RI 9478

REPORT OF INVESTIGATIONS/1993

Evaluation of Catalyzed Diesel Particulate Filters Used in an Underground Metal Mine

By John J. Baz-Dresch, Kenneth L. Bickel, and Winthrop F. Watts, Jr.

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Bruce Babbitt, Secretary

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Library of Congress Cataloging in Publication Data:

Baz-Dresch, John J.
Evaluation of catalyzed diesel particulate filters used in an underground metal mine / by John J. Baz-Dresch, Kenneth L. Bickel, and Winthrop F. Watts, Jr.

p. cm. — (Report of investigations; 9478)

Includes bibliographical references (p. 13).

Supt. of Docs. no.: I28.22:199

1. Diesel motor exhaust gas—Purification. 2. Air filters—Testing. I. Bickel, Kenneth L. II. Watts, W. F. (Winthrop F.). III. Title. IV. Series: Report of investigations (United States. Bureau of Mines); 9478.

TN23.U43 [TN305] 622 s—dc20 [622'.82] 93-5103 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	μm	micrometer
cm	centimeter	mt	metric ton
gal	gallon	mt/d	metric ton per day
h	hour	N•m	newton meter
hp	horsepower	N•m/min	newton meter per minute
Hz	hertz	pct	percent
in	inch	ppm	part per million
in H_2O	inch of water	rpm	revolution per minute
kPa	kilopascal	t	ton
kW	kilowatt	t/d	ton per day
L	liter	wt pct	weight percent
lb•ft	pound foot	yd^3	cubic yard
lb•ft/min	pound foot per minute	$/h	dollar per hour
m^3	cubic meter	$/mt	dollar per metric ton
mg/sm^3	milligram per standard cubic meter	$/t	dollar per ton
min	minute		

EVALUATION OF CATALYZED DIESEL PARTICULATE FILTERS USED IN AN UNDERGROUND METAL MINE

By John J. Baz-Dresch,[1] Kenneth L. Bickel,[2] and Winthrop F. Watts, Jr.[3]

ABSTRACT

Catalyzed diesel particulate filters (CDPF's) reduce the concentration of diesel particulate matter (DPM) and may reduce the emissions of carbon monoxide (CO) and hydrocarbons (HC) in diesel exhaust. Asamera Minerals' Cannon Mine first installed CDPF's in 1987, and currently has 12 diesel-powered vehicles equipped with CDPF's.

The Cannon Mine and the U.S. Bureau of Mines collaborated to evaluate the durability and performance of a CDPF. One of the CDPF's used at the mine was periodically evaluated in the USBM's diesel emissions laboratory after 839, 1,584, and 2,881 h of in-mine service. The objectives of this report are to present results from the USBM's evaluation of this CDPF, to describe the Cannon Mine's experience and cost analysis of using CDPF's, and to make recommendations for the future use of CDPF's.

CDPF's improve air quality at the Cannon Mine, but they frequently become plugged and are subject to excessive mechanical shocks and stress, shortening their useful life. Mine records indicate that CDPF's account for 0.8 to 4.9 pct of the vehicles' operating cost at the mine. CDPF life to date has ranged from 1,671 h to more than 5,992 h. Laboratory tests of the CDPF determined that DPM removal efficiency decreased and regeneration temperature increased over time.

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INTRODUCTION

DESIGN AND OPERATION OF CDPF's

CDPF's are used to filter DPM from diesel exhaust. The CDPF has a catalyst-coated, porous, ceramic substrate enclosed in a steel housing with longitudinal channels (*1*).[4] In the inlet end, every other channel is plugged with ceramic material, while the adjacent channel is plugged at the outlet end (fig. 1). 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. CDPF's remove 63 to 95 pct of the DPM from exhaust (*2-4*). 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 operate frequently at high power, e.g., engines on vehicles that climb a ramp many times each shift.

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 backpressure on the engine increases. When the correct conditions are achieved in the CDPF, the DPM burns and the backpressure decreases. This self-cleaning process is called regeneration. Typically, complete regeneration occurs when the temperature in the CDPF exceeds 400° C for approximately 15 to 20 min (*5-6*).

If the CDPF reaches regeneration temperature frequently during a vehicle's duty cycle, the engine backpressure will remain within acceptable limits. However, if the vehicle's duty cycle or 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 laboratory investigation of uncontrolled regeneration (*7*) showed exhaust temperatures can exceed 925° C and CO emissions can exceed 5,000 ppm. This study concluded that as long as the engine backpressure 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 to apply a catalyst to the ceramic substrate is to lower the regeneration temperature, but some catalysts also reduce CO and gaseous HC emissions. The catalyst is applied on a washcoat, the composition of which varies by manufacturer. The washcoat improves performance by increasing the surface area of the substrate and improves catalyst binding (*8*). The strength of the substrate may also be enhanced by the washcoat (*9*). The catalyst formulations are proprietary. They are either base metal or noble metal, and new formulations are currently under development for heavy-duty diesel engines. One study of a CDPF on a mining engine tested over a transient engine cycle reported a decrease in CO emissions of 79 pct and HC emissions of 59 pct (*2*). A fuel containing less than 0.05 pct sulfur should be used with a CDPF to minimize the formation of sulfate particulates.

The objectives of this report are to present results from the U.S. Bureau of Mines' evaluation of a CDPF used at the Cannon Mine, to describe the mine's experience and cost analysis of the CDPF's, and to make recommendations for the use of CDPF's. This work was done as part of a USBM program to improve the health of the Nation's miners.

CANNON MINE—A FILTER USER AND TEST SITE

The Cannon Mine of Asamera Minerals is a 1,294-mt/d (1,427-t/d) underground gold mine located on the outskirts of the city of Wenatchee, WA. Declining ore reserves have recently forced a drop to 967 mt/d (1,065 t/d). Wenatchee lies on the eastern slope of the Cascade Mountains midway between Seattle and Spokane.

