

Study to Assess the Performance of Ceramic Diesel Particulate Filters for Reducing Diesel Emissions

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ABSTRACT: The Mine Safety and Health Administration and Greens Creek, Kennecott Minerals participated in a collaborative study to verify the efficiency of catalyzed ceramic diesel particulate filters for reducing diesel emissions. The purpose of the study was to determine the reduction in emissions and personal exposure that can be achieved when ceramic filters are used.

The study was conducted over a two week period. Three shifts were sampled with ceramic after-filters installed; and three shifts were sampled without the after-filters installed. Personal samples were collected to assess worker exposures. Area samples were collected to assess engine emissions. Both gaseous and diesel particulate measurements were taken.

Results indicated that ceramic diesel particulate filters may have a significant impact on personal exposures. Other factors such as intake air, stope ventilation parameters, and isolated atmospheres in vehicle cabs also impact diesel particulate matter exposures.

1 INTRODUCTION

This study was conducted in cooperation with the Greens Creek Mining Company and the Mine Safety and Health Administration (MSHA). The study was conducted on January 21 – 29, 2003.

The purpose of this study was to verify the effectiveness of catalyzed ceramic diesel particulate filters for reducing diesel emissions. The goal was the identification of site-specific, practical mine-worthy filter technology. Practical mine-worthy filter technology means feasible, effective, and durable filters which will enable the mine to comply with the diesel particulate matter (DPM) concentration limits specified in 30 C.F.R. §57.5060. These filters should consistently reduce DPM emissions by no less than 80% in actual conditions of use. These filters should provide this reduction without causing equipment damage or failure nor otherwise create safety hazards or health hazards such as unhealthful or impermissible levels of any air contaminant.

This series of tests was designed to determine the reduction in emissions and personal exposure that can be achieved when ceramic filters are installed on diesel equipment operating in a production stope. Relative engine gaseous and diesel particulate matter

emissions were also determined for this equipment under a specific load condition.

2 BACKGROUND

Greens Creek, Kennecott Minerals Company (the “Company”) operates an underground metal mine (the “mine”) on Admiralty Island, south of Juneau, Alaska. The mining project is a Joint Venture between Kennecott Minerals and Hecla Mining Company. The ore body was discovered in 1975. Exploration drilling began in 1978, initial mine development in 1987, and full production in 1989. The mine was closed in 1993 due to low metal prices, and has been reopened since 1996 after completion of mine development work.

The Company utilizes a conventional stoping to develop a multilevel mine. Ore is shot in a heading and then loaded with a front-end-loader and transported to the surface by large diesel ore trucks equipped with Detroit Diesel, Series 60 (12.7 L) DDEC engines. The polymetallic (silver, zinc, gold, and lead) ore is transported to a surface mill and concentrator, which in turn produces three separate concentrates. These concentrates are shipped to

various smelters throughout the world on a regular basis.

Since March 3, 2000, the mine has been testing on-board regenerating, 15 x 15 Engelhard, platinum catalyzed, diesel particulate filters on large horsepower production equipment. The focus of in-mine testing, to date, has been to assure that the filters could be properly installed and did not pose operational problems such as high engine back pressures, causing engine damage, or decreased performance. The longest running filter has been used for approximately 5,000 hours, since January 2001. The mine has purchased a total of 11 filters and installed 7 filters, five of which were in service prior to or at the time of the study.

3 SAMPLING AND ANALYSIS PROCEDURE

3.1 Diesel Particulate Sampling

In order to assess the performance of the diesel particulate filters, tests were conducted on a production unit when the filters were in use and on the same or similar production unit when the filters were not in use. Where possible, the same production equipment was used for both test configurations. DPM samples were collected using the SKC DPM sampling cassette with impactor and a cyclone. Samples were collected on three stope-loading cycles for each configuration of ceramic filter. Approximately 21 DPM samples were collected on each shift to assess ceramic filter performance. These samples included:

- 16 Area samples at 4 locations for emissions:
 - 6 samples at Intake 1 with filters,
 - 6 samples at Return 2 with filters,
 - 2 samples each at Intake 2 and Return 1,
- 2 Area samples (inside and outside loader cab), and
- 3 Personal samples (loader operator and 2 truck drivers).

Area samples for emissions were taken only in the test areas. Samples were collected up-wind and down-wind of the entrance to the stope. The minimum sample time was determined by the production cycle. Samples were collected during production and continue to be collected for ½ to 1 hour after the production in the stope was completed. Personal samples were collected for the full shift.

