420° C after 1,584 hours of vehicle operation (*16*).

VEHICLE APPLICATION

VEHICLE SELECTION - An LHD used for moving rock at an underground metal mine was selected for using the CDPF/OCC. LHDs are typically large vehicles working heavy-duty cycles, with high exhaust temperatures. They generate large quantities of exhaust that can diminish air quality in mines. These machines often work in development or production areas that usually have less airflow than other areas of the mine.

The CDPF/OCC was installed on an Elphinstone R1500 LHD, equipped with a Caterpillar 3306 PCTA diesel engine. The specifications for the LHD and its engine are listed in table 1.

Table 1.-- Load-Haul-Dump Specifications

Loader Make and Model	Elphinstone R1500
Rated capacity	9000 kg
Bucket size	5.7 m^3
Overall length	9195 mm
Overall width	2440 mm
Overall height	2200 mm
Operating weight	25,100 kg
Laden weight	34,100 kg
Engine Make and Model	CAT 3306 PCTA
Displacement	10.5 L
Cylinders	6 in-line
Aspiration	Turbocharged-aftercooled
Rated Power	175 kW @ 2200 rpm
Exhaust Gas Flow	2547 m^3/h @ 457° C

The LHD's duty cycle was 1) loading ore into its bucket from a drawpoint, 2) hauling the load 13 to 48 m, 3) dumping down an orepass, and 4) returning unloaded to the drawpoint. The vehicle hauled 35 to 50 loads per hour, depending on the haul distance.

The exhaust temperature was measured downstream of the turbocharger during normal vehicle operation to determine if the vehicle was suitable for the CDPF/OCC. A 1-1/2-hour temperature trace is shown in figure 1. Because the temperature exceeded 450° C most of the time, the loader was considered an excellent choice for the CDPF/OCC.

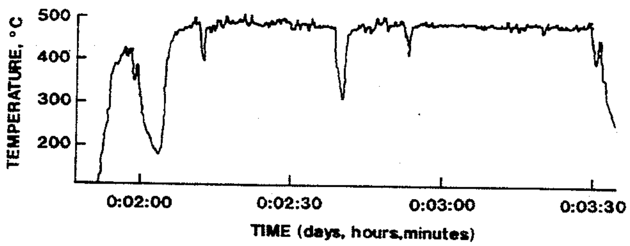

Figure 1.--LHD exhaust gas temperature trace.

CDPF/OCC DESIGN AND INSTALLATION - The CDPF and OCC were sized according to the exhaust gas flow. A base metal catalyst was applied to the CDPF to reduce its regeneration temperature, and the OCC used a precious metal catalyst because it is very efficient at reducing CO and HC. Specifications for the CDPF and OCC are given in table 2. Due to limited space on the vehicle, the CDPF and the OCC were housed in one canister (figure 2). The OCC was placed inside the outlet cone.

Table 2.--CDPF/OCC Specifications

CDPF Model	Mine-X sootfilter 15 x 15
Substrate	Ceramic wall-flow monolith
Diameter x height	381 by 381 mm
Cell density	100 cpsi
Wall thickness	0.43 mm
Catalyst	Base Metal
OCC Model	Mine-X DC10
Substrate	Metal flow-through honeycomb
Diameter x height	216.7 by 100 mm
Cell density	200 cpsi
Catalyst	Noble metal on stabilized alumina washcoat

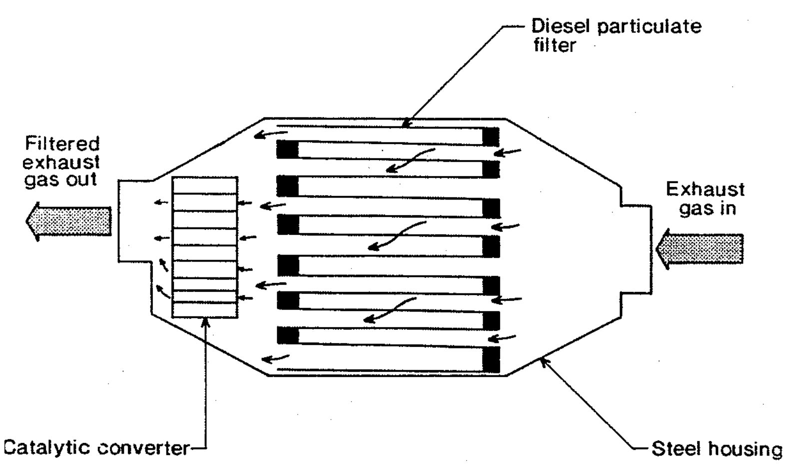

Figure 2.--Schematic of CDPF/OCC.

