A Comprehensive diesel particulate matter investigation in a U.S. industrial commodity mine

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ABSTRACT: Diesel Particulate Matter (DPM) measurements were undertaken at FMC's Trona mine in Wyoming using both shift average and real time monitoring methods. The DPM survey was conducted in two periods. In a primary survey, the mine was divided into several sections. Each included two stations that covered all the entries including belt drifts. Two Airtec analyzers were used for real time measurement by placement upstream and downstream of sources. Thirteen Elf pumps were employed taking Total Weighted Average concentrations. The stations covered mains, sub-mains, development and Longwall (LW). DPM concentration was measured in the main exhaust shaft. A vehicle monitoring log was constructed consisting of vehicle type, direction of travel and time. The log was then used in analysis to determine the DPM spread rate in the different entries up and down stream with respect to the vehicle location. Airflow measurements at the stations were taken during the survey. The survey results also identified the vehicles with higher emission rates that were due to be taken to the DPM maintenance workshop for service. The secondary survey was conducted during a LW move where intense activities were taking place in both recovery and installation set-up face movement operations. The surveys were done for several cycles. It started at the beginning of the recovery cycle with supports, loaded on haulers, leaving the recovery face, travelling in the headgate and approaching the set-up room before returning, unloaded, to the recovery face. The stationary measurements were taken by using the Airtec devices along the recovery and set-up faces by placement upstream and downstream of DPM sources. The equipment measurements were taken by putting the MAHA analyzer on the shield haulers. The results were analyzed to understand the DPM spread during the move while the machines were under load hauling the supports to the set-up face and traveling back under normal conditions. Local ventilation changes were recommended to improve the ventilation during the move. The mine's underground transportation fleet consists of over 250 diesel vehicles. ECOM gas and MAHA DPM analyzers, located in the mine's underground emission shop were used to obtain various vehicle emission rates. The measurements were taken under various conditions such as stall, idle and running conditions. The correlation of the workshop and field measurements was investigated with regard to the machine activity, fuel usage and atmospheric conditions. The results were used to calibrate and validate the DPM surveys and improve the preventive maintenance program.

1 INTRODUCTION

DPM has been classified as a potential occupational carcinogen by the National Institute for Occupational Safety and Health (NIOSH).The Mine Safety and Health Administration (MSHA) rule governing DPM exposures in metal and nonmetal mines cites total carbon (TC), a summation of elemental carbon (EC) and organic carbon (OC) obtained by NIOSH Method 5040, as a surrogate for determining DPM exposures (Noll, 2006). MSHA personnel use the 1973 sampling criteria outlined by the American Conference of Government Industrial Hygienists (ACGIHR) for collecting compliance-based respirable and inhalation samples in metal/nonmetal mines. Instrumentation developments are allowing improved real time monitoring of ventilation parameters particularly DPM.

DPM is within the aerodynamic particle size range of the samplers used for respirable and inhalable dust measurements. Therefore, if a sampler used by MSHA to collect inhalable or respirable dust samples in underground metal/nonmetal mines was used to collect DPM, both the DPM and mine ore dust would accumulate on the sample filter (Noll, 2006).

Therefore, U.S. Bureau of Mines (BOM) researchers developed a size-selective sampler that allowed only particulate matter with an aerodynamic diameter less than 0.8 µm to pass through the device and be collected on a downstream filter.(Cantrell, 1997) Since the aerodynamic diameter of most ore dust is typically greater than 0.8 µm, and the aerodynamic diameter of most DPM is less than 0.8 µm, (Cantrell, 1991) the impactor segregates most of the DPM from the ore dust and permits only DPM to be collected. Research results show that the classification efficacy, in preventing dust to pass through this impactor, is greater than 90%. To comply with the requirement and lower the DPM exposure, mines are implementing a variety of control technologies such as emission based maintenance programs where adjustments or repairs are performed on the vehicles (McGinn, 2000).

2 MEASURING METHODS

Several methods were used to measure DPM. The survey was focused on area sampling throughout the mine. The DPM sampling requirement as stated §57.5071, MSHA compliance sampling procedures were followed during the survey.