In addition to the DPM samples, the following data will be collected:

- Airflow in the stope,
- Nitrogen Dioxide measurements at the 4 area sample locations,
- Engine and emission data,
- Filter data,
- Time and motion data, and

- Engine tail pipe emissions with and without ceramic filters including:
- Gaseous emissions and Bosch numbers on the two trucks and loader (minimum).

In addition to collecting samples to assess performance of the catalyzed ceramic filters, DPM samples were collected to evaluate the performance of an environmental cab on loader LR 46. One area sample was collected inside and one area sample was collected outside the cab.

Both area and personal samples were collected with SKC, Inc., diesel particulate sampling cassettes. This cassette includes a submicron impactor and tandem quartz fiber filters. All samplers used a 10-millimeter nylon pre-separator cyclone. Samples were collected with SKC and MSA pumps pre-calibrated at 1.7 liters per minute (Lpm) and post-checks were made on all pumps used. At the time of the survey, all pumps were functioning properly.

Diesel particulate samples were analyzed at the MSHA Pittsburgh lab using NIOSH Method 5040. Elemental and organic carbon masses were determined from the samples collected. This process uses a thermal/optical carbon analyzer to determine the elemental and organic carbon matter per square centimeter of filter surface. Total carbon was estimated by multiplying the elemental carbon by a factor of 1.3 and determined by adding the organic carbon mass to the elemental carbon mass. Concentrations of total carbon were calculated from the following formulas:

Total Carbon Concentration ($\mu\text{g}/\text{m}^3$) =

$$\frac{\text{EC}(\mu\text{g}/\text{cm}^2) \times \text{A}(\text{cm}^2) \times 1,000 \text{ L}/\text{m}^3 \times 1.3}{1.7 \text{ Lpm} \times \text{time}(\text{min})}$$

and

$$\frac{[\text{EC}(\mu\text{g}/\text{cm}^2) + \text{OC}(\mu\text{g}/\text{cm}^2)] \times \text{A}(\text{cm}^2) \times 1,000 \text{ L}/\text{m}^3}{1.7 \text{ Lpm} \times \text{time}(\text{min})}$$

MSHA's compliance limits are based on an 8-hour equivalent exposure concentration and are referred to as shift weighted averages (SWA). The SWA is calculated using 480 minutes as the sampling time.

3.2 Evaluation of Engine and Ceramic Filter

The engine, in each of the test vehicles, was tested using a repeatable engine load test to determine the raw gaseous emissions before and after the catalyzed ceramic filter. This test was done prior to and repeated after the on-section test with the ceramic filters installed. The test was conducted using MSHA's ECOM multi-gas analyzer. Carbon Monoxide (CO), Carbon Dioxide (CO₂), Nitric Oxide (NO), and Nitrogen Dioxide (NO₂) were measured.

The exhaust gas was sampled in the exhaust system upstream of the DPM filter location.

In addition to measuring the raw gaseous emissions, a smoke test was conducted before and after the on-section test with the ceramic filters installed. A sample of raw exhaust was collected before and after the ceramic filter on the ECOM's filter paper and the filter paper coloration was compared to a Bosch smoke number. This test was conducted under the engine operating condition at torque stall. Torque stall condition represents a loaded engine condition that would produce higher amounts of DPM. A 1.62 L sample of exhaust gas was passed through a quartz fiber filter. The degree of black/gray/white on the filter paper was compared to a Bosch smoke scale.

3.3 Data Analysis

Because of the low emissions for the DDEC Series 60 engines and the short production cycle in a stope, this test was not able to resolve the reduction in engine emissions with a high degree of certainty. This study did determine:

- The results for the tail pipe test for each piece of equipment, with and without ceramic filters installed,
- the change in full shift personal exposure with and without ceramic filters installed,
- the level of NO₂ in the stope with and without the ceramic filters installed,
- the difference between measurements inside and outside the loader cab, with and without the ceramic filters,
- the potential impact of directing airflow into the stope through the use of an auxiliary fan and tubing system, and
- diesel emissions within the test areas with and without ceramic filters installed.