In September 1987, the Cannon Mine became the first U.S. mine to install a CDPF, and the mine has continued to use CDPF's to reduce DPM emissions from underground diesel equipment. Currently, the mine has CDPF's installed on one roof-bolting jumbo, one road grader, five 23.6-mt (26-t) trucks, two 3.8-m^3 (5-yd^3) load-haul-dumps (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.

In 1990, Asamera Minerals and the USBM entered into a cooperative agreement to study the durability and performance of a CDPF, over time. The CDPF was installed on a 3.8-m^3 (5-yd^3) LHD powered by a Deutz[5] F10L413 FW engine rated at 172.3 kW (231 hp) at 38.3 Hz (2,300 rpm). The duty cycle of this LHD is similar to other LHD's in many trackless underground mines using truck haulage. The LHD often loads trucks rather than tramming to the ore pass. When loading a truck, the LHD makes four passes in the muck pile, then either idles while waiting for another truck or shuts down while the operator drives the truck to the ore pass. When loading in this location is completed, the LHD is driven to a new

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

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

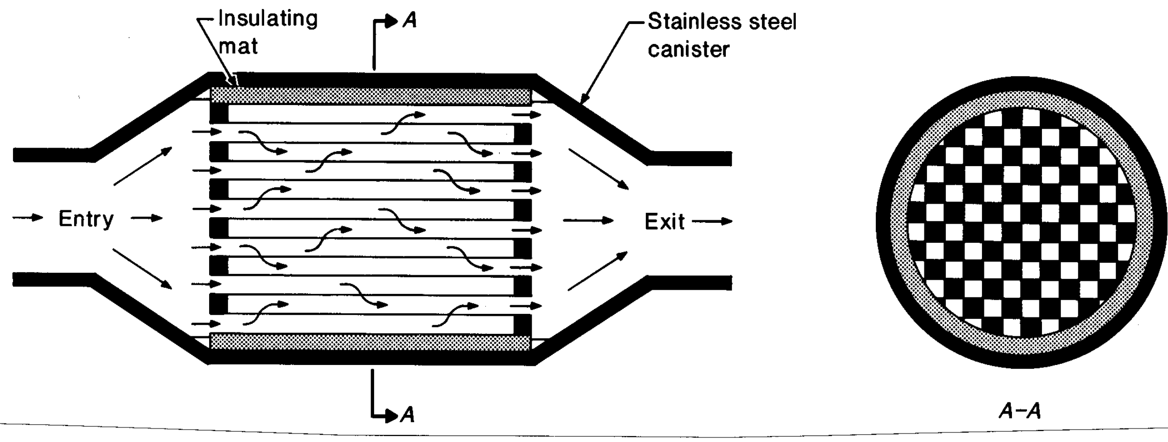

Figure 1.—Schematic of CDPF.

location. Temperature traces of the LHD's exhaust obtained prior to installation of the CDPF indicate that exhaust temperatures periodically exceed 400° C and are sufficient to initiate regeneration. However, concerns now exist that the exhaust temperature may not be sustained long enough to allow sufficient regeneration.

The CDPF replaced the LHD's catalytic converter and muffler and was installed on the right side of the LHD next to the engine compartment just after the point where the right and left exhaust manifolds merge. The exhaust pipe from the left side of the engine runs behind the engine, merges with the exhaust from the right side of the engine, and then enters the CDPF. This does allow the exhaust from the left side to cool before entering the CDPF.

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 (*10*). 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 washcoat and catalyst increased 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. The objective of the laboratory investigation was to determine whether the regeneration temperature, collection efficiency, and CO and HC removal efficiency changed with use.

PREVIOUS IN-MINE EVALUATIONS OF CDPF's

Previous evaluations of CDPF's used in underground mines have shown mixed results. A study of 18 CDPF's in Canadian 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 (*11*). However, similar problems of inadequate regeneration, which 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 diesel particulate filters (DPF's) and CDPF's on 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. DPF's and CDPF's are said to decrease vehicle maintenance costs (*12*) by reducing the frequency of vehicle removal from service because of exhaust smoke. However, this may lead to higher engine maintenance costs over the long term, because maintenance personnel frequently use smoke characteristics as an indicator of engine problems.

Another study (*13*) 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. Ash accumulation was apparent because the baseline backpressure had increased from 2.5 to 4.0 kPa (10 to 16 in H_2O).

LABORATORY TEST PROCEDURE

The CDPF was evaluated in the USBM's diesel research laboratory (*14*) after 839, 1,584, and 2,881 h of in-mine service over a period of 21 months. The test procedure was designed to determine the CDPF's particulate collection efficiency, its effect on CO and HC emissions, and its regeneration temperature. Regeneration temperature is defined as the temperature at which the amount of DPM being collected equals the amount being regenerated, as measured by the change in pressure across the CDPF. Engine baseline emissions and emissions with the CDPF were collected each time the CDPF was evaluated. No attempt was made to duplicate the exhaust flow conditions the CDPF experienced in the mine.

Testing was conducted using a Caterpillar 3304 prechambered, naturally aspirated engine rated at 74.6 kW (100 hp) at 36.7 Hz (2,200 rpm) with a peak torque of 380 N•m (280 lb•ft) at 20 Hz (1,200 rpm). This engine is smaller than the 172.3-kW (231-hp) engine used at the mine, with a lower exhaust flow. The CDPF has a lower space velocity when used on the Caterpillar engine. This probably resulted in higher DPM collection efficiencies and enhanced CO and HC removal. A low-sulfur fuel (0.03 to 0.04 wt pct) was used for all tests.

The CDPF was prepared for laboratory evaluation by placing one 0.16-cm (0.63-in) diameter k-type thermocouple 2.5 cm (1.0 in) into the center of the substrate face on both the inlet and outlet ends to measure temperatures (fig. 2). The thermocouples were installed through thermocouple fittings welded to the canister.

