Mine Health and Safety Council

SIM 150601 PHASE 1

DEVELOP METHODOLOGIES FOR THE MEASUREMENT OF DIESEL EXHAUST EMISSIONS (DEE) AND DIESEL PARTICULATE MATTER (DPM)

Milestone 14:
Final Report

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>3OH-BaP</td>
<td>3-hydroxybenzo[a]pyrene</td>
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<tr>
<td>APF</td>
<td>Assigned Protection Factor</td>
</tr>
<tr>
<td>APS</td>
<td>Aerodynamic Particle Sizers</td>
</tr>
<tr>
<td>BAM</td>
<td>Beta-Attenuation Monitor</td>
</tr>
<tr>
<td>BaP</td>
<td>Benzo[a]pyrene</td>
</tr>
<tr>
<td>BC</td>
<td>Black Carbon</td>
</tr>
<tr>
<td>BRA</td>
<td>Baseline Risk Assessment</td>
</tr>
<tr>
<td>CL</td>
<td>Ceiling Limit</td>
</tr>
<tr>
<td>CO</td>
<td>Carbon Monoxide</td>
</tr>
<tr>
<td>COP</td>
<td>Code of Practice</td>
</tr>
<tr>
<td>CPC</td>
<td>Condensation Particle Counter</td>
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<tr>
<td>DEA</td>
<td>Department of Environmental Affairs</td>
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<tr>
<td>DEE</td>
<td>Diesel Exhaust Emissions</td>
</tr>
<tr>
<td>DMA</td>
<td>Differential Mobility Analyser</td>
</tr>
<tr>
<td>DMPS</td>
<td>Differential Mobility Particle Sizers</td>
</tr>
<tr>
<td>DMR</td>
<td>Department of Mineral Resources</td>
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<tr>
<td>DPM</td>
<td>Diesel Particulate Matter</td>
</tr>
<tr>
<td>EC</td>
<td>Elemental Carbon</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust Gas Recirculation</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>g/hr</td>
<td>grams per hour</td>
</tr>
<tr>
<td>HAS</td>
<td>Health and Safety Authority</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbons</td>
</tr>
<tr>
<td>HSA</td>
<td>Health and Safety Authority</td>
</tr>
<tr>
<td>HSE</td>
<td>Health and Safety Executive</td>
</tr>
<tr>
<td>HVS</td>
<td>High Volume Samplers</td>
</tr>
<tr>
<td>IARC</td>
<td>International Agency for Research on Cancer</td>
</tr>
<tr>
<td>IBRA</td>
<td>Issue Based Risk Assessment</td>
</tr>
<tr>
<td>ICMM</td>
<td>International Council on Mining and Metals</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IS</td>
<td>Intrinsically Safe</td>
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</table>
ISO  International Standards Organisation
kW  kilowatt
LDV  Light Duty Vehicles
LED  Light-Emitting Diode
LHD  Load Haul Dump
L/min  Litres per minute
MAAP  Multi-Angle Absorption Photometer
MPSS  Mobility Particle Size Spectrometers
MSHA  Mine Safety and Health Administration
mg/m$^3$ milligrams per cubic metre
NIOSH  National Institute of Safety and Health
NO  Nitric Oxide
NO$_2$  Nitrogen Dioxide
NOx  Nitrogen Oxides
nm  nanometre
OC  Organic Carbon
OEL  Occupational Exposure Limit
OEM  Original Equipment Manufacturer
OPC  Optical Particle Counters
OPS  Optical Particle Sizers
OSHA  Occupational Safety and Health Administration
PAH  Polycyclic Aromatic Hydrocarbon
PASS  Photo-Acoustic Soot Sensor
PDMS  Polydimethylsiloxane
PEL  Permissible Exposure Limit
PM  Particulate Matter
PM$^{0.1}$  Particulate Matter 0.1 micron or less
PM$^{2.5}$  Particulate Matter 2.5 micron or less
PM$^{10}$  Particulate Matter 10 micron or less
PMC  Particle Mass Concentration
PNOC  Pollutants Not Otherwise Classified
PPE  Personal Protective Equipment
PSAP  Particulate Soot Absorption Photometer
SABS  South African Bureau of Standards
Definitions

DEE A collective term used for all the pollutants that are emitted during the combustion of diesel. This includes hydrocarbons, gases (e.g. CO, NO, NOx), carbon-based particulate matter, metal ash, sulphates and unburnt fuel vapour.

DPM Respirable particulate matter that is formed as a result of poor combustion of diesel

Technology Scientific knowledge that is applied in a practical manner; e.g. laser light scattering

Methodology Application of one or more technologies to measure DEE and/or DPM; e.g. laser light scattering plus size selection is applied to measure submicron particle size distribution

Fit for purpose Verified or well equipped to provide reliable results within the context of the mining operation and for the intended application
Executive Summary

Introduction

In South Africa much concern has been expressed about diesel exhaust emissions (DEE) and diesel particulate matter (DPM) from diesel-powered equipment, as they present an ongoing health risk to underground workers. Negative health effects, including cancer, are associated with the components of both DEE and DPM that are formed in the incomplete combustion of diesel fuel and lubricant oil.

With current technology, a solution may be found to provide continuous monitoring of harmful, ambient concentrations of DEE and DPM in underground mining environments. The research project SIM 150601 Phase 1: “Develop methodologies for the measurement of diesel exhaust emissions (DEE) and diesel particulate matter (DPM)” was initiated by the Mine Health and Safety Council (MHSC) as a first step in the identification and implementation of such technology in South African mines.

Objectives

The objectives of this project were to:

- Develop methodologies for the measurement of diesel exhaust emissions (DEE) and diesel particulate matter (DPM); and
- Develop a Guidance Note and Standard Operating Procedure (SOP) for the implementation of developed DEE and DPM methodologies.

Methodology

An initial literature review to provide a context for the study established that DPM is a composite of various particles, representing small nuclei of diameters in the ultrafine range (PM$_{0.1}$) up to agglomerates of these particles with diameters of PM$_{10}$ and greater. DEE consists of PM, gases, metal ash and other components. The literature review identified commercially available methodologies with the potential for implementation in suitable underground environments. The availability of a single-source sensor was not immediately apparent from this investigation, however.

As one of the study specifications was to determine the number of machines per category of diesel-powered equipment used in South African mines, a survey to assess this was drawn up. A questionnaire was developed alongside the survey to establish the challenges faced by the mining industry with regard to measuring DEE and DPM. An electronic, web-based version of the survey and questionnaire was developed, which allowed the information to be captured directly on a web-based database as respondents answered the questionnaire.

A total of 84 participants were directly targeted. Where relevant, for example in the case of the Mine Ventilation Society of South Africa to its members, the participants were requested to distribute the survey and questionnaire further. Most of the targeted participants were mines or companies servicing the mines that were analysing the DPM exposure concentrations of their employees.
From the literature review and the responses obtained from the survey and questionnaire, evaluation and selection criteria were developed for measuring methodologies. From these criteria, methodologies were selected for further testing.

Selected methodologies were first tested in a controlled environment. All raw exhaust measurement methodologies were compared with the NIOSH 5040 laboratory method. Laboratory analysis took place at the CSIR Laboratory, which is a South African National Accreditation System (SANAS) accredited laboratory for NIOSH 5040. Controlled testing was carried out at the Sasol Fuels Application Centre, where emissions were tested using different engine cycles (e.g. idle or under load) according to ISO standard test methods.

The measurement methodologies were then evaluated in a mining environment (i.e. personal, workplace, mining workshop and other relevant sites). The ease of implementation was assessed during this stage.

In accordance with the outcomes of the testing stages and the responses to the survey and questionnaire, a Guidance Note for the measurement of DEE and DPM in the workplace and raw exhaust was developed. SOPs for the different methodologies for implementation by the mining industry were developed in support of the Guidance Note.

Results and conclusions

Although the survey and questionnaire were distributed widely, only 18 responses were received in which Sections 1 and 2 had been completed. Five respondents completed only Section 1 (fleet information).

Information about the fleet was received from the South African Mining Industry (SAMI) as captured on the database. Although it did not cover the entire SAMI fleet, the information covered the four dominant mining provinces and six largest mining commodities. Points worth noting from the responses regarding the fleet were that most diesel-powered equipment was used in the development or production functions of the mine; that maintenance was conducted according to a fixed schedule or engine hours; and that diesel-powered equipment was chosen mostly for its cost effectiveness.

The responses regarding DEE and DPM measurement indicated that respondents are positively inclined to monitor exposure and most respondents have implemented in-house limits for DPM. Points worth noting are that respondents prefer methods that are aligned with legislation, that are user-friendly and that can be integrated with other information such as medical surveillance.

The information provided by the respondents to the questionnaire was used to select and evaluate certain DEE and DPM measurement methodologies. These methodologies were evaluated through controlled testing, followed by mine testing.

During the controlled testing, the selected methodologies performed well and were relatively easy to implement. Five test modes were selected, ranging from idle speed under no load (Mode 1) to 100% load (Mode 5). The highest particulate emissions occurred at 100% load, which would represent the worst-case scenario in terms of emission concentration. However, diesel powered-equipment does not typically operate under these conditions but rather under a medium load over a full shift. For this reason a realistic engine test mode should be chosen.
for raw exhaust measurements. At full load the exhaust gas temperature is extremely high (209°C at a distance of 0.5 m from the outlet) and, combined with high emission concentrations, this may not be suitable for the operator taking the measurement and/or the methodology that is applied. It may require that a position further than 0.5 m away from the tailpipe is selected. However, this could result in the dilution ratio between the raw exhaust and the diluted emissions increasing substantially and becoming too variable. As a result, the emission concentration may not be representative of the engine emissions. Additional aspects of each methodology that should be considered are discussed in the SOP.

The mine testing evaluated the practical implementation of the DEE and DPM methodologies at a coal mine, which has different challenges from hard rock mines. The majority of the methodologies were not intrinsically safe and for this reason most of the testing was conducted at the mine’s engineering workshop on surface.