The CDPF/OCC 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 much smaller size (figure 3). The

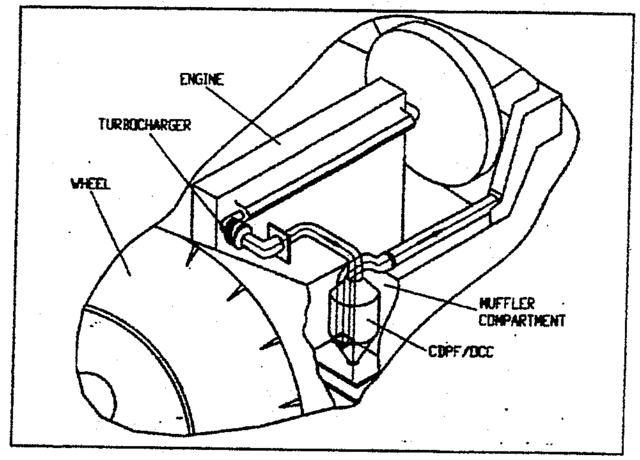

Figure 3.--Schematic of CDPF/OCC installation on LHD.

clearance between the CDPF/OCC and compartment walls was about 15 mm. The muffler compartment was not high enough to accommodate the CDPF/OCC, 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 engine area and exhaust system of the vehicle is shown in figure 4.

A control panel was installed in the operator's cab. The control panel had exhaust temperature and backpressure gauges for monitoring filter performance. A warning light was also provided to alert the operator when the backpressure reached 10 kPa.

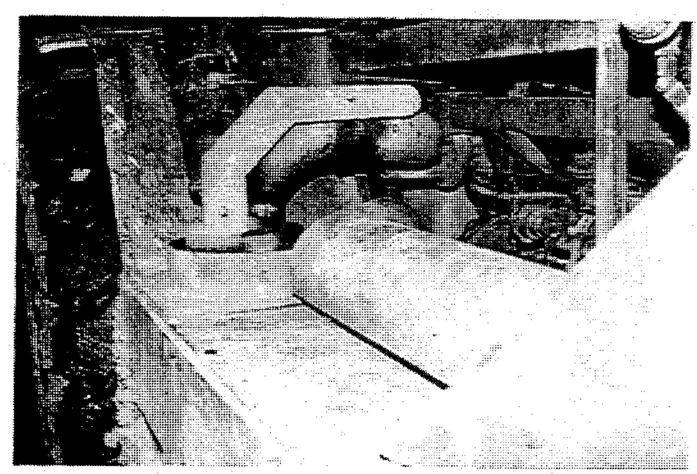

Figure 4.--Engine area and exhaust system of LHD.

EXPERIMENTAL METHODS

TEST FACILITY AND ENGINE - All laboratory tests of the CDPF/OCC were conducted in the USBM's Diesel Emission Research Laboratory (*17*). Testing was conducted using a Caterpillar 3304 prechamber, naturally aspirated engine, rated at 74.6 kW at 2200 rpm, with a peak torque of 380 N·m at 1,200 rpm. This engine is smaller than the 172.3 kW engine used at the mine. A low sulfur fuel (0.03-0.04 wt percent) was used for all tests.

TEST PROCEDURE - The CDPF/OCC was evaluated in the laboratory after 308 and 1200 hours of in-mine service. The test procedure was designed to determine the CDPF/OCC's particulate collection efficiency and its effect on CO and HC emissions. Testing was also conducted to measure regeneration temperature, the temperature where the amount of DPM being collected equals the amount being regenerated, as measured by the change in pressure across the CDPF/OCC. Engine baseline emissions and emissions with the CDPF/OCC were collected each time the unit was evaluated. No attempt was made to duplicate the conditions the CDPF/OCC experienced in the mine.