An initiative in some mines has been to limit the number of vehicles in the mining section or panel by the use of a Tag Board or Traffic Controller at the panel travel road entrance to manage exhaust DPM and gases. Diesel tags or tokens are used to control the number of vehicles entering a section or panel and so limit level of pollution. Summation of DPM levels from points monitored throughout a panel demonstrates increasing DPM levels from influence of additional equipment in series within the ventilation circuit (Gillies, 2012). An alternative approach is to invest in underground continuous real-time monitoring of exhaust gases, DPM and section air quantity and integrate this information to determine whether an additional vehicle can enter without exceeding diesel target limit. This optimizes the access of diesel vehicles and replaces the existing manual tag board system. Real-time DPM monitoring allows the industry to pin-point high exposure zones such as those encountered where various vehicles work in areas of constrained or difficult ventilation. Identification of high DPM zones allows efficient modification of mine ventilation, operator positioning and other work practices to reduce underground miners' exposures.

2.1 *NIOSH 5040*

The NIOSH 5040 method is an established technique for measuring both organic and elemental carbon. The process involves drawing sampling air through a DPM cassette at a flow rate of 1.7 liters per minute to collect soot onto quartz filters inside the cassette. After sampling, punches of these filters are placed inside a 5040 oven for analysis. The oven first measures organic carbon (OC) by progressively increasing its temperature up to 870 °C in four steps in a pure helium environment. The lack of oxygen prevents EC from reacting. OC is oxidized to carbon dioxide and is reduced to methane. The methane is measured using a flame ionization detector (FID). EC is then measured by reducing the oven temperature and then raising it back up to 900 °C in a helium/oxygen atmosphere (Janisko, 2008). EC reacts with oxygen to form carbon dioxide. Once again, the carbon dioxide is reduced to methane and the methane is measured with an FID.

Because a suitable reference material is not available for determining the organic and elemental carbon content of a complex carbonaceous aerosol, only the accuracy of the method in the determination of total carbon (TC) could be examined (NIOSH Manual). During the survey, 13 Elf pumps were at the stations. The cassettes were then sent to the laboratory and the results were adjusted to calculate the concentration for the period of 8 hours.

2.2 *Real Time Monitoring*

Several monitoring devices were used to measure DPM concentration. The FLIR Airtec, only became commercially available in 2011 subsequent to NIOSH development (Noll et al., 2007). It measures the Elemental Carbon (EC) component of DPM by a laser scattering approach. Results from the Airtec can be compared directly with SKC system DPM evaluations. Both new instruments have been evaluated underground in robustness and reliability testing in coal and metal/non-metal mines. Two Airtec units were used in this study, up and down stream and the results were compared against the NIOSH method.

2.3 *Tailpipe Monitoring*

The MSHA tailpipe particulate method, which is similar to the American Society for Testing and Materials (ASTM) approach, requires dilution of the exhaust prior to collecting a sample (MSHA 2009; ASTM 2002). This method, as well as the required laboratory instruments can be time-consuming and the logistical requirements made it unfeasible in many areas of an underground mine (Noll et al., 2013). Several studies have published data evaluating the use of different instruments.

The Emission Shop at FMC Trona Mine is equipped with a MAHA MPM-4M DPM and ECOM Gas analyzer. The study was undertaken to investigate the correlation of the results from Emission

Shop data and actual field measurement. For this purpose the MAHA MPM-4M unit was installed on a Fletcher Prime Mover, Shield Hauler during a LW move. The results were then compared against the Airtec readings. The MPM-4M is a rugged, practical and easily operated diesel particulate measuring instrument specifically designed for measuring particle concentrations in the exhaust of mining engines. Using advanced laser light-scattering technology coupled with integrated sample preconditioning, the MPM-4M can accurately and instantly measure diesel particulate concentrations in the exhaust from all engine types, including exhaust which has passed through water scrubbers. Table 1 is an example of the emission shop tailpipe DPM measurements emitted from LHD.

Table 1. DPM concentration on a LHD.

	Pre-scrubber	Post-scrubber
Stall test Result	14.4	13.1
Average Conc (Idle)	8.2	9.2
Average Conc (Power)	26.8	20.9
Min Reading	2.1	2.8
Max Reading	113	75.3

3 TEST DESCRIPTION (CASE STUDY)

The DPM test was conducted in two stages. The primary survey covered the south of the mine where a majority of diesel equipment commutes on a regular basis. For this reason, the mine was divided into four sections. The secondary survey was done during the LW move where the support haulers were moving the shields from recovery room to the set up face. Moving LW is considered the most concentrated diesel activity in the mine.

