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Underground Metal Mine Air Quality Measurements to Determine the Control Efficiencies of Combined Catalyzed Diesel Particulate Filter and Oxidation Catalytic Converter Systems

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In-mine studies were conducted as part of a collaborative study with the U.S. Bureau of Mines to assess the effects of diesel emission after-treatment control devices on mine air quality. An oxidation catalytic converter (OCC) was replaced with a combined catalyzed diesel particulate filter (CDPF) and OCC unit in one mine, designated mine Q. In a second mine, designated mine T, the OCC was replaced with a CDPF. In each mine, emissions from one diesel-powered mine vehicle were monitored with the two control configurations. In mine Q, the vehicle studied was an Elphinstone R1500 load-haul-dump vehicle equipped with a Caterpillar 3306 PCTA diesel engine used to move ore from a drawpoint to an ore pass. In mine T the vehicle studied was a Tamrock model 2S-TR1 diesel-hydraulic, roof-bolting jumbo powered by a 61-kW (82-hp) Deutz F6L912W diesel engine, which used diesel power to install roof bolts. Control efficiencies for diesel particulate matter (DPM) concentrations in the vicinity of the mine vehicle operator, calculated as the percentage reduction in concentration in the condition with the CDPF installed, were 61 percent for mine Q and 82 percent for mine T. Control efficiencies for tailpipe DPM were 95 percent for mine Q and 74 percent for mine T. Control efficiencies as determined from calculated air quality index (AQI) values were 32 percent for mine Q and 63 percent for mine T; exhaust quality index (EQI) control efficiencies were 85 percent for mine Q and 30 percent for mine T. The AQI and EQI values provide measures of the health effects of combined concentrations of DPM and gaseous emissions in the mine ambient air. Control efficiencies for DPM and DPM-associated organics (including polynuclear aromatic hydrocarbons) collected with high-volume samplers were about 70 percent or greater in both mines. Mutagenic activity decreased by an amount approximately equal to the decrease in DPM in mine T, but increased by over 100 percent in mine Q. These findings indicate that replacement of an OCC with a CDPF or with a combined CDPF and OCC had overall positive effects on the mine air quality, but the increased mutagenicity in the DPM from mine Q suggests that further study is needed. JOHNSON, J.H.; CARLSON, D.H.; BAGLEY, S.T.; GRATZ, L.D.: UNDERGROUND METAL MINE AIR QUALITY MEASUREMENTS TO DETERMINE THE CONTROL EFFICIENCIES OF COMBINED CATALYZED DIESEL PARTICULATE FILTER AND OXIDATION CATALYTIC CONVERTER SYSTEMS. APPL. OCCUP. ENVIRON. HYG. 11(7):728–741; 1996.

While there is currently no federal standard for diesel particulate matter (DPM) concentrations in the ambient air of either coal or noncoal mines, DPM has become a concern in recent years because the National Institute for Occupational Safety and Health (NIOSH) has stated that whole diesel exhaust is a potential occupational carcinogen.[(1)] The DPM is almost entirely in the respirable range and contains several components, including types of polynuclear aromatic hydrocarbon (PAH) compounds, that may have potential health effects.[(2)] Catalyzed diesel particulate filters (CDPFs) are currently being introduced into noncoal mines throughout the United States and Canada to reduce this concern by collecting the DPM at the source. The CDPF is a catalyst-coated, porous, ceramic substrate enclosed in a steel housing with longitudinal channels.[(3)] In the inlet end, every other channel is plugged with ceramic material, while the adjacent channel is plugged at the outlet end. The exhaust gas enters a channel and is forced to pass through the porous channel walls where filtering takes place. The exhaust exits through adjacent channels.

The two mines studied had different CDPF configurations. In mine Q the CDPF was combined with an oxidation catalytic converter (OCC), as shown in Figure 1; this combined CDPF and OCC has been described in the literature.[(4)] In mine T the CDPF was not combined with an OCC; this application has also been described in the literature.[(3)]

These nondisposable DPM control devices are designed for up to 2000 engine operating hours or more. Their capacity is, however, limited, and if the collected DPM is not removed continuously, the ceramic particle filter will become loaded after just a few hours of DPM collection.[(5–9)] A DPM-loaded particle filter will restrict the free flow of exhaust, affecting engine performance and causing overheating that shortens engine life.

Numerous means have been devised and tested for regenerating the ceramic filters with some measure of success as discussed in a number of articles published in a 1986 review of heavy-duty diesel emission control technology.[(5,6)] Most attempts have been directed at controlling DPM combustion by reducing ignition temperatures through the use of catalysts, additives, and other means to remove the collected particulate as a gaseous combustion product. Other than the use of catalysts, as in the current studies, various ways of heating the

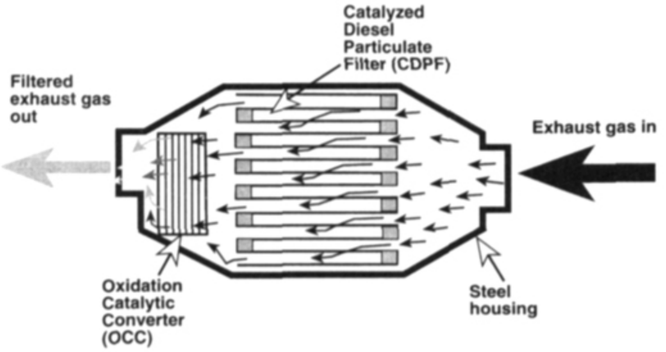

FIGURE 1. Schematic of a combined CDPF and OCC as used in mine Q (from Reference 4).

ceramic at regular intervals have been tried, including attempts to apply frequent heavy engine loads during actual mining, installing electric heating elements in the ceramic, and scheduled removal of the filter at regular intervals to burn off the accumulated particulate. Continuous, low temperature combustion of the collected DPM regenerates the filter without damaging the ceramic.[5–9] None of the methods to control regeneration is 100 percent effective under all mine vehicle operating conditions. Thus, at lower engine loads and speeds, a ceramic particle filter may become loaded to where the resulting elevated exhaust manifold pressures and temperatures cause rapid combustion, which may seriously damage the ceramic matrix and allow a portion of the DPM to bypass the filter. Since mine personnel have no way of knowing that such damage has occurred unless tailpipe emission monitoring is carried out on a periodic basis, a ceramic filter may be used over a long period of time in a damaged condition. For these reasons, most ceramic particle filters are recommended for use only under conditions involving frequent high engine loads. No effort was made during the in-mine studies presented here to determine the extent of auto regeneration during in-production use of the control system.

Safety concerns resulting from the unavailability of technology to ensure continuous DPM burnoff, and thereby eliminating the high exhaust temperatures associated with rapid burnoff, are the reason ceramic filters are currently used only in noncoal mines. Obviously, DPM removal efficiency is dependent not only on the efficiency of the control device, but on installation and maintenance practices of the particular mine and the mine's capability for diagnosing problems. For this reason, underground evaluation of the control devices, as well as installation and maintenance practices, are needed to determine the effects of the controls on mine ambient air DPM concentrations in a production mine situation. The research discussed here addresses only the concentrations produced using new devices installed by trained individuals and does not fully address the performance of the devices in long-term in-mine use.

The key objectives for this portion of the study were to:

1. determine the concentration of DPM, carbon monoxide, carbon dioxide, nitric oxide, nitrogen dioxide, and sulfur dioxide, and the air quality index (AQI) and exhaust quality index (EQI) in two metal mines using diesel-powered haulage vehicles;
2. determine the control efficiencies of the properly working CDPF and the CDPF combined with an OCC, and compare their effects on DPM and other pollutants from mine ambient air and tailpipe measurements; and
3. evaluate the chemical and biological characteristics of the DPM with the control devices off and on by quantifying levels of selected key PAH compounds and mutagenic activity.

Methods

Description of Diesel Equipment and Mines Studied

In each mine, emissions from one diesel-powered mine vehicle were monitored with each control configuration. The configuration with the CDPF installed will be referred to here as the control-on condition, and the condition with the CDPF off will be referred to as the control-off condition. In mine Q the vehicle studied was an Elphinstone R1500 load-haul-dump (LHD) vehicle equipped with a Caterpillar 3306 PCTA diesel engine used to move the ore from a drawpoint to an ore pass. This operation was ideal from an emission monitoring point of view because the LHD vehicle used to test the control system remained in a short (less than 100 m) section of drift during the entire set of tests. The control-on condition was a CDPF and OCC combined in a single unit. For control-off measurements, mine Q replaced the combined unit with another type of OCC that was normally used in the mine. Figure 1 shows a combined CDPF and OCC such as that used in mine Q.