DPM COLLECTION EFFICIENCY TESTING AND GAS SAMPLING - The CDPF/OCC collection efficiency was determined under steady-state engine conditions. The CDPF/OCC was evaluated at the ten steady-state modes described in table 3. These modes were selected because MSHA has proposed them as engine test conditions for determining a "particulate index." The particulate index would be used by mine operators and by MSHA for evaluating and approving minimum dilution air quantities in mine ventilation plans (*2*). The engine conditions also produce a wide range of exhaust temperatures, including several modes where the CDPF will regenerate.

During the collection efficiency tests, DPM samples were obtained with and without the CDPF/OCC installed. One sample was obtained at each mode and sampling times varied from 15 to 30 minutes without the CDPF/OCC, and 60-minute samples were collected with the CDPF/OCC installed. CO and HC emissions were measured in the raw exhaust. The methods for DPM and gas sampling are described in reference 17. The CDPF/OCC temperature was measured at the inlet face of the CDPF substrate.

Table 3.--Ten steady-state engine conditions

Mode	Speed (rpm)	Load (percent)
1	2200	100
2	2200	75
3	2200	50
4	2200	25
5	2200	10
6	1500	100
7	1500	75
8	1500	50
9	1500	25
10	1500	10

REGENERATION TEMPERATURE TESTING - During the regeneration temperature test, the engine was operated at a constant speed of 1800 rpm and the load was increased from 27.1 N·m to 339 N·m at a rate of 1.02 N·m/min. The CDPF/OCC temperature increased slowly, from about 170° C to 520° C. The pressure drop across the CDPF/OCC was monitored to determine when it was stable. The temperature of the CDPF/OCC at that condition was defined as the regeneration temperature. At this condition, the amount of DPM accumulating in the CDPF is the same as the amount being burned off, as measured by the pressure drop across the CDPF/OCC. The ramp test differs from the steady-state tests used to determine collection efficiency, because the temperature slowly increases with load as opposed to remaining constant for each steady-state mode. Slowly increasing the exhaust temperature allows the regeneration temperature to be determined.

RESULTS AND DISCUSSION

MINE EXPERIENCE - The performance of the emissions control system was evaluated in the mine. The mine evaluation was concerned mostly with proper CDPF regeneration. Since a low filter pressure drop is an indication of good regeneration, weekly backpressure readings were taken at an engine stall condition using the CDPF/OCC control panel. Measurements were conducted by mine maintenance personnel during the first 220 hours (5 weeks) of operation. During this period the CDPF/OCC backpressure was stable at about 5 kPa. Once, a backpressure of 7.5 kPa was observed after the LHD was used for road maintenance. The vehicle did not work as hard during that time, resulting in DPM accumulating in the CDPF.

Visible smoke was eliminated completely by the CDPF/OCC except at some startup times. The operators experienced no loss of power or any other unfavorable effects. The noise attenuation of the unit was found to be equal or better than that of the original muffler. Approximate emissions measurements using Draeger tubes showed CO concentrations from 0 to 100 ppm, while the mine recommended maximum level was 150 ppm.

Apart from the weekly monitoring conducted by the mine crew, the backpressure of the CDPF/OCC unit was recorded on the LHD twice. The first recording was taken after installing the unit, the second 261 engine hours later. The results for both backpressure and exhaust gas temperature are shown in figure 5. Time units are (days : hours : minutes), so the first recording covers 20 hours and the second over 42 hours. Both recordings were taken during the vehicle's regular duty cycle. The temperature was consistently above 450° C. The backpressure on the new, clean unit was about 5.5 kPa. After 261 hours, it increased to 6 kPa with very short periods exceeding 6 kPa. Both recordings show consistent maximum backpressure levels, indicating continuous regeneration of the CDPF.

LABORATORY RESULTS - Regeneration Temperature - The regeneration temperature decreased from 415° C after 304 hours, to 405° C after 1200 hours. One study of three base-metal CDPFs has shown that the regeneration temperature increased by 20 to 50° C after thermal aging using a diesel fuel burner for regeneration (*18*). This was not observed on the CDPF/OCC after 1200 hours of use.