3.1 *Primary Test (Regular Mining)*

The four divided sections were chosen in a way to cover the main developments. Each station consisted of the main roads, back road and belt drifts. At each station, a real time Airtec was placed at the main drift that mostly is used as a transportation drift. The Elf pumps were placed in the main roadway as well as the other drifts to measure the DPM's TWA concentration. Figure 1 shows the instruments placement pattern at each station. 9 Shaft is one of the mine's exhaust shaft for the south part of the mine. Therefore two Elf pumps were placed to monitor the DPM concentration at 9 Shaft. The Elf pumps also were place outby the main shop regulators. Currently the shop is ventilated by approximately 50m^3/s. The air is considered fresh air and the sampling results show that the DPM concentration is lower at the main development. The stations layout is shown in Figure 1.

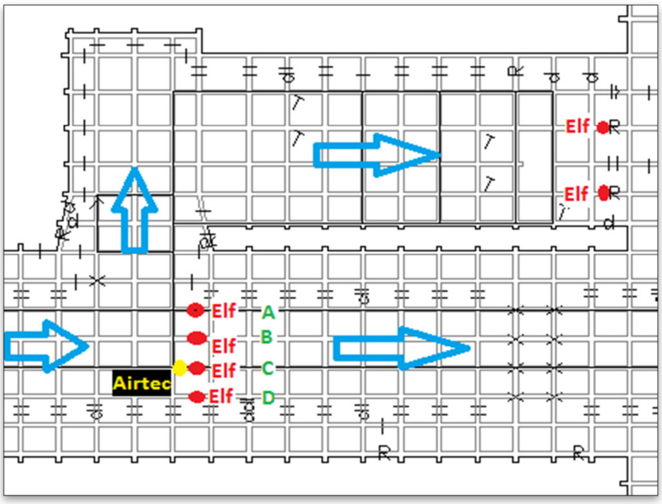

Figure 1. Instrument placement pattern at each station.

The leapfrogging approach was used to measure the DPM concentration up and downstream. A vehicle monitoring log was constructed consisting of vehicle type, direction of travel and time. The logged data was then used to analyze the DPM concentration graphs. Furthermore, the data used to identify which equipment emitted DPM at higher rates.

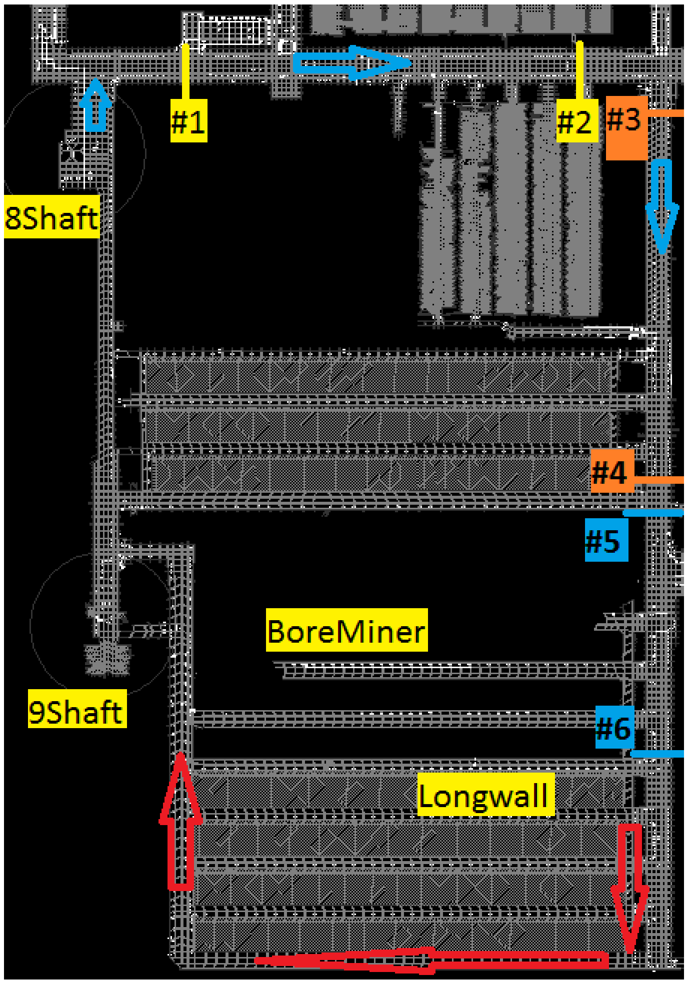

Figure 2. Station layout throughout the mine.