During idle mode, it was found that the instruments responded well, and measurements could be taken (although idle emissions are not necessarily representative of actual operation or engine health). However, when high idle was introduced the conditions around the tailpipe of the machine became unsafe and were outside the operating conditions of the measurement methodologies. Full load was not attempted as the anticipated DPM, NOx emissions and smoke would have been much higher when compared to high idle. Although high idle and full load were not completed, the testing attempted at high idle confirmed that excessive emissions created an unsafe environment for the operator taking the measurement.

The outcomes of the controlled and the mine testing indicate a potential for most of the methodologies that were evaluated to be implemented in the mining industry.

The Guidance Note aimed at providing the end-user with a framework in which to implement a DEE and DPM measurement methodology. The responsibility of DEE and DPM measurement is the responsibility of multiple disciplines at a mining operation such as Ventilation, Occupational Hygiene and Engineering.

The SOP provides detailed and practical information on the implementation of each of the five recommended DEE and DPM methodologies. The SOP was developed in accordance with current information and methodologies available to the SAMI. In future there may be more options in or improvements to the recommended methodologies.

**Recommendations**

In accordance with the outcomes of this project, it is recommended that a comprehensive and integrated methodology be developed. A potential comprehensive methodology is the semiconductor sensor of the CSIR, which can measure gases and fine particulates simultaneously. It is also recommended that certain ISO standards for the measurement of airborne pollutants in workplace air are adopted by the South African Bureau of Standards. In the interest of worker health, it is recommended that the Department of Mineral Resources promulgate national occupational exposure limits (OELs) for DPM since OELs already exist for gases found in diesel exhaust. Lastly the Guidance Note and Standard Operating Procedure developed as part of this project can serve as a framework within the SAMI and it is recommended that end-users are trained in the implementation of this framework.
1. Introduction

Diesel exhaust emissions (DEE) were classified as a Class 1 Human Carcinogen by the International Agency for Research on Cancer (IARC) in 2012 following sufficient evidence that prolonged exposure increased the risk of developing lung cancer (IARC, 2012). During an ideal combustion process of diesel fuel (which is made up of hydrocarbons), only compounds such as carbon dioxide (CO₂), water, oxygen and nitrogen gas should form and these compounds are inherently not harmful to humans. Unfortunately, the combustion process is not ideal: during incomplete combustion of diesel fuel and lubricant oil, harmful components are formed such as carbon monoxide (CO), nitrous oxides (NOx), sulphur oxides (SOx), hydrocarbons (HC) and particulate matter (PM) (Ono-Ogasawara et al, 2004). Negative health effects are associated with each of these compounds, or, as is the case with HC and PM, groups of compounds.

In South Africa much concern has been expressed about DEE and diesel particulate matter (DPM). Through the tripartism of the Mine Health and Safety Council (MHSC), the research project SIM 150601 Phase 1: “Develop methodologies for the measurement of diesel exhaust emissions (DEE) and diesel particulate matter (DPM)” was initiated. Accurate measurement of cancer-causing compounds is necessary as part of the effective control and reduction of these compounds in an effort to create a safer working environment for mine employees.

2. Background

A literature review was carried out to assess which technologies and measurement methodologies were available for this study.

2.1. Components of diesel exhaust emissions (DEE)

Diesel exhaust emissions (DEE) contain recognised health hazards such as diesel particulate matter (DPM), polycyclic aromatic hydrocarbons (PAHs), heavy metals and nitrogen oxide (NOx) (Krzyżanowski et al, 2005), and other compounds. These materials are produced in the combustion process and found in emissions, mainly in the form of aerosols.

2.1.1. Gases

Carbon monoxide (CO) is a colourless and odourless gas. During inhalation CO replaces the oxygen in the bloodstream and, as a result, organs of the body are deprived of much-needed oxygen. Prolonged exposure or short-term exposure to high concentrations of CO may result in headaches, nausea, tissue damage and, in extreme cases, even death.

“Nitrous oxides” (NOx) is the term used for nitrogen oxide (NO) and nitrogen dioxide (NO₂), the latter being the most harmful to humans. NOx causes inflammation of the respiratory airways and, with prolonged exposure, may result in partial or even complete loss of lung function. When NOx mixes with water vapour, it forms nitric acid, a corrosive acid that causes damage to the eyes, skin and the respiratory tract.

Sulphur dioxide (SO₂), which is generated by the combustion of engine lubricants and diesel fuel with high sulphur levels, may form different oxides of sulphur, sulphates (i.e. particulate sulphate) or, in the presence of water vapour, sulphuric acid. Sulphur oxides (SOx) have
negative health effects on the respiratory system (i.e. asthma or chronic bronchitis), the eyes (i.e. irritation or corneal haze) and the heart (i.e. heart failure).

2.1.2. Polycyclic aromatic hydrocarbons (PAHs)

PAHs are a group of hydrocarbons and comprise different organic carbon-based, aromatic (i.e. cyclic) compounds. They can take a highly volatile form (i.e. gas that evaporates easily) or a semi-volatile form (i.e. fine particulate of agglomerates that remains suspended in the air). Some of these compounds, such as benzo[a]pyrene (also known as BaP), are already classified as human carcinogens. A particular diesel-powered machine can generate different combinations and concentration levels of PAHs during a normal production shift. The United States of America (USA) Environmental Protection Agency (EPA) has identified 16 priority PAHs. The World Health Organization (WHO) added 17 additional PAHs to make a total of 33 PAHs under its regulation (Poster et al., 2006). In Europe, ambient air legislation targets BaP (value of 1 ng/m$^3$ for an averaging period of 1 year) as this compound carries the highest toxic load (toxicity multiplied by concentration) of any airborne PAH (Pandey et al., 2011; Rengarajan et al., 2015). Pyrene has also been found to be a good marker for DEE in underground load haul dump (LHD) vehicles (Geldenhuys et al., 2015). By measuring one or two PAHs, it is possible to implement control measures to safeguard employees against these and several other harmful PAHs.

2.1.3. Heavy metals

The interest in heavy metals arises mainly from an engine maintenance perspective. The lubricant oil is usually tested for the presence of wear metals (e.g. iron, chrome, lead), which is an indicator of the engine health. The information is used to schedule preventative maintenance interventions. In addition, recent research has analysed DEE for heavy metals from an occupational hygiene perspective (Mahlangu et al., 2016).

2.1.4. Particulate matter (PM)

DPM is a broad category of particulate contaminants that can result from the incomplete combustion of diesel fuel in internal combustion engines.

PM, in particular the particles that are smaller than 10 micron, has been identified as a concern for human health owing to its direct and broad impact on the respiratory organs (Durant et al., 1996; Krzyżanowski et al., 2005). Studies suggest that fine particles (defined as PM$_{2.5}$) and ultrafine particles (PM$_{0.1}$) are particularly associated with acute and chronic respiratory and cardiovascular health conditions, because the fine and ultrafine particles can easily penetrate deep into the lungs (Kenny et al., 1997; Ristovski et al., 2012).

It is generally reported that most PM in diesel exhaust originates from, and is contained in, soot. Soot formation is a complex topic, although broadly soot concentrations in exhaust emissions are found to be at their peak when diesel combustion engines are run without sufficient oxygen to combust the fuel completely. This state can occur in a variety of conditions, although poor maintenance (e.g. blocked injectors that result in an incorrect spray pattern, worn injector nozzles, or worn turbocharger) and high sulphur fuel are conducive to higher soot, and hence DPM, concentrations in exhaust emissions.
This problem is further exacerbated by current prevalent technologies that attempt to reduce the other harmful component in diesel exhaust, the aforementioned NOx component, to comply with emission regulations. There may be a trade-off in diesel combustion between DPM and NOx, for example, but the approach is dependent on the prevailing legislated engine emission limits. These technologies can increase the production of soot particles by changing the oxygen-fuel balance during the combustion process. A specific example of such a prevalent technique is the Exhaust Gas Recirculation (EGR) technique, which is used to achieve a lower peak combustion temperature and hence lower NOx, but which leads to an oxygen-lean environment that is conducive to soot generation.

2.2. Legislation

With regard to the negative health effects of DEE, international legislation related to the compounds contained in DEE can be classified into two groups:

- Occupational exposure limits (OELs) aim to protect employees against high concentrations of harmful pollutants in the workplace and are classified into different categories. Eight-hour Time Weight Average (TWA) limits are used to describe the exposure of an employee during a typical 40-hour work week (ISO, 2015). The Short-term Exposure Limit (STEL) applies to harmful compounds where an exposure concentration may be exceeded over a short time period such as 15 minutes. A Ceiling Limit (CL) applies to harmful compounds where exposure above this level may be fatal. In determining the limits of exposure in the workplace, it is assumed that the employees are generally in good health.

- Environmental air quality standards are national regulations that aim to protect the general population against harmful pollutants. These standards are much stricter than the OELs as they take into account that the population contains vulnerable groups (such as small children, sick people, pregnant females and the elderly) that may be exposed to the pollutants on a constant basis.

A short discussion follows to summarise the international approach to these pollutants.

2.2.1. European Union (EU) and United Kingdom (UK) legislation

In Europe and the UK, the pollutants of concern are CO, HC, NOx and PM and these are legislated according to emission standards for non-road diesel engines (European Commission, 1998). The emission standard is specific for each pollutant and depends on the type of engine technology, i.e. Stage. These emission standards influence the engine development by engine manufacturers. PM is determined according to ISO 8178 (ISO, 2012), which is a standardised cycle test for engines according to eight stages of operation.

The focus is on the emission source: reduce the emission of the pollutant at the source before there is a negative impact on the air quality. Each European country has a different approach to the enforcement of the EU standards and traffic officials are empowered with testing equipment to measure specific parameters, such as CO and PM.

