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Use of baseline personal DPM exposure data for mine ventilation planning- A South African Journey

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ABSTRACT: The use of diesel engine locomotives in South African mines can be traced to Van Dyk Consolidated Mines Ltd on the Witwatersrand gold mines in 1928 as a replacement for battery locomotives. The advantages and disadvantages were recognized in those days, and surprisingly, there are no significant additions to this list, but only refinements. In the absence of any Occupational Exposure Limit (OEL) for Diesel Particulate Matter (DPM) in SA, the Mine Safety and Health Administration (USA) rule is currently being used as a benchmark for the ventilation engineering designs. This paper discusses the ongoing SA journey of measurement and limitations of exposure data for ventilation planning and regulatory purposes. The currently accepted DPM limits are based upon the belief that they are economically and technically feasible for the mines to reach and are not necessarily health based. For SA underground platinum mines, a median TC/EC ratio of 1.8 with a range of 1.2 to 5.8 was observed. For SA coal mines, a median TC/EC ratio of 1.44 with a range of 1.25 to 2.13 was observed. While it is common practice in the USA to use the ratio of TC/EC for metal mines to be 1.3, the ratio found in local platinum mines is 2.2 and for coal mines, the ratio was 1.53 which is lower than Australian studies, i.e., 1.96. It has been shown that a need for critical analysis of TC/EC ratios exists, and possible reasons for variance must be understood before stringent adoption of overseas recommended limits for DPM. It is hoped that the findings from this paper would provide input to scientific approaches in developing appropriate conversion factors, limits for DPM and also in ensuring appropriate error factors (currently 1.14 for TC and 1.2 for EC) for compliance determination.

1 Introduction

The use of diesel engine locomotives in South African mines can be traced to Van Dyk Consolidated Mines Ltd on the Witwatersrand gold mines in 1928 as a replacement for battery locomotives. The advantages and disadvantages were recognized in those days, and surprisingly, there are no significant additions to this list, but only refinements. The recognized advantages were viz., no installation cost, high mobility, greater power. The disadvantages were, viz., heat input into the air, noxious gases exhausted into the air, danger of explosions (in coal mines) or fires. The mining regulations at the time required that the proportion of CO and CO_2 should not be more than 0.01 % and 0.1 % respectively. This translated to a dilution factor of 0.0168 $m^3/s/kW$ for the diesel engines used at the time (Barratt, 1941). In the last decade or two, the solid component of the diesel exhaust, called DPM has been recognized as a health hazard. Unlike the gold and platinum mines, which are generally at low levels of diesel mechanization, coal mines use large numbers of diesel vehicles for transportation, materials handling and other support operations like longwall, and section belt moves. In recent years, small diesel vehicles are commonly used for worker transportation from surface to underground. In South Africa, DPM research in the 1990's was focused on diesel exhaust and control measures in underground workings (Haase, Unsted and Denysschen, 1995; Unsted, 1996). However, advances in DPM measurement technology has resulted in OELs for DPM being set in most of North America, Australia and Europe. With the impending legislation surrounding DPM in SA and in the absence of any previous work specific to DPM measurement, this paper discusses the ongoing SA journey of measurement and limitations of exposure data for ventilation planning and regulatory purposes.

2 Background

2.1 DPM Basics

The incomplete combustion of diesel fuel in diesel engines results in the formation of solid and liquid particles in the exhaust stream. In recent years, DPM has been classified (NIOSH, 1988; IARC 1989) as a suspected Human Carcinogen (Class-2). Evidence of worker health impact from inhaling diesel exhaust gases and particulates are documented elsewhere (HEI, 1995). DPM is defined as a sub-micron (< 1.0 micron) physical aerosol component of diesel exhaust, which is made up of solid carbon particles which attract and adsorb organic chemicals such as polycyclic aromatic hydrocarbons (PAHs), condensed liquid hydrocarbons and inorganic compounds such as sulphate compounds.

The carbon component found in diesel emissions, known as total carbon (TC), is the combination of organic carbon (OC) and elemental carbon (EC) and usually makes up about 85 % of DPM. EC is the pure carbon particles that are the basic building blocks of DPM. OC is the group of complex carbon compounds found in DPM, including hydrocarbons such as aldehydes and PAHs but excluding inorganic substances such as sulphates.

DPM levels in underground mines depend on the amount, size, workload of diesel equipment, fuel used, ventilation and, the effectiveness of control technology that may be in place. Due to its sub micron size, DPM is not easily removed from the air stream and will not settle to the ground easily due to gravity. Once airborne, a portion of DPM is likely to remain airborne all the way to the mine return air. This means that DPM not only affects the workplace where it is produced, it also contaminates workplaces downwind, requiring control at source.

