EVALUATION OF SAMPLING METHODS TO MEASURE EXPOSURE TO DIESEL PARTICULATE MATTER IN AN UNDERGROUND METAL MINE

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ABSTRACT

Diesel is an efficient fossil fuel converting a large fraction of its available energy into useable work. A negative aspect to the use of diesel fuel is the resultant emissions and their role as an adverse environmental agent. Medical studies have documented adverse health effects of exposure to diesel emissions. In 1988, the National Institute for Occupational Safety and Health [NIOSH] recommended that diesel exhaust be regarded as a "potential occupational carcinogen", and stated that reductions in workplace exposures would reduce cancer risks. Diesel emissions are aerosols that consist, in part, of an elemental carbon (EC) carrier particle onto which adsorbed organic chemicals are bound. These bound organic chemicals make up approximately 30-40% of the particle and are classified as organic carbon (OC). The sum of EC and OC characterize the total carbon (TC) fraction of diesel emissions and TC is the surrogate commonly used when performing air sampling to estimate occupational exposure to diesel particulate matter (DPM). Diesel powered equipment is used in 14,000 mining operations in the United States and the Mine Safety and Health Administration (MSHA) estimates that approximately 230,000 mine workers are potentially exposed to DPM. Currently, the MSHA-approved air-sampling protocol to appropriately quantify exposure to DPM employs the use of an SKC®impactor (cutpoint = 0.9µm). The use of this device inherently involves a lag-time before an accurate exposure determination can be made. Currently no standardized sampling method exists that would provide real-time DPM exposure results. The purpose of this study is to investigate the presence of a correlation between a TSI® DustTrak™ real-time aerosol monitor and an SKC® impactor when measuring DPM concentrations in an underground mine.

INTRODUCTION

Diesel is an efficient fossil fuel converting a large fraction of its available energy into useable work. This efficiency makes diesel a popular choice of fuel for many different industrial and domestic applications. A negative aspect to the use of diesel fuel is the resultant emissions and their role as an adverse environmental exposure agent. In a recent publication documenting global trends in air pollution, it was suggested that emissions from diesel-powered engines are the most significant contributor to urban air pollution worldwide.[1]

Published studies have documented the health effects of exposure to diesel emissions.[1-3] These studies report that the acute effects of exposure to diesel emissions include upper respiratory irritation, headache, nausea, weakness and tightness in the chest. Of particular concern are the reported chronic health effects of exposure to diesel emissions, which include respiratory disease, lung cancer, reduced lung capacity, chronic obstructive lung disease, pneumonia and heart disease. Of the many potentially hazardous compounds found in diesel emissions, polycyclic aromatic hydrocarbons (PAH) have garnered the greatest attention due to their classification as a human carcinogen. In 1988, the National Institute of Occupational Safety and Health [NIOSH] recommended that diesel exhaust be regarded as a "potential occupational carcinogen", and stated that reductions in workplace exposures would reduce cancer risks.[4] Similarly, in 1989, the International Agency for Research on Cancer declared that "diesel engine exhaust is probably carcinogenic to humans".[5]

Emissions generated from diesel engines are produced by the combustion of diesel fuel. Diesel emissions are aerosols that consist, in part, of an elemental carbon (EC) carrier particle onto which up to 18,000 other chemical compounds can be adsorbed.[6] These adsorbed chemicals make up approximately 30-40% of the particle and are classified as organic carbon (OC). The sum of EC and OC characterizes the total carbon (TC) fraction of diesel emissions and is the surrogate commonly used when performing air sampling to estimate occupational exposure to diesel particulate matter (DPM).[7]

Diesel powered equipment is used in 14,000 mining operations in the United States and the Mine Safety and Health Administration (MSHA) estimates that approximately 230,000 mine workers are potentially exposed to DPM.[8] Due to this large worker population and the close confines in an underground mine, exposure to DPM has been a subject of increasing concern because of its suspected relationship with health problems. In worst-case environments, it has been confirmed through air sampling that underground miners can be exposed to DPM a magnitude ten times higher than what is typically found in other industries.[9] In an effort to better protect the health of underground metal and nonmetal miners, MSHA recently revised its Final Rule regulating DPM exposures.[10] According to this Final Rule, on July 19, 2003, MSHA will enforce an interim DPM permissible exposure limit (PEL) of 400_{TC} $\mu g/m^3$ (average 8-hour equivalent full-shift airborne concentration) and on January 19, 2006, MSHA will enforce a final DPM permissible exposure limit of 160_{TC} $\mu g/m^3$ (average 8-hour equivalent full-shift airborne concentration).