DPM sample results, airflow, and engine emission data were tabulated. Emissions within the test area were determined by taking the difference between the up-wind and down-wind concentration and multiplying by the airflow.

$$\text{Emissions} = (C2 - C1) \times Q$$

This gives the total emissions. The with- and without-filter scenarios were used to calculate reduction in emissions. The personal samples, emission data and airflow can be used to evaluate the current control strategy and to model future control strategies.

4 STUDY RESULTS AND DISCUSSION

4.1 Results of Tail Pipe Tests

During typical mining operations, the mine utilizes one front-end-loader (FEL) and two or three haul trucks to remove ore from a stope. During the study, all of the equipment utilized was equipped with Detroit Diesel, Series 60 (12.7 L) DDEC engines. This engine is approved by MSHA (7E-B049-0). It is rated at 475 horsepower at 2100 RPM. The approved ventilation rate is 28,000 cfm and the Particulate Index (PI) is 8,500 cfm. The engine on the FEL had been de-rated to 300 horsepower. The corresponding ventilation rate and PI would be approximately 20,000 cfm and 5,000 cfm, respectively. All of the haul trucks and the loader utilized in the stopes where sampling occurred were equipped with working Engelhard DPM filters during the first three days of the study. The ceramic filters were heavily catalyzed and used with passive regeneration. As part of the study, tail pipe sampling was conducted on the FEL and four trucks with- and without-ceramic filters installed.

The Engelhard DPM filters installed on the machines were based on a Corning cordierite filtration media that is wash coated with a platinum catalyst. The platinum catalyst is a second generation coating which means less platinum deposited on the cordierite. The platinum based catalyst provides the means for passive regeneration at a specific exhaust gas temperature. Passive regeneration occurs when the exhaust gas temperature duration is sufficient during the duty cycle of the machine to burn off the deposited DPM on the filter. This is successfully accomplished at an exhaust gas backpressure that does not increase above the recommended value specified by the engine manufacturer. During the study, all indications were that the filters were properly regenerating during the normal production duty cycle of the machines.



Figure 1. Installation of an Engelhard DPM Filter on a Haul-truck.

During visual inspection of the ceramic filters by the Company and subsequently by MSHA personnel, it was noted that some of the 15 x 15 Engelhard filters had rotated in the canisters and were cracked. The filter that prior to the study was reported to have operated over 5,000 hours on a haul truck had completely failed. This filter was replaced. Two similar filters installed on haul trucks, which had operated for approximately 2,500 hours, also rotated and displayed cracks along the outer perimeter of the ceramic media. Figure 1 shows a typical installation of an Engelhard DPM filter installed on a haulage truck. From information presented by the Mine and visual inspection of the 5 ceramic filters that were currently being used, the rotation appeared to begin after approximately 600 hours of use. Cracks occur between 600 hours and approximately 2,500 hours of use. Cracking of the media continues until the filter completely fails. MSHA discussed the problem with the Company and the filter manufacturer. Although the filters used in the study displayed some damage, they effectively filtered the DPM.

The gaseous exhaust emissions were measured with MSHA's ECOM AC portable gas analyzer on the four pieces of equipment used during the study. These measurements were made at four engine operating points. Based on the comparison of data, all of the engines tested were performing in the approved range. For each piece of equipment tested there was a general decrease in CO downstream of the ceramic filter and there was a general increase in the NO₂ downstream of the ceramic filter.

As part of the tail pipe emission tests, a smoke test was conducted upstream and downstream of the ceramic filter. The purpose of this test was to determine how well the filters were working by visually evaluating a smoke dot on a sample filter paper. Due to time restraints in the mine, the smoke tests were performed using a quartz fiber filter instead of a standard filter paper normally used for determining a Bosch Number. Therefore, the Bosch Numbers assigned to the quartz filter paper are only being used as a relative number for the purpose of this report. As discussed below, the DPM collected on the quartz fiber filter was used for a quantitative analysis.

Bosch Numbers range from 0 (no observed color) to 9 (black). Testing of the ceramic filters on loader LR-46 and haul truck HT-21 gave Bosch numbers reducing from 8 to 1. This range of Bosch numbers between unfiltered and filtered exhaust indicates the ceramic filters were working properly. HT-23 presented a less effective result with a reduction in Bosch number from 8 to 3. This Bosch number range indicates that this filter was less effective than the LR-46 or HT-21 filters but much better than the HT-24 filter.