Mine T used a Tamrock model 2S-TR1 diesel-hydraulic, roof-bolting jumbo powered by a 61-kW (82-hp) Deutz F6L912W engine, which used diesel power to install roof bolts. A new CDPF was mounted for the control-on condition. For the control-off condition, the CDPF was replaced by an OCC that was normally used in the mine.[10]

Operating conditions were not nearly as ideal for control efficiency determinations in mine T, where the bolter was moved daily or at an even greater frequency. No two bolter locations had the same air flow, vehicle position with respect to air flow direction, or instrument position relative to the vehicle location and air flow direction.

Mine Ambient Air Measurement Locations

Measurement locations included:

1. an upstream location to make corrections for the background concentrations (background concentrations are subtracted from concentrations measured on the diesel vehicle and downstream to calculate the control efficiency of the device);
2. an on-vehicle location where instruments sampled air in the vicinity of the diesel vehicle operator; and
3. a downstream location where the air passed by the vehicle and diluted its exhaust flow.

Figure 2 is a schematic showing a typical in-mine measurement situation. Meaningful in-mine measurements to determine the effectiveness of controls are difficult to make and interpret for the following reasons:

1. frequent changes in the location and relative positioning of air flow, vehicle position, and instrument position;
2. frequent changes in vehicle orientation and the position of

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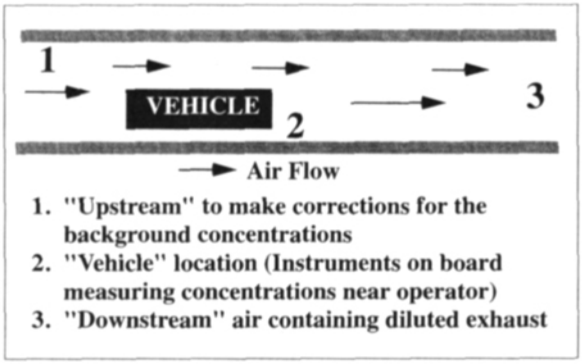

FIGURE 2. Locations measured in mine ambient air.

the vehicle tailpipe in the air stream and with respect to the on-board instruments;

3. frequent changes in vehicle operators and the way they operate;
4. stratification of exhaust due to temperature differences between the exhaust and the mine ventilation air;
5. frequent changes in vehicle engine load and speed conditions depending on the mine conditions;
6. difficulty in locating air that is truly upstream of the vehicles under study for background measurements and corrections;
7. the possibility of multiple sources of upstream air into the study area, as well as potential for contamination of the upstream air by other vehicles and by recirculation;
8. difficulty in optimizing the locations of measurement instruments while ensuring that instruments and personnel will be safe from being run over by production equipment working in the study area;
9. possible contamination from personnel carriers and other vehicles which may enter the study area for short periods of time during the study.
10. contamination from pollutants from other sources, such as airborne particulate from lubricants spilled on hot vehicle parts.

Each location was sampled over as large a portion of the 8-hour work shift as possible, typically 5 to 6 hours. Two work shifts of measurements without the CDPF and three with the CDPF installed were made in both mines. In addition to the mine air measurements, diesel exhaust pollutant concentration measurements were made under steady-state conditions in the tailpipe of the single diesel vehicle being tested in each mine.

On each day of sampling, DPM and gaseous pollutants were measured simultaneously at each of three underground locations using portable instruments. Mine ambient air sampling equipment and methods were the same as those used in a similar study in underground coal mines.[11]

1. Triplicate time-weighted average DPM and respirable coal dust concentration measurements were made using personal dichotomous samplers which separate respirable DPM from respirable dust from other sources.[12–14]
2. Triplicate time-weighted average nitrogen dioxide and nitric oxide concentrations were measured using nitrogen dioxide and NO_x (nitrogen oxides) personal passive (Palmes) samplers.[15]
3. Time-weighted average carbon monoxide and carbon dioxide concentrations were measured using one gas sample collection bag filled by a constant low flow sampler drawing in mine air throughout the sampling period. At the end of the sampling period the bag was connected to portable carbon dioxide and carbon monoxide instruments to measure the concentrations.
4. A fuel sample was collected and analyzed for its sulfur mass content and the ratio of hydrogen to carbon atoms in the fuel. This hydrogen to carbon ratio and the sulfur content were needed to calculate the theoretical quantity of sulfur dioxide produced per unit of carbon dioxide by combustion of the fuel.[16,17]
5. Sulfate measurements were made by water extraction of dichotomous sampler back-up filters and ion chromatography analysis of the extracted sulfate.

Tailpipe Measurements of DPM and Gaseous Diesel Emissions

Tailpipe measurements were made using an emissions measurement apparatus (EMA), as previously described.[18–22] The control-on and control-off conditions in the two mines were as already discussed for the mine air measurements. Instruments and procedures are described in Carlson *et al.*[11] For tailpipe testing, the engine of the LHD vehicle in mine Q was loaded using the torque converter stall condition as described in Carlson *et al.*[11] For tailpipe measurements on the mine T bolter, the engine was operated at the same high idle engine condition as used when installing bolts, although there may be slight differences in that no bolts were installed during the tailpipe measurements.

Chemical and Biological Characterization

In-mine samples for chemical and biological characterization were collected using high volume samplers with size-selective impactors at upstream and downstream locations in each mine. These samplers had flow rates of 1.13 m^3/min. The slotted impactors had cut sizes of 3.5, 2.0, and 0.95 μm. Exposed filters were shipped to our laboratories using the same procedures as described for filters from samplers in an underground coal mine (mine S in Carlson *et al.*[11]).

As in the coal mine study,[11] the samplers in the downstream area were primarily operated only when the diesel test vehicle was operating; filters were changed when an excessive pressure drop occurred. Total collection times for each pair of filters varied from 15 to 75 minutes in mine Q and from 25 to 175 minutes in mine T. Data from these samplers represent potential maximum diesel-related emissions in the downstream area. The upstream samplers were generally operated continuously, with filters changed only if excessive filter loading occurred (as monitored by pressure drop); these sampling times varied from 110 to 268 minutes in mine Q and from 44 to 265 minutes in mine T. Upstream measurements represent potential background contributions to diesel emissions in the downstream areas from diesel vehicles operating in other areas of the mine.

DPM and soluble organic fraction (SOF) levels were determined from the final filter in the sampler, that is, the 20 ×

24-cm back-up filter (cut point size of 0.95 μm), using the same procedures as described elsewhere.[11] The individual extracts from all downstream or upstream filters collected the same day were pooled for PAH and biological activity determinations to reflect average levels over each day's entire sampling period.

The same PAH compounds were selected for quantification using the same analytical procedures as in our related study, that is, analysis for fluoranthene (FLU), benz[*a*]anthracene (B*a*A), and benzo[*a*]pyrene (B*a*P) via high performance liquid chromatography with fluorescence detection.[11]

Biological activity of the SOF was determined using tester strain TA98 without S9 metabolic activation in the same modified microsuspension version of the *Salmonella typhimurium*/microsome mutagenicity bioassay or Ames assay that was used in a study in underground coal mines.[11] Spontaneous revertant levels (mean ± SD of three assays) were 36 ± 2.9 revertants/dish. Responses with 2-nitrofluorene (mean ± SD) of two assays) were 904 ± 24 at 400 ng/dish.

All high volume sample derived DPM, SOF, PAH, and mutagenic activity data were converted to a volumetric concentration basis using the total volume of mine air sampled (in cubic meters) for each sample or combined samples. The mean of the daily mean values was calculated from the DPM and SOF data for each sampling location. A mean for each mine and sampling location was calculated from the PAH and biological activity data.

Data Analysis

The data analyses make use of AQI and control efficiency calculations. These concepts are introduced below.