3.1.1 *Leapfrogging station #1 & #2*

Station # 1 was chosen inby the main shop split as shown in Figure 2. About 110m^3/s of air enters the split. Approximately 50m^3/s enters the shop and the rest flows inby the station #1. Station #2 was chosen about 2.7 km inby the first station. A total of 9 Elf pumps were placed in both station and shop south regulator. Figure 6 shows the pumps that were hung from the top. Results from the Airtecs are presented in Figure 3 and Figure 4. The vehicle log data shows that 140 pieces of diesel equipment traveled inby or outby of Station #1. The direction of travel can be used to explain the peak points.

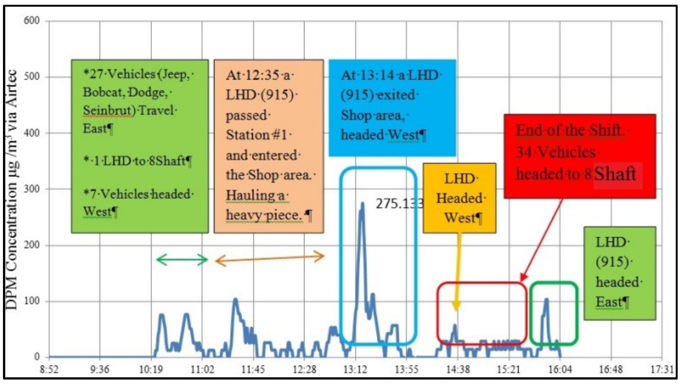

Figure 3. EC concentration via Airtec at station 1.

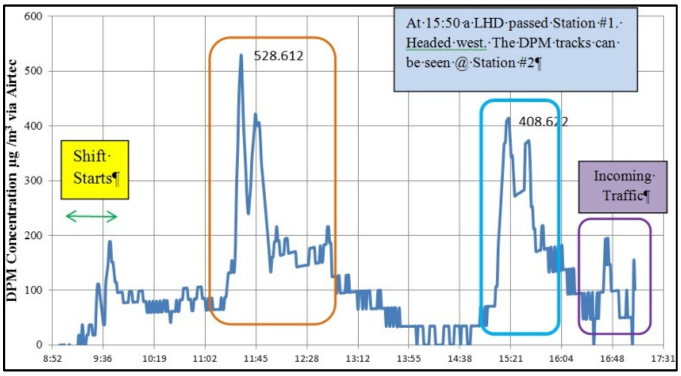

Figure 4. EC concentration via Airtec at station 2.

It was observed that LHD units are the main contamination sources. The intake air from 8 Shaft dilutes the air after the shop split. The DPM concentration increases inby the first station. In part due to air leakages through the stoppings and the rock (these are old working areas where the floor is cracked due to the excessive floor heave). The vehicles emit considerable levels of DPM especially when they are under load.

The Elf results were compared against the Airtecs as shown in Table 2. The results show that DPM concentration at shop area is significantly lower than the reading in the Main Developments. The Airtec and NIOSH 5040 cassettes results are in the acceptable range.

The leapfrogging was conducted in between all the stations. It was obsereved that LHDs are the main DPM source.

Table 2. NIOSH 5040 via Elf and Airtec TWA results.

Station #	Organic µg/m3	Elemental µg/m3		Total µg/m3	
	NIOSH 5040	NIOSH 5040	Airtec	NIOSH 5040	Airtec
#1 A	38	21		59.5	
#1 B	33	34		75	
#1 C	30	30	26	69	65
#1 D	25	11		41	
Shop	57	25		81	
#2 A	40	57		105	
#2 B	30.4	31.5		68.9	
#2 C	46.7	99.2	93	151.8	14
#2 D	44	83		148	
9Shaft	38	19		66	

3.1.2 *Entire mine sampling*

Further DPM sampling was conducted across the entire mine. The purpose of this sampling was to understand the DPM spread throughout the mine and dilution rate (required fresh air to reduce the concentration). Thirteen Elf pumps were distributed in all of the Main Developments, bore miner panels, LW headgate and tailgate, diesel shop regulator and 9 Shaft. The concentration was adjusted according to running time period on each pump.

Two Airtec monitors were placed at the same station for a period of about three hours. The results show readings were approximately 3% different. One of the Airtec monitors was then moved down to station #6. Figure 5 shows the DPM concentration for the entire mine as measured by Elf pumps (NIOSH 5040) and the real time Airtec units.