When performing air sampling to estimate occupational exposure to DPM consideration must be given to particle size. It has been reported that 95% of all diesel aerosols are sub-micron in size.[6] Given this, estimation of DPM concentration is accomplished through the use of a particle size selective sampling device.[8,9] Currently, the most common MSHA-approved air-sampling protocol to appropriately characterize and quantify exposure to DPM employs the use of an SKC® impactor (cutpoint = 0.9μm).[7] Application of the SKC® impactor air-sampling protocol requires that an exposure sample be submitted to a laboratory for analysis. This process inherently involves a lag-time before an accurate exposure determination can be made, during which miners are potentially overexposed to airborne levels of DPM. Therefore, the availability of a real-time monitor that could instantaneously quantify exposures to DPM would allow for the implementation of control measures at the moment increased DPM airborne concentrations are detected. Currently no standardized sampling method exists that would provide real-time DPM exposure results.

The purpose of this study is to investigate the presence of a correlation between a TSI® DustTrak™ real-time aerosol monitor and an SKC® impactor when measuring DPM concentrations in an underground mine. Instrument correlations will be evaluated through the performance of side-by-side sampling at active mining sites in the underground metal mine. If a correlation does exist between the two instruments, it will provide a mine operator with a tool to instantaneously quantify DPM exposures.

METHODS AND MATERIALS

This study was conducted in a precious metal underground mine located in the Western United States. At the time of the study, the mine employed approximately 1,100 personnel. Palladium and platinum accounted for 75% and 25% of the mine's production, respectively. Byproducts of the mining process were small amounts of gold, silver, rhodium, copper, nickel and cobalt. The mine's daily mining rate was 2,500 tons of ore per day resulting in total annual production of 560,000 ounces of precious metal.

More than 80% of mining performed at this mine was mechanized. The majority of ore produced was derived using a mechanized ramp and fill mining method. Other mechanized mining methods employed at the mine were sub-level stoping and cut and fill. All air sampling was conducted in an area of the mine where multiple ore headings were active, requiring the use of diesel-powered face haulage equipment. The types of diesel-powered equipment in use included load-haul-dumps (LHDs), muckers, graders, maintenance vehicles, automatic drillers, supply hauling equipment and tractors. The engine brake horsepower ratings of all diesel-powered equipment ranged from 50 to 277. At the time of the study, the underground environment was damp, with many sections of the floors and walls continuously saturated with mine wastewater. The height and width dimensions of each active heading were approximately 12 feet by 12 feet. Area air sampling for DPM was performed at six different locations of the mine over four consecutive days. Sampling locations were determined based on the scheduled mining activity for that particular day with the intention of collecting DPM samples where moderate to high concentrations would be expected.

For the measurement of DPM three sampling baskets were loaded with samplers at the start of each workshift and hung from the ceiling of the mineshaft at three different locations on the 3200-foot level of the mine. This process was repeated each day over the four-day duration of the sampling campaign. Each sampling basket contained three SKC® impactors and one TSI® DustTrak™. The height at which a sampling basket was hung ranged from 6-12 feet above the mine floor. The sampling height was dependent on the access clearance needed for the diesel-powered equipment operating in that area of the mine. The co-location of the triplicate impactors and the real-time monitor was performed to evaluate the presence of a correlation between sampling devices through regression analysis of sampling results.