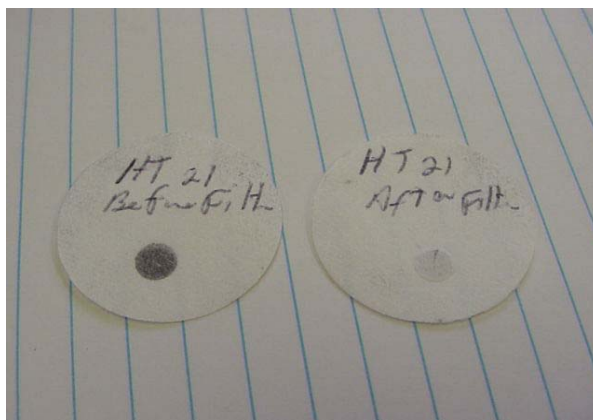
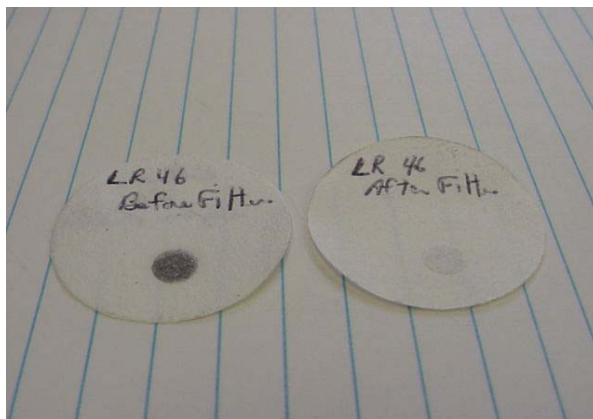
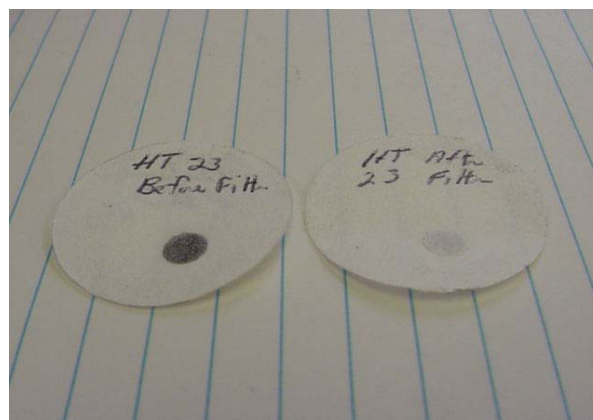


Figure 2. Smoke Test Comparison Between Damaged and Undamaged DPM Filters.

The smoke test of the DPM filter on haul truck HT-24 indicated a smoke number reduction from 9 to 7. This is the filter that had rotated in the housing. The Bosch numbers confirmed that it was not functioning as efficiently as the other filters. The ceramic filter on this truck was replaced with an undamaged filter prior to in-mine testing. An example of the color comparison between the damaged and undamaged filters is shown in Figure 2.

In addition to the visual method to assign a Bosch number, tests were conducted upstream and downstream of the ceramic filters using quartz fiber filters for the smoke test medium. This allows the DPM sample to be analyzed and quantified using the NIOSH 5040 analytical method. These results show a 84.8 to 99.0 percent reduction in total carbon reduction and a 91.7 to 99.6 percent reduction in elemental carbon. Even though there was some leakage due to filter rotation on several filters, the elemental carbon filter efficiency remained above 90 percent.

4.2 Change in Full Shift Personal Exposure

A diagram of a typical stope sampled during the study is presented in Figure 3. Area sample package locations, appropriate airflow direction and other pertinent information are also shown in this figure. The following paragraphs summarize the sampling results. Raw data is available upon request.

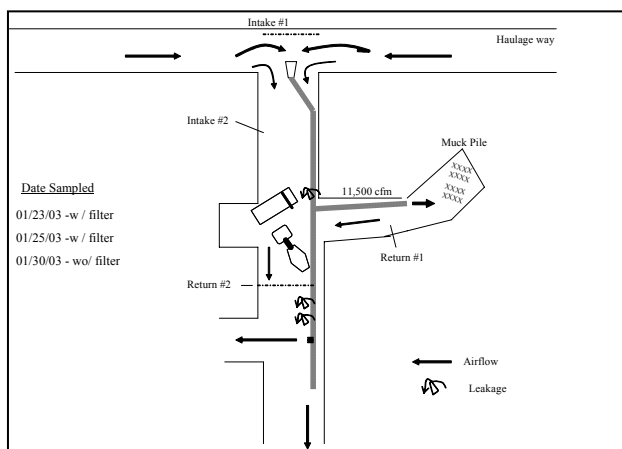


Figure 3. Diagram of Stope 625.

