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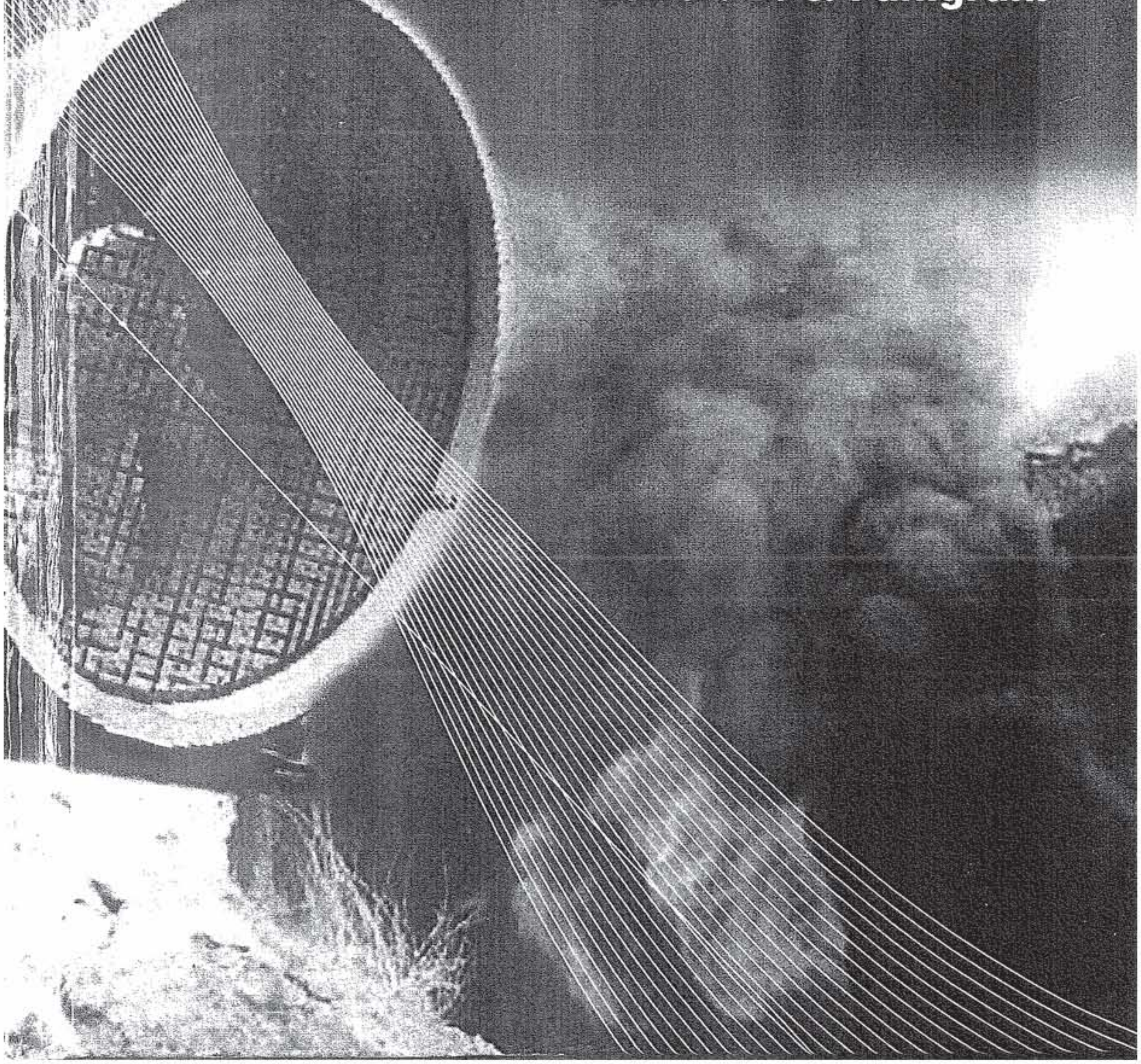

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CONTROLLING AND MONITORING DIESEL EMISSIONS IN UNDERGROUND MINES IN THE UNITED STATES

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ABSTRACT

The exposure of mine workers to diesel particulate matter (DPM) and gases is an issue of great concern to the underground mining community in the United States. Approximately 30 000 underground miners are potentially exposed to high concentrations of DPM. In January 2001, the U.S. Mine Safety and Health Administration (MSHA) promulgated rules setting compliance standards for both underground coal and metal / nonmetal mine workers. As industry works to achieve compliance with these standards, mine operators are looking for feasible methods for reducing DPM concentrations in their mines. In addition, the industry needs methods to accurately measure DPM to ensure that the control strategies they adopt are working successfully.

The Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) conducts research to evaluate control technologies and monitoring instrumentation that can be used to reduce the diesel particulate matter (DPM) exposure of mine workers. An overview of the strategies being utilized in underground US mines to reduce DPM concentrations will be presented. Also, updates on the development of diesel monitoring instruments such as the continuous elemental carbon monitor or the Personal Dust Monitor for DPM measurement will be provided.

KEYWORDS: *Diesel particulate matter; control technology; monitoring; gas measurements; mining*

1. INTRODUCTION

The use of diesel-powered equipment by the underground mining community has continuously increased over the last several decades. In the United States for example, approximately 150 pieces of diesel equipment were being operated in underground coal mines in 1974 and by 1995 that number approached 3000 units (MSHA 2001a). A similar trend is seen in underground metal/nonmetal mines (M/NM), where the use of diesel equipment first started in 1936 and by 2001 there were over 4000 units operating in underground M/NM mines in the United States (MSHA, 2001b). This extensive utilization of diesel-powered equipment generates the potential for exposure of underground miners to particulate matter and gaseous emissions from this equipment and creates an important challenge for the mining industry in the U.S. and worldwide to control these emissions. In recent years, studies have shown that long-term exposure to combustion-related fine particulate pollution, including diesel particulate matter (DPM), is an important risk factor for cardiopulmonary and lung cancer mortality (Pope, 2002). Therefore, health issues associated with exposure to DPM are receiving substantial attention from the public, government agencies, and academia.

In January of 2001, the U.S. Mine Safety and Health Administration (MSHA) promulgated rules setting compliance standards for both underground coal and M/NM mineworkers. The underground coal rule (30 CFR 72.520) controls the exposure of the miners by limiting the emission rate from newly introduced and existing diesel-powered equipment. Engine emission rates are calculated using the emission rate determined through MSHA engine certification and the MSHA-accepted PM reduction factor for the emission control technology being implemented. An engine/control system must be verified to meet an emission rate of 2.5 g/hr for permissible and heavy-duty or < 5 g/hr for outby light-duty equipment. MSHA determined that due to the absence of an accurate method for sampling DPM in underground coal mines, a performance rule was not feasible, thus air sampling, to measure DPM in the workplace is not required under this rule.

The underground metal/nonmetal rule (30 CFR 57.5060) requires the mine operators to limit a miner's personal exposure to DPM to an average eight-hour equivalent concentration of 160 ug/m^3 total carbon, as measured by NIOSH Analytical Method 5040 (NIOSH 1999). This limit went into effect on May 20, 2008. As industry works to achieve compliance with these regulatory limits, mine operators are looking for feasible methods for reducing DPM concentrations in their mines. In addition, the industry needs methods to accurately measure DPM to ensure that the control measures they adopt are working successfully.

NIOSH-PRL has promoted an integrated approach to controlling DPM. This integrated approach adopts a holistic strategy of integrating all departments of a mine including management, production, maintenance, and safety. This paper will present an overview of the integrated approach and review the strategies being used by US mines to reduce the concentrations of DPM emitted from the tailpipe, as well as present results from research evaluating these strategies. It will not discuss, in detail, control strategies such as ventilation or enclosed cabs, which have been shown to successfully reduce DPM concentrations but are outside the scope of this paper. Finally, this paper will present information on two monitors being developed to enable the real-time measurement of DPM.

2. INTEGRATED APPROACH TO CONTROLLING DIESEL PARTICULATE MATTER EMISSIONS

The integrated approach to DPM control is a strategy, promoted by NIOSH in collaboration with our stakeholders, which systematically resolves issues associated with diesel emissions by integrating solutions, from each of the independent departments, throughout the mine as a whole. NIOSH has found that DPM exposure control is complicated but manageable when the proper people and proper system are put into place and allowed to succeed. With this approach, mines learn how to properly understand the issues to be solved, tackle each issue systematically and thoroughly, research and try several different solutions, and finally implement the solutions that are most feasible for that mine. The integrated approach can be separated into five basic steps shown below:

1) Find a management supported leader or DPM champion
2) Get control over engine-out emissions (replace older/dirty engines, establish an emission's based maintenance program)
3) Look for administrative controls and gain an understanding of equipment inventory and usage,
4) Ensure adequate ventilation,
5) Examine additional control options including aftertreatment systems and alternative fuels.