2.2 DPM Exposure Limits

There have been several changes worldwide (mainly, USA, Canada, and Australia) to the DPM exposure limits and measurement techniques (e.g., use of EC as a DPM surrogate). In USA, for metal mines, the current DPM limit enforced by the MSHA is 350 $\mu g/m^3$ TC or 270 $\mu g/m^3$ EC. The final limit of 160 $\mu g/m^3$ TC will become effective on May 20, 2008. For coal mines, currently, there are no personal OELs but instead a tail pipe emission limit of not greater than 2.5 grams per hour of DPM as measured in a laboratory test, is enforced. For the current exposure limits, the TC/EC ratio used by the MSHA is 1.3. There is no clear indication yet if the TC/EC ratio of 1.3 will be used at the final DPM limit of 160 $\mu g/m^3$ TC. The ratio plays an important role as the EC is the most sensitive and specific marker of DPM. The proposed MSHA limits are based upon the belief that it is economically and technically feasible for the mines to reach and are not fully health based.

In SA, it is not known when or how the Department of Minerals and Energy Affairs (DME) will respond with similar compliance limits, but there is a DPM task team, which is investigating the possible exposure limits to the SA mining industry. In the absence of any regulatory limits, the industry is proactively pursuing the issues of personal DPM exposure levels in order to cater for any anticipated legislative controls as part of the legislated risk assessment process (Mine Health and Safety Act, 1996).

2.3 Personal DPM Sampling

Sampling of worker exposure to DPM is important in order to assess the risk associated with DPM exposure. Therefore, to evaluate the exposure of workers to DPM, personal DPM sampling strategy is followed in SA. Also, by measuring personal exposure, a mine would be able to estimate the engine exhaust using the known ventilation air quantities. It is believed that the personal DPM measurement will enable verification of the state of maintenance of an engine and the need for tailpipe exhaust measurement or control measures. Personal DPM exposure monitoring is similar to sampling of dust in mines except that the DPM sampling filter cassette is different. The DPM sampler consists of a cyclone, a pre-packed filter cassette with SKC jewel impactor, a length of tubing, lapel clips and a constant flow sampling pump (Figure 1). The purpose of the impactor is to eliminate respirable coal dust particles larger than 0.9 μm in size. The presence of this impactor reduces, but does not completely eliminate the potential for other carbon-based compounds such as coal dust to interfere with the DPM analysis.

Figure 1. DPM sampler (right) worn by surface operator (left) and an underground LHD operator (centre).

It is now commonly accepted that the respirable combustible dust (RCD) method developed in Canada is not favored due to accuracy limitations as levels are reduced, and the use of EC as the DPM surrogate. Regardless of the method used to analyze the sample, DPM sample collection is similar to the gravimetric sampling requirements as per DME Sampling Guidelines (2002) except the following points discussed hereafter.

The pump flow rate is set at 2.0 Lpm in accordance with the supplier specification (SKC DPM cyclone) and the minimum sampling period is 300 minutes. Ideally, blank filters from each batch of filters (i.e. pack of 10) should be kept as field blanks for analysis as a quality control (background DPM levels). However, due to the high cost of DPM sampling, it is advised that appropriate judgment be made based upon the availability of resources. After a DPM sample is collected, it must be sent to an accredited laboratory for analysis (CSIR-Johannesburg, the only accredited laboratory in SA). If the DPM sample is collected to quantify the volatile organic compounds (VOCs), the DPM sample must be stored in a refrigerator immediately after sampling.

2.4 DPM Analyses

Figure 2 shows a photographic view of the DPM samples (soot colored) for analyses.

Figure 2. DPM Samples sent for NIOSH 5040 analyses.

The most commonly used analytical method to measure workers' exposure to DPM is the NIOSH 5040 method, which measures EC, OC and TC. The detailed information on the NIOSH 5040 method is available elsewhere (NIOSH 5040, 1999).

2.5 DPM Calculations

This section of the paper gives a brief summary of the DPM calculations. The DPM sample results for EC, OC and TC are usually reported in units of µg/cm² based on a DPM filter portion of about 1.5 cm², which is the area of the standard punch provided by the laboratory. To obtain the EC or OC concentration for the sample period, the following equation is used.

$$DPM_{ST} = \frac{((M - B)) \times A \times 1000)}{FL \times ST} \qquad (1)$$

Where:

DPM_{ST} = sample DPM concentration measured in µg/m³
M = sample DPM (EC or OC) in µg/cm²
B = control filter DPM (EC or OC) in µg/cm²
FL = sample flow rate in litres per min
ST = sampling time in min
A = DPM filter deposition area, cm²

An 8-hour time-weighted average DPM sampling concentration (DPM_{ST}) is obtained as follows:

$$TWA - 8h = \frac{((DPM_{ST} \times ST)}{480} \qquad (2)$$

For example, the NIOSH 5040 method recommends a filter deposit area of 8.55 cm² for a 37 mm filter when using a three piece style cassette. However, a study by NIOSH (Noll et al., 2005) using SKC impactor produced areas of DPM deposit between 8.11 and 8.21 cm². For calculation purposes, the value used by the MSHA (USA) of 8.04 cm² is recommended (Haney, 2006). It was noted during a few initial platinum baseline studies, a DPM filter deposition area of 8.4 cm² was used.