AIR QUALITY INDEX AND EXHAUST QUALITY INDEX. An AQI[23] was calculated from mine ambient air measurements at the upstream, vehicle, and downstream locations for each day's measurements. This index makes it possible to evaluate diesel emission controls based on the combined health effects of DPM, carbon monoxide, nitric oxide, nitrogen dioxide, and sulfur dioxide concentrations. The AQI equation was modified[11] as follows: (1) substitution in the AQI equation of the DPM concentration measured using personal dichotomous samplers for that measured as respirable combustible dust (RCD) and (2) calculation of the sulfur dioxide concentration from the measured fuel sulfur content, the measured carbon dioxide concentration, and the percentage of the fuel sulfur converted to sulfur dioxide (determined by calculation using measured sulfate data). The AQI was then calculated using the following formula:

$$\text{AQI or EQI} = \frac{CO}{50} + \frac{NO}{25} + \frac{RCD}{2} + 1.5\left(\frac{SO_2}{3} + \frac{RCD}{2}\right) + 1.2\left(\frac{NO_2}{3} + \frac{RCD}{2}\right) \quad (1)$$

where:

- CO = carbon monoxide concentration
- NO = nitric oxide concentration
- NO_2 = nitrogen dioxide concentration
- SO_2 = sulfur dioxide concentration
- RCD = respirable combustible dust (DPM substituted in article)

All of the gaseous constituents are reported in parts per million (volume/volume) or volume percent; the RCD is measured in milligrams/cubic meter. It had been estimated by the developers of the index that a value of 3 or less for V ($V_{ambient}$ later became AQI and $V_{exhaust}$ became EQI) would minimize the risk to the health of workers in dieselized underground mines. They suggested that the risk at a level between 3 and 4 could be alleviated by the use of personal protective equipment, but that a level in excess of 4 would indicate that the quantity of ventilation air should be increased.

Dainty *et al.*[24] also show how an EQI would be applied:

> *"V" was formulated as an ambient criterion; it follows logically that substitution of the concentrations of the same substances in the raw exhaust in the expression will yield $V_{exhaust}$. As the ambient goal is a value of 3, $V_{exhaust}$ divided by 3 yields the number of equivalent volumes of fresh air which must be added to the exhaust to achieve the recommended ambient level: a ventilation criterion. If "V" is recalculated for exhaust levels after a treatment device is fitted, the impact of the treatment device may be quantified by comparison with "V" for the untreated exhaust, and dividing by 3 as before yields a ventilation recommendation for the treated exhaust.*
>
> *$V_{ambient}$ was named the Air Quality Index, or AQI, and $V_{exhaust}$ was designated the Exhaust Quality Index, or EQI. The EQI was adopted as the agreed method of ranking the effectiveness of exhaust control technologies by the Collaborative Diesel Research Advisory Panel.*[24]

The EQI[23] was calculated using the same equation but substituting the diesel engine tailpipe raw exhaust concentrations into Equation 1.

CONTROL EFFICIENCY CALCULATIONS. Control efficiencies (percentage decreases in pollutant concentrations due to control) were calculated for DPM, for the various gases, and for chemical species and biological activity of the DPM. The equations used for the control efficiency calculations are as follows:

Correct for background:

$$DPM_{\text{VEHICLE LOC.}} - DPM_{\text{UPSTREAM}} = DPM_{\text{CORRECTED}}$$
$$CO_{2\,\text{VEHICLE LOC.}} - CO_{2\,\text{UPSTREAM}} = CO_{2\,\text{CORRECTED}} \quad (2)$$

Normalize:

$$\frac{DPM_{\text{CORRECTED}}}{CO_{2\,\text{CORRECTED}}} = \text{Norm. DPM} \quad (3)$$

Control efficiency:

$$100 \times \frac{\text{Norm. DPM}_{\text{NO CONTROL}} - \text{Norm. DPM}_{\text{CONTROL}}}{\text{Norm. DPM}_{\text{NO CONTROL}}} \quad (4)$$

A control efficiency is also calculated for the AQI. A positive AQI control efficiency indicates that the control device has a positive overall effect on the mine air quality. A positive AQI control efficiency minimizes the concern that a device may be lowering the concentration and reducing the health effects of one pollutant, while at the same time having the opposite effect on another more harmful pollutant. Unfortunately, the AQI does not make use of the chemical and biological data associated with the vapor phase organics and the SOF associated with the DPM.

A concentration theoretically cannot be reduced more than

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100 percent, and therefore positive control efficiencies greater than 100 percent indicate suspect data in the measurements or calculations. Such errors can occur as a result of significant changes taking place between measurements with and without the control device installed or inability to properly locate upstream sampling instruments in the same fresh air as that flowing past the diesel equipment and the downstream sampling locations. Negative control efficiencies of several hundred percent are not impossible, since these only indicate that use of the control device has resulted in large concentration increases.

Because the sulfur dioxide concentrations are calculated from the carbon dioxide concentrations, any reductions in sulfur dioxide due to control are not accounted for in the calculated values. Therefore, the control efficiency for sulfur dioxide cannot be accurately determined. The calculated values presented assume sulfur dioxide control by the CDPF to be zero.

Because mine ventilation and vehicle operating conditions frequently change in a mine, it is important to normalize the measured concentrations prior to using them to calculate the control efficiency. Normalization, as the efficiency equations above indicate, was accomplished here by dividing the concentrations of diesel-produced pollutants by the concentrations of diesel-produced carbon dioxide emitted at the same time.[25]

This carbon dioxide normalization expresses the pollutant concentrations in terms of concentration per percent carbon dioxide. The normalized concentrations are largely unaffected by either vehicle use or ventilation variables, as can perhaps be most easily understood from the following example: If the vehicle operates twice as much, the carbon dioxide concentration as well as the concentrations of the other pollutants would be expected to double (same quantity emitted, but emitting during twice as much time). However, the normalized concentrations would remain unchanged. Likewise, if dilution ventilation air doubles, the carbon dioxide concentration would be reduced in half, as would the concentrations of the other diesel pollutants, and the normalized concentration would remain unchanged. The normalized concentration would, however, be reduced by half if a given pollutant concentration were reduced by half by control and the carbon dioxide concentration was unchanged. None of the control devices tested to date affects the carbon dioxide concentration significantly.

Results

Control Device Effects On DPM

Table 1 presents unnormalized, uncorrected average mine air gaseous pollutant and DPM concentrations and the AQI for upstream, on-vehicle, and downstream locations in mines Q and T, with and without the test control devices. When considering unnormalized data, it is important to keep in mind the fact that increases or decreases may be due to mine ventilation and vehicle operation variables, both of which are removed by normalization. All of the concentration data in the tables and figures are unnormalized, uncorrected data. However, all control efficiencies are calculated using normalized data. Carbon dioxide data are also presented for the downstream location because these data were used to normalize the chemical and biological characterization data obtained from this location. Table 2 shows the uncorrected, unnormalized tailpipe data for the vehicle studied in each mine. Normalization does not significantly improve the calculated tailpipe control efficiency data because there are no ventilation changes to affect the readings. However, the effects of engine loading variations, if they occur, are reduced by normalization.

Figure 3 compares mine Q and mine T control-off and control-on vehicle location DPM concentrations. The mine air DPM concentration was reduced from 0.70 to 0.37 mg/m^3 in mine Q, but increased from 0.37 to 0.45 mg/m^3 in mine T. The mine T control-on DPM increase is probably not due to the control device, but to observed changes in diesel activity and mine ventilation air flow rates which were considerably higher during the control-off condition.

Concentrations were normalized to calculate the control efficiencies and corrected for upstream concentrations. In mine Q the control efficiencies represent control by replacement of the normally used OCC with a combined CDPF and OCC; in mine T the control efficiencies represent replacement of the normally used OCC with a CDPF.

DPM control efficiencies are shown in Figure 4 for mines Q and T. For mine Q the mean control efficiency for DPM was 61 percent based on mine Q vehicle-location data and 95 percent based on tailpipe data. For mine T these values were 82 percent for bolter location data and 63 percent for bolter tailpipe data.

Control Device Effects on Other Diesel Exhaust Pollutants

Control efficiencies were also calculated for the gaseous pollutants carbon monoxide, nitric oxide, nitrogen dioxide, and sulfur dioxide, and also for the AQI and EQI. Control efficiencies for tailpipe data include range bars which represent the range of control efficiencies used to calculate the average. These bars are not presented for the mine ambient air data because the averaging was performed prior to the calculations of control efficiencies.

Data comparing the on-vehicle control-off and control-on nitrogen dioxide concentrations are presented in Figure 5. Mine Q nitrogen dioxide concentrations were increased from 0.10 to 0.43 ppm by control and mine T concentrations from 0.25 to 0.64 ppm. The nitrogen dioxide concentrations were so low that the control efficiencies are not presented because they would not be reliable. No tailpipe nitrogen dioxide data were available for either mine.