A summary of the personal diesel particulate samples collected with and without the ceramic filters are given in Table 1. During all sampling, the equipment operators remained inside the cabs while loading in a stope. When ceramic after-filters were utilized on the production equipment, the highest personal TC exposure (EC x 1.3) was 139 $\mu\text{g}/\text{m}^3$. When filters were not utilized on the production equipment, personal TC exposures ranged from 240 to 423 $\mu\text{g}/\text{m}^3$. Without the after-filters, exposures would meet the interim exposure limit of

400 $\mu\text{g}/\text{m}^3$. With the after-filters the TC exposures would have met the existing final DPM limit.

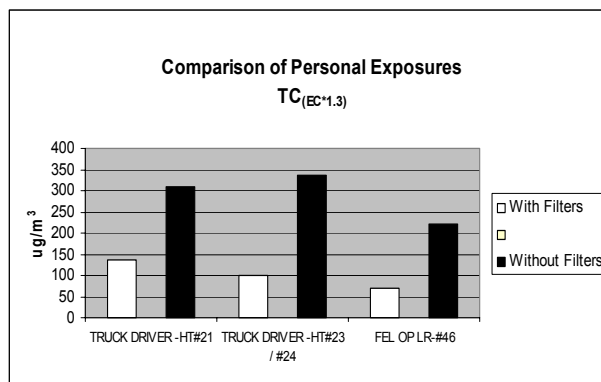


Figure 4. Comparison of Personal Exposures with and without After-filters Installed.

Figure 4 shows a comparison of personal exposure for the two truck drivers and FEL operator, with and without the filters installed. The percent reduction in the personal samples between with and without using the filters is shown in Figure 5 in terms of $\text{TC}_{(\text{EC} \times 1.3)}$ and $\text{TC}_{(\text{EC} + \text{OC})}$. For $\text{TC}_{(\text{EC} \times 1.3)}$ the percent reduction ranged from 57 to 70 percent. For $\text{TC}_{(\text{EC} + \text{OC})}$ the percent reduction ranged from 41 to 62 percent. Note that the Driver of HT-38 is not shown due to lack of data with a filter installed.

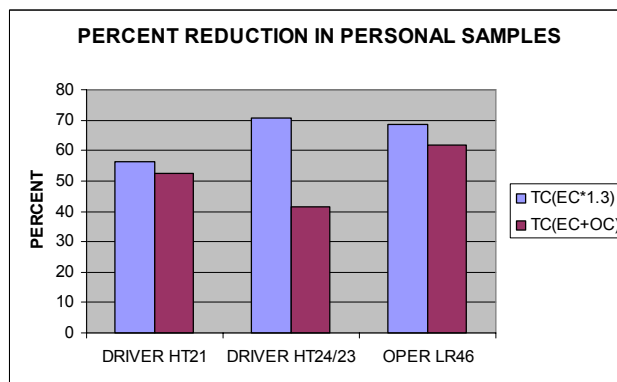


Figure 5. Percent Reduction in Personal Samples with After-filters Installed.

The reduction in personal exposure is not indicative of after-filter performance because other factors such as variation in production, ventilation, up-wind equipment use and cabs, influence personal exposure.

4.3 Level of NO_2 in the Stope

Personal gaseous exposures were measured using long term diffusion stain tubes. Due to logistic problems, these measurements could not be made on the first day of the study. A summary of personal gaseous CO and NO_2 measurements taken on equipment operators with and without the ceramic filters are given in Table 2. In general the data indi-

cates that the CO levels decreased by approximately one-half when the catalyzed filters were being used. While there appears to be an increase in NO₂, when catalyzed filters are being used, it is unclear whether this increase is due to data variability, changes in ventilation rate or use of the catalyzed filters. The approved ventilation rate for a single engine is 28,000 cfm. The airflow in only one of the production stopes exceeded this level.