2.2.2. United States of America (USA) legislation

The USA Mine Safety and Health Administration (MSHA) has set environmental limits for CO (50 ppm), NO\textsubscript{2} (5 ppm), NO (25 ppm) and PM (1 mg/m\textsuperscript{3}) for underground mines (MSHA, 2014).
In terms of DPM, a permissible exposure limit (PEL) of 160 µg/m$^3$ Total Carbon (TC) for underground mine employees has been implemented.

The USA EPA has limits for HC, NOx, CO and smoke (EPA, 2016). These limits are specified per kilowatt (kW) rating of the engine and the Tier certification (specified in the USA as grams per brake horse power hour). The test methods for these limits are also detailed and specified in the EPA regulation (Winberry et al, 1999).

2.2.3. South African legislation

South Africa’s national air quality standards for ambient air specify the priority pollutants as SO$_2$, NO$_2$, CO, ozone, benzene, lead and PM$_{10}$ (particulates below 10 micron). These pollutants are specified over different periods (e.g. hours, days or one year, depending on the pollutant) (DEA, 2009).

National emission standards relate to combustion installations or large facilities that emit SO$_2$, NOX and PM (DEA, 2012).

The Department of Mineral Resources (DMR) has promulgated OELs for some of the compounds found in DEE (DMR, 2006):

- CO: 30 ppm;
- NO: 25 ppm;
- NO$_2$: 3 ppm; and
- Pollutants not otherwise classified (PNOC) (respirable): 3 mg/m$^3$.

The national limits for new vehicles sold in South Africa are Euro II (light duty) and Euro II (heavy duty on-road). However, no national limits are specified regarding the concentrations of the various compounds that are emitted by new off-road, diesel-powered equipment.

2.3. Detection technology

The composition of DEE and DPM provides a challenge for finding a suitable measurement methodology. The appropriate measurement technology depends on the prevailing legislation. If an OEL for the workplace concerns a short-term exposure (i.e. an interval of 15 minutes) or a full-shift exposure (i.e. typically eight hours) limit, the measurement technology should be capable of measuring according to the legislated limit. Continuous and long-term (i.e. days or months) measuring is required for compliance with environmental limits.

The sections below present currently available measurement methodologies that can potentially be used in the detection of DEE and DPM, along with a taxonomy of different sensing methodologies. Commercial brand names are provided for the benefit of the reader and do not constitute an endorsement of the products in any way. Only a limited number of examples are given for each type of technology.

2.3.1. Classification of PM-detecting sensor types

Fine and ultrafine particles can be detected by many types of equipment (Weidemann et al, 2016). This makes the choice of which sensor technology to employ in a continuous monitoring project complicated. The composite PM in diesel emissions can range in size from
nanometers (nm) to micrometres (µm), which makes the choice of equipment even more challenging. Furthermore, when talking about the measurement of DPM, or PM in general, two separate types of measurements are generally required for a full representation; i.e. the concentration and the size of the particles. Sampling factors have an impact on the measurement and need to be taken into account if possible in presenting measurement results.

The scope of this study is the identification of existing techniques that can be adopted to detect DPM in the environments with restricted ventilation such as in underground mining working sites. An identified required characteristic of such sensors is that they are reasonably deployable on an ad-hoc basis and that they are compact in size. It follows that standard devices used in PM detection by environmental monitoring agencies are not necessarily viable owing to size and portability constraints (i.e. they are usually the size of a small building). This study therefore investigates the various portable sensors that constitute current state-of-the-art fine and ultrafine PM-detection technology.

Fixed installations used for monitoring PM in atmospheric and pollution monitoring deploy High Volume Samplers (HVS) as their primary detection technology (Durant et al, 1996). PM detection also typically forms part of conventional air pollution-monitoring systems – which are mainly based on sophisticated and well-established instruments. In order to guarantee data occurrence, these instruments use complex measurement methods and several assisting tools, which include a temperature controller, relative humidity controller, filter (in particular for PM) and built-in calibrator. As a consequence, these instruments are expensive high-power consumers, which are large and heavy. They also require a continuous mains power supply. As mentioned in the previous paragraph, this type of device is not under consideration in the current study due to the problems regarding the size and portability constraints of the domain. These systems are mentioned, however, to illustrate why low-cost portable sensors cannot achieve the same data accuracy and quality as conventional monitoring instruments.

The technologies involved in the detection of PM vary according to the measurement metric obtained from the transducer or detector of the instrument. These metrics provide a taxonomy of techniques that are listed in this section.

2.3.2. Particle number concentrations

Particle number concentrations can be measured through the following four techniques:

- Scanning Mobility Particle Sizers (SMPS);
- Aerodynamic Particle Sizers (APS);
- Optical Particle Sizers (OPS); and
- Differential Mobility Particle Sizers (DMPS).

SMPS and DMPS are essentially the same type of instrument as they both contain an impactor, neutraliser, Differential Mobility Analyser (DMA) and Condensation Particle Counter (CPC). They are referred to as "Mobility Particle Size Spectrometers" (MPSS). OPS and APS measure larger particles that mainly result from mining activities. MPSS measure particles down to 5 to 10 nm, which are representative of combustion-related emissions.
2.3.3. Particle mass concentration

The particle mass concentration of PM can be monitored with the techniques described below.

2.3.3.1. Tapered Element Oscillating Microbalance (TEOM) analysers

TEOM analysers are widely used in conventional air pollution-monitoring systems. The operating principle of TEOM is the measurement of the oscillation frequency of the tapered glass tube, which is proportional to the mass of the tube. The PM deposited on the small filter paper inside the tube changes the mass (tube and filter) and therefore also the oscillation frequency of the tube. By measuring the oscillation frequency change of the tube and the volume of air sampled, researchers are able to deduce the mass concentration (µg/m$^3$) of PM in ambient air.

This type of sensor is affected by the change in humidity, and therefore preconditioning of the sampled air with dryers is used to mitigate this effect.

This sensor type delivers high data resolution and accuracy – but this sensor technology is mostly used in systems that are large, heavy and expensive.

The 1405 TEOM™, Continuous Ambient Particulate Monitor is an example of a platform that continuously monitors PM but is small enough to be deployed in working environments. It is foreseen that this could potentially be used as part of a calibration and validation methodology but probably not as a final solution, owing to its cost.

2.3.3.2. Beta-Attenuation Monitor (BAM)

BAM is considered the most widely used PM measurement sensor type in conventional air pollution-monitoring processes. This system measures the sampled air through a size-selective inlet with or without a dryer element that reduces the relative humidity in the sampled air. The air then passes through a paper filter, which collects all the PM on the filter. The paper filter with PM is exposed to the Beta radiation source. After the measurement time-period, the mass of the PM on the filter is calculated by measuring the radiation intensity of the filter.

The Met One's E-BAM portable BAM is an example of a portable continuous monitor – although a limitation of this technology is that it cannot resolve PM in the ultrafine range (PM$_{0.1}$) owing to the small mass concentration, which is an important component of the hazard posed by DPM.

2.3.3.3. Black smoke method

The black smoke technique collects PM samples on a paper filter over a certain period, usually a day. The darkness of the paper filter is then measured by a reflectometer and converted to the PM’s mass concentration. This makes the monitoring equipment relatively simple and robust but requires offline batch processing.

2.3.3.4. Optical analysers

The optical type of analysis is based on the measurement of light properties in interaction with ambient PM. These analysers can be small, lightweight and battery operated. On the basis
of the optical measurement principle used, the optical analysers can be classified into three categories: direct imaging, light scattering and light obscuration analysers.

Light scattering uses a high-energy laser as a light source. A single particle passes through the detection chamber, or in front of the laser, and the laser light is scattered by the particle. A photo detector sensor detects the scattered light. Analysis of the light allows the deduction of the size of the particle. The concentration of PM can be deduced by totalling the light count. This technology is used in Optical Particle Counters (OPC). Particle counts need to be converted to mass concentration by calculation, and this can introduce errors that affect the precision and accuracy of this type of sensor. Examples of OPC technology currently available are the TSI SIDEPAK Personal Aerosol Monitor, MAHA Particle Size Analyser, the Saxon Junkalor DPM1.0 monitor and the Dpm-RT instrument. The Airtec Real-time DPM monitor is based on similar technology and the use of a size-selector ensures that only particles that are smaller than one micron are measured.

Direct imaging uses halogen light to illuminate the particles, and the shadows of the particles are detected by a video camera. The video is analysed by pattern-recognition software that measures the PM's attributes. Both size and count of the particles can be directly inferred. The Dusttrak II Aerosol Monitor 8532, available from TSI, uses this technique to monitor continuous PM concentration from PM$_1$ to PM$_{10}$ (notably, this does not include ultrafine PM$_{0.1}$ and only particles of above 0.3 µm).

Nephelometer (i.e. light obscuration) analysers use an infrared (IR) light-emitting diode (LED) as a light source and a silicon IR detector to measure the total light scattered by the PM. By analysing the intensities of the scattered light and the shape of the scattering pattern, both the size distribution and the mass concentration can be determined directly. An example of a portable nephelometer-based sensor is the DataRAM pDR-1000AN Monitor, which monitors real-time PM$_{0.1}$ to PM$_{10}$ exposure with continuous logging.

2.3.3.5. Aerosol electrometer

In diffusion chargers, aerosol samples are collected in the device and pass through an ionizer, which carries the positive particles. The charged aerosol goes through a trap to remove the excess of ions and through a DMA to separate charged particles. The particles go to an electrometer, where the aerosol charge is measured by measuring the electrical current. According to Giechaskiel et al (2014), sensors using this approach tend to show simple design, low cost and high sensitivity. The Electrical Aerosol Detector 3070a implements this technology.

2.3.3.6. Photoacoustic spectroscopy

During photoacoustic spectroscopy, particles are heated through the absorption of light from a chopped (modulated) laser beam. The absorption of energy by particles leads to modulated expansion and contraction of the particulates, which cause a sound wave that is pre-amplified by resonance and recorded by a microphone. An example of such an instrument is the AVL483 Micro Soot Sensor from Horiba.
2.3.3.7. Specific selected components of PM

Dedicated instruments focus exclusively on the concentration of specific, important sub-components of PM. In particular, dedicated sensors detect black carbon (BC) and ultrafine particles (UFP).