Figure 6 shows that the on-vehicle nitric oxide concentrations were 2.4 ppm for the control-off and 2.8 ppm for the control-on condition. For mine T the nitric oxide concentrations were 2.9 ppm for the control-off and 8.6 ppm for the control-on condition. Tailpipe nitric oxide concentrations (Figure 7) show that nitric oxide may increase in the control-on condition in mine Q, but the mine T change is only very slight, if at all.

Mine Q on-vehicle data show a slightly negative (−5%) control efficiency for nitric oxide (Figure 8), while the mine T on-vehicle data show a positive (48%) control efficiency. Tailpipe control efficiency data, which are believed to be more accurate (Figure 8), indicate little if any effect, with only −3 percent for mine Q and −5 percent for mine T.

Figure 9 indicates that on-vehicle carbon monoxide con-

TABLE 1. Average Mine Ambient Air Gaseous and DPM Concentrations at Upstream, Vehicle, and Downstream Locations in Mines Q and T With and Without the Test Control Devices: Unnormalized, Uncorrected Data

	Mine Q[A]		Mine T[A]	
Component	**Control Off[B]**	**Control On[B]**	**Control Off[B]**	**Control On[C]**
Carbon dioxide (%)				
Upstream	0.05	0.059 ± 0.005	0.05 ± 0.014	0.05
Vehicle	0.081 ± 0.001	0.090 ± 0.008	0.058 ± 0.004	0.15 ± 0.07
Downstream	0.076 ± 0.034	0.12 ± 0.01	0.053 ± 0.01	0.165 ± 0.078
Carbon monoxide (ppm)				
Upstream	0.5 ± 0.7	0.5 ± 0.5	0.75 ± 0.35	0.25 ± 0.35
Vehicle	1.25 ± 1.06	1.33 ± 0.577	1.0	2.5 ± 0.7
Nitric oxide (ppm)				
Upstream	0.32 ± 0.05	0.573 ± 0.35	1.67 ± 1.89	0.235 ± 0.08
Vehicle	2.45 ± 0.35	2.77 ± 0.9	2.87 ± 0.12	8.6 ± 3.1
Nitrogen dioxide (ppm)				
Upstream	0.04 ± 0.01	0.03 ± .01	0.195 ± 0.09	0.09 ± 0.07
Vehicle	0.1	0.43 ± 0.15	0.25 ± 0.035	0.64 ± 0.24
Sulfur dioxide (ppm)				
Upstream	0.12	0.187 ± 0.035	0.305 ± 0.29	0.31
Vehicle	0.336 ± 0.01	0.399 ± 0.05	0.51	2.45 ± 1.3
DPM (mg/m^3)				
Upstream	0.285 ± 0.92	0.21 ± 0.04	0.193 ± 0.188	0.045 ± 0.005
Vehicle	0.7	0.367 ± 0.06	0.368 ± 0.09	0.45 ± 0.29
AQI				
Upstream	0.626 ± 0.18	0.53 ± 0.11	0.669 ± 0.61	0.288 ± 0.015
Vehicle	1.63 ± 0.041	1.18 ± 0.22	1.17 ± 0.162	2.71 ± 1.44

[A]Presented as mean (±SD) for two to three sampling dates per condition; one to six values per sampling date.
[B]Mean of samples on two sampling dates.
[C]Mean of samples on three sampling dates.

centrations were very low, may be affected very slightly by control, and, for all practical purposes, are the same in both mines. The Figure 10 tailpipe carbon monoxide concentration data indicate that for mine Q, the tailpipe carbon monoxide concentrations were unusually high, with values of 3045 ppm for the control-off and 2771 ppm for the control-on condition. For mine T the tailpipe carbon monoxide concentrations were low, at 24 ppm with the control off, but increased markedly, to 145 ppm with the control on. Very high tailpipe carbon monoxide concentrations on mine Q vehicles show that carbon monoxide from diesel exhaust could, in a poorly ventilated area, be a serious safety and health concern.

Figure 11 carbon monoxide control efficiencies for mine Q were negative (−13.5%) based on vehicle (LHD) location data and positive (32.3%) based on tailpipe data. For mine T they were positive (32.5%) based on vehicle (bolter) location data and negative (−557%) based on tailpipe data, which cannot be explained.

TABLE 2. Average Tailpipe Gaseous and DPM Concentrations for Mine Vehicles in Mines Q and T With and Without the Test Control Devices: Unnormalized, Uncorrected Data

	Mine Q[A]		Mine T[A]	
Component	**Control Off[B]**	**Control On[B]**	**Control Off[C]**	**Control On[D]**
Carbon dioxide (%)	7.6 ± 1.0	9.54 ± 0.24	7.7 ± 0.42	7.1 ± 0.35
Carbon monoxide (ppm)	3045 ± 642	2720 ± 194	23.7 ± 0.02	144 ± 24
Nitric oxide (ppm)	340 ± 69	460 ± 27	403 ± 24	394 ± 37
Nitrogen dioxide (ppm)	NA[E]	NA[E]	25 ± 3.7	NA[E]
Sulfur dioxide (ppm)	54 ± 0.6.5	69	156 ± 8.6	145.5 ± 7.0
DPM (mg/m^3)	407 ± 135	25 ± 35	60 ± 4.6	21 ± 6.3
EQI	725 ± 250	105	216 ± 6.0	130 ± 11.2

[A]Presented as mean (±SD).
[B]Average of five samples for each of two vehicles, engine rpm not available.
[C]Average of two samples for one vehicle, engine speed 2300 rpm.
[D]Average of two to four samples for each vehicle, engine speed 2300 rpm.
[E]NA = not available or no data.

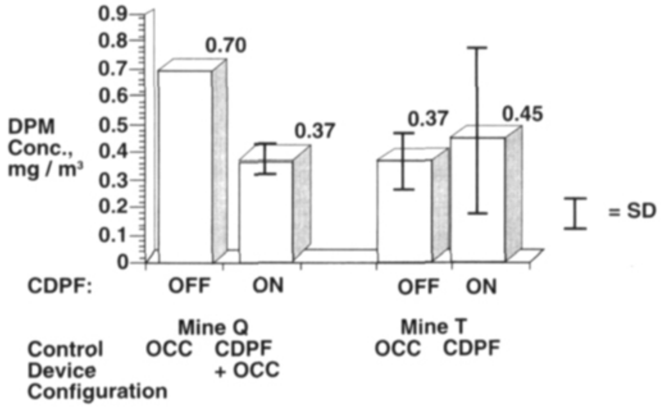

FIGURE 3. DPM concentrations at vehicle location in mines Q and T with CDPF off and on.

When the combined CDPF and OCC was installed in mine Q, the AQI (unnormalized data) was reduced at the on-vehicle location, as shown in Figure 12. However, the AQI increased as a result of replacing the OCC with the CDPF in mine T. The unnormalized data are misleading here because this air quality degradation with the control on was really due to the fact that there was significantly less air flow in mine T during the control-on condition tests.

Figure 13 presents the AQI and EQI control efficiencies. These values indicate that the control-on conditions have a positive effect on the AQI and EQI in both mines. There are some variations in the control efficiencies calculated from on-vehicle and tailpipe measurements. Thus, for mine Q the control efficiency values are 32 percent for measurements at the on-vehicle location and 85 percent in the vehicle tailpipe. For mine T the values are 64 percent for measurements at the on-vehicle location and 35 percent in the vehicle tailpipe. As mentioned earlier, we have somewhat more confidence in the tailpipe values because they are affected by fewer variables that are difficult to measure and control.

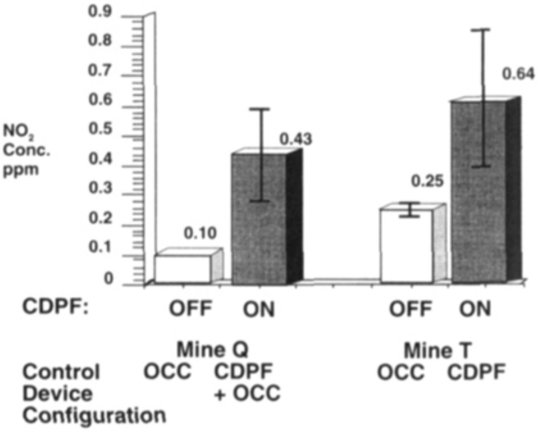

FIGURE 5. Mines Q and T vehicle location nitrogen dioxide concentration with CDPF off and on [nitrogen dioxide permissible exposure limit (PEL) 3 ppm].