The TSI® DustTrak™, employed to measure DPM in real-time, is a 90° light scattering device which directly measures particulate mass concentration in mg/m^3. For the performance of this study the DustTrak™ was configured using a sampling head having a 50% cut point of 1µm. For the estimation of the average particulate mass concentration for the duration of the sampling period, the logging interval of each DustTrak™ was set at one minute. The pump flowrate associated with each DustTrak™ was pre- and post- calibrated to the required flow rate of 1.7 liters per minute (lpm). A Gilian® Gilibrator™ was used to pre- and post-calibrate the DustTraks™. No post-calibration flow rates where in excess of 5% error.

The SKC® impactor is a sampling device used by MSHA during DPM compliance evaluations and has a 50% cut point of 0.9µm. For use in this study, each impactor was housed in a Dorr-Oliver cyclone according to the MSHA DPM sampling protocol. The inclusion of the Dorr-Oliver cyclone in the sampling train served as a pre-separator of non-respirable particulate, thus preventing the impactors from becoming loaded with the larger, non-diesel particulate (mine dust) commonly found in underground mines. At the conclusion of each sampling period, the cyclones and associated tygon® tubing were washed, rinsed and dried in preparation for the next sampling day. Mine Safety Administration® Escort ELF™ pumps were used to provide negative pressure to collect DPM on the SKC® impactor filter media. Each pump was pre- and post-calibrated using a Gilian® Gilibrator™ to a flow rate of 1.7 lpm as prescribed by the NIOSH 5040 method for the collection of DPM.[11] No post-calibration flow rates were in excess of 5% error.

The research team remained in the mine for the duration of each sampling period. Efforts were made to monitor the sampling baskets and perform pump checks on an hourly basis. Thirty-six SKC® impactor DPM samples were submitted to an American Industrial Hygiene Association [AIHA] accredited laboratory for analysis of EC and OC using the NIOSH 5040 Method.[11] Logged data was downloaded from the DustTrak™ to a computer hard drive daily using TrakPro™ v3.32 software.

RESULTS

Sample results for the collection of diesel particulate matter using SKC® impactors and DustTrak™ are summarized in Table 1. The reported results for EC, OC, and TC represent the average of the triplicate SKC® impactor sample results collected at a specific location over an entire sampling period. For the analysis of EC and OC, the analytical limit of detection (LOD) was 1 µg/cm^2 and 2 µg/cm^2, respectively. EC and OC results reported as below the LOD were considered as results at the LOD. Each EC and OC result was converted to concentration values in units of µg/m^3 and then added together to acquire TC. Those concentrations associated with results below the LOD are indicated in Table 1 by a (<) sign in front of the value. Figure 1 below shows the results of regression analysis between the impactor-derived TC concentrations and the average DustTrak™ mass concentrations. Each point on the graph represents a TC concentration associated with a mass concentration obtained from a co-located DustTrak™.

Date	Mine Location	OC µg/cm^3	EC µg/m^3	TC* µg/m^3	DustTrak™ µg/m^3
1/14/00	Mine Shaft	<17	<17	<34	120
1/14/03	Ore Face	98	370	470	2100
1/14/03	Mine Shop	<19	<19	<37	51
1/15/03	Mine Shaft	<19	<18	<36	25
1/15/03	Ore Face	130	350	490	1800
1/15/03	Mine Shop	<19	36	<54	93
1/16/03	Ore Dump	<16	<16	<32	97
1/16/03	Ore Face	48	78	130	680
1/16/03	Mine Shop	<20	41	<61	240
1/17/03	Ore Face	51	110	160	340
1/17/03	Ore Face	84	210	300	630
1/17/03	Mine Shop	30	42	72	200