Pressure ports were installed at the inlet and outlet of the canister to monitor the pressure drop across the CDPF. The difference in pressure between the inlet and outlet of the CDPF is an indication of how much particulate is trapped. When the CDPF is regenerating, the pressure drop decreases.

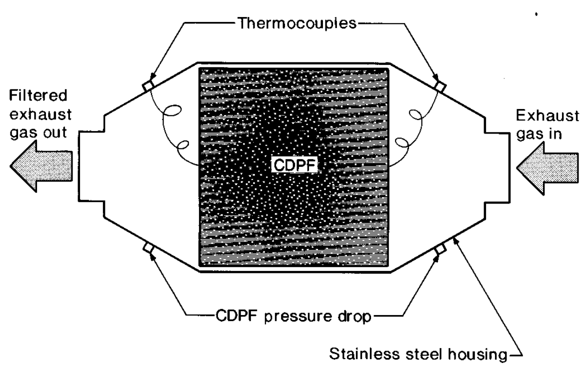

Figure 2.—Location of thermocouples and pressure ports on CDPF.

Upon arrival at the USBM, the CDPF was examined visually for physical damage and for evidence of plugging. If plugging was suspected, the CDPF was installed in the laboratory and the engine backpressure was measured. If the backpressure exceeded the manufacturer's recommended maximum, it was removed and blown out with compressed air to remove as much DPM as possible. This reduced the potential for an uncontrolled regeneration. Testing proceeded only when engine backpressure was less than 7.5 kPa (30 in H_2O).

DPM COLLECTION EFFICIENCY AND EMISSIONS SAMPLING

The CDPF collection efficiency was evaluated at the six steady-state modes described in table 1. These modes were selected because they represent operating modes an LHD might experience in a mine (*15*) and because they have a wide range of exhaust temperatures, including modes 3 and 6 where the CDPF should regenerate.

Table 1.—Six steady-state engine conditions

Mode	Speed		Load,
	Hz	rpm	pct
1	20	1,200	50
2	20	1,200	75
3	20	1,200	100
4	30	1,800	50
5	30	1,800	75
6	30	1,800	100

During the collection efficiency tests, DPM samples were obtained with and without the CDPF installed. One to three samples were obtained at each mode. Sampling times were 15 to 30 min without the CDPF installed, and 60 min with the CDPF installed. CO and HC emissions were measured as described by others (*14*).

REGENERATION TEMPERATURE TESTING

The regeneration temperature was determined using an engine ramp test procedure. The engine was operated at a constant speed of 30 Hz (1,800 rpm) and the load was increased from 27.1 N•m (20 lb•ft) to 339 N•m (250 lb•ft) at a rate of 1.02 N•m/min (0.75 lb•ft/min). The CDPF temperature increased slowly, from about 170° to 520° C. The pressure drop across the CDPF was monitored to determine the regeneration temperature. The ramp test differs from the steady-state tests used to determine collection efficiency because the exhaust temperature slowly increases with load, allowing the regeneration temperature to be determined, as opposed to remaining constant for each steady-state mode test.

LABORATORY RESULTS

REGENERATION TEMPERATURE

The regeneration temperature of the CDPF increased from 405° C after 839 h to 450° C after 2,881 h. Possible explanations for this temperature increase are (1) DPM and ash buildup covered much of the active portion of the catalyst, reducing catalyst effectiveness by masking sites for catalytic activity, and (2) catalyst performance was affected by poisoning, sintering, or some other cause (*16*). One study of three base-metal CDPF's has shown that the regeneration temperature increased by 20° to 50° C after thermal aging using a diesel fuel burner for regeneration (*17*).

GASEOUS EMISSIONS

The CDPF, depending on the engine mode, reduced CO emissions (table 2) from 21.3 to 64.8 pct after 839 h, from 14.3 to 57.5 pct after 1,584 h, and from 2.9 to 42.1 pct after 2,881 h of in-mine service. A 14.9-pct increase in CO emissions was observed at mode 6 after 2,881 h. The CDPF regenerates at mode 6, and the amount of CO emitted depends on the particulate loading and rate of regeneration (*7*).

The CDPF was also effective at reducing HC emissions (table 2), with reductions of 5.4 to 89.7 pct after 839 h, 23.1 to 76.5 pct after 1,584 h, and 39.4 to 83.2 pct after 2,881 h. Similar CO and HC reductions with increasing temperature were observed by Bagley (*2*) in a study of a CDPF using a platinum-based catalyst.

A wide range of CO and HC removal efficiency is expected over the six steady-state modes because removal efficiency is primarily dependent upon CDPF temperature for catalyst activation (*2*).

Table 2.—Effect of CDPF on CO and HC emissions at different temperatures, over time

Time of operation, h	Mode	CO concentration, ppm		HC concentration, ppm		Reduction in CO emissions, pct	Reduction in HC emissions, pct	CDPF temperature, °C
		Without CDPF	With CDPF	Without CDPF	With CDPF			
839	1	57.2	45.0	25.7	24.3	21.3	5.4	235.0
	2	66.0	26.8	43.4	15.3	59.4	64.7	334.0
	3	203.3	73.8	39.4	6.3	63.7	84.0	537.0
	4	91.1	46.0	59.4	28.6	49.5	51.9	294.0
	5	104.5	36.8	68.2	15.2	64.8	77.7	405.0
	6	124.3	63.7	64.2	6.6	48.8	89.7	577.0
	Mean	107.7	48.7	50.1	16.1	51.3	62.2	397.0
	STD	52.9	17.3	16.5	9.1	16.2	31.0	136.3
1,584	1	45.3	38.8	45.1	34.7	14.3	23.1	256.0
	2	64.1	39.3	54.2	25.0	38.7	53.9	344.0
	3	290.7	152.4	47.4	13.6	47.6	71.3	547.0
	4	82.7	50.6	64.8	38.7	38.8	40.3	293.0
	5	93.6	45.5	74.0	25.9	51.4	65.0	400.0
	6	195.7	83.2	63.0	14.8	57.5	76.5	576.0
	Mean	128.7	68.3	58.1	25.5	41.4	55.0	402.7
	STD	95.1	44.4	11.1	10.2	15.1	20.3	132.6
2,881	1	60.8	44.8	66.3	36.0	26.3	45.7	243.0
	2	71.9	41.6	78.5	29.3	42.1	62.6	342.0
	3	410.6	398.8	78.2	21.0	2.9	73.1	568.0
	4	98.2	70.8	78.2	47.4	27.9	39.4	292.0
	5	111.9	67.3	88.4	32.9	39.9	62.7	396.0
	6	135.7	156.0	87.0	14.6	-14.9	83.2	568.0
	Mean	148.2	129.9	79.4	30.2	20.7	61.1	401.5
	STD	131.4	138.2	7.9	11.5	22.3	16.4	138.7

STD Standard deviation.