4.4 *Difference Between Measurements Inside and Outside the Loader Cab*

The results of the area samples collected inside and outside the cabs, with and without the filters are given in Table 3. Without the filters, the average DPM concentration outside the cab was 1351 $\mu\text{g}/\text{m}^3$ and the concentration inside the cab was 271 $\mu\text{g}/\text{m}^3$. With the filters, the average DPM concentration outside the cab was 193 $\mu\text{g}/\text{m}^3$ and the concentration inside the cab was 49 $\mu\text{g}/\text{m}^3$. This data indicates that under current conditions ventilation alone would not be adequate to maintain ambient diesel particulate concentrations below the interim standard. Either cabs or after-filters are needed to meet the interim standard. Both cabs and filters are needed to meet the existing final DPM limit.

The use of filters reduced the ambient concentration by 85 percent. The FEL cab filtration system reduced DPM concentrations inside the cab by 75 percent when after-filters were used and by 80 percent when after-filters were not in use. This data indicates that under current conditions ventilation alone would not be adequate to maintain ambient diesel particulate concentrations below the interim standard. Either cabs or after-filters are needed to meet the interim standard and both cabs and filters are needed to meet the existing final DPM limit.

4.5 *Potential Impact of Ventilating Stopes with an Auxiliary Fan and Tubing System*

In the drawing supplied by the Company for the original test plan, stopes were ventilated by a free standing fan setting on the floor at the mouth of the stope, blowing into the stope without ventilation tubing. During the study, this ventilation practice was not observed. All stopes were ventilated by fans using rigid and bag tubing to direct the airflow into the stopes. However, fans in two of the stopes were installed inside the mouth of the stopes rather than in the main intake. This practice causes recirculation of air and decreases the amount of fresh air available to ventilate a stope.

Airflow to the stopes from the auxiliary fan and tubing systems ranged from 11,500 to 39,000 cfm. Airflow in the intake to the stope ranged from

23,000 cfm to 58,500 cfm. Typically, the FEL loaded one truck at a time in the stope during the loading cycle. For the 300 horsepower FEL and a 475 horsepower truck, (725 horsepower), 100 cfm/hp would have required 72,500 cfm. The sum of the gaseous ventilation rates would be 45,600 cfm and the sum of the rates times the Particulate Indices would be 13,000 cfm.

The airflow supplied in the stopes was close to the Particulate Index, indicating a diesel particulate concentration increase, above the intake levels of approximately 1000 $\mu\text{g}/\text{m}^3$. DPM concentrations outside the cabs, without filters were consistent with this value. The low airflow relative to the gaseous airflow values indicated that elevated concentrations of gaseous emissions can occur either with or without the catalyzed ceramic filters.

4.6 *Diesel Emissions within the Test Areas*

Due to time and production constraints, only one stope per day could be directly monitored for emissions. The average of the area sample packages collected at locations designated as Intake 1 and Return 2 were utilized to determine the diesel emissions generated in the stope during production activity.

Diesel emissions within the test area were determined by using the DPM concentrations entering the stope (Intake 1) and leaving the stope (Return 2). The results of the area samples and airflow measurements collected to assess emissions within the test areas (with and without ceramic filters installed) are given in Table 4. The average increase in concentration from stope intake to return when filters were used was 8 $\mu\text{g}/\text{m}^3$. The average increase in concentration from stope intake to return when filters were not used was 301 $\mu\text{g}/\text{m}^3$. The average diesel emission in the stopes when ceramic filters were utilized was 0.82 gm/hr and average diesel emission in the stopes when ceramic filters were not utilized was 22.46 gm/hr. Even though three trucks were operated during the tests with no filters, no adjustment in the number of vehicles operated was made to compare emissions because the time of the trucks inside the stope, with or without filters was similar. The average reduction in emissions, based on the DPM concentration, was 97 percent. The average reduction in emissions, based on engine emissions, was 96 percent.

Table 4 also shows that the average intake to the stope was reduced when ceramic filters were used. While this could have occurred and would not have been unexpected, the study was not designed to demonstrate this situation. The increased intake levels, without the filters, could have been attributed to the deeper location of operations in the mine and the increased amount of upwind equipment.