The BC mass loading can be measured by both the multi-angle absorption photometer (MAAP) and the particulate soot absorption photometer (PSAP). The number of UFP is measured by ultrafine particle counters (UPC).

2.3.4. Gas-detection technology

Gas-detection systems are designed to measure the concentration of gas molecules in the atmosphere, specifically in the DEE of diesel-powered equipment. Different technologies are available depending on the need (i.e. continuous vs spot measurements) and the expected concentration of the gases (e.g. ambient vs exhaust emissions).

2.3.4.1. Electrochemical gas sensors

Gases migrate through a barrier and are chemically oxidised or reduced; the current that is produced from this chemical reaction is an indication of the concentration of the gas. Selectivity of the sensor may be a challenge in environments where multiple gases at high concentrations are present.

2.3.4.2. Infrared (IR) point sensor

An IR beam passes through a volume of gas and the sensor energy is absorbed at a certain IR wavelength. The wavelength where absorption occurs is specific to a gas molecule and the amount of absorption is an indication of the gas concentration.

2.3.4.3. Semi-conductor sensors

Semi-conductor sensors measure the concentration of a gas through a chemical reaction that occurs between the gas and the sensor; i.e. the electrical resistance is lower during the reaction. Typically, CO gas sensors are based on this technology, where small and simple gas molecules are detected. Breathalysers employ this technology to detect the amount of alcohol in exhaled breath. New developments in sensor technology can also detect more complex gas molecules in exhaled breath (Sikhwivhilu et al, 2012; Mwakikunga, 2013). This technology may be improved to measure higher concentrations of complex gases that are found in DEE.

2.3.5. Indirect analyses

One of the most common methods used to determine personal exposure to airborne pollutants is indirect analyses. An air sample is taken on a membrane filter (or sampling media) in the workplace and then sent away for analysis by a laboratory. The NIOSH 5040 method is a thermo-optical technique that distinguishes between Elemental Carbon (EC) and Organic Carbon (OC). NIOSH 5040 is known for the measurement of EC as a marker for DPM (Birch, 2003). As the sample is taken on a filter membrane, additional analysis can be conducted on the filter for other pollutants, such as metals or PAHs (Mahlangu et al, 2016).
The atmospheric fate of PAHs is strongly dependent on their phase distribution; i.e. whether the PAH is associated with particles or is present in its gaseous form. Lighter PAHs tend to be present largely in the gas phase and are less associated with PM than the heavier PAHs under the same conditions (Vione et al, 2004). PAHs are complex HCs and portable, real-time techniques for measuring them are not available. However, when a sample is taken on a sampling medium the PAHs may be characterised in the laboratory using gas chromatographic techniques. Novel sampling techniques have been developed to sample the semi-volatile organic compounds (SVOC) and the volatile organic compounds (VOC) separately from one another. It has been found that the composition is different in the two phases and this may have implications for the design of the personal exposure monitoring programme (Geldenhuys et al, 2015).

2.4. Proposed solutions

DPM is a composite of various particles, representing small nuclei of diameters in the ultrafine range (PM$_{0.1}$) up to agglomerates of these particles with diameters of PM$_{10}$. DEE consists of PM, gases, metal ash and other components. The availability of a single-source sensor to detect these various forms is not immediately apparent from this literature study investigation. It is foreseen that a combination of low-cost instruments will be used, validated and calibrated by rigorous sample collection and inspection through more intensive, offline methods.

This literature study identified commercially available methodologies that can potentially be implemented in suitable underground environments.

The development of a new sensor specifically for the purpose of this project is feasible if an appropriate underlying sensing methodology can be found. It is foreseen that through the evaluation of different commercial sensors and components, a suitable technology may be identified.

The possibility of modifying some of the commercially available technologies for a different application may also be considered.

Commercially available portable industrial sensors have been identified that use different sensing techniques. This is not an exhaustive list, and it is foreseen that further investigation into these broad technology groups may identify more suitable candidates for this study.

3. Objectives

DEE and DPM present an ongoing health risk to underground workers. With current technology, a solution may be found to provide continuous monitoring of harmful concentrations of DEE and DPM. This study is the first step in the identification and implementation of such technology in South African mines. The objectives of this study were to:

- Develop methodologies for the measurement of diesel exhaust emissions (DEE) and diesel particulate matter (DPM).
- Develop a Guidance Note and Standard Operating Procedure (SOP) for the implementation of developed DEE and DPM methodologies.
4. Methodology

In order to address the stated objectives, the following methodology was employed.

4.1. Development of a national survey and questionnaire

One of the study specifications was to determine the number of machines per category of diesel-powered equipment used in South African mines, for which a survey was drawn up. At the same time, a questionnaire was developed to determine the challenges faced by the mining industry with regard to the measuring of DEE and DPM. The survey was incorporated into the questionnaire, which can be found in Annexure A. An electronic, web-based version of the survey and questionnaire was developed. As recipients responded to the questions, the information was captured directly on the web-based database. The survey and questionnaire can be accessed through the following link:

https://getfoureyes.com/s/d436N/

The survey and questionnaire were distributed to various stakeholders within the national target population. The following groups were targeted, as different perspectives were required:

- Underground mines making use of diesel-powered equipment;
- Occupational Hygiene Consultants that service underground mines;
- The members of the Mine Ventilation Society of South Africa;
- The Group Environmental Engineers and the Emerging Miners of the Chamber of Mines;
- The members of the South African Institute of Occupational Hygiene;
- The Department of Minerals and Resources; and
- Engine manufacturers.

A total of 84 participants were directly targeted. Where relevant, the participants were requested to distribute the survey and questionnaire further (e.g. the Mine Ventilation Society of South Africa to its members). The majority of the targeted participants were mines or companies servicing the mines that were analysing the DPM exposure concentrations of their employees.

Information needed to be obtained on the practical requirements of mines with regard to measurement techniques and/or instrumentation (e.g. portable, simple and robust, or flexible). All the information was compiled in an electronic database for easy reference and future use.

4.2. Testing and evaluation of methodologies

Evaluation and selection criteria were developed for measuring methodologies, based on the literature review and the responses obtained from the survey and questionnaire. From these criteria, methodologies were selected for testing. For testing the methodologies, only essential parts or instrument accessories were purchased (if required) and rented or demonstration models were used where possible.

The evaluation criteria listed in Annexure D were developed according to the responses from the online survey respondents. A weighting was included to account for the scoring that was
obtained on certain answers; i.e. some aspects were of greater importance to the respondents than others. The weighting for the criteria was determined by calculating the total score for each answered question; e.g. if a question parameter was the most important to the respondent, it would score a 5. The criteria for the question were then weighted to count up to 100%.

The weighting aimed to differentiate the importance of parameters to the end-user and was used to shortlist methodologies for testing. Short-listed methodologies were first tested in a controlled environment. Laboratory analysis took place at the CSIR Laboratory, which is a South African National Accreditation System (SANAS) accredited laboratory for NIOSH 5040. **Controlled testing was carried out at the Sasol Fuels Application Centre**, where emissions were tested using different engine cycles (e.g. idle, under load) according to ISO standard test methods.

The measurement methodologies were then evaluated in a mining environment (i.e. personal, workplace, mining workshop and other relevant sites). The ease of implementation was assessed during this stage.

The two testing stages are discussed below.

### 4.2.1. Controlled testing

**The controlled testing was carried out at the Sasol Fuels Application Centre in Cape Town.** A test cell with a diesel engine connected to a dynamometer was used so that the engine speed and torque could be controlled (cf. Wattrus et al, 2016). The facility was used as it enabled the engine performance and the exhaust emission concentrations to be controlled.

Sasol's in-house laboratory instruments were connected to the engine exhaust to monitor soot emissions and various gases to observe the consistency of the emission concentrations:

- The Horiba MEXA series 7000 was used to measure concentrations of NOx (nitrogen oxides), CO (carbon monoxide), THC (total hydrocarbons) and CO₂ (carbon dioxide); and
- The AVL483 Micro Soot Sensor took real-time measurements of the soot (i.e. elemental carbon) concentration in the raw exhaust by using a photo-acoustic soot sensor (PASS).

These instruments for the measurement of exhaust emissions are used according to international standard methods. During the initial set-up of the experimental design, a standard ultra-low sulphur European diesel was used.

The Sasol instruments measured raw exhaust from the inside of the tailpipe. In addition, a soot sensor was positioned at a distance of 0.5 m away from the exhaust. This distance was determined by measuring the soot and gas emissions at different distances from the tailpipe outlet and assessing the optimum position for measuring exhaust emissions in close proximity to the outlet of the tailpipe. The emissions measured 0.5 m away from the tailpipe outlet were labelled “Dilute” in contrast to the raw exhaust emissions, which were measured directly in the tailpipe and were labelled “Raw.”
The following DEE and DPM methodologies were selected for the controlled testing stage in accordance with the outcomes of the questionnaire and the evaluation and selection criteria (Annexure D):

a) NIOSH 5040: Standard method that is currently used for personal DPM exposure monitoring. This methodology is also applied for area monitoring in workplaces. During the controlled testing, the methodology was applied for area monitoring close to the tailpipe. This methodology was named “5040 Dilute”.

b) Modified NIOSH 5040: The standard NIOSH 5040 was modified for sampling raw exhaust as the standard methodology was not designed to withstand high temperatures and high levels of moisture. A metal probe was fixed in the tailpipe of the exhaust and a length of tubing was connected directly to an SKC DPM cassette with a 1.0 micron impactor, with a tissue quartz filter, and then to the sampling pump. This methodology was named “5040 Raw”.

c) Sub-micron particle mass concentration (PMC) analyser: This instrument is a PMC analyser with a 0.1 micron impactor and is designed for raw exhaust emission monitoring. The technology employed is laser light scattering. The tubing of the instrument is heated to reduce the moisture content. This methodology was named “Sub-micron PMC”. Two instruments from different suppliers were available for the mine testing (only) and were named “Sub-micron PMC 1” and “Sub-micron PMC 2” (with 1.0 micron impactor) respectively.