DPM COLLECTION EFFICIENCY

The DPM collection efficiency of the CDPF after 839 h, as described in table 3, ranged from 85.5 to 94.5 pct at modes 1 to 5. At mode 6, where the CDPF regenerates, its DPM collection efficiency was 48.1 pct. The lower collection efficiency at mode 6 may be due to the release of sulfate (*18*). Particles can be driven off the CDPF during regeneration when oxidation and breakup of the collected DPM occur, leading to lower collection efficiencies (*19*).

The collection efficiency of the CDPF after 1,584 h decreased at five of the six engine modes by at least 15 pct when compared with the testing at 839 h. The collection efficiency ranged from 81.9 pct at mode 5 to 41.2 pct at mode 3. The collection efficiency after 2,881 h ranged from 82.2 pct at mode 2 to 28.5 pct at mode 3. When compared with collection efficiency data after 1,584 h, a decrease in collection efficiency of 15 pct or more occurred at modes 3 and 4. Problems that occurred during the filter weighing procedure prevented obtaining an accurate measure of collection efficiency at mode 6.

The lowest collection efficiencies were at modes 3 and 6, where regeneration occurs, probably due to the release of sulfur stored during testing at lower exhaust temperatures, which is released as particulate matter.

No damage could be seen on the inlet or outlet faces of the ceramic substrate after 2,881 h, but internal damage is suspected because of the lower collection efficiency. The damage could have occurred because of mechanical shock and vibration, cracking or melting of the ceramic due to uncontrolled regeneration, or a cracked substrate, resulting from repeated thermal stresses during repeated regeneration.

Table 3. - CDPF particulate collection efficiency

Time of operation, h	Mode	DPM concentration, mg/sm³		CDPF collection efficiency, pct
		Without CDPF	With CDPF	
839	1	21.1	3.0	85.5
	2	24.0	2.1	91.2
	3	137.7	17.7	87.1
	4	44.7	3.2	92.7
	5	34.5	1.9	94.5
	6	40.3	20.9	48.1
	Mean	50.4	8.1	83.2
	STD	43.7	8.7	17.5
1,584	1	24.6	9.6	60.9
	2	23.1	9.0	60.8
	3	143.9	84.6	41.2
	4	42.6	9.9	76.8
	5	38.0	6.9	81.9
	6	63.2	31.4	50.3
	Mean	55.9	25.2	62.0
	STD	45.5	30.5	15.4
2,881	1	43.1	9.0	79.1
	2	43.2	7.7	82.2
	3	164.1	117.3	28.5
	4	40.3	16.3	59.6
	5	28.6	6.4	78.4
	6	NAp	NAp	NAp
	Mean	63.9	31.3	65.5
	STD	56.4	48.2	22.6

NAp Not applicable.
STD Standard deviation.

SUMMARY OF LABORATORY RESULTS

1. The regeneration temperature of the CDPF increased from 405° to 450° C after 839 and 2,881 h of operation, respectively.

2. The CDPF reduced CO emissions by 21.3 to 64.8 pct and HC emissions by 5.4 to 89.7 pct after 839 h, depending on the engine mode. The CDPF was still effective at lowering CO and HC emissions after 1,584 h and 2,881 h, although its CO conversion efficiency was reduced considerably at modes 3 and 6, when the CDPF was regenerating. In most instances the emissions reductions were within 20 pct of the reductions measured after 839 h.

3. The collection efficiency of the CDPF decreased when measured after 1,584 h of operation, and again after 2,881 h, suggesting damage to the substrate. Its collection efficiency after 2,881 h showed a wide range from 82.2 to 28.5 pct.

4. A CDPF can lower DPM concentrations in exhaust. Depending on the type of catalyst used, it can also reduce emissions of CO and HC. Its performance, however, will change with use. This change could be due to physical damage to the ceramic or to a change in the catalyst that affects performance.

CANNON MINE'S EXPERIENCE WITH CDPF'S

CLEANING OF CDPF'S

Cleaning of plugged CDPF's with a water-pressure washer without detergent is a common practice at the Cannon Mine, because not all the CDPF's regenerate properly. It is not known exactly how cleaning affects filtration efficiency and catalyst performance, but it is suspected that using a pressure washer to clean CDPF's may be detrimental to the ceramic substrate. Water may cause dynamic fatigue by accumulating in cracks in the ceramic substrate and expanding as the CDPF heats up. This causes further cracking of the ceramic material, which will eventually degrade performance (*20*).

On average, it takes a mechanic approximately 1 h to remove, clean, and reinstall a CDPF. The estimated cost for cleaning a CDPF is $24.50, assuming $18.15/h for the mechanic and 35 pct for fringe benefits.

Other reported methods that are used to clean plugged filters include oven baking, compressed air cleaning, and water-pressure washing with nonphosphate detergent (*21*). Oven baking simulates what actually happens on the vehicle but requires a large oven with vents. The manufacturer's recommendations should be followed in each case.