5 FINDINGS AND CONCLUSIONS

- The results of the raw exhaust gas measurements conducted during the study indicated that the engines were operating properly.
- The ceramic filters installed on the machines used in this study did not adversely effect the machine operation. Even with some apparent visual cracking from the rotation of the filter media, the ceramic filters effectively removed DPM. The filters passively regenerated during machine operation.
- The Bosch smoke test provides an indication of filter deterioration; however the colorization method does not quantify the results.
- Personal DPM exposure was reduced by 57 to 70 percent when after-filters were used.
- CO levels decreased by up to one-half when the catalyzed filters were being used. There appears to be an increase in NO₂ when catalyzed filters are being used, however, it was unclear whether this increase was due to data variability, changes in ventilation rate or the use of the catalyzed filters.
- The use of cabs reduced DPM concentrations by 75 percent when after-filters were used and by 80 percent when after-filters were not in use.
- Ventilation airflow was provided to the stopes through fans with rigid and bag tubing. Airflow was the same or greater than the Particulate Index, but typically lower than the gaseous ventilation rate.
- The use of ceramic after-filters reduced average engine emissions by 96 percent.
- The reduction in personal exposure was not indicative of only after-filter performance because other factors such as ventilation, up wind equipment use and cabs also influence personal exposure.

Table 1. Summary of Personal DPM Sample Exposure with and without Filters

	TC = 1.3 x EC			TC = OC + EC		
	Truck Dr. HT #21	Truck Dr. HT#23/24	FEL Oper. LR #46	Truck Dr. HT #21	Truck Dr. HT#23/24	FEL Oper. LR #46
Without Filters						
1/28/03	280	324	185	267	340	173
1/29/03	423	405	240	417	410	223
1/30/03	223	283	240	275	294	229
Average	309	337	222	320	348	208
With Filters						
1/24/03	138	106	37	159	273	57
1/25/03	132	93	103	145	134	103
Average	133	100	70	152	204	80

Percent Reduction					
TC = 1.3 x EC			TC = OC + EC		
Truck Dr. HT #21	Truck Dr. HT#23/24	FEL Oper. LR #46	Truck Dr. HT #21	Truck Dr. HT#23/24	FEL Oper. LR #46
57	70	68	53	41	62

Table 2. Summary of Personal Gaseous Exposure with and without Filters

	CO			NO ₂		
	Truck Dr. HT #21	Truck Dr. HT#23/2 4	FEL Oper. LR #46	Truck Dr. HT #21	Truck Dr. HT#23/2 4	FEL Oper. LR #46
Without Filters						
1/28/03	6	6	13	0	0	0
1/29/03	11	9	19	0	0	1
1/30/03	0	6	15	0	0	3
Average	6	7	16	0	0	1.3
With Filters						
1/24/03	--	--	--	1	1	4
1/25/03	8	6	6	1	1	3
Average	8	6	6	1	1	3.5

Table 3. Summary of Front End Loader Cab Performance Based On Inside and Outside of Cab DPM Measurements.

Date Sampled	TC = 1.3 x EC			TC = OC + EC		
	DPM Conc. Outside Cab, µg/m ³	DPM Conc. Inside Cab, µg/m ³	Percent Reduction	DPM Conc. Outside Cab, µg/m ³	DPM Conc. Inside Cab, µg/m ³	Percent Reduction
Without Filters						
1/28/03	1079	363	66	926	334	64
1/29/03	1345	240	82	1158	211	82
1/30/03	1630	211	87	1438	217	85
Averages:	1351	271	80	1174	254	78
With Filters						
1/24/03	203	46	77	229	62	73
1/25/03	182	53	71	187	62	67
Averages:	193	49	75	208	62	70

Percent Reduction With vs. Without Filters			
TC = 1.3 x EC		TC = OC + EC	
Outside Cab	Inside Cab	Outside Cab	Inside Cab
85	82	82	76

Table 4. Summary of Emissions Data From Area Samples Based on TC = 1.3 x EC.

Date	Stope	Stope Intake Concentration* µg/m ³	Stope Return Concentration* µg/m ³	Stope Airflow cfm	Stope DPM Emissions gm/hr
Without Filters – Includes 3 trucks and 1 FEL					
01/28/2003	030	307	816	39000	33.78
01/29/2003	490	123	408	23000	11.13
01/30/2003	625	536	647	34000	6.41**
Average		322	623		22.46
With Filters – Includes 2 trucks and 1 FEL					
01/23/2003	625	206	221	34000	0.86
01/24/2003	446	156	164	58500	0.78
01/25/2003	625	134	135	34000	0.03**
Average		165	173		0.82

Percent Reduction		
Stope Intake Concentration	Stope Return Concentration	Stope DPM Emissions
49	72	96.3

* Average Concentration

** Not included in average because FEL went beyond Return 2 Sample location.