Finally, at each step in the process it is necessary to have a DPM measurement program that allows for documentation of the efficacy of each step in reducing the DPM concentration in the mine. The remainder of this paper will address the steps in more detail and end with a discussion of instrumentation which can be used to measure DPM.

2.1 Management Supported Leader

The management supported leader under the integrated approach serves as the focal point for the program and NIOSH has labeled this person the DPM champion. Successful management of worker exposure to diesel exhaust requires that the DPM champion has adequate expertise, the authority to manage and coordinate efforts within and throughout various mine organizational structures, and the respect and cooperation of the workers. The DPM champion must have the expertise to explain the intricacies of the diesel regulations as well as an understanding of the many control options to be used. Although many mines attempt to place a mechanic in this role, since they have the greatest knowledge on the workings of the diesel equipment, NIOSH has found that often a mechanic does not have the authority to institute all the necessary changes required in the integrated approach. Because it is the DPM champion's responsibility to bring together all persons whose actions can influence the emissions of DPM, NIOSH has found that a person currently holding authority in the organization is the best choice. The DPM champion must have the ability to assemble all the people with influence over the departments affecting DPM emissions, lead the discussion on the DPM problems and their potential solutions, and work cooperatively with each department to reach solutions to address the ultimate goal of controlling DPM in the most cost-effective and reliable manner.

2.2 Control over Engine-Out Emissions

Gaining control over the engine-out DPM emissions is the important starting point for the integrated approach. A reduction in the amount of DPM emitted by the engine is a reduction in the amount of DPM which must be otherwise controlled using alternative control strategies. In many instances, reducing these engine-out emissions may be the only step necessary to meet DPM compliance standards. The two main approaches that can be used to reduce engine-out emissions are maintenance and administrative controls.

2.2.1 Maintenance: Since the introduction of diesels into underground mining, the need for a good maintenance program has always been recognized. However, this recognition has not always resulted in the adoption and disciplined implementation of proper maintenance practices being applied to every diesel engine or vehicle in operation in underground mines. Nevertheless, it is extremely important to realize that the very first step on the path to reducing worker exposures to DPM is to implement an effective diesel vehicle/engine maintenance protocol and apply it to every diesel unit that operates underground. The early work in this area was performed by the U.S. Bureau of Mines (Waytulonis, 1987). The University of Minnesota's Center for Diesel Research (Spears, 1997) developed procedures for using tailpipe gas measurements as a diagnostic for engine maintenance. A comprehensive study on the relationship between diesel engine maintenance and tailpipe emissions was completed by McGinn (2000) under a research effort by the Diesel Emissions Evaluation Program (DEEP). McGinn developed a maintenance auditing procedure (McGinn *et al.*, 2000) and guidelines (McGinn, 1999), which were implemented in a hardrock mine with demonstrable results. The guidelines and training of the mine personnel involved participation by mine management, machine operators, mechanics, and most importantly the engine and vehicle manufacturers' service representatives. Dramatic reductions in exhaust PM and CO emissions were observed in some cases when good maintenance practice was applied. These documents can be found on the DEEP website at www.deep.org/research.html.

There are several important reasons to provide the best possible engine maintenance when considering or implementing control technology. The first reason is that the lowest emissions resulting from the application of any control technology are obtained when starting with the lowest possible engine-out emissions. The second reason is that ventilation requirements and PM emission rates determined through MSHA's engine certification process were obtained using a properly tuned, well-maintained (new) engine. It is important that the engines in the field have emission characteristics no worse than those of the certified engine so that calculations that use the MSHA ventilation and PM emission rates to ensure safe levels of toxic gases, to estimate workplace diesel particulate levels, or to compare particulate emission rates among engines are valid. In addition, excessive emissions from poorly maintained engines may jeopardize the performance of aftertreatment technologies. For example, excessive emissions of the ash caused by burning crankcase oil might result in clogging and premature failure of a diesel particulate filter (DPF). In summary, the very first step in applying control technology to reduce workplace exposures to diesel exhaust is to implement an effective maintenance program and closely monitor its effectiveness.