BACKPRESSURE ALARMS

Backpressure alarms were installed on all vehicles equipped with CDPF's at the Cannon Mine to indicate to the equipment operator when the CDPF requires regeneration. When the exhaust backpressure alarm activates, it is necessary, as discussed earlier, to raise the engine's exhaust temperature to initiate regeneration.

The backpressure alarms installed on Asamera's equipment consist of a "black box" with a red light that is mounted in the engine compartment. The unit (fig. 3) is connected to the inlet of the CDPF with a metal tube. A red light is also installed on the dashboard in the operator's compartment that glows when the backpressure exceeds a preset value, indicating the CDPF requires regeneration.

Only 2 of the original 12 backpressure alarms are currently operational. Production equipment is not removed from service to repair a backpressure alarm, and frequently pressure tubes and wires are not reattached after engine repairs are completed. Production and maintenance personnel, both staff and hourly, must be aware of the purpose of these alarms and trained to maintain them. Operators must ensure that regeneration occurs frequently to avoid damage to the CDPF, in order to protect the mine's large investment in CDPF's.

Fatigue-induced breaks and leaks in the metal tube and fittings of the backpressure alarm are reported by Asamera's maintenance personnel to be at least partly responsible for backpressure alarm failure. These leaks are caused by engine vibration and stresses developed from operating a machine in a harsh mine environment.

New backpressure alarms, which take advantage of improved technology to improve durability and performance, need to be developed. One such system combines sensors to monitor backpressure with thermocouples to monitor exhaust temperature on the inlet and exit of the CDPF. Digital readouts in the operator's cab display current conditions, and indicator lights flash when the exhaust temperature and/or backpressure exceeds acceptable limits. This type of monitoring system is advantageous because it provides information when the CDPF is undergoing regeneration, but it is more costly. The monitoring system must be made to withstand the mine environment and be simple to maintain.

CDPF USAGE AT CANNON MINE

This section describes, in detail, the Cannon Mine's experience with CDPF's on specific machines. The reported engine hours are based upon the hour meters on the respective engines. Vehicle operating costs include operating and maintenance labor, fringe benefits, wear and repair parts, consumable repair items, tires, and fuel, but do not include bonus, sales tax, or amortized capital costs. These costs are derived from the detailed cost records kept by the mine.

Load-Haul-Dumps, 6.1 m^3 (8 yd^3)

The first installation of a CDPF in a U.S. underground mine was in September 1987, on a 6.1-m^3 (8-yd^3) LHD, which is powered by a 201-kW (270-hp) Caterpillar 3306 prechambered, turbocharged, aftercooled engine (fig. 4). Prior to CDPF installation, the filter manufacturer performed a temperature trace of the engine's exhaust. The exhaust temperature was well over the 400° C required for regeneration of the CDPF. The manufacturer stated that an exhaust temperature of 400° C must be sustained for 25 pct of the unit's duty cycle for the CDPF to properly regenerate (*22*). Based on this information, the mine installed the CDPF on the LHD, but the exhaust temperature was not measured with the CDPF in place to ensure that the manufacturer's recommended requirements were met.

The CDPF immediately improved mine air quality by reducing the black smoke emitted from the tailpipe. However, the ceramic substrate of the CDPF broke apart after 2,960 h of use and the CDPF was replaced. The replacement CDPF now has 3,483 h of use. The total time that this LHD has been equipped with a CDPF providing exhaust filtration is 6,443 h as of June 30, 1992.

Black smoke is now being emitted from the tailpipe, indicating that the replacement CDPF has reduced

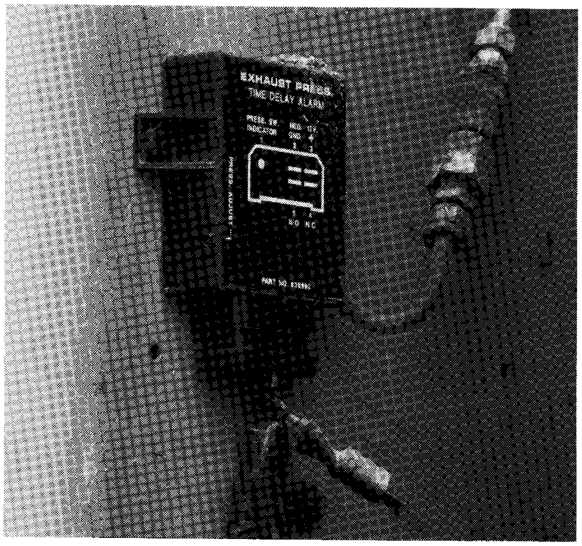

Figure 3.—Mounted backpressure alarm.

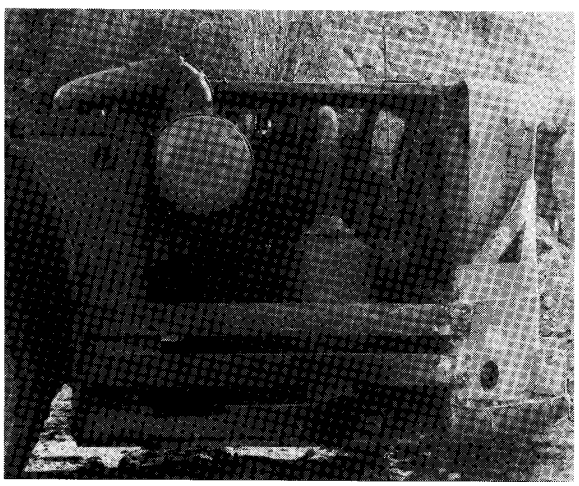

Figure 4.—Load-haul-dump, 6.1 m³ (8 yd³).

filtration efficiency. Both CDPF's were removed and cleaned on several occasions, because the filters were plugged because of incomplete regeneration. The backpressure alarm is no longer operational on this LHD.

The total cost of the two CDPF's, one backpressure alarm, and one site visit by the filter manufacturer to obtain an exhaust temperature trace and to provide installation assistance was $15,626. The 1991 operating costs for this unit, including the cost of the CDPF, were $83.84/h. This gives a cost for exhaust filtration of $2.43/h for the 6,443 h or 2.9 pct of hourly operating cost.