d) FLIR Airtec DPM monitor: This instrument was originally developed by NIOSH (USA) for the real-time personal monitoring of DPM exposure. This methodology was also validated against the laboratory method NIOSH 5040. During the controlled testing, the methodology was applied for area monitoring close to the tailpipe as well as in the extraction duct (i.e. ambient conditions). This methodology was named “Airtec Dilute”.

e) Modified FLIR Airtec DPM monitor: The standard methodology was modified for sampling raw exhaust as the standard methodology was not designed to withstand high temperatures and high levels of moisture. A metal probe was fixed in the tailpipe of the exhaust and a length of tubing was connected directly to the SKC DPM cassette with a 1.0 micron impactor (no filter) and then to the sampling pump. The DPM was deposited onto a tissue quartz filter inside the instrument. This methodology was named “Airtec Raw”.

f) Denuder tubes (Geldenhuys et al, 2015): The denuder tubes were developed by the University of Pretoria to sample semi-volatile organic compounds in the gas-and particle-associated phases separately. The denuder consisted of two multi-channel silicone rubber tubes that contained 22 parallel polydimethylsiloxane (PDMS) rubber tubes to capture gaseous compounds. The two traps were separated by a quartz fibre filter that was held in position by a Teflon connector. The particles were captured in the quartz fibre filter. Both the filter and the PDMS traps were analysed after sampling using thermal desorption gas chromatography-mass spectrometry (TD-GC-MS). This methodology was named “Denuder”.

g) Gas detection system for raw exhaust: A detection system for the monitoring of gases in raw exhaust was used. This instrument made use of electrochemical gas sensors and measured CO, NO, NO\textsubscript{2} and NO\textsubscript{x} in raw exhaust. This methodology was named “Electrochemical Raw”.

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h) Personal gas detection system: A detection system for the measurement of gases in ambient air was used. This instrument made use of electrochemical gas sensors and measured CO, methane, oxygen and hydrogen sulphide. This instrument was designed to be a warning system and not a personal monitoring device. However, the aim was to determine whether this instrument could potentially be used to assess over-exposures to gases in close proximity to raw exhaust emissions. This methodology was named “Electrochemical Dilute”.

i) Semi-conductor sensors: The CSIR has developed a gas analyser to detect the concentrations of gas in exhaled breath. The patented technology is based on semi-conducting sensors and has the ability to detect simple gases such as CO and NO$_2$ by scanning the gate voltage of a LaGIDDs FET transistor. The project team aimed to assess the capability of the technology to measure complex gases and sub-micron particles in close proximity to raw exhaust emissions. This methodology was named “Semi-conductor sensors”.

Different test modes had to be used to assess how the methodologies performed under different emission concentrations. Five different test modes were established according to the performance of the engine. The engine ran for 10 minutes in each mode and measurements were taken over this period.

Three test positions or points were assessed: inside the tailpipe (for testing raw exhaust), a fixed position away from the exhaust outlet (for testing dilute emissions) and ambient measurements in the test cell extraction ducting (i.e. atmospheric or highly diluted).

Some of the methodologies under evaluation were designed for raw exhaust and could be taken inside the tailpipe of the engine. For the other methodologies, a position away from the exhaust had to be chosen. The position for the “Dilute” testing was assessed by measuring the gas concentrations at different positions away from the exhaust to minimise concentration variability while ensuring concentrations were within range for these instruments.

A select number of measurements were taken in the extraction duct of the facility. All the raw exhaust was extracted from the engine and passed to the extraction duct before it was emitted into the outside atmosphere. The measurements were taken directly in the extraction duct with minimal adjustments to represent ambient monitoring in the mining workplace when the effectiveness of the ventilation was assessed.

4.2.2. Mine testing

A volunteer subject mine was used for the testing. During past research projects related to DEE and DPM, testing was carried out at trackless, hard rock mines (e.g. gold and platinum). For this project, it was decided to conduct the mine testing in a coal mine as the fiery mine environment poses different challenges when compared to a trackless, hard rock mine. One such challenge was that the ventilation rates in these mines are high so that potentially flammable gas concentrations can be reduced to safe levels, resulting in area and personal exposure measurement concentrations that are highly diluted.

Five mine employees from the Ventilation, Occupational Hygiene and Environment (VOHE) departments were included in the evaluation as these departments were selected by the questionnaire respondents as best suited for DEE and DPM testing.
The work experience levels of the mine employees ranged from a Professional-In-Training (PIT) (i.e. less than one year) to 18 years’ experience in VOHE. The mine employees were asked questions to assess how familiar they were with the equipment and what their impressions were of the methodologies.

In this particular mine, the dominant diesel-powered machines were people transporters, light duty vehicles (LDV), load haul dump (LHD) trucks and tractors. The mine made use of electrical continuous miners and shuttle cars to extract and move the ore. LHDs were used to sweep or clean up after the shuttle cars and to make belt extensions.

The type of engine that was used to measure the DEE and DPM was an LHD with Tier 2 engine technology. The engine had worked 2153 hours since the last engine replacement in September 2017. The machine was fitted with a water-based scrubber box as per the requirements for a fiery mine. At the time of the mine testing, the mine was using 50 ppm sulphur diesel. The same LHD that was measured underground was used during the testing at the engineering workshop on surface.

The test positions were similar to the controlled testing:

- Raw: inside the tailpipe of the exhaust for the methodologies with suitable probes; and
- Dilute: a fixed distance from the outlet of the exhaust. In this case a safe distance was found to be ± 1.5 m away from the exhaust outlet and at a height of ± 0.2 m from the ground (that was in line with the exhaust outlet).

The nine DEE and DPM measurement methodologies that were assessed during the controlled testing (refer to Section 4.2.1) were taken to the subject mine for evaluation.

Instrumentation and equipment were required to be intrinsically safe (IS) before going into an underground fiery mine section. Unfortunately, not all the methodologies were found to be IS and for this reason the majority of the testing was conducted at the surface workshop. Only the 5040, Airtec and Denuder methodologies were IS, and measurements with these methodologies could be taken underground.

4.3. Guideline and Standard Operating Procedure (SOP)

In accordance with the outcomes of the testing stages and the responses to the survey and questionnaire, a Guidance Note for the measurement of DEE and DPM in the workplace and raw exhaust was developed. SOPs for the different methodologies for implementation by the mining industry were developed in support of the Guidance Note. These have been attached as Annexure E.

5. Results and Discussion

5.1. Survey and questionnaire

The complete responses to the questionnaire can be found in Annexure B. Although the survey and questionnaire were distributed widely, only 18 responses were received in which Sections 1 and 2 had been completed. Five respondents completed only Section 1 (fleet information). A few points are highlighted from the responses that were received from the majority of the respondents.
In terms of the fleet, the responses that were received were that:

- Most of the diesel-powered equipment was used in the development or production functions of the mine;
- Maintenance was usually undertaken according to a fixed schedule or in terms of the number of engine hours;
- When new engines were purchased, the criteria were mostly the cost-effective option or “Buy Quiet” or the preferred service provider;
- The majority of the responding mines were using 50 ppm sulphur diesel; and
- Not many of the responding mines were using fuel additives.

Some of the responses that were received about the measurement of DEE were that:

- The preferred measurement for DEE was with a gas meter and the gases measured were CO, NOx and SOx. Where possible, the majority of the respondents would have liked to measure PM of below 10 micron as well.
- The majority of the respondents preferred spot measurements followed by full-shift measurements.
- The highest importance for a DEE methodology was whether it was aligned with legislation, followed by whether it was a user-friendly methodology.

Some of the responses that were received regarding the measurement of DPM were that:

- All of the responding mines (apart from one) were actively measuring DPM according to NIOSH 5040 and had established in-house limits that ranged between 0.16 and 0.35 mg/m$^3$ TC.
- The respondents preferred full-shift sampling over the spot measurements.
- The integration of the information with other information (such as medical surveillance) was of the highest importance when compared to the other listed factors, including alignment with legislation and user-friendliness of the methodology.

Overall responses in relation to DEE and DPM methodologies indicated that:

- The majority of respondents would prefer full-shift sampling followed by spot measurements that could be taken in a workplace.
- Compliance with legislation and employee wellness and comfort would be the dominant drivers for DEE and DPM measurements at the responding mines.
- The majority of the mines responded that the Ventilation and Occupational Hygiene departments would be responsible for the monitoring once legislation on DEE and/or DPM was passed.
- The respondents would prefer handheld methodologies followed by machine-installed methodologies.

5.2. Summary of the fleet survey

Annexure C contains the fleet information that was received from the South African Mining Industry (SAMI) as captured on the database. Although it did not cover the entire SAMI fleet, the information covered the four dominant mining provinces and six largest mining
commodities (Table 1). The engine manufacturers were also contacted, but no responses to the fleet survey were received from them.

<table>
<thead>
<tr>
<th>Provinces</th>
<th>Chrome</th>
<th>Coal</th>
<th>Diamond</th>
<th>Gold</th>
<th>Manganese</th>
<th>Platinum</th>
<th>Grand Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauteng</td>
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<td></td>
<td>176</td>
<td>53</td>
<td></td>
<td></td>
<td>229</td>
</tr>
<tr>
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<td></td>
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<td></td>
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<td>993</td>
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</tr>
<tr>
<td>Grand Total</td>
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<td>315</td>
<td>485</td>
<td>53</td>
<td>109</td>
<td>1079</td>
<td>2154</td>
</tr>
</tbody>
</table>

Unfortunately, incomplete information was received regarding the engine technology and type of fuel used.

5.3. Controlled and mine testing

The results of the different measurement methodologies that were evaluated during the controlled and mine testing are provided and discussed in the following sub-sections.