Examination of a 1-week-old mine T CDPF showed some black spots on the upstream end, but the downstream end was very clean, as would be expected for an undamaged ceramic matrix. The maximum exhaust pressure that could be produced by increasing the engine idle speed was found to be 25 cm of water, indicating that the CDPF was apparently autoregenerating to remove the collected DPM.

Chemical and Biological Characterization: Unnormalized Data Collected by High Volume Samplers

Table 3 is a summary of the downstream data (unnormalized and uncorrected) obtained using the high volume samplers in mines Q and T. As noted in our underground coal mine study,[11] the primary intent of using the high volume samplers was to obtain sufficient DPM mass to quantify the levels of associated organics (SOF), biologically relevant PAH, and mutagenic activity. As noted previously, the same type of diesel vehicle operation was not monitored in each of the metal

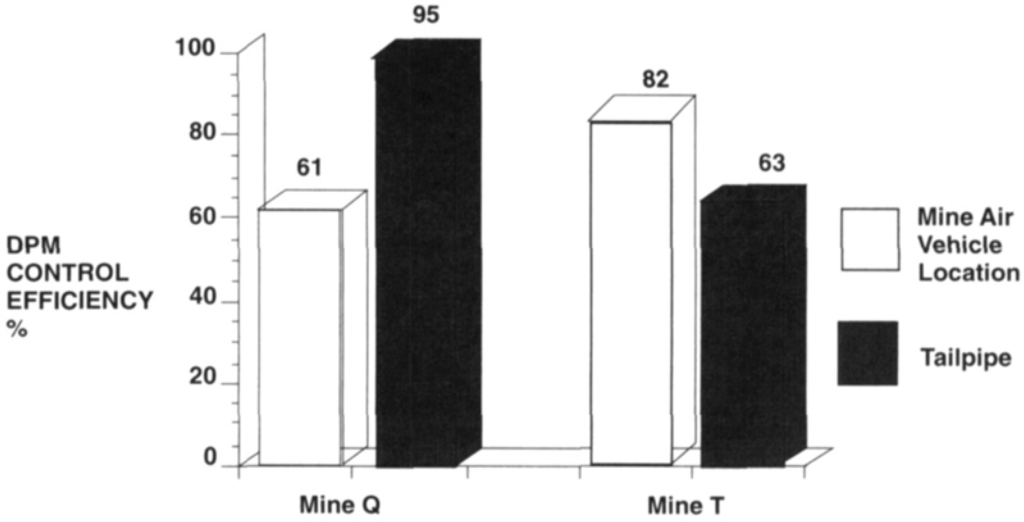

FIGURE 4. Corrected and normalized vehicle location and tailpipe DPM control efficiencies for mines Q and T.

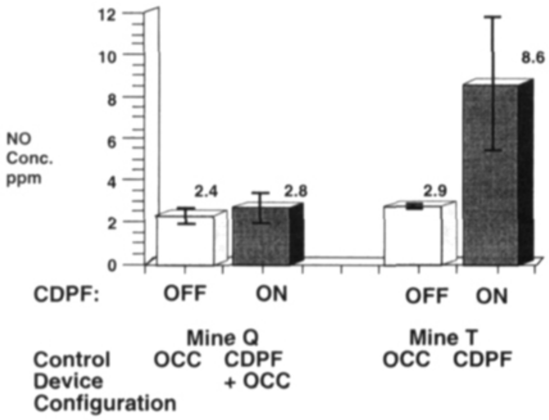

FIGURE 6. Mines Q and T vehicle location nitric oxide concentration with CDPF off and on (nitric oxide PEL 25 ppm).

mines. Therefore, the sampling sites designated as upstream and downstream in each mine were not exact replicas. Additionally, the routine use of OCCs as control devices in each mine meant that DPM and associated components collected at the upstream sites on all sampling dates and at the downstream sites with the test control devices off may also have been affected by the use of emission control devices.

In general, the downstream data were highly variable within and between mines. This can be best illustrated by referring to Figure 2 and the list of mine conditions that affect control efficiency data. Some of the sources of this variability include differences in mine sampling locations and periods, ventilation patterns, diesel equipment type and operation, and control devices used, both in routine operation and being tested in this study. Large differences occasionally occurred within and between sampling dates in both mines. This could reflect differences in diesel activity during the sample collection periods, particularly for the high volume samplers which were operated only when diesel vehicles were operating.

The DPM levels, in particular, measured in mine Q using the high volume samplers are considerably higher than those found with personal dichotomous samplers at the vehicle location for the control-off and control-on conditions. Values found in mine T are about the same (see Table 1 for personal dichotomous sampler data). In mine Q the high volume samplers were operated for a total time of 1 to 3 hours per day, compared with 5 to 6 hours per day for the personal samplers. In mine T the high volume samplers were operated over time periods closer to those for the personal samplers, that is, approximately 3 to 6 hours per day versus 5 to 6 hours per day, respectively. High volume sampler operating times were determined largely by the pressure drop across the filter and the resulting time before a new filter had to be inserted. Downstream concentrations may be higher than concentrations measured on the vehicle if the vehicle exhaust pipe is facing downstream. However, if the vehicle exhaust pipe faces upstream, the on-vehicle concentrations will probably be higher. Details on the vehicle orientation over the measurement periods were not recorded.

Higher downstream DPM levels using the high volume samplers in mine Q could also be due to factors outlined for coal mines:[11] shorter sampling times than for personal samplers, a larger fraction of which represented intense diesel operation; a slightly larger impactor particle-size cut point (0.95 versus 0.8 μm); and possible reentrainment of rock particles, resulting in rock particles contributing to the mass collected on the back-up filters. However, rock dust should make only a negligible contribution to the detected SOF, PAH, and mutagenic activity. SOF levels were, in fact, very low in the downstream areas of each mine. Because these catalyzed control devices affect the SOF levels (as hydrocarbons) in particular,[10,26] the SOF results probably reflect the effects of the OCC and/or CDPF on the emissions. The high volume sampler DPM and DPM-component values in mine Q may, therefore, represent potentially worst-case levels that might occur in the downstream sampling areas, while the levels found in mine T may be more representative of shift average values.

The PAH (nanograms/cubic meter) and mutagenic activity (revertants/cubic meter) levels are also presented in Table 3. In mine Q the uncorrected, unnormalized level of the most volatile PAH compound (FLU) was reduced with the test control device, while levels of the other measured DPM-associated PAHs (B*a*A and B*a*P) were increased slightly with the combined CDPF and OCC. In mine T the levels of FLU and B*a*A decreased, while the level of B*a*P appeared to increase. About the same levels of direct-acting DPM mutagenic activity were found in the downstream samples for each mine for the control-off condition; however, the mutagenic activity detected in mine Q on a mass basis (revertants/microgram) was about half that found in mine T (1.3 versus 2 revertants/μg, respectively). The activity levels (revertants/cubic meter and revertants/microgram) decreased in mine T with the CDPF (from 25 to 40%), but increased in mine Q with the CDPF and OCC (about 700%).

Control Efficiencies

Normalized and corrected control efficiencies for all of the high volume sampler-related data are presented in Figures 14 and 15 for mines Q and T, respectively. Normalization had a very large effect on the metal mine data because of very large

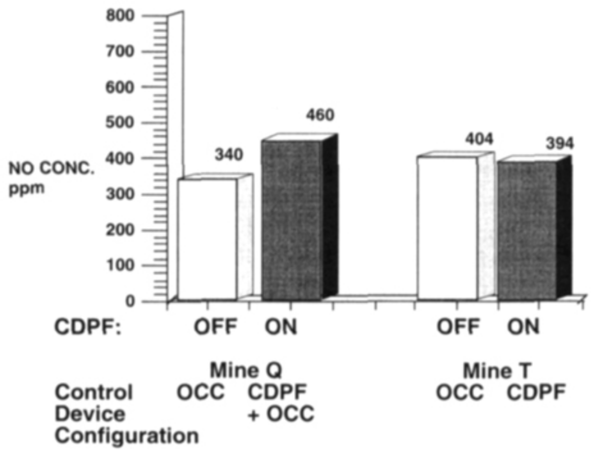

FIGURE 7. Mines Q and T tailpipe nitric oxide concentrations with CDPF off and on.