Gaseous Emissions - The CDPF/OCC, depending on engine mode, reduced CO emissions (table 4), from 8.5 to 95.0 percent after 308 hours, and from 1.5 to 86.0 percent after 1200 hours of in-mine service. The CDPF/OCC was also effective at reducing HC emissions, with reductions of 43.1 to 97.6 percent after 308 hours, and 13.7 to 85.9 percent after 1200 hours. The amount of reduction increased with exhaust temperature. Similar reductions in CO and HC emissions with increasing temperature were observed in a study of a CDPF using a platinum-based catalyst (*6*), and in an evaluation of OCCs at simulated altitudes (*19*).

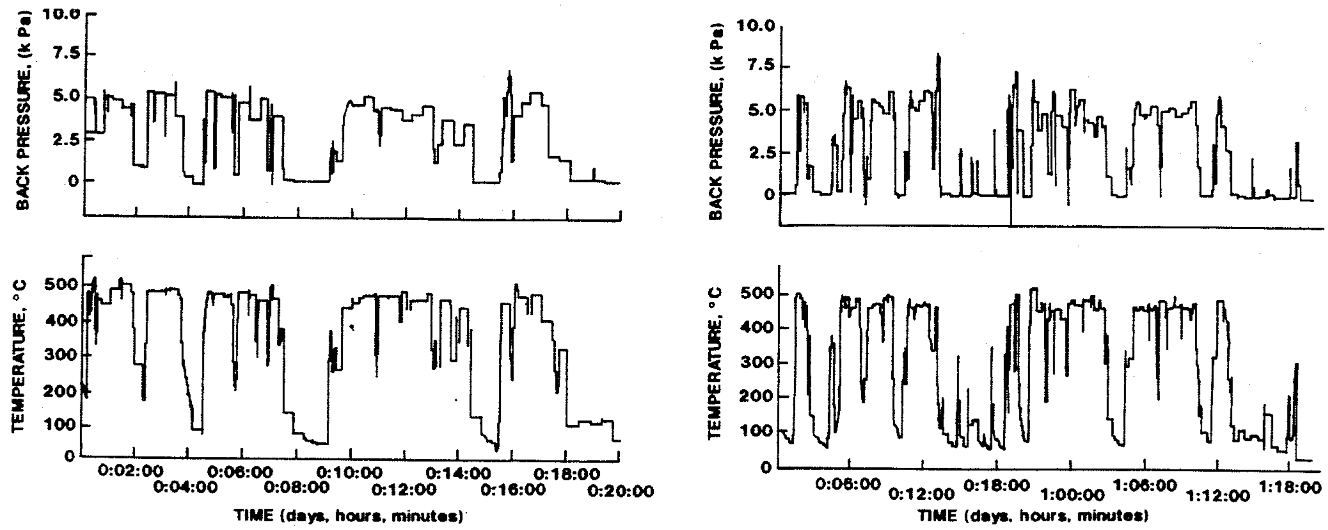

Figure 5.--Backpressure and exhaust gas temperature traces when CDPF/OCC was new (left) and after 261 hours (right).