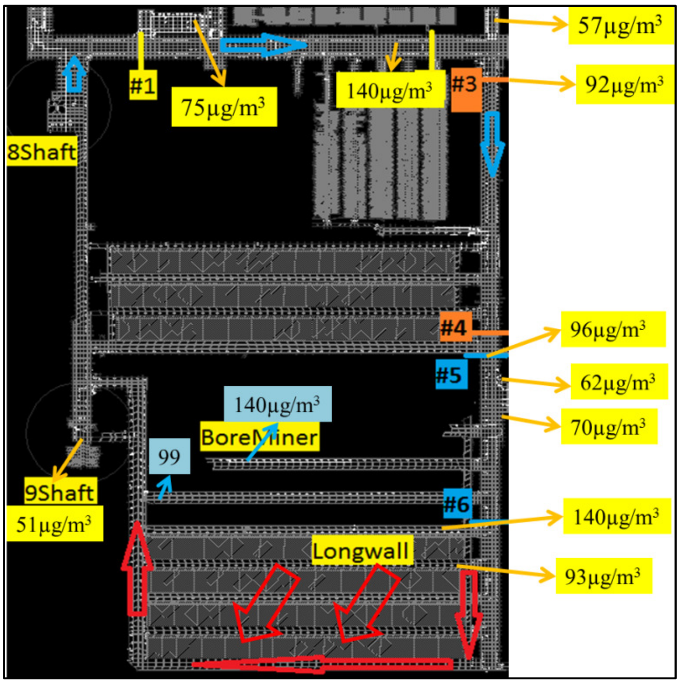

Figure 5. EC concentration via Airtec at station 2.

Examining the results from Elf pumps are shown in Figure 5. The concentration at station #1 (3ME 55 1/2 XC) is relatively high (140 µg/m^3). Approximately 60,000 m^3/s of intake air (57µg/m^3) from 5 Shaft enters the intersection. This air reduced the concentration to 92µg/m^3. The survey results show that the DPM concentration slightly increases between station #3 and #4. The fresh air enters the split at station #4 (592 S, station #5) which reduced the DPM concentration to 62µg/m^3. The air then enters the production faces at 299 East Development. The DPM concentration significantly increased to 140 µg/m^3 at 9HG development as the result of higher than usual traffic at this active face.

The vehicle log was analyzed. A total number of 78 pieces of diesel equipment passed by the log station (at station #5) The LHD activities matched the Airtec readings as shown in Figure 6. The LHD activities are shown in Table 4.

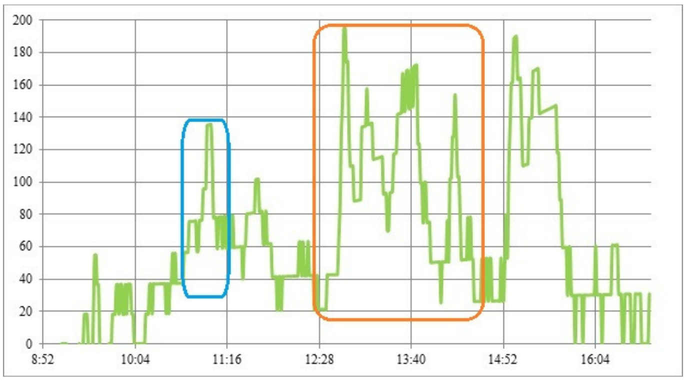

Figure 5. EC concentration via Airtec at log station.

Table 4. Vehicle log at station #5.

Equipment type	Time	Direction of Travel
LHD (913)	9:46	In
LHD (915)	10:22	Out
LHD (915)	10:38	Out
LHD (915) X 2	112:00 @ station 3	In
LHD (915)	14:05	Out
LHD (913)	15:04	In

3.2 *Secondary Tesr (Longwall Move)*

More DPM sampling was conducted during the LW move. Two Airtec units were placed at the LW Set-up face at 0 room and 2 Room as shown in Figure 6. The sampling was conducted when there were several shields stacked up, ready to transport in the recovery room. The Fletcher Prime Mover shield haulers loaded the shields at the recovery face, moving in 0 Room towards set up face. As each hauler neared the set-up face, they needed to move to 2 Room to get properly oriented to unload the shields. After the shields were unloaded and the empty haulers headed back to the recovery face. The complete loop travel lasted approximately 50 minutes. Figure 6 shows the Airtec monitors locations. The Airtec stations are marked as the Red star. The shield haulers move from 0 Room to 2 Room. The support was unloaded at 2 room. The 30X machine was used to pick and haul it back to the face. The shield haulers then travelled back to the set up room.