Load-Haul-Dumps, 3.8 m³ (5 yd³)

A CDPF was installed in the first quarter of 1990 on a 3.8-m³ (5-yd³) LHD powered by a 172-kW (231-hp) Deutz F10L413W engine. Because of the exhaust system design of this LHD discussed previously, the optimal installation would have had two small CDPF's on this LHD rather than one large CDPF. Each CDPF would serve one exhaust manifold, rather than a single large CDPF serving both exhaust manifolds. However, it was impossible to retrofit this machine with two CDPF's because of limitations posed by the engine compartment.

This LHD is primarily used for loading trucks. Four passes are made to fill a truck, after which time the LHD is either idled until another truck arrives or is shut down while the LHD operator drives the truck to the dump point, allowing the CDPF to cool down between loading cycles. This duty cycle has a peak exhaust temperature that is sufficient to initiate regeneration, but is probably too short to sustain regeneration long enough to prevent a gradual buildup in exhaust backpressure.

Three months after a single CDPF was installed, the filter broke apart at the center body-end-cone joint. The CDPF was returned to the manufacturer for inspection and was replaced. It is probable that the CDPF broke because of stress imparted by normal engine movement, since the CDPF was mounted rigidly without any flexible exhaust pipe to isolate it from engine vibration. A new CDPF was installed with a flexible exhaust pipe, but it also broke in the same area. This CDPF was repaired and reinstalled, and there have been no further problems with breakage of the filter housing.

The CDPF and backpressure alarm cost $8,466. The CDPF has operated for 4,653 h at a cost of $1.82/h. Operating costs for this LHD during 1991 were $114.83/h and filtration cost accounts for 1.6 pct of the LHD's operating cost. This CDPF also required pressure washing on several occasions.

The CDPF evaluated in the USBM's laboratory was mounted on a 3.8-m³ (5-yd³) LHD, which was powered by an air-cooled, prechambered, Deutz F10L413 FW engine, rated at 172.3 kW (231 hp) at 38.3 Hz (2,300 rpm). The CDPF was installed during July 1990, at a cost of $4,175, and was used for a total of 2,881 h. The CDPF was not reinstalled after 2,881 h because the laboratory evaluation showed a decrease in filtration efficiency and an increase in regeneration temperature. The estimated cost to operate this scoop during the 1991 calendar year was $81.95/h, which included the $1.45/h cost of the CDPF. This represents almost 1.8 pct of the operating cost of this LHD.

Load-Haul-Dumps, 4.6 m³ (6 yd³)

Two new 4.6-m³ (6-yd³) LHD's equipped with Deutz F10L413 FW, 172-kW (231-hp) engines were purchased with factory-installed CDPF's. These LHD's were equipped with two CDPF's, one for each exhaust manifold.

These LHD's are primarily used for loading trucks. The duty cycle is the same as for the 3.8-m^3 (5-yd^3) LHD's, except that a truck can be loaded with three cycles, providing even more time for the CDPF to cool down between trucks.

The backpressure alarms on both LHD's are no longer functional, because of missing wires and tubing, but during the time that they were operational they indicated regeneration problems and/or consistently high backpressure.

The duty cycle of these LHD's is sufficient to initiate regeneration, but probably insufficient to sustain regeneration. This results in a gradual buildup of exhaust backpressure, necessitating removal of the CDPF for pressure washing. This reinforces the need to have temperature traces of a multishift duration performed on equipment before installing the CDPF. Ordering factory-installed CDPF's solves the problem of locating the CDPF's on the vehicle, but might create a problem if the duty cycle of the vehicle is insufficient to sustain regeneration.

The two CDPF installations had accumulated 8,337 h of use as of December 31, 1992. The CDPF's, backpressure alarms, and factory installation for the two LHD's cost $19,970. The LHD operating costs for 1992 were $70.56/h. Since the purchase of these LHD's, the CDPF's have accounted for 3.6 pct of the operating cost per hour.

Trucks, 23.6 mt (26 t)

The mine has five 23.6-mt (26-t) trucks with Caterpillar 3406 prechambered, turbocharged, and aftercooled engines that are equipped with CDPF's. The duty cycle of these trucks is probably adequate for the use of CDPF's, but these CDPF's are more susceptible to damage from operation and the mine environment. The trucks spend a significant portion of time operating under high-engine-load conditions such as being driven fully loaded up a 15-pct ramp. Temperature traces performed by the CDPF manufacturer indicated periods of time with exhaust temperatures above 400° C. However, full shift temperature traces were not recorded, so it is possible that regeneration is incomplete.

Regeneration problems and/or ceramic substrate damage are strongly suspected. Black exhaust smoke is frequently observed, the CDPF's have required pressure washing, and none of the backpressure alarms are functional. The CDPF's installed in these trucks are prone to damage due to impact against the mine rib. When a CDPF is hit, the substrate is frequently crushed at the point of impact, which affects filtration efficiency. Figures 5 through 7 show the damage sustained by a CDPF in use on a 23.6-mt (26-t) truck and by a CDPF that was removed from service.

A total of 13 CDPF's were used, or are presently in use, on these trucks at a capital cost of $106,123, including the cost of the backpressure alarms, which amounts to about 3 pct of the total. These trucks have accumulated a total of 41,135 h with an average filtration cost of $2.58/h. The average operating cost of the trucks during 1991 was $80.13/h. CDPF's account for 3.2 pct of the operating cost for these trucks.