3 Results and Discussions

A summary of 8-hr time weighted average EC concentrations (µg/m³) assuming zero exposure for the unsampled portion of the remaining shift is shown in Figures 3 and 4 for coal and platinum mines. The data analyses indicated that the ratio of TC/EC for the underground coal mine DPM sample was 1.52 which was lower than the Australian finding of 1.96 (Roger and Mace, 2005). For the underground platinum mines, the average TC/EC ratio was 2.12. These differ from the findings from the US metal/nonmetal mines (31-mine study), i.e., 1.3. The OC levels in surface mines were much higher than the underground mines for both coal and platinum mines. Due to the limitations of the TC/EC ratio due to interferences of coal dust, adsorption of vapor phase OC on quartz filters, size and concentration of dust etc. the use of TC/EC ratio be carefully applied (Noll and Birch 2004; Birch and Noll, 2004). Depending on the effects of the interferences, the TC/EC ratio might not be an accurate conversion factor (Noll, 2007).

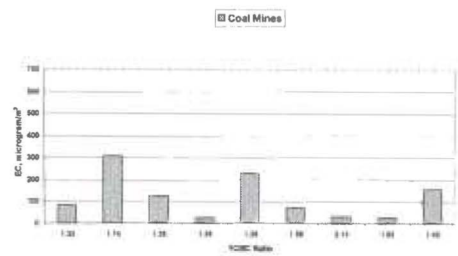

Figure 3 EC levels (8-hr TWA) in Coal Mines.

In coal mines, the average OC to EC ratio for all underground measurements was at 50% indicating the presence of coal dust particles in the collected DPM samples. There may also be other sources of OC such as vapor phase OC. From coal mines, it was noted that the highest measured DPM levels was during belt move operations involving the contractors with a specialized crew of approximately 10 workers who completed the belt extension within approximately 4 hours, involving extensive use of up to 3 LHD diesel vehicles. It must be noted that, in coal mines, the highest exposure shifts, such as belt extension, do not happen everyday and a worker present during these activities is usually on the fresh air side of the belt.

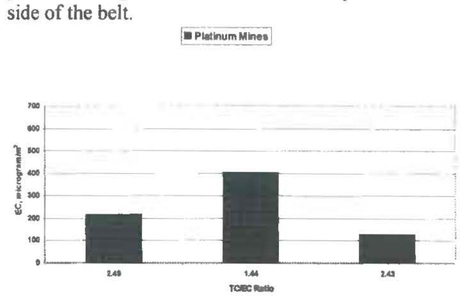

Figure 4 EC levels (8-hr TWA) in Platinum mines.

The DPM measurement data in coal mines indicate that at surface mines or under normal underground mining conditions, the DPM exposure is well below the anticipated future DPM compliance limits. The reasons for high DPM exposures can be attributed to the increased number of diesel operating engines, diesel vehicle conditions, engine maintenance and hard working engines during the belt moves and continuous idling of diesel engines. The disruptions in section ventilation layout during belt moves may have contributed to the high DPM exposure. It is understood that all of the diesel engines use water-cooled scrubber filtration systems. It was noted that all the SA mines use low-sulphur diesel fuel (< 500 ppm). Another interesting observation was that even though there was no diesel equipment present during a normal coal cutting operation, the section environment still contained DPM levels (example., a CM section where there was no LHD present during the shift had measured levels of 27.22 μg/m^3 EC).

4 Use of Personal DPM Data for Ventilation Planning Purposes

In the USA, the effective underground coal DPM standard is for each piece of diesel-powered equipment to emit no more than 2.5 grams per hour of diesel particulate matter (DPM). Figure 5 shows the relationship between the number of diesel-operated vehicles emitting a fixed DPM emission of 2.5 grams/hour at the tailpipe, DPM concentration (TC) in μg/m^3 and ventilation quantity in m^3/s. This model can be used to determine the ventilation quantity or specific need for the diesel engine control requirements after the personal measurement data. For example, if the personal DPM exposure level of the LHD driver during a belt extension was 1054 μg/m^3. From the plot (Figure 5), the following interpretations can be made, viz., firstly, the belt extension area where the LHD operator was busy was not well ventilated due to obvious ventilation disruptions caused by the belt move; secondly, assuming the area was well ventilated, indicating that the LHD emission was above the coal mine DPM standard of 2.5 grams/hour.