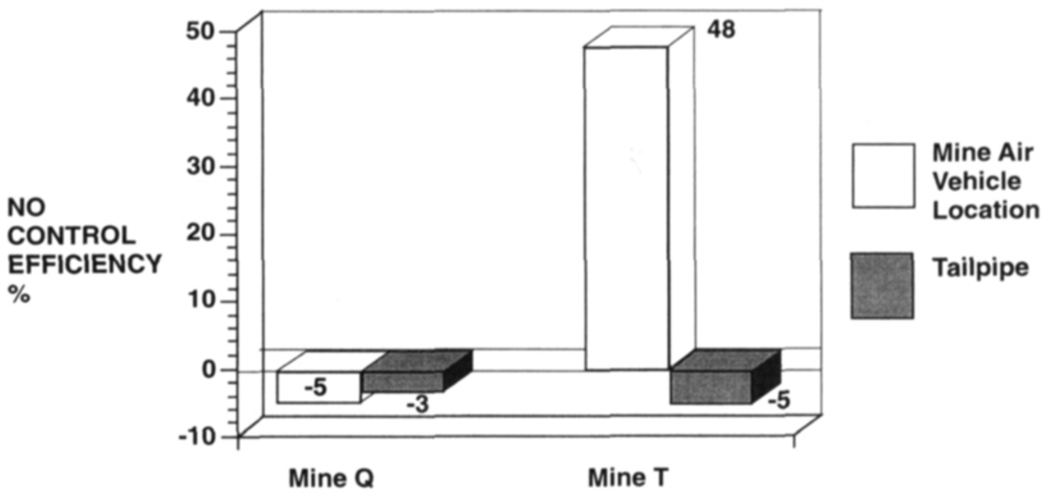

FIGURE 8. Corrected and normalized vehicle location and tailpipe nitric oxide control efficiencies for mines Q and T.

ventilation changes and therefore very large changes in the mean carbon dioxide levels between the control-on and control-off measurements (Table 1). Some of the high volume sampler upstream data were much higher than would be expected, particularly in mine T. Variations in the upstream levels (especially those due to diesel equipment operated with OCCs) may greatly impact the calculated control efficiencies in the downstream test areas, with some of the measured parameters having negative control efficiencies and some having calculated efficiencies greater than 100 percent. Control efficiencies greater than 100 percent result from the calculation when the upstream level of a pollutant exceeds the downstream level. In most cases the normalized or normalized and corrected control efficiencies were very similar.

In mine Q data obtained with the high volume sampler indicate that the replacement of the OCC by the combined CDPF and OCC resulted in about 80 percent control efficiencies for DPM and SOF in the downstream area (Figure 14 data normalized for carbon dioxide levels and corrected for upstream values). Replacing the OCC with the CDPF resulted in calculated control efficiencies for mine T DPM levels that were slightly greater than 100 percent; this result was due to measured upstream levels that were as high as those measured downstream. When normalized for carbon dioxide levels (based on data in Tables 1 and 3), this DPM control efficiency was 85 percent. However, replacing the mine T OCC with a CDPF lowered SOF levels by only 45 percent (Figure 15).

It should again be noted that upstream corrections are predicated on the fact that the upstream measurements are truly made in upstream air. Correcting the data using upstream values which are apparently not truly in the fresh air that is upstream of the vehicle and downstream measurement locations also caused problems with PAH measurements. Thus most of the PAH control efficiencies were close to 100 percent in both mines, using data that were upstream corrected (Figures 14 and 15). In mine Q the FLU removal efficiency was calculated to be slightly greater than 100 percent (108%); for B*a*A it was about 160 percent, possibly reflecting variations in analytical techniques, but probably due to upstream concentrations that were as high as those measured at the downstream locations. These control efficiencies dropped to 83 percent for FLU and 44 percent for B*a*A using data that were not corrected for upstream levels (data not shown in figures or tables),

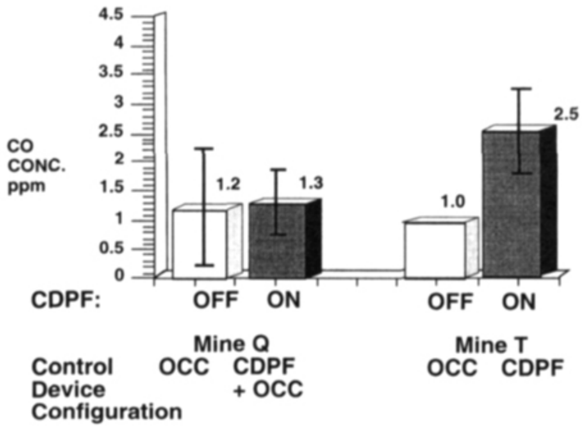

FIGURE 9. Mines Q and T vehicle location carbon monoxide concentration with CDPF off and on (carbon monoxide PEL 50 ppm).

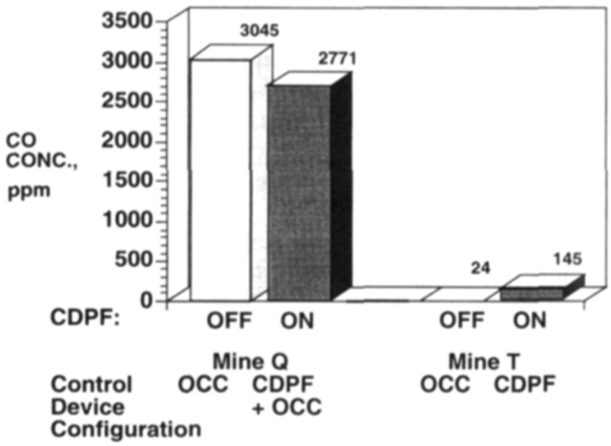

FIGURE 10. Mines Q and T tailpipe carbon monoxide concentration with CDPF off and on.

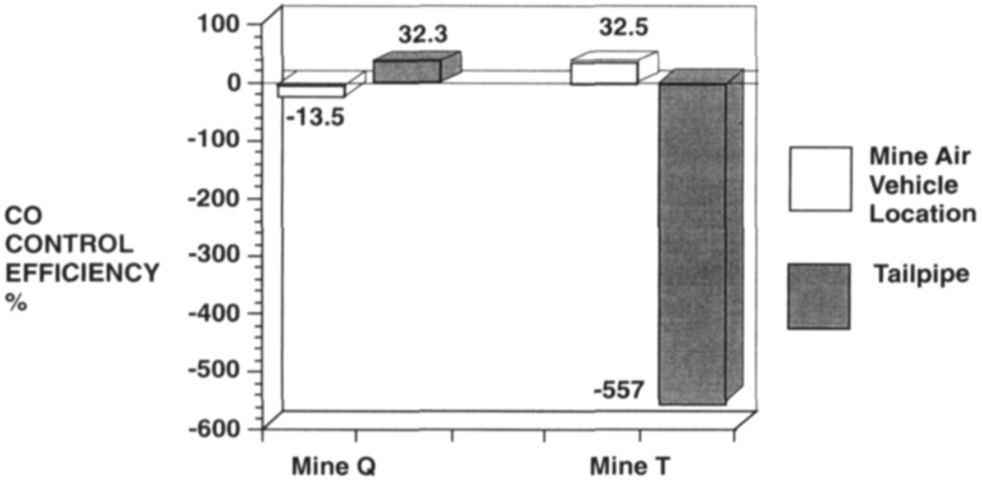

FIGURE 11. Corrected and normalized vehicle location and tailpipe carbon monoxide control efficiencies for mines Q and T.

indicating the possible impact of mine air recirculation and upstream measurements in the air that was not truly upstream air on these downstream PAH concentrations.

Replacement of the OCC routinely used in mine T by the CDPF reduced mutagenic activity, resulting in nearly 100 percent control efficiency (Figure 15). In contrast, replacement of the OCC with the combined CDPF and OCC in mine Q resulted in an increase (−245% control efficiency) in DPM-associated mutagenic activity levels (Figure 14). For mine Q the downstream DPM-associated mutagenic activity also appeared to be greatly impacted by mutagenic activity from the upstream sites. Thus, the corrected-only control efficiency was −705 percent (increased by about seven times, not shown in figures or tables), but the normalized-only efficiency was −94 percent (almost doubled as calculated from the data in Tables 1 and 3). For mine Q, in particular, the upstream mutagenic activities on a mass basis (revertants/microgram) were always greater than the downstream values and the activities on a concentration basis (revertants/cubic meter) were often similar to the downstream values.[27]

Discussion

As discussed earlier, there are numerous variables which can neither be easily measured nor controlled that affect the concentrations of diesel emissions in the underground mine air. These variables may, under certain conditions, produce large, unexplainable changes in the measured concentrations. Thus, while it is possible to make accurate measurements underground, it is much more difficult to control conditions to the extent needed to compare two different conditions such as control-on and control-off conditions, as was attempted here. Obviously some of the data discussed here demonstrate the effects of this uncontrolled variability in production underground mine conditions.