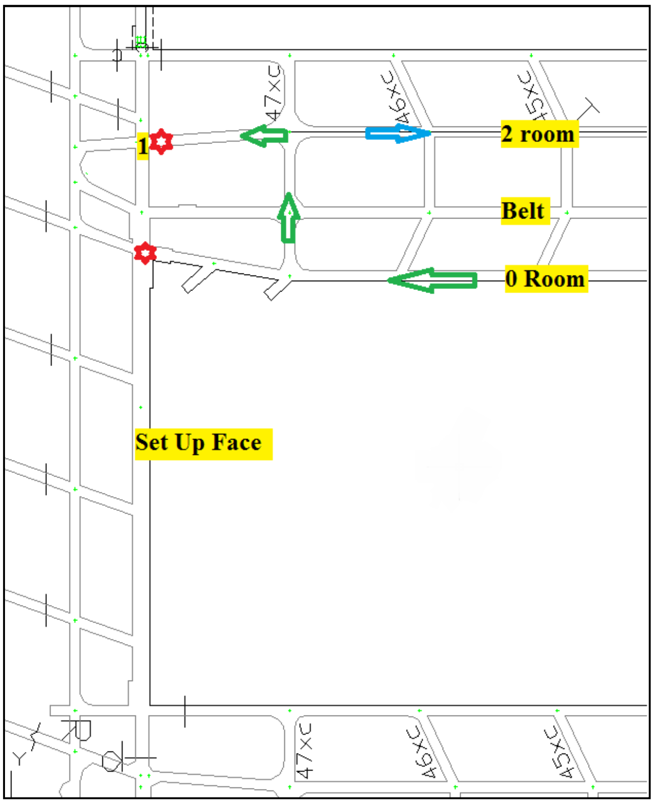

Figure 6. Airtec station and haulers pattern at the face.

3.2.1 *Direct tailpipe sampling*

Direct tailpipe sampling was conducted on one of the shield haulers. The MAHA MPM-4M instrument was installed directly on the machine. An inverter was used to power the MAHA. The unit was measured real time DPM concentration. The unit was hooked directly to the Fletcher's main exhaust tailpipe to measure the DPM amount emitted to the mine atmosphere. Figure 7 shows the MAHA unit placed on the shield hauler. The MAHA is designed for operation in harsh conditions with an advanced microprocessor that monitors the test and auto-zeroes the unit before every test.

Per §57.5071 if exposure exceeds PEL, the corrective action must be initiated by the next work shift. In order to determine the air required to dilute the DPM, the exhaust gas emitted by the mine's operating diesel engines must be estimated. In order to do this estimates of each vehicle running percent must be made.

MSHA evaluates diesel engines and provides data for determining the air required to dilute diesel exhaust gases and diesel particulate matter concentrations to suggested levels (MSHA, 2001). For each engine tested by MSHA, the approval number, engine specifications and model number, engine rating (kW and rpm) and ventilation and diesel particulate indices are available. The results of the tests provide two indices, a gas index and a particulate index. The diesel particulate index is the estimated air flow needed to dilute the weighted average DPM emitted during the MSHA test to a concentration of 1000 μg/m^3.

Figure 7. MAHA set up on the Fletcher Shield Hauler.

3.2.2 *Results and discussion*

During the test the number vehicles in the block were monitored and 28 vehicles travelled in and out of the block. This number excluded the forklift, shield haulers and 30X machine. The monitoring started at 15:40 by placing the Airtec in 0 Room at the LW set-up face. Figure 8 show the EC concentrations measured by one of the Airtec units.

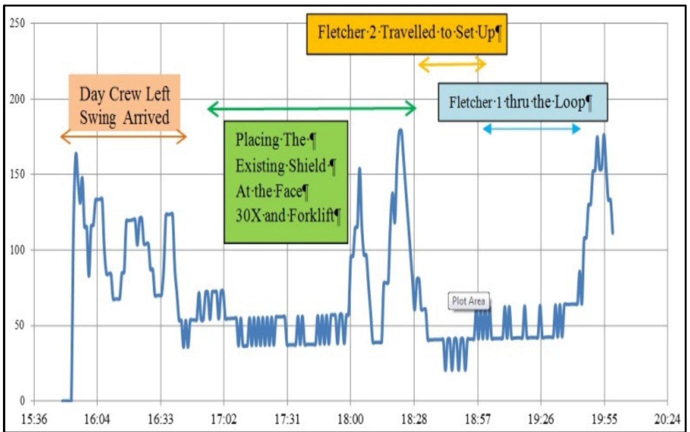

Figure 8. EC DPM concentration readings via Airtec μg/m^3.