2.2.2 Administrative controls: Effective administration of equipment usage can greatly assist in reducing the DPM concentrations in underground mines and is an important step in the integrated approach. To begin this process it is first necessary to evaluate the equipment inventory and equipment usage. Under this process the following steps are useful:

1) List every piece of equipment being used, engine model, MSHA Particulate Index (PI) and ventilation number
2) Know how and where each is used and its per shift fuel consumption (tied to total emissions)
3) Be concerned with engines/equipment with high fuel consumption and high PI/horsepower (hp) ratio; consider replacing such engines/equipment
4) Question the equipments necessity and see if it is possible to reduce the number of the fleet. In certain instances it may be possible to reduce the number of vehicles in a work area or reduce the size of the diesel engine being used, both instances may result in a reduction in DPM concentration in the work area.

Once the equipment usage has been optimized there are several other administrative controls that may reduce emissions and DPM concentrations and these include (i) minimize engine idling, (ii) avoid lugging engines (low RPM high load) and (iii) maintain clean fuel and lube oil. Finally traffic control has been shown to be effective in reducing the DPM concentrations in work areas. This type of control would entail routing traffic away from a miners work area, routing haul trucks in return air especially when ascending ramps while loaded and limiting horsepower in a work area based on available ventilation.

When considering administrative controls it is important for each mine to attempt different approaches and discover which administrative controls are most feasible for their circumstances.

2.3 Ventilation

Ventilation is the most widely used method for DPM control and the reduction is directly proportional to the increase in airflow. A doubling of the airflow into a working face will result in a 50% reduction in the DPM concentration at that face. As a guideline for estimating the amount of ventilation to control DPM, MSHA publishes a particulate index (PI) for each approved engine. This information can be found at http://www.msha.gov/01-995/dieselpart.HTM. The PI establishes the airflow quantity required to dilute DPM emissions to 1000 $\mu g/m^3$. The measurement of carbon dioxide is also a helpful tool in assessing the effectiveness of ventilation. The area CO_2 concentration (increase over that in the incoming air) is a measure of the amount of ventilation air relative to the amount of total fuel being burned in the area (work being done and/or number of diesel powered vehicles) and is a very good measure of the adequacy of ventilation to dilute diesel exhaust. An increase in the CO_2 concentrations in a work area can be an indication that the number of vehicles operating in that area is too high for the ventilation rate.

2.4 Aftertreatment Technologies

Aftertreatment technologies including diesel oxidation catalysts (DOC's), diesel particulate filters (DPF's) and disposable filter elements (DFE's) are very effective in removing DPM from the exhaust of diesel-powered equipment (Johnson 2008). These aftertreatment systems are placed in the exhaust system just after the combustion chambers and are gradually becoming more utilized for underground mining applications (Bugarski, 2006a). Figure 1 shows a schematic of the basic concept of filtering where engine emissions (blue arrows) enter at one end of the filter and then must physically flow through the filter wall, which removes the DPM, before exiting the filter. Figure 2 presents a picture of both the inlet and outlet of a filter showing that the black diesel soot is only seen on the inlet side of the filter. Disposable and non-disposable filters have been successful in efficiently removing DPM on mining equipment.

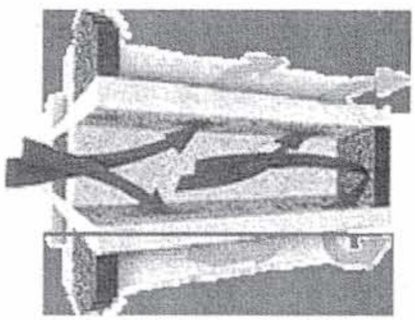

Figure 1: Basic concept of filtering

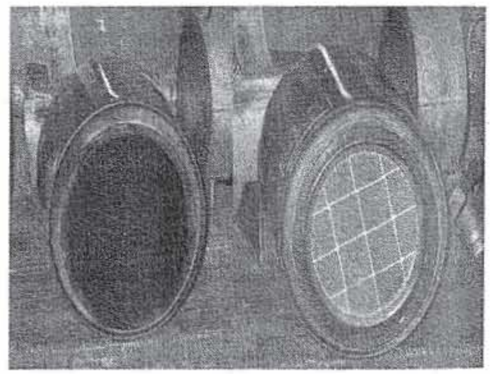

Figure 2: Entrapment of soot at inlet of filter

NIOSH has completed extensive research on the effectiveness of DPF's, DFE's and DOC's to control DPM and a summary of the results from these studies are presented in Table 1. The results presented in Table 1 are from three types of DPF systems representative of the systems currently available to the underground mining industry to curtail DPM emissions from diesel-powered equipment.