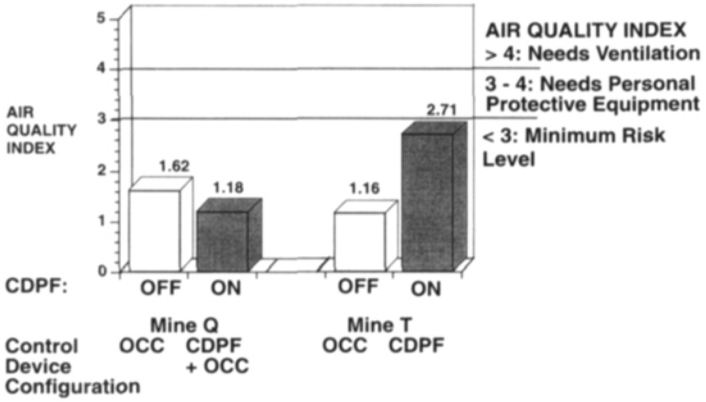

FIGURE 12. Mines Q and T vehicle location AQI with CDPF off and on.

Of special concern are the variables associated with recirculation in the mine ventilation system in that such recirculation is often difficult to measure or control, but has a marked effect on the upstream concentrations and resultant upstream-corrected concentrations that are measured on and downstream of the diesel equipment being tested. Likewise, the effects of vehicles that somehow contaminate what should be fresh upstream air are hard to assess. It could be argued that attempts to conduct experiments of the level of sophistication presented here in the production underground mine environment are futile.

On the other hand, if the measurements were made only in the tailpipe or in another controlled environment, various important differences between the controlled environment and uncontrolled production mine conditions would possibly be overlooked. Tailpipe measurements in the laboratory are very costly to set up, and the engines may not be representative of those that are used in the mines. Tailpipe measurements underground, such as those presented here where the EMA was used to make the measurements, involve only one engine load and speed condition, and it is possible that controls may perform entirely differently under the test conditions than at the conditions used in production. Likewise the effects of continual changes in loads and speeds may be overlooked.

Thus the data reveal even more than a simple controlled experiment. For example, they show that it is difficult to control one area of a mine because of effects from other mine areas. They may also indicate that there are other sources of pollutants, such as hydraulic and engine oil spills, and point out the need to look at these other sources of pollutants.

The study results using portable samplers (data presented in

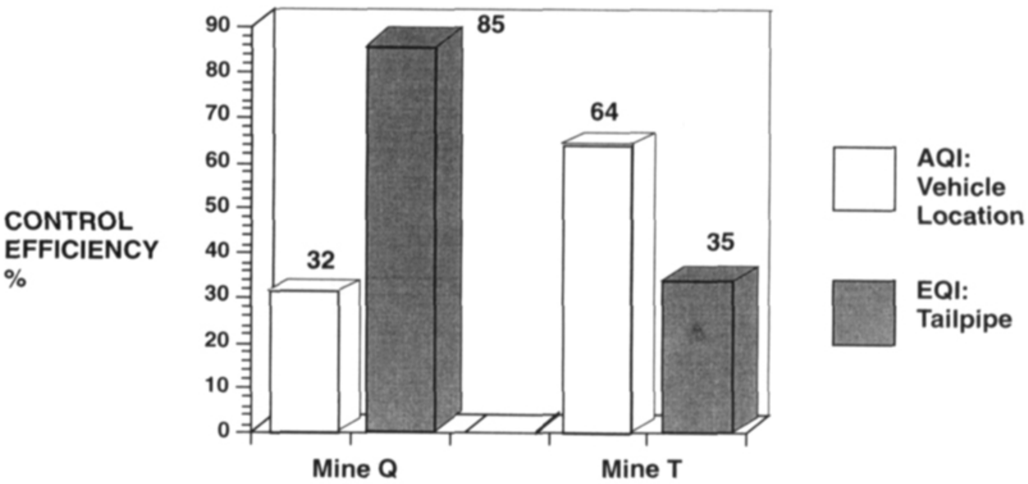

FIGURE 13. Corrected and normalized vehicle location and tailpipe AQI and EQI control efficiencies for mines Q and T.

Tables 1 and 2 and Figures 3 to 13) indicate that replacement of an OCC with a combined CDPF and OCC unit in mine Q and with a CDPF alone in mine T improved the air quality in terms of the effects of control on DPM and on the air quality and exhaust quality indexes. The data, for the most part, indicate that these replacements were very effective in controlling DPM, but had little effect on the gaseous pollutants carbon monoxide and nitric oxide. Nitrogen dioxide concentrations were very low, making the calculations of control efficiencies of questionable reliability.

In this article, as in our article dealing with an underground coal mine,[11] the DPM concentrations measured using personal dichotomous samplers (Table 1) were substituted for RCD in the AQI equation. The procedure, which also involved calculation of the sulfur dioxide concentration needed for the AQI calculation, worked out well. Use of DPM from the dichotomous samplers appears to more accurately meet the original intent of the developers of the AQI where RCD was only a means of estimating the DPM concentration for the calculation.[23,24] Substituting the DPM values measured by personal dichotomous samplers for RCD in the AQI equation makes it possible to calculate the AQI in both metal/nonmetal and coal mines, something that has not been accomplished at all in coal mines because the RCD measurement was unable to distinguish between DPM and organic material contents in the ore itself, including coal dust. Measurements to estimate the organic material contents in the ore dust and correct the RCD values for these made it possible to use the RCD values in metal mines. However, the calculated RCD values were still questionable because of the unknown relationship between organics in the ore sample used to measure the organic concentration and the organic concentration in the respirable dust.

The sulfur dioxide concentration needed to calculate the AQI was determined by calculation. The calculations use stoichiometric relationships between the exhaust carbon dioxide and sulfur dioxide concentrations based on the fuel sulfur content and its carbon to hydrogen ratio. Also included were sulfate measurements in the mine air during control-off and control-on conditions to estimate the percentage of fuel sulfur converted to the sulfur dioxide and sulfate forms.

The EMA tailpipe emissions measurement apparatus was found to be a very useful means of measuring the exhaust concentrations and calculating the control efficiencies for DPM and the gaseous diesel emissions as well (Table 2). This measurement, which was made in the shop prior to and after removing the control device, requires very little time and eliminates numerous variables affecting the calculated control efficiency using mine ambient air measurements. We, therefore, have much more confidence in the tailpipe EQI than in the mine ambient air data. EMA tailpipe nitrogen dioxide data were missing in the control-on condition, and the tailpipe nitrogen dioxide values are assumed to be the same in the

TABLE 3. Diesel-Related Emissions Obtained from Mines Q and T, Using High Volume Samplers, With and Without the Test Control Devices

	Mine Q		Mine T	
Component	Control Off	Control On	Control Off	Control On
DPM (mg/m^3)	3.53 ± 2.48	1.76 ± 0.26	0.78 ± 0.53	0.86 ± 0.22
SOF (mg/m^3)	0.07 ± 0.01	0.04 ± 0.01	0.05 ± 0.04	0.19 ± 0.19
FLU (ng/m^3)	24.0 ± 24.6	8.24 ± 5.44	4.90 ± 1.52	2.70 ± 0.95
B*a*A (ng/m^3)	2.28 ± 2.26	2.65 ± 2.29	1.20 ± 0.91	1.02 ± 0.31
B*a*P (ng/m^3)	1.47 ± 1.51	2.72 ± 2.25	0.61 ± 0.12	1.10 ± 0.13
Activity (rev/m^3)	0.09 ± 0.02	0.34 ± 0.34	0.12 ± 0.06	0.05 ± 0.01

Presented as mean (±SD) for two to three sampling dates.