5.3.1. Test modes

During the controlled testing, the engine was operated at various speed levels to assess the variability of the emissions. The point at which the maximum power corresponded with the maximum speed of the engine was at 4000 rpm. This point was defined as Mode 5, 100% load or full throttle. The other points were at different increments between idle and full throttle.

Five test modes were selected at an optimum speed for the type of engine that was used in the test (4000 rpm):

- Mode 1: Idle speed (~8 Nm torque)
- Mode 2: High idle (10 Nm)
- Mode 3: 25% throttle (46.5 Nm)
- Mode 4: 50% throttle (93 Nm)
- Mode 5: 100% throttle (186 Nm)

Figure 1 shows the variation in the soot concentration (i.e. BC), based on different loads on the engine at a set speed of 4000 rpm.
The lowest soot concentrations were measured at idle speed in contrast to the highest soot concentrations, which were measured at 100% load. It would be ideal to measure exhaust emissions while a diesel-powered machine is standing still and idling. However, this concentration is not representative of the soot emissions produced when the machine is working or operating at different engine loads.

Unfortunately, not all of the five modes that were developed during the controlled testing could be replicated in the real mining environment with the same precision as in the controlled environment. It was decided to try to replicate the following modes during the mine testing on the LHD at the surface workshop namely, Mode 1 (idle), Mode 2 (high idle) and Mode 5 (100% load). The service technician indicated that when the empty bucket of the LHD was lifted during idling, this action would place some load on the engine; i.e. high idle. Mode 5 could be replicated by lifting the bucket and applying full load to the engine.

The high idle test was planned for 10 minutes. However, within one minute the test was stopped as the sheer volume of emissions was high enough to provide a health and safety hazard for the testing operators (Figure 2). The operator that was conducting the raw exhaust testing wore a personal detection system that measured the gases CO, CH₃, O₂ and H₂S. Within one minute from the start of the test, the detection system set off an alarm because the CO concentration had exceeded the STEL of 100 ppm.
Full load was not attempted as the conditions were expected to be far worse than at high idle.

5.3.2. Position for the “Dilute” measurements

Some of the methodologies were not designed for raw exhaust measurements inside the tailpipe. For this reason, the aim was to find a position away, but close enough to the tailpipe to take measurements (i.e. dilute measurements). During the controlled testing stage, tests were conducted to find the ideal position for the “dilute” measurements.

Figure 3 illustrates the variability in the CO$_2$ concentrations at different positions. The dilution ratio between the raw exhaust and the diluted exhaust (i.e. ambient exhaust) was 1:5. The position in the tailpipe (-0.1 m) provides is the point of no dilution and provides the best stability. However, the position at 0.5 m would be more representative of dilute exhaust measurements with adequate reproducibility to determine trends. The position of 0.5 m away from the exhaust would also be more suited for methodologies that were not designed for raw exhaust measurements and might be safer for the operator taking the measurement in terms of the conditions (temperature, humidity and emission concentration).
During the mine testing, testing was conducted underground and at the surface workshop. Figures 4 and 5 show the manner in which the “raw” and “dilute” sampling was conducted at the workshop.

Figure 3: CO₂ concentrations at various positions away from the exhaust

Figure 4: Position for the “raw” sampling

Figure 5: Position for the “dilute” sampling
5.3.3. DEE and DPM methodologies

5.3.3.1. NIOSH 5040 methodology

The standard gravimetric sampling method for DPM was used to take measurements of the dilute exhaust emissions close to the tailpipe during the underground mine testing. A modification was made to accommodate the raw emission sampling.

Figure 6 shows the results from the 5040 raw and dilute measurements that were taken underground during the mine testing. The total carbon concentrations at high idle were higher than on idle for the 5040 raw measurements. However, no substantial difference was found between the idle and high idle results for the 5040 dilute. One possibility is that, with a ventilation rate of 1.5 m/s in that mining section, the emissions may have diluted quite rapidly after exiting the tailpipe.

![5040 results for underground measurements](image.png)

Figure 6: Results for 5040 underground measurements

5.3.3.2. Airtec methodology

The FLIR Airtec was used to compare the raw exhaust, dilute and extraction duct (i.e. atmospheric) emissions during the controlled testing. Figure 7 shows that the total carbon concentrations that were measured in the extraction duct were much lower when compared to the diluted emissions. Both concentrations were substantially lower than the raw exhaust concentrations. All three sets of data followed a similar pattern over the five test modes.
Figure 7: Comparison between the raw, dilute and extraction duct emissions using the Airtec methodology

5.3.3.3. Comparison of methodologies that sample onto a filter

Figure 8 shows the total carbon results that were measured during the controlled testing according to NIOSH 5040 for the different methodologies that used a filter for sample collection: 5040 and Airtec (raw and dilute for both). The biggest variance in the controlled testing results can be seen in Mode 5 (100% load), followed by Mode 3 (25% load). The variance in the total carbon results for Modes 1, 2 and 4 is similar. Two sets of data were gathered for the 5040 Raw and Dilute respectively, hence the reference to Raw 1 and 2 and Dilute 1 and 2.
Figure 8: Total carbon results over the five test modes

Figure 9 summarises the 5040 and the Airtec measurements (raw and dilute) that were taken at the mine’s surface workshop. The same LHD that was measured underground was measured on surface.

Figure 9: Results for the 5040 and Airtec methodologies during the mine testing
The high idle result for the Airtec dilute may not be accurate as there was a malfunction on the pump during the measurement.

5.3.3.4. Electrochemical Raw methodology

Figure 10 depicts the results for the Electrochemical Raw methodology (i.e. multi-gas analyser) during the controlled testing. There was more variability in the trends of the individual gas concentrations over the five test modes. The different gases did not show the same trend over the five test modes. This can be expected as the gas composition changes with the load on the engine. The smallest variations in the gas concentrations were found in Mode 3.

![Image of Electrochemical Raw methodology results over the five test modes during controlled testing](image)

Figure 10: Electrochemical Raw methodology results over the five test modes during controlled testing

Table 2 summarises the concentrations that were measured in the tailpipe by the electrochemical raw gas analysers when the engine was idling in the mine testing.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Concentration (Idle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (ppm)</td>
<td>201</td>
</tr>
<tr>
<td>NO (ppm)</td>
<td>596</td>
</tr>
<tr>
<td>NOx (ppm)</td>
<td>614</td>
</tr>
<tr>
<td>NO₂ (ppm)</td>
<td>15</td>
</tr>
</tbody>
</table>
The analyser gave an error message at the start of the test, which may have been the result of the high moisture content in the tailpipe, which was close to the outlet of the water-scrubber. No results were available for the engine at high idle as the test was stopped owing to safety concerns. The conditions, including the excess moisture, exceeded the operating limits of the electrochemical raw gas analysers.

### 5.3.3.5. Personal gas detection system

The personal gas detection system did not give a warning alarm during any of the controlled tests or in the idle mode mine test. These systems are designed to provide an alarm when the STEL for the respective gas is exceeded. No warnings during the controlled testing may have been the result of the good ventilation in the test cell. However, within one minute of the start of the high idle mine test, the alarm sounded to indicate that the CO concentration had exceeded the STEL of 100 ppm. The test was aborted and no further tests were conducted with higher engine loads.

### 5.3.3.6. Sub-micron particle mass concentration (PMC) methodology

Figure 11 depicts the concentrations that were measured by the sub-micron PMC during the controlled testing. It is not clear why the average result for Mode 3 is zero, as the range of results for that test mode was between 0 and 25.7 mg/m$^3$.

![Sub-micron particle mass concentration](image)

**Figure 11:** Sub-micron PMC results over the five test modes for the controlled testing

Table 3 summarises the concentrations that were measured in the tailpipe during the mine testing by the two sub-micron PMCs during the idle mode. The results for the two sub-micron PMC instruments were similar but the concentrations that were measured were much higher than what was measured during the controlled testing (< 5 mg/m$^3$). This outcome was
expected, bearing in mind that the engine technologies used in the controlled and mine testing were different.

Table 3: Results for the sub-micron PMC

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Concentration (Idle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-micron PMC 1 (mg/m³)</td>
<td>14.3</td>
</tr>
<tr>
<td>Sub-micron PMC 2 (mg/m³)</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Both instruments gave error messages at the start of the test, which may have been the result of the high moisture content in the tailpipe, close to the outlet of the water-scrubber. Shortly after initiating the high-idle mode, the test was stopped owing to concerns about the safety of the testing operator and the instrumentation. The conditions exceeded the operating limits of both sub-micron PMCs.

5.3.3.7. Temperature near the tailpipe

The temperature 0.5 m away from the exhaust outlet increased over the five test modes of the controlled testing by between 25 and 209°C (Figure 12). The increase in temperature is a concern in terms of the safety of the operator taking the measurements.

![Figure 12: Temperature at the exhaust outlet over the five test modes](image)

There is also a concern about the safety of the equipment under these conditions: the tubing and size selectors (i.e. cyclones) of the dilute 5040 and Airtec methodologies were not greatly affected by the high temperatures during the controlled testing. However, the styrene cassettes holding the filter media for sample collection melted completely during Mode 5.
Only the idle mode was tested during the mine testing, so the impact of temperature on the equipment during the other modes was not assessed. However, given the severe conditions that were observed during the high-idle mode, it is assumed that the temperatures generated during these modes will also exceed the operating conditions of most personal exposure and area-monitoring instruments. Exhaust analyser-type instruments should be able to sample at full load in the tailpipe under these temperature conditions.

5.3.3.8. Denuder tubes methodology

Figure 13 presents the PAH data that was obtained during the controlled testing for the five modes of testing (Mode 1 to Mode 5) and compares the data obtained from the raw exhaust and the dilute emissions.

The primary trap, at the inlet of the Denuder tube, captured PAHs in the gas phase. The secondary trap, on the outlet side of the Denuder tube (i.e. downstream from the primary trap and the filter), also captured PAHs in the gas phase which had passed through the first trap or which had desorbed from particles collected on the filter during sampling. The filter, situated between the primary and secondary traps, captured the PAHs in the particulate phase.