The shield hauler activities were logged. Table 4 shows the vehicle activity log for 65DT (Fletcher Shield Hauler). The shield haulers are equipped with SintAC Diesel Particulate Filter (DPF) with an active regeneration system. The SinTAC is an active DPF system for diesel applications in the lower to middle performance range with low to middle performance power consumption. The SintAC system is comprised of a diesel particle filter using sintered metal technology, and a fully automatic, autarchic regeneration unit. It is capable of regenerating the soot accumulated in the filter at any engine operating state without any support from the engine management system and without intervention by the operator. When sufficient soot has accumulated in the filter the control unit automatically triggers a regeneration. Figure 9 shows the MAHA's logged data.

Table 4. Vehicle log at station #5.

Location	From	To	Activity
Set Up	18:00	18:08	Preshift and Idling
2 Room	18:08	18:29	Idling, Waiting
2 Room	18:29	18:52	Back up to Set up and Unload
2 Room	18:52	19:18	Fuel and Traveling to Recovery
Recovery	19:18	19:24	Loading
0 Room	19:24	19:48	Traveling to Set Up

In order to reach the operating temperature necessary for a regeneration, the computer activates the heater integrated in the filter system by means of a relay as necessary. In order for all the soot to burn-off in a short time leaving practically no residue, an additive is added automatically to the diesel fuel by the dosing system. This additive lowers the ignition temperature of the soot and increases the burn-off speed.

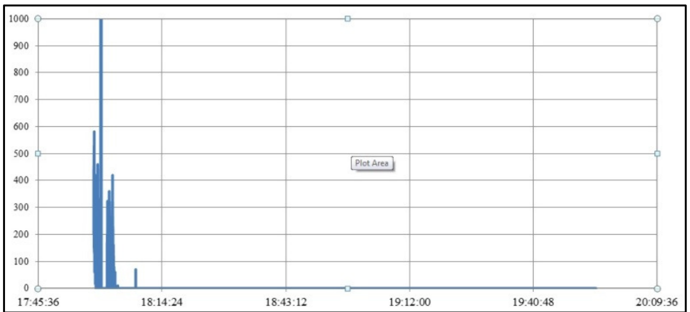

Figure 9. EC DPM concentration readings via Airtec μg/m^3.

The results show the hauler emits considerable amount of DPM right after the engine is started. However this heavy emission declines rapidly as the engine reaches a stable operating condition about 5 minutes. No significant emission was recorded throughout the test. According to the Fletcher User's Manual the regeneration may have automatically occurred after the operator started the engine. The regeneration may activate several times a day during longer operation. Regeneration starts automatically if the soot deposit in the filter exceeds a certain value,.

A maximum PEL (Permissible Exposure Limit) of 37μg/m^3 was recorded at the set up face. This number was measured for the period of approximately 5 hours. It can be concluded that the shield haulers do not increase the DPM concentration. The 30X and 25X machines as well as the forklift are the main emission contributor during the move. The other transportation diesel equipment contribute significantly as well.

4 DIESEL PARTICULATE FILTERS

A variety of DPFs were considered and some tested to reduce the emission rate on LHDs. As part of this improvement, the Diesel Shop installed a Puritech DPF on a LHD. The machine was recently rebuilt with an Airflow Catalyst DPF and Caterpillar 3304 turbo-charged engine. The emission test was conducted and DPM was reduced to less than 0.1% mg/m^3 proving the filter was 99.9% efficient. Figure 9 & 10 show the MAHA DPM test before and after Puritech installation. The NO_x concentration also was reduced by 10%. Figure 11 shows the filter installed on a LHD.

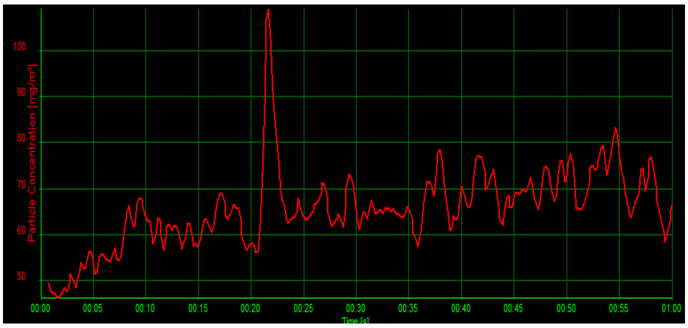

Figure 9. DPM concentration, pre-filter.