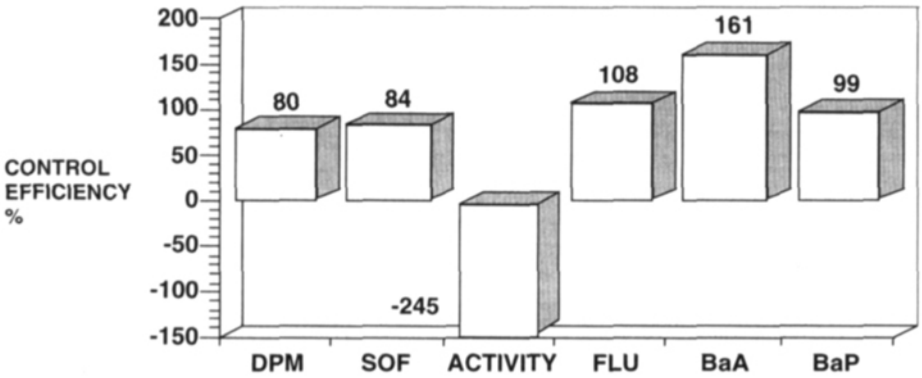

FIGURE 14. Corrected and normalized downstream location DPM, SOF, activity, and PAH control efficiencies from mine Q high volume samplers.

control-on and control-off conditions. The calculated EQI is not very sensitive to nitrogen dioxide, in that even assuming the nitrogen dioxide concentration to be zero in this control-on condition only changes the calculated EQI control efficiency by 5 percent.

The mine T CDPF did pass some particulate in the tailpipe measurements, thus partially accounting for the low efficiency of the EQI which is very sensitive to DPM. Also, the EMA-measured carbon monoxide increased by a factor of 5 for the control-on condition, the other primary reason for the low 35 percent EQI control efficiency.

Mine T mine air data, in particular, demonstrated the importance of data normalization by dividing the measured mine air pollutant concentrations by the simultaneously measured diesel-produced carbon dioxide concentrations in the determination of control efficiencies. Thus it was possible, using the normalized concentrations, to determine that the CDPF actually effected positive control of DPM in mine T, although the mine ventilation was so much greater for the control-off condition that unnormalized DPM concentrations were much lower, although they would be expected to be much higher.

DPM control efficiencies using the downstream location, high volume sampler data are similar to those reported in this article from low flow rate, personal dichotomous samplers (i.e., approximately 70% or greater control efficiencies for the control-on condition in both mines; Figures 4, 14, and 15). Similar ranges of control efficiencies were reported with these types of control devices in controlled laboratory studies conducted at the Bureau of Mines Twin Cities Research Center.[26,27] Reductions in SOF levels in mines Q and T were much less than the >90 percent reductions found in laboratory studies,[26,27] particularly for replacement of an OCC with the combined CDPF and OCC.

A laboratory study under transient engine operating conditions[10] with an OCC on diesel engines typical of those used in mining operations showed significant reductions in nearly all PAH levels in the DPM and in the vapor phase when compared with the control-off condition without any control device. However, when the exhaust temperature is near or below the minimum required for operation of the OCC, as during periods of engine idling or low load/speed conditions, vapor phase oxidation in the OCC is much less efficient. Under these conditions, the CDPF may be a more efficient PAH control device, since at these cooler temperatures the PAH compounds found in greater concentrations in the particle phase could be stored in the CDPF along with the DPM. Subsequent oxidation during periods of increased engine load (higher temperatures) would probably release them. A CDPF on a diesel engine typical of those used in mining operations has been shown under laboratory transient engine load and

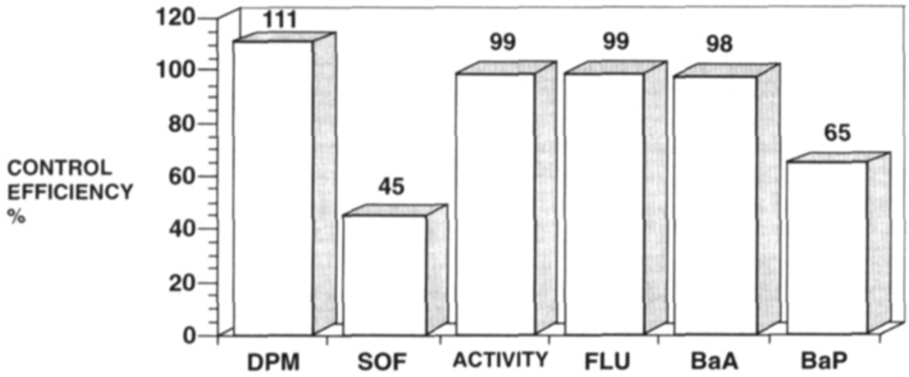

FIGURE 15. Corrected and normalized downstream location DPM, SOF, activity, and PAH control efficiencies from mine T high volume samplers.

speed test conditions to be very effective in reducing DPM-associated PAH (by 98% or more).[26] The net effect of using the combined OCC and CDPF control technologies should be to reduce PAH emissions, with the magnitude of this reduction dependent on engine operating conditions (especially changes that affect exhaust temperatures). Reductions in the measured PAH concentrations by replacement of an OCC with a combined CDPF and OCC were in fact found when the downstream data were corrected and normalized.

In mine T the replacement of an OCC with the CDPF was found to produce positive control efficiencies for all three PAH compounds when the levels are normalized using the diesel-produced carbon dioxide concentrations in the same mine area and corrected for upstream PAH levels (Figure 15). These reductions are probably dependent on engine exhaust temperatures in the same manner as proposed for the combined CDPF and OCC device. For vehicle duty cycles resulting in considerable periods of time where the exhaust temperature is below the OCC operating temperature, the CDPF would be expected to be more efficient; during extended periods of high temperature operation, fewer differences in PAH emissions between the two devices would be expected.

The only potentially adverse effect of the combined CDPF and OCC on mine Q downstream DPM-associated emissions was the increase in mutagenic activity, which may be related to increases in biologically active compounds other than those reported on as part of this study. Some of these increases may also have been related to material transported from the upstream sites, as the upstream samples had even higher levels of mutagenic activity on the dates the combined CDPF and OCC device was being tested. Large increases in mutagenic activity on a mass basis (revertants/microgram) were also found in controlled laboratory studies with this same control device as compared with no control device at all; however, the activity on a concentration basis (revertants/cubic meter) decreased due to the greater decreases in the SOF levels.[27] In contrast, DPM-associated mutagenic activity decreased when the CDPF in mine T replaced the OCC; a similar reduction in activity was found during laboratory studies with a CDPF as compared with no control device.[26]

Conclusions

Data on the various pollutants in mines Q and T lead to the following conclusions:

Diesel Particulate Matter Pollutants

1. Measurements at the LHD location in mine Q showed that replacement of an OCC normally used with the combined CDPF and OCC reduced DPM concentrations by 61 percent. Measurements at the bolter location in mine T revealed that replacement of an OCC normally used with a CDPF reduced DPM concentrations by 82 percent.
2. EMA parked-vehicle tailpipe measurements on the mine Q LHD vehicle with the engine loaded at the torque converter stall load and speed condition showed that replacement of the OCC with the combined CDPF and OCC reduced DPM concentrations by 95 percent.
3. EMA parked-vehicle tailpipe measurements on the mine T bolter with the engine operated at the high idle condition used during bolting showed that replacement of the OCC with the CDPF reduced DPM concentrations by 63 percent.

Gaseous Pollutants

4. Concentrations of gaseous pollutants were not markedly affected by the replacement of the OCC either with the combined CDPF and OCC or by the CDPF alone.

Exhaust Quality Index

5. The EQI calculated from the mine Q LHD vehicle tailpipe measurements was reduced by 85 percent compared with the AQI reduction of 32 percent.
6. The EQI control efficiency from the mine T bolter tailpipe measurements was 35 percent compared with the 63 percent for the AQI control efficiency.

Chemical and Biological Characterization

7. As determined from studies with the high volume sampler, replacement of an OCC with either a combined CDPF and OCC or with a CDPF alone resulted in approximately 80 percent or greater reductions in DPM concentrations and at least 40 to 80 percent reductions in SOF concentrations in the downstream in-mine test areas.
8. Use of either control device typically resulted in approximately 80 percent or greater reductions in levels of DPM-associated FLU, B*a*A, and B*a*P.
9. Replacement of an OCC with the combined CDPF and OCC increased DPM-associated mutagenic activity by at least 100 percent in mine Q, while replacement with the CDPF alone decreased mutagenic activity by 99 percent in mine T.

Acknowledgments

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