![Figure 13: Total PAH concentration from controlled testing (Schoonraad and Forbes, 2018)](image)

The highest concentrations of the particulate emissions (filter) were measured for Mode 5 (100% load) for both the raw and the dilute emissions. This finding corresponds to the Soot, 5040 Raw and Sub-micron PMC readings for the same testing mode.

Mode 1 (idle) provided the lowest overall concentrations for PAHs in the gas and particulate phases. These results correspond with those of the Soot, Airtec, NO and NO₂ concentrations
in that Mode 1 (idle) gave the lowest readings and may not be the most representative condition or test mode to use when measuring DEE and/or DPM.

The highest concentration of PAHs was found in the primary trap for Mode 2 Raw, which captured the PAHs in the gas phase. The second-highest concentration of gas-phase PAHs was found in the primary trap for Mode 2 Dilute.

Table 4 provides a list of the PAHs that were detected with their abbreviations, as a key for understanding the abbreviations presented in Figures 14 and 16.

<table>
<thead>
<tr>
<th>PAH</th>
<th>Abbr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene</td>
<td>Nap</td>
</tr>
<tr>
<td>Acenaphthylene</td>
<td>Acy</td>
</tr>
<tr>
<td>Acenaphthene</td>
<td>Ace</td>
</tr>
<tr>
<td>Fluorene</td>
<td>Flu</td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>Phe</td>
</tr>
<tr>
<td>Anthracene</td>
<td>Ant</td>
</tr>
<tr>
<td>Fluoranthene</td>
<td>FluAn</td>
</tr>
<tr>
<td>Pyrene</td>
<td>Pyr</td>
</tr>
<tr>
<td>Benz(a)anthracene</td>
<td>BaA</td>
</tr>
<tr>
<td>Benz(a)pyrene</td>
<td>BaP</td>
</tr>
</tbody>
</table>

Naphthalene was the most abundant PAH in the gas and particulate phases for the controlled testing (Figure 14).

![Gas phase PAHs](image)

![Particulate phase PAHs](image)

Figure 14: The relative abundance of PAHs in the gas and particulate phases from the controlled testing (Schoonraad and Forbes, 2018)

The PAH concentrations in the gas phase (particularly in the primary trap) dominated in the mine testing (Figure 15). The PAH particulate concentrations were noteworthy during the high
idle testing mode. During the idle mode, the PAH concentrations were very low. It is possible that the low PAH concentrations in the particulate phase were the result of the water-scrubber (WS), which was designed to lower the exhaust temperature to prevent the ignition of flammable methane found in coal mines and, incidentally, to remove the particulates from the emissions.

![Figure 15: Total PAH concentrations for the mine testing](image)

Figure 15 shows the relative abundance of the different PAHs that were detected in the gas and particulate phases of the mine testing. Naphthalene was the most abundant PAH in the gas phase (similar to the controlled testing). However, in the particulate phase, Pyrene was the most abundant PAH.

![Figure 16: The relative abundance of PAHs found in the mine testing](image)
The Denuder results provide detailed information about the semi-volatile organic compounds that are found in the gas and particulate phases of the DEE. This technique has potential application in the mining industry for characterising DEE.

5.3.3.9. Semi-conductor sensors

Semi-conductor sensors operate on the principle that a gas molecule interacts with the sensor and provides a response at a certain gate voltage unique to the gas. The theory is that DPM particulates are small enough (less than one micron) to interact with the sensor. For this reason, it is anticipated that a response should be registered at a given gate voltage.

![Graph](attachment:graph.png)

Figure 17: The resistance of the sensor (i.e. “concentration”) versus the gate voltage of detection for ambient conditions.

Figure 17 shows the background concentrations in the controlled testing environment. One would expect to see the known gases such as CO more prominently.

The results from the testing modes of the dilute emissions are illustrated in Figure 18. There are responses across the spectrum from a gate voltage of -30 V to 10 V. This means that there are compounds in the DEE that create a response from the sensor. However, these compounds could not be identified in this project as the DEE is a complex mixture. It will require further investigation and the use of the other measurements that were taken in this study to identify which gases or ultrafine particulates were detected by the sensor. As this technology is still under development, the outcome of the methodology was promising but inconclusive.
5.3.3.10. Assessment of the methodologies by the VOHE mine employees

The mine employees were asked if they recognised or were familiar with any of the methodologies. They responded as follows:

- Most of the employees were familiar with the 5040 (raw and dilute) methodologies as these are routinely used to assess the personal exposure of employees to airborne pollutants.
- Most of the employees were also familiar with the Electrochemical Dilute methodology as this is routinely used as a warning system for flammable gases in their fiery mine.
- All the employees were familiar with one of the Sub-micron PMC methodologies as they had been offered training on this instrument earlier in the day. They were also at ease with using the instrument and found it user-friendly.
- Another sub-micron PMC from a different supplier was made available for testing. The mine staff was not familiar with this methodology because it was new to the country. However, they were also at ease with using the instrument and found it user-friendly.
• The employees were not familiar with the Denuder and the Semi-conductor methodologies. This was expected since these methodologies are research outputs that have not been commercialised yet.

• The mine employees were not familiar with the Airtec (raw and dilute) methodology. Although this methodology has been applied in hard rock mines during recent years, it is not certified as IS and is thus not applicable to the coal mining workplace yet.

• As expected, the PIT was not familiar with any of the methodologies as he was new to the mine.

6. Guideline and Standard Operating Procedure (SOP)

A Guidance Note and SOP for the measurement of DEE and DPM were developed on the basis of the outcomes of the survey and questionnaire and the testing stages (controlled and mine testing). The comprehensive Guidance Note and SOP can be found in Annexure E.

The Guidance Note aimed at providing the end-user with a framework in which to implement a DEE and DPM measurement methodology. DEE and DPM measurement is the responsibility of multiple disciplines at a mining operation, such as Ventilation, Occupational Hygiene and Engineering.

Measurements are taken within a specific context that should be well documented and updated as circumstances change. The contextual information that an end-user needs to document is illustrated in Figure 19 and discussed in more detail in Annexure E.

The Guidance Note explains the frequency of measurements, factors to consider when choosing a methodology and how to implement the selected methodology.

The SOP provides detailed and practical information on the implementation of each of the five recommended DEE and DPM methodologies. The SOP was developed in accordance with current information and methodologies available to the SAMI. In future there may be more options or improvements to the recommended methodologies.
7. Conclusion

Information was obtained from the SAMI about the diesel fleet. Although the information was not comprehensive, it covered the six largest mining commodities in the country.

The questionnaire provided valuable feedback on the needs and requirements of the mining industry regarding DEE and DPM measurement. This information was used to select and evaluate certain methodologies.

During the controlled testing, the selected methodologies performed well and were relatively easy to implement. The 5040 and Airtec methodologies showed similar patterns in their total carbon concentrations over the five test modes. The multi-gas analyser showed the anticipated variability between the different gases over the five test modes. There was a steady increase in the sub-micron particle size over the five test modes, with the exception of Mode 3.

The highest particulate emissions occurred at 100% load, which would represent the worst-case scenario in the mining environment. However, the temperature at a distance of 0.5 m at this load is extremely high (209°C) and may not be suitable for the operator taking the measurement and/or the methodology that is applied. This high temperature may also require that a position further than 0.5 m away from the tailpipe is selected. Unfortunately, the dilution
ratio between the raw exhaust and the diluted emissions may increase substantially and become too variable. As a result, the emission concentration may not be representative of the engine emissions. This change in emission concentration is illustrated in Figure 3, which compares the raw, dilute and atmospheric emissions.

The mine testing evaluated the practical implementation of the DEE and DPM methodologies. The DEE and DPM methodologies were evaluated at a coal mine that has different challenges than hard rock mines. The majority of the methodologies were not IS and therefore for these methodologies the testing was conducted on surface at an engineering workshop.

The testing modes idle and high idle could be replicated to some extent. They were not exactly the same as the modes that were created during the controlled testing. However, in a real mining environment, one would aim to achieve a testing range of between idle and full load with the best consistency achievable in the workplace.

During idle the instruments responded well and measurements could be taken. However, when high idle was introduced, the conditions around the tailpipe of the machine became unsafe and were outside the operating conditions of the measurement methodologies. Full load was not attempted as the emissions would have been much higher when compared to high idle.

Although high idle and full load were not completed, the testing attempted at high idle confirmed the concerns that the research team had during the controlled testing and that they had anticipated for the mine testing; i.e. excessive emissions created an unsafe environment for the operator taking the measurement.

How well the methodologies were known to the mine employees ranged from unknown to well known in line with the range of experience that the employees had in the VOHE environment and the availability of the methodologies to the mining industry. The employees found the methodologies to be sufficiently user-friendly. This is a positive outcome in light of the potential uptake of the methodologies at the end of the project.

The outcomes of the controlled and the mine testing indicate a potential for most of the methodologies that were evaluated to be implemented in the mining industry.

The methodologies that may not be practically implementable yet are:

- Personal gas detection system: This is a warning system and not a monitoring system for DEE and DPM emissions. The role of this methodology will predominantly be to monitor the testing operator’s personal exposure to gas emissions close to the tailpipe of a diesel machine.
- Semi-conductor sensors: These sensors are still under development and although the sensors showed a response to the DEE and DPM, further investigation is required. For this reason, the methodology is currently not available in a format that can be used.

Although not one comprehensive methodology could be identified for the measurement of DEE and DPM, five methodologies are recommended for implementation in the SAMI. These methodologies are locally available and can be implemented with relative ease in the absence of national limits.
The testing stages provided sufficient information for the development of a Guidance Note for the measurement of DEE and DPM. Five methodologies are recommended for implementation and the SOP provides practical information. The recommended methodologies are:

- NIOSH 5040;
- Airtec Real-time DPM;
- Sub-micron PMC analysis;
- Electrochemical gas sensors; and
- Denuder tubes.