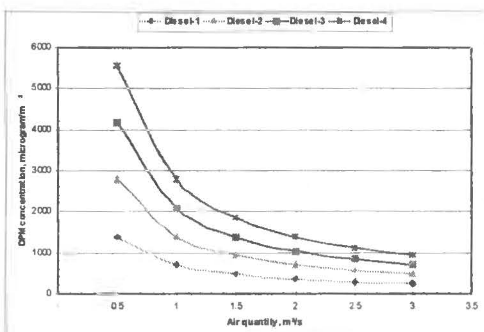

Figure 5. Relationship between air quantity and DPM.

In an another example, an average of three personal DPM samples collected during the belt extension, i.e., 534 μg/m^3 (1039 μg/m^3; 240 μg/m^3; 321 μg/m^3) with a worst case scenario of 3 LHDs operating with an assumed air quantity of 30 m^3/s at the belt extension area, would result in an estimated DPM emission of 20 grams/hour which is 8 times the current tailpipe standard, indicating that the current controls do not provide sufficient protection against DPM exposure. This would indicate a requirement for both control measures, i.e., increased ventilation during the belt extension, as well additional engine control devices.

The control parameters that are available for lower DPM exposure are viz., use of low sulphur fuel; good engine maintenance; exhaust aftertreatment, good ventilation control, control of the number of diesel vehicles and non-idling in the section. Therefore, for high exposure activities, this would require applying engineering controls at the diesel engine and generalized controls such as increasing ventilation to a given workplace. However, this must be done in conjunction with appropriate economic and technical analyses and risk assessment of controls. For example, during the belt move operation, section ventilation requires control of air movement so as to dilute the DPM and exhaust it to the return air as soon as possible by using brattices or small jet fans. Other engine based control methods involve after-treatment filters such as a commercially available disposable diesel emission filter. Various practical information on maintenance of the diesel engines can be found at the MSHA website (http://www.msha.gov). This information can be used on selected high DPM emitting engines.

5 Summary and Conclusions

The preliminary SA personal DPM exposure measurements and the data on TC/EC ratios have highlighted the DPM issue and shown the limitations of the stringent adoption of overseas limits. The currently accepted DPM limits are based upon the belief that it is economically and technically feasible for the mines to reach and are not necessarily health based. For the SA underground platinum mines, a median TC/EC ratio of 1.8 with a range of 1.2 to 5.8 was observed. For the SA coal mines, a median TC/EC ratio of 1.44 with a range of 1.25 to 2.13 was observed. This is in comparison to the median TC/EC ratio of 1.3 with a range of 1.25 to 1.67 that was observed for valid samples in the 31-Mine Study (USA). While it is common practice in the USA to use the ratio of TC/EC for DPM sample in metal mines to be 1.3, the average ratio found in platinum mines was 2.2 and for coal mines, the ratio was 1.53 which is lower than the Australian studies, i.e., 1.96.

The influence of this TC/EC ratio is significant in terms of their use in the standard development. Recently, it was noted that in the USA, an average exposure level of MSHA compliance samples collected during a 10 month period (Pomroy, 2007) was 181 μg/m^3 TC and 21 % of the mines were cited for noncompliance. Interestingly, at the proposed limit of 160 μg/m^3 TC, most mines probably would be out-of compliance based on the above data.

It is believed that TC/EC ratios are influenced by interferences of coal dust, adsorption of vapor phase OC on quartz filters, size, and concentration of dust, engineering controls and operating conditions. It is accepted that the actual TC/EC ratio could vary from mine to mine, and even from one section in a mine to another, based on the mix of controls at a mine. It was noted that clean engines have more of an impact on reducing OC levels. Alternative fuels, ventilation, and work practices seem to lower EC and TC at similar rates, while diesel particulate filters

(DPF) and environmental cabs appear to be more effective in reducing EC levels (EPA, 2005).

While the TC/EC ratios are being debated overseas and the results of NIOSH DPM health effects study is awaited, many SA mines are carrying out baseline exposure measurements to understand the range of TC/EC ratios for varying mining conditions and engine controls. The preliminary measurements have provided an understanding of personal DPM exposures in the SA mines. It has been shown that a need for critical analysis of TC/EC ratios exists, and possible reasons for such variance must be understood before stringent adoption of overseas recommended limits for DPM. Furthermore, the collation of appropriate ratios (TC/EC or OC/EC) from various local measurements would provide enough data for discussion purposes. It is hoped that the findings from this paper would provide an input to scientific approaches in developing appropriate conversion factors and limits for DPM and also in ensuring appropriate error factors (currently 1.14 for TC and 1.2 for EC) for compliance determination.

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