*TC = OC + EC; all values rounded to two significant digits

Table 1. DPM Samples Results

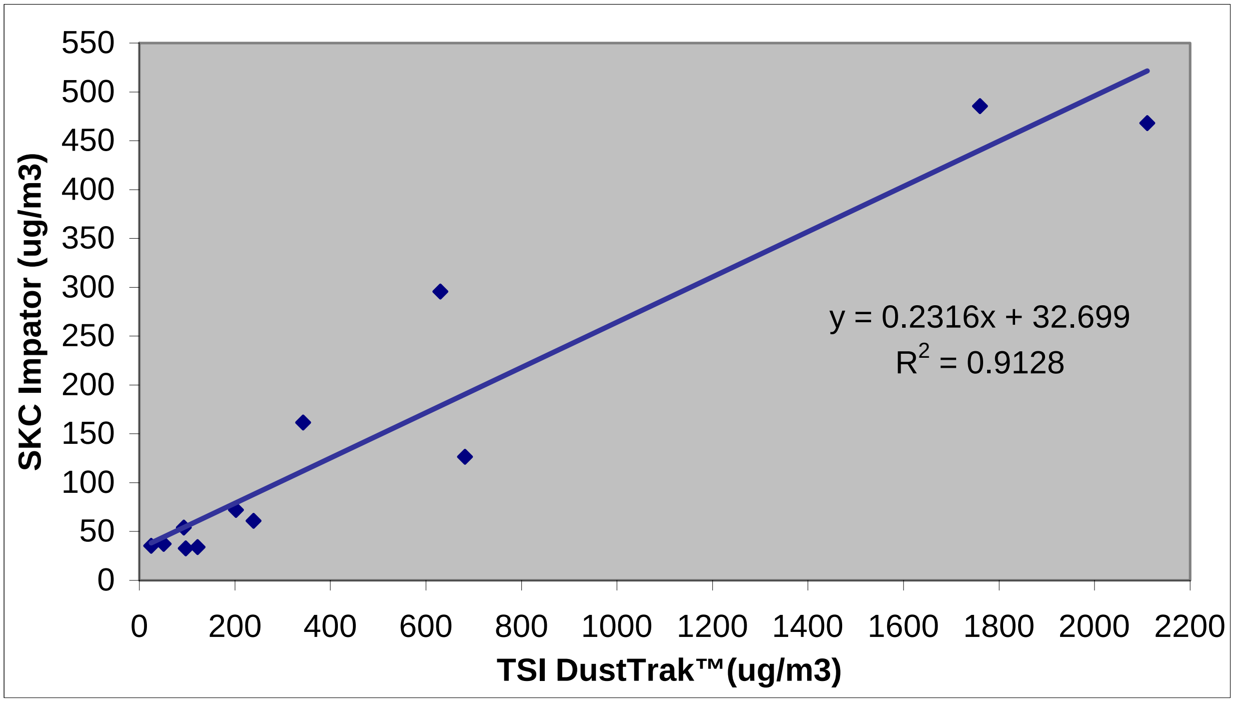

Figure 1. Correlation between TSI® DustTrak™ and SKC® Impactor

DISCUSSION

Analysis of the relationship between the SKC® impactor concentration results and the DustTrak™ concentration results reveal a good correlation ($R^2 = 0.91$) between the two sampling devices. Use of the equation defining the correlation's best-fit line provides an estimate of the SKC® impactor concentration when using TSI® DustTrak™ in an underground mining environment similar to that monitored in this study. It should be noted that the acquisition of accurate concentration measurements when using photometers like the TSI® DustTrak™ depend on comparison of the instrument's calibration aerosol with the aerosol being measured. For this study the calibration factor for the TSI® DustTrak™ (1.0) was not adjusted since the research objective was the relative correlation between the two aerosol collection devices and not the absolute magnitude of DPM concentration levels. If accurate DPM concentrations were desired, then the TSI® DustTrak™'s calibration factor would need to be adjusted to match the aerosol being sampled per the manufacturer's instructions.

CONCLUSIONS

Side-by-side comparison of the SKC® impactor and the TSI® DustTrak™ shows a good correlations ($R^2 = 0.91$) when measuring DPM in the study's underground mining environment. The strength of this correlation suggests that the TSI® DustTrak™ particulate monitor can be used to accurately estimate the magnitude of time-integrated DPM concentrations. This finding will assist the mining industry in assessing personal exposures to DPM in real-time, eliminating the lag time involved in the analysis of time-integrated samples. Instantaneous assessment of airborne DPM allows for the immediate implementation of control mechanisms, thereby providing better health protection to affected miners.

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