Table 4.--Effect of CDPF/OCC on CO and HC concentrations

Time of operation (hours)	Mode	CO concentration (ppm)		HC concentration (ppm)		Reduction in CO (pct)	Reduction in HC (pct)	CDPF temperature (° C)
		With CDPF/OCC	Without CDPF/OCC	With CDPF/OCC	Without CDPF/OCC			
308	1	9.4	168.2	6.5	85.4	94.4	92.4	584
	2	6.9	137.2	3.8	65.6	95.0	94.2	435
	3	12.4	161.5	12.9	82.2	92.3	84.3	336
	4	14.0	154.4	22.2	82.9	90.9	73.2	25
	5	42.0	164.4	40.3	82.1	74.5	50.9	211
	6	11.3	155.9	1.8	74.8	92.8	97.6	546
	7	11.7	119.2	7.4	88.1	90.2	91.6	353
	8	9.2	83.0	16.4	75.8	88.9	78.4	257
	9	42.4	91.2	44.1	77.5	53.5	43.1	183
	10	148.1	161.9	47.0	85.3	8.5	44.9	142
1200	1	15.8	98.0	11.5	62.5	83.9	81.6	576
	2	16.9	121.1	8.8	62.2	86.0	85.9	442
	3	24.5	150.1	20.9	82.7	83.7	74.7	340
	4	49.2	149.2	45.6	83.2	67.0	45.2	258
	5	120.0	149.8	74.9	86.8	19.9	13.7	214
	6	22.6	128.3	22.1	91.4	82.4	75.8	540
	7	21.4	124.6	24.1	107.7	82.8	77.6	354
	8	24.5	92.8	37.7	123.0	73.6	69.4	257
	9	74.3	99.1	59.5	111.2	25.0	46.5	182
	10	140.4	142.5	59.3	90.9	1.5	34.8	140

DPM Collection Efficiency - The DPM collection efficiency of the CDPF/OCC after 308 hours, as shown in table 5, ranged from 41.0 to 93.5 percent. The lowest collection efficiencies were observed at modes 1 and 6. The exhaust temperatures at both of these modes exceeded 540° C, and the CDPF was regenerating. The lower collection efficiency could be due to the release of sulfate (*20*), and to particles driven off during regeneration when oxidation and breakup of particulate collected within the CDPF occurs (*21*). It is also possible that oxidation and breakup of particulate that may have accumulated on the OCC was occurring at these high exhaust temperatures.

The collection efficiency after 1200 hours varied with engine condition compared to the testing conducted at 308 hours.

During testing after 1200 hours, problems that occurred during the filter weighing procedure prevented obtaining an accurate measure of collection efficiency at mode 1. The largest change was noted at mode 6, where the collection efficiency decreased from 43.4 percent to 18.9. The collection efficiency at all other conditions exceeded 60 percent. The low collection efficiencies at mode 6 could be due to the release of sulfate and particulate.

Table 5.--CDPF/OCC particulate collection efficiency

Time of operation (hours)	Mode	DPM concentration (mg/sm^3) With CDPF/OCC	Without CDPF/OCC	CDPF collection efficiency (pct)
308	1	37.0	62.7	41.0
	2	15.3	46.7	67.2
	3	4.8	73.8	93.5
	4	9.7	87.8	89.0
	5	14.0	93.1	85.0
	6	36.7	64.8	43.4
	7	6.8	33.5	79.7
	8	11.5	50.6	77.3
	9	17.4	50.4	65.5
	10	18.9	60.6	68.8
1200	1	41.4	NA	NA
	2	9.9	31.2	68.3
	3	3.0	59.4	95.0
	4	8.8	73.8	88.1
	5	19.9	78.6	74.7
	6	33.4	41.2	18.9
	7	2.4	26.7	91.0
	8	7.3	63.8	88.6
	9	23.1	60.5	61.8
	10	17.4	48.3	64.0

NA = Not Available

SUMMARY

A new exhaust control system consisting of a CDPF and OCC, was designed and installed on a mine production vehicle. The CDPF/OCC is the first installation in the U.S. of a CDPF on a mining vehicle with a turbocharged engine at high altitude, and the first installation of both a CDPF and an OCC on a mine vehicle.

Visible smoke was eliminated completely by the CDPF except during startup. The operators had experienced no loss of power. The noise attenuation of the CDPF/OCC was found to be equal or better than that of the original muffler. Measurements using Draeger tubes showed CO concentrations less than 100 ppm, while the mine typically observed CO concentrations of 150 ppm. Backpressure measurements taken while the vehicle was operating indicated that the CDPF was regenerating well, demonstrating that this was a good application for this device.

The system was removed from the LHD and evaluated in the laboratory after operating for 308 and 1200 hours. After 308 hours of operation, laboratory testing revealed its collection efficiency varied from 41.0 to 93.5 percent, depending on engine operating condition. Its regeneration temperature was about 415° C. It reduced HC emissions by up to 97.6 percent, and CO by as much as 95.0 percent. When tested in the laboratory after operating for 1200 hours on the vehicle, no significant change in performance was observed.

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