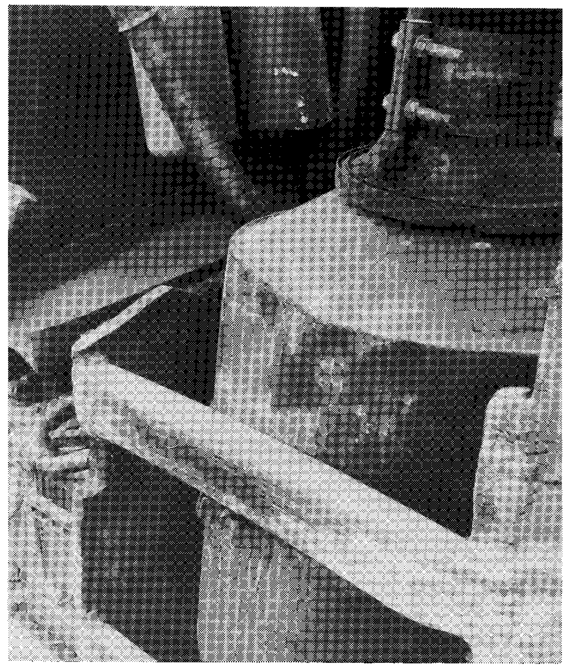

Figure 5.—Truck, 23.6 mt (26 t), with dent in CDPF.

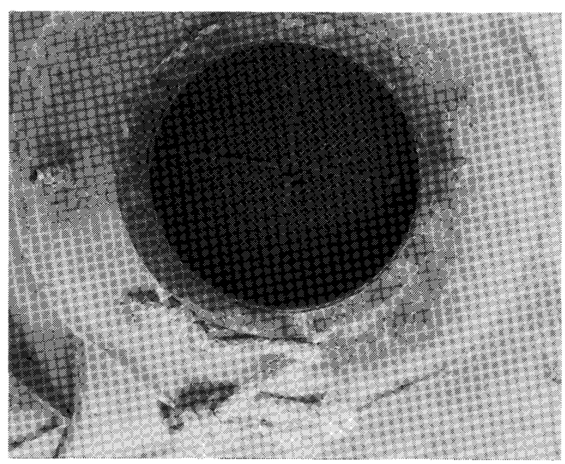

Figure 6.—CDPF with damage to inlet end.

Road Grader

A CDPF was installed in April 1989 on a road grader (fig. 8) powered by a 93-kW (125-hp) Caterpillar 3304 engine at a cost of $4,545 including the backpressure alarm. The CDPF failed in June 1992, after 1,671 h of use, although the backpressure alarm remained intact and appeared operational. For that period the cost of operation was $2.72/h. The road grader's operating cost for 1991 was $55.50/h, which included the cost of the CDPF. The cost of the CDPF represents 4.9 pct of the road grader's operating cost.

This CDPF showed a gradual decline in filtration efficiency, as increasing amounts of black smoke were observed in the exhaust stream. Several times the CDPF was removed from the road grader and pressure washed with water to remove some portion of the collected DPM and to reduce backpressure. After cleaning, visual observations suggested that the CDPF appeared to trap more of the DPM, but eventually the backpressure built up to unacceptable levels and further cleaning was required. At the time of the last cleaning, light could be seen through the CDPF and it was considered to have failed.

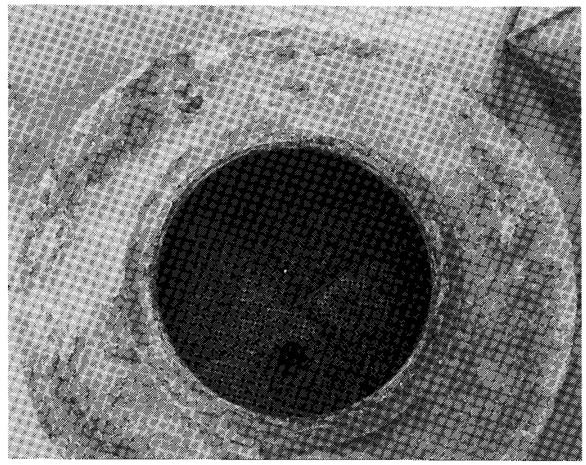

Figure 7.—CDPF with damage to exhaust end.

Figure 8.—Road grader with CDPF.

Roof-Bolting Jumbo

A diesel-hydraulic roof-bolting jumbo (fig. 9) powered by a 61-kW (82-hp) Deutz F6L912W engine was equipped with a CDPF in October 1988. The unit's diesel engine provides power both to move the unit from location to location and to operate the hydraulic systems that power the drilling and bolting functions. The jumbo installs roof bolts throughout the mine, but stays in a given location for anywhere from a few hours to several days, with the diesel engine running under heavy load for a large portion of the shift. This duty cycle is ideal for a CDPF, because the high exhaust temperatures promote regeneration and mechanical stresses are limited when the jumbo is not moving.

This CDPF has accumulated 5,992 h of use as of June 30, 1992, and the backpressure alarm on the roof bolter remains functional. The CDPF and backpressure alarm cost $4,345. The bolting jumbo's operating costs for 1991 were $92.35/h, which included the CDPF cost, but not the cost of the roof bolts. The CDPF accounts for 0.8 pct of the drill's operating cost per hour over the life of the filter to date.

This CDPF has failed to regenerate properly on several occasions and has required pressure washing. The condition of the ceramic substrate is unknown, but it appears to be providing some exhaust smoke reduction.

Tractor

A 34-kW (45-hp) farm tractor, used for personal transportation by the underground mine foremen, was equipped with a CDPF. The duty cycle included driving up and down ramps and over level ground and periods of idling. The temperature trace performed on the tractor engine prior to installation of the CDPF showed that the exhaust temperature was well in excess of the 400° C required to initiate filter regeneration. High temperatures were apparently not maintained for a sufficient duration, however, because the CDPF failed to regenerate properly, leading to the buildup of excessive backpressure and stalling of the engine. This CDPF was removed from service after about 2 weeks and this installation of a CDPF was judged a complete failure. No backpressure alarm was used in this installation.