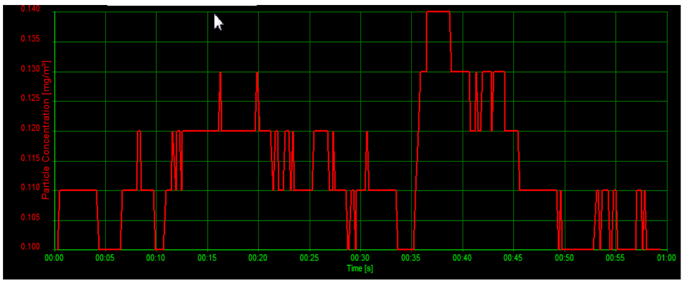

Figure 10. DPM concentration, post filter.

The filter was found to be plugged after one day of usage. It was determined that fuel was not getting injected into the exhaust stream. This stopped the expected increase in the exhaust temperature required the unit into a regenerative state. Further investigation showed that the filter, as delivered from the manufacturer, will only work on Tier 3 or higher engines.

The TF Hudgins HJS SMF-AR DPF will be installed on the machine on the next step. It is similar technology to Mann Hummel. Currently there are two Man Hummel filters are being used at the Mine. These filters perform well and require minimal maintenance.

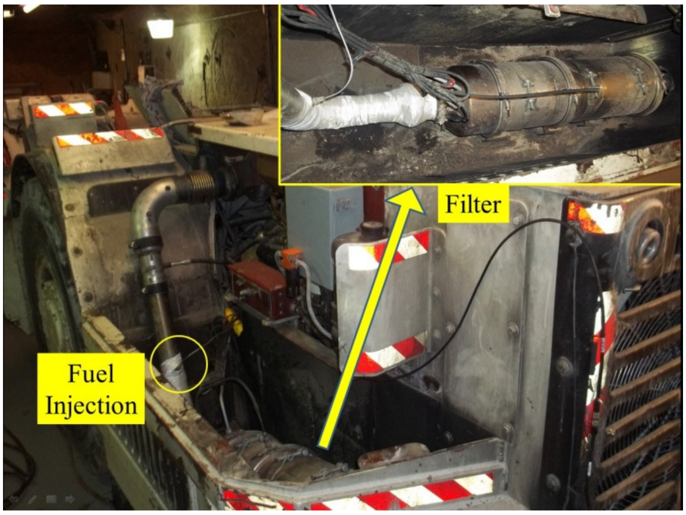

Figure 11. Puritech installation on a LHD.

5 DETERMINATION OF MINE AIR REQUIREMENT

The air quantity required for a mine can be determined using a cookbook approach. A list of operating engines should be created in tabular form. The list should contain important information about each vehicle such as the equipment, and engine type (new direct, old direct or indirect injection), year of manufacturer, model, age, size, percent operating time, catalytic efficiency, filter efficiency and finally, the engine emission. The suggested air quantity from any engine nameplate should not be used as the only metric as this value is for diesel exhaust gases and it is generally lower than airflow needed for DPM dilution. Once this information is compiled, the estimated total mine air is the sum of the engine air quantity requirements operating in the mine. This technique assumes that all of the mine air will be efficiently used to dilute the DPM and that the air exiting the mine will be at the regulatory limit (Grau, et. al, 2008).

6 CONCLUSIONS

Following is the review of the results and observations:

- The DPM survey throughout the mine proves that the LHDs (915 and 913) are the main emission sources. High DPM concentration was measured at the main development (station #1), bore miner panel face as a result of high traffic and lower air quantity.
- The real time Airtec monitor readings and Elf NIOSH 5040 readings were overlapped. The MAHA MPM-4M results were also compared against the Airtec monitors.

- It was observed that Fletcher Prime Mover shield haulers are extremely clean and do not emit a considerable amount of DPM. The older Wagner 30X and 25X and other diesel equipment are the main DPM sources during the LW move.
- Man trips (Jeeps, Sein bruts, Bobcats) contribute a considerable amount of DPM to the atmosphere. The yearly preventative Maintenance program could determine the exhaust DPM rate for each vehicle. This result would help us to calculate the required air quantity to dilute the contaminant.
- 8 Shaft Diesel Shop: The results from all the survey show that the DPM level at the Shop regulators are lower than 3ME readings. Therefore the execution of ventilation project to rerouting approximately 20 m^3/s air may reduce the DPM concentration at station #1 (station #2).
- The DPF filters with active regeneration system seem to capture 99.9% of DPM and require minimal maintenance.

7 ACKNOWLEDGMENT

The survey was prepared with the support of FMC Corporation, especially Westvaco mine management, diesel shop coordinator Brian Hooten and safety department personnel. The assistance of Missouri S&T faculty and students is gratefully acknowledged.

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