1. A DPF system manufactured by Catalytic Exhaust Products (CEP), Toronto, ON, Model 912-SXT with uncatalyzed Corning EX-80 Cordierite element (31 cell per cm^2 and 0.3 mm wall thickness) (Cordierite DPF).
2. A DPF system manufactured by DCL International Inc., Concord, ON, Model Minex Sootfilter 5.66×10 with uncatalyzed Ibiden silicon carbide element (31 cell per cm^2 and 0.36 mm wall thickness) (SiC DPF).
3. A DPF system manufactured by Mann+Hummel GMBH, Speyer, Germany, Model SMF-AR with uncatalyzed sintered metal element (10 µm mean pore size, 45% porosity, and 0.38 mm wall thickness) used with Satacen 3 fuel additive (SM DPF).

The DPF systems with Cordierite and silicon carbide wall flow monoliths are listed by MSHA as being 85 and 87 percent efficient, respectively, in the removal of total

DPM mass (MSHA 2007). The SM DPF system was recently added to the MSHA list as 81 percent efficient. As shown in Table 1 NIOSH results agree well with the MSHA efficiencies.

Table 1: Efficiencies of DPF's

Cordierite DPF	SiC DPF	Sintered Metal DPF	DFE
> 87%	> 90%	> 91%	> 80%

When compared with DPFs and DFEs, the DOC produced relatively modest effects on aerosol mass concentrations. The effects of the tested DOC on total mass concentrations were found to be influenced strongly by engine operating mode. However, the most substantial reductions of 42 percent in mass concentration occurred when the engine was operated under the highest work load scenario (intermediate speed and 100% load).

2.5 Biodiesel

Although DPF systems are gradually becoming more utilized for controlling DPM emissions from underground mining vehicles (Bugarski 2006a, b) their acceptance has been hindered by their relative complexity, implementation issues and expense. Changing the fuel supply from petroleum diesel to biodiesel blends is considered by a number of underground mine operators to be a viable alternative for controlling DPM emissions. The major advantages of biodiesel over petroleum-based diesel fuels are greater cetane number, absence of aromatics and sulfur, and high oxygen content. In addition, biodiesel was shown (Williams, 2006; Boehman, 2005) to lower the balance point temperature of passively regenerated DPFs and therefore could potentially facilitate regeneration and the implementation of DPF systems in underground mines.

In NIOSH testing, biodiesel fuels reduced total mass concentrations for all engine operating modes. With few exceptions, reductions in total mass concentrations rose with an increase in biodiesel fraction with 100% biodiesel reducing the DPM concentrations by slightly greater than 50%.

3. MONITORING

The previous section in this paper discussed a strategy to be used to reduce the concentration of DPM in underground mines. However, as mines work toward implementing this strategy it is essential that they understand the importance of monitoring the effectiveness of this strategy. A proper monitoring program will enable the mines to identify and quantify problems with the implementation of their controls. A monitoring program should include a regular sampling schedule for both ambient concentrations of DPM and concentrations emitted from the equipment tailpipe. This data will allow the mine personnel to constantly assess the effectiveness of the DPM controls. Once the controls are implemented, continuous sampling will show a failure of these controls through a resulting increase in measured DPM concentrations. This section of the paper will present information and data about two different types of monitors that can be used to accurately measure the concentration of DPM or a reasonable surrogate.

Diesel exhaust is a complex mixture made up largely of particulate elemental carbon (EC), commonly referred to as "soot", and particle bound organic carbon (OC). Total carbon (TC) is the summation of EC and OC. In the US, DPM is regulated in M/NM mines through the measurement of TC. The standard sampling method requires time weighted personal samples to be collected during a work shift and then sent to a laboratory for NIOSH 5040 analysis. This process may take several weeks before a mine receives the sampling results making it difficult to ascertain the effectiveness of control strategies. As a result, NIOSH has been developing and testing two continuous monitors to give mine personnel real-time information on the effectiveness of implemented controls. These monitors are the DPMonitor and a personal dust monitor modified for diesel measurement (D-PDM).