ESTIMATED COST OF USING LOW-SULFUR DIESEL FUEL

Low-sulfur diesel fuel is recommended for use with CDPF's because the formation of sulfate particles is reduced and there is less chance for catalyst poisoning (*18*). During 1991, the Cannon Mine purchased 850,246 L (223,749 gal) of diesel fuel at a cost of $157,421, or $169,857 with 7.9-pct sales tax. With 1991 production

Figure 9.—Roof-bolting jumbo with CDPF.

listed at 469,754 mt (517,669 t), diesel fuel amounted to a cost of \$0.335/mt (\$0.304/t) mined, or \$0.362/mt (\$0.328/t) after taxes. If it is assumed that low-sulfur diesel fuel will cost an additional 5 pct, diesel fuel costs will rise to \$165,292, or \$178,350 with a 7.9-pct sales tax. This yields a diesel fuel cost of \$0.352/mt or \$0.380/mt (\$0.319/t or \$0.345/t) after taxes. This is an increase in mine production costs of \$0.017/mt (\$0.015/t) before taxes or \$0.018/mt (\$0.017/t) after taxes. It is highly unlikely that the increase in diesel fuel cost is offset by savings in prolonged CDPF life; however, mine air quality is improved by the minimization of sulfate aerosol formation.

SUMMARY OF CANNON MINE'S EXPERIENCE WITH CDPF'S

CDPF's on diesel engines will, in the right application, do a good job of removing much of the DPM. However, the Cannon Mine's experience with CDPF's has shown that CDPF's are costly and frequently require cleaning, that backpressure alarms fail frequently, and that proper vehicle screening prior to CDPF installation is critical if these problems are to be minimized.

The miners, support personnel, and staff of the Cannon Mine feel that CDPF's have improved air quality. When a CDPF is working properly, the cloud of black smoke usually so noticeable with a diesel engine is absent or nearly absent. However, these improvements in air quality are costly. Table 4 summarizes the costs of using CDPF's at the Cannon Mine. Some installations of CDPF's at Asamera were inappropriate because of engine compartment limitations, insufficient exhaust temperature to ensure regeneration, or inadequate protection from the rigors of the mine environment. Merely obtaining an exhaust temperature trace prior to installing a CDPF is not necessarily adequate to ensure that the exhaust temperature is sufficiently hot for long enough periods of time to properly regenerate the filter. A detailed examination of the machine's duty cycle using an onboard data logger is the best way to ensure proper application of the CDPF.

Table 4.—CDPF operating costs at Cannon Mine

Vehicle	Cost, \$/h	Operating costs, pct
6.1-m^3 LHD	2.43	2.9
3.8-m^3 LHD[1]	1.82	1.6
3.8-m^3 LHD[2]	1.45	1.8
4.6-m^3 LHD[3]	2.39	3.6
23.6-mt truck[3] ...	2.58	3.2
Roof grader	2.72	4.9
Roof bolter	.76	.8

LHD Load-haul-dump.
[1]Evaluated in mine.
[2]Evaluated in USBM laboratory.
[3]Average operating costs are shown.

RECOMMENDATIONS

CDPF's are best suited for vehicles with consistently heavy duty cycles that produce exhaust temperatures adequate for regeneration. The ability of the catalyst to lower the temperature at which regeneration occurs will degrade with time, hindering regeneration. This results in DPM buildup in the CDPF that can lead to plugging of the filter and decreasing filtration efficiency. The following recommendations are made to help ensure proper CDPF operation.

1. Use low-sulfur fuel. A fuel sulfur level of 0.05 wt pct or below is recommended. This will limit the production of sulfate and lower the risk of catalyst poisoning by sulfur.

2. Perform vehicle screening. The exhaust temperature of each candidate vehicle should be measured over several days of use. A rule of thumb is that the CDPF temperature should exceed 400° C for at least 25 pct of its duty cycle. The duration of the periods the CDPF is above 400° C and peak temperatures of the CDPF are also factors to be considered. The portion of the time the CDPF must exceed 400° C to achieve proper regeneration may vary with the catalyst used in the filter. The exhaust temperature should be measured where the CDPF will be installed. On a V-type engine, where two CDPF's are recommended, the temperature of each exhaust bank should be determined. If the vehicle's duty cycle changes, or if there is a change in engine condition, the exhaust temperature should be remeasured to ensure that the CDPF will regenerate adequately.

3. Minimize loss of exhaust heat and backpressure. The CDPF should be installed as close to the exhaust manifold as possible. Consideration should be given to insulating the exhaust line to the CDPF, especially if exhaust temperatures are marginal for regeneration (*23*). The number of pipe bends and length of exhaust pipe should be kept to a minimum to reduce backpressure.

4. Monitor backpressure. A backpressure gauge should be installed in the operator's cab. When the backpressure becomes excessive (exceeding 30 kPa (40 in H_2O) for most engines) the CDPF should be regenerated by operating the vehicle at a high-load condition. If necessary, the DPM

can be removed by blowing out with compressed air, steam cleaning with or without nonphosphate detergent, or baking in an oven. Backpressure alarms require frequent maintenance to remain operational. Equipment operators and mechanics must be adequately trained in their use and maintenance. Improved backpressure alarms need to be developed specifically for mine vehicles.

5. Periodically inspect the CDPF, gauges, and alarms. The inlet and outlet faces of the CDPF should be inspected periodically because DPM buildup on the inlet face can indicate a regeneration problem. Inspection can be done each time the vehicle is brought into the shop for preventive maintenance. Backpressure gauges and alarms should also be checked at this time. If cracking or melting of the ceramic is observed on the inlet or outlet face, the collection efficiency of the CDPF has diminished. While it may still be capable of filtering particulate, consideration should be given to replacing the CDPF. The time at which the CDF is replaced is dependent upon a number of factors, including the amount of substrate damage, the appearance of smoke, and the cost of replacement.

6. Educate operators and mechanics. Vehicle operators and mechanics should be instructed in how a CDPF works, how to determine if it is becoming plugged, what to do if it does become plugged, and the need for operational backpressure alarms.

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