3.1 The DPMonitor

The NIOSH developed DPMonitor is capable of measuring EC, at concentrations typically measured in underground mining operations, in near real time. This instrument uses a laser diode absorption technique similar to that used in conventional NIOSH 5040 analysis instruments. However, the DPMonitor is portable, lightweight and designed for near real time analysis. This instrument can be attached to a miner's belt or to a piece of equipment to provide measurements of current EC concentrations, which can then be plotted against time. This information can be used effectively when evaluating DPM control options. A picture of the DPMonitor is presented in Figure 3. Figure 4 presents data from the DPMonitor during tests evaluating the efficiency of an environmental cab. This data clearly shows that the environmental cab is effective in reducing the EC concentration and is an example of how this instrument can be used to assess the effectiveness of a control program.

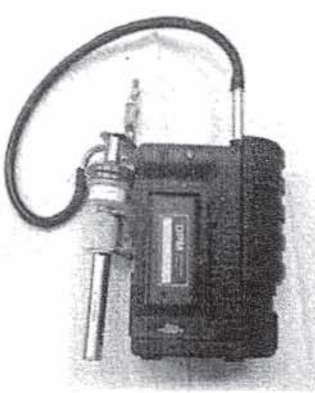

Figure 3: DPMonitor

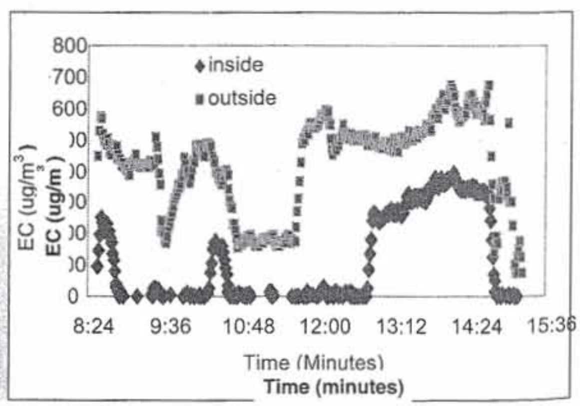

Figure 4: Interior and exterior cab EC concentration using a 5-minute average during test 1

3.2 The Personal Dust Monitor

A second real-time monitor being evaluated by NIOSH is a modified personal dust monitor (manufactured by Thermo Fisher scientific) or D-PDM. The D-PDM uses a tapered element oscillating microbalance to measure ambient submicrometer particles. Typically, more than 90% of submicrometer aerosols in underground mines are DPM. The D-PDM has the advantage of measuring the mass, in near-real-time, of many types of aerosols regardless of size, chemical composition, or refractive index. An example of results from preliminary tests of this modified instrument is shown in Figure 5. In this example the D-PDM data shows an increase in the concentration of submicrometer particles with the arrival of the diesel equipment (Gillies, 2009).

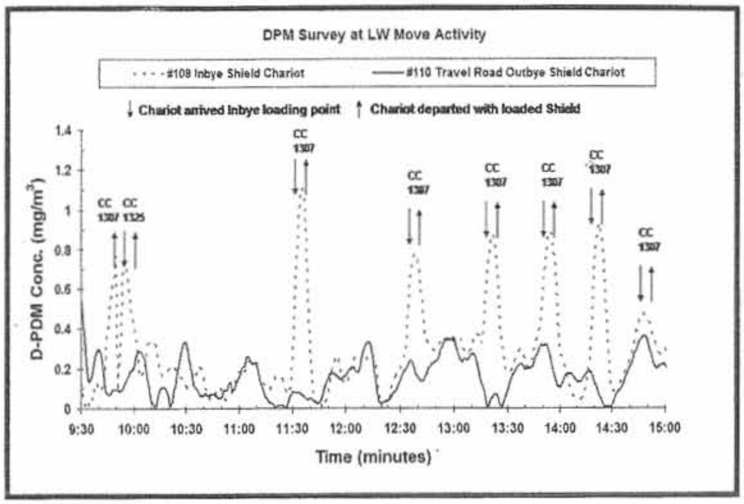

Figure 5: Diesel vehicle activities as measured by D-PDM

4. SUMMARY

As US mines continued to increase the utilization of diesel equipment in their mines, MSHA was enacting successively stricter diesel exposure limits. These factors created the need for improvements in diesel engine performance and control technologies. Through implementation of the integrated approach, US mining companies have substantially lowered the exposure of their workers to DPM. The continued development and refinement of real-time instrumentation to monitor diesel exhaust will further aid mining operations in their pursuit to limit exposures to DPM.

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