8. Recommendations

The following recommendations are made, based on the outcomes of this project:

- The Guidance Note and SOP as provided in Annexure E provide a framework for the end-user. It is recommended that end-users are trained in the implementation of this framework when the Guidance Note and SOP are rolled out to the SAMI.
- Although five methodologies were recommended, there is still a need for one comprehensive and integrated solution. It is recommended that the CSIR’s patented semi-conductor sensor technology is developed further into an implementable solution as the measurement of gases and fine particulates can be made simultaneously. The sensors are locally manufactured and can be designed according to the needs of the SAMI.
- It is recommended that the MHSC request the SABS to adopt ISO standards that are relevant to the measurement of airborne pollutants in workplace air (e.g. ISO 13137, 7708 and 15757).
- Given the potential for overlap, it is recommended that the Guidance Note is integrated with the outcomes of the project CoE 150602 so that there is a consolidated approach for the SAMI with regard to DPM.
- The survey showed that one of the major drivers for the measurement of DEE and DPM is legislation. In the interest of worker health, it is recommended that the DMR promulgate national OELs for DPM since OELs already exist for gases found in diesel exhaust. National limits by the DMR for raw exhaust emissions are not recommended as the OELs will provide sufficient information on the impact of controls. Raw exhaust measurements should be used to establish trends and assess the impact of control measures on the machine itself (i.e. control at the source).
9. Acknowledgements

The authors wish to acknowledge the following individuals and companies for their valuable support and contributions:

- Sasol Fuels Application Centre and, in particular, Mark Watrus during the controlled testing;
- AngloCoal Greenside Collieries during the mine testing;
- University of Pretoria, in particular Prof. Patricia Forbes and Genna-Leigh Schoonraad; and
- CSIR Air and Dust Laboratory, Dräger, Disprotech, South Deep Gold Mine, AMS Haden and the University of Pretoria for the use of their instrumentation.

10. References


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Annexure A: SIM 150601 Questionnaire

The following questionnaire was sent to the participants. The questionnaire could be accessed and completed online via the following link: https://getfoureyes.com/s/d436N/

Dear Participant,

The Mine Health and Safety Council's (MHSC) research project entitled: SIM150601 "Develop Methodologies for the Measurement of Diesel Exhaust Emissions (DEE) and Diesel Particulate Matter (DPM) is currently in progress.

Part of the project is to obtain the following information from the South African underground mines:

- The number of diesel powered equipment in each category; and
- To assess the needs and requirements for DEE and DPM measurement methodologies.

To this end, we would like to request your assistance in the completion of the questionnaire. The information will only be used for research purposes and the mine specific information will be kept confidential.

There are two sections to this questionnaire and based on your responsibilities, you may be able to complete one or both sections:

1. Fleet Survey; and
2. Questionnaire on the measurement of Diesel Exhaust Emissions (DEE) and Diesel Particulate Matter (DPM).

Please answer the following questions and provide sufficient information based on your area of responsibility at the underground mining operation where you are currently based.

The following definitions are provided for clarity:

- Diesel Exhaust Emissions (DEE): raw exhaust emitted by diesel powered equipment (DPE) that is a combination of gases, hydrocarbons and particulate matter.
- Diesel Particulate Matter (DPM): ultrafine, carbon-based particulate matter (elemental, organic and total carbon) where elemental carbon (EC) is used as the marker.
- Diesel powered equipment (DPE): any equipment that uses diesel as the fuel to operate.

We would appreciate completion hereof before 26 April 2017.

We thank you in advance for your assistance.

If you have any questions, feel free to contact Cecilia Pretorius (Principal Investigator).
Section 1: Fleet Survey

Please provide a summary of the diesel powered equipment (DPE) at your underground mine in an excel spreadsheet (Annexure X). The minimum information required for each type of DPE is:

1. Categories of DPE (e.g. LHD, shuttle cars, utility vehicle)
2. Engine technology (e.g. Tier 0, Tier 1 etc.)
3. Number of DPE per category
4. Power rating (kW) for each type of DPE
5. Engine capacity (litres)
6. Type of after-treatment fitted (e.g. catalytic converters, diesel particulate filters, purifiers, none etc.)
7. Average number of engine hours per category
8. Average number of machine/DPE hours per category

Please provide the additional information as they relate to your operation:

1. Which function uses the largest number of DPE? (1=lowest; 5=highest):
   - Development
   - Utility vehicle
   - Production
   - People transportation
   - Other (please specify):

2. What is the maintenance regime at your mine (choose one or more as applicable):
   - scheduled based on the number of engine hours
   - scheduled based on the number of machine/DPE hours
   - only during breakdowns
   - as specified by original equipment manufacturer
   - Other (please specify):

3. Which of the engineering criteria listed below are applicable to your operation when new machines are purchased (choose one or more)?
   - No criteria is specified
   - Cost-effective option
   - Minimum emission rating requirement
   - Buy Quiet
   - Preferred service provider
   - Please elaborate on the option that is applicable to your operation:
   - Other applicable criteria (please specify):

4. What is the sulfur content (ppm) in the diesel that is used at your mine:
   - 10 ppm S diesel
   - 50 ppm S diesel
   - 500 ppm S diesel
   - Biodiesel

5. Are diesel fuel additives used: Yes or No
   - If Yes, please specify the additive that is used?

6. Contact person with whom we can verify or clarify information:
   - Name:
   - Email:
   - Phone (landline/cellphone):
Section 2: Questionnaire on the measurement of Diesel Exhaust Emissions (DEE) and Diesel Particulate Matter (DPM)

Please answer the following questions as they relate to your responsibilities at the underground mining operation. The following questions aim to establish the industry’s needs and requirements for DEE and/or DPM measurement methodologies.

1. Do you have established limits for DEE at your mine? Yes or No
   a. If yes, please specify these limits?
   b. If No, please provide reason(s):
2. Do you measure for DEE at your mine? Yes or No
   a. If yes, what type of measurement methodology do you use? (select one or more)
      i. Gas meter
      ii. Smoke meter
      iii. Opacity meter
      iv. Particle size meter
      v. Other (please provide details):
      vi. If you are unsure, please provide the make and model of the instrument(s):
   b. Which department is responsible for measuring DEE at your mine?
      i. Ventilation
      ii. Occupational Hygiene
      iii. Engineering
      iv. Supply Chain
      v. Health and Safety
      vi. Other (please provide details):
3. Do you have established limits for DPM at your mine? Yes or No
   a. If yes, please specify these limits?
   b. If No, please provide reason(s):
4. Do you measure DPM at your mine? Yes or No
   a. If yes, what type of measurement methodology do you make use of now? (select one or more)
      i. Gravimetric sampling according to NIOSH 5040
      ii. Real-time DPM monitor
      iii. Respirable Combustible Dust (RCD)
      iv. Other (please provide details):
      v. If you are unsure, please provide the details of the methodology:
   b. If No, please provide reason(s):
5. In your own words, please describe the ideal measurement methodology for DEE:
6. What are the technological challenges with regard to the measurement of DEE at your mine? (select one or more)
   a. Not available
   b. Not robust enough
   c. Not user-friendly
d. Not selective for specified parameters  
e. Not sensitive for required concentration levels  
f. Not portable enough for operational requirements  
g. Lead-time on results too long  
h. Other (please specify):  

7. In your own words, please describe the ideal measurement methodology for DPM:  

8. What are the technological challenges with regard to the measurement of DPM at your mine? (select one or more)  
a. Not available  
b. Not robust enough  
c. Not user-friendly  
d. Not selective for specified parameters  
e. Not sensitive for required concentration levels  
f. Not portable enough for operational requirements  
g. Lead-time on results too long  
h. Other (please specify)  

9. Which DEE parameters does your operation currently measure (choose one or more):  
a. Gases (CO, NOx, SOx)  
b. Coarse particulate matter (> 10 micron)  
c. Fine and ultrafine particulate matter (< 10 micron)  
d. Hydrocarbons (volatile and semi-volatile)  
e. All of the above  
f. None of the above  
g. As specified by legislated limits  
h. Specific combinations (please specify):  

10. Which DEE parameters would your operation measure if suitable methodologies were available (choose one or more):  
a. Gases (CO, NOx, SOx)  
b. Coarse particulate matter (> 10 micron)  
c. Fine and ultrafine particulate matter (< 10 micron)  
d. Hydrocarbons (volatile and semi-volatile)  
e. All of the above  
f. None of the above  
g. As specified by legislated limits  
h. Specific combinations (please specify):  

11. Which DPM parameter does your operation currently measure (choose one or more):  
a. Elemental carbon (EC)  
b. Organic Carbon (OC)  
c. Total Carbon (TC)  
d. All of the above  
e. As specified by legislated limits  

12. Which DPM parameter would your operation measure if suitable methodologies were available (choose one or more):  
a. Elemental carbon (EC)  
b. Organic Carbon (OC)  
c. Total Carbon (TC)  
d. All of the above  
e. As specified by legislated limits
13. Rank the lead time categories below as it applies to the need of your operation to obtain DEE and/or DPM measurement results (1=lowest; 5=highest):
   a. Real-time/immediate
   b. One to five hours
   c. End of shift (8 – 12 hours)
   d. Five to ten days
   e. Two to three weeks

14. Rank the preferred measurement methodology for your operation (1=lowest; 5=highest):
   a. Personal exposure monitoring (time-weighted average over a full shift)
   b. Area monitoring (full-shift)
   c. Source emission monitoring (raw exhaust emitted by DPE)
   d. Other (please specify):

15. What is the end-user requirement of the DEE and/or DPM measurement methodology for your operation:
   a. Low skills required (self-explanatory answer)
   b. Moderate level of skills to do some form of data evaluation
   c. High level of skills to do extensive data evaluation and interpretation

16. Rank the DEE measurement duration alternatives listed below, based on your preference/operational needs (1=lowest; 5=highest):
   a. Spot-check (short interval, typically 1-5 minutes)
   b. Short duration (less than one hour)
   c. Medium duration (full-shift 8 – 12 hours)
   d. Long duration (days or weeks)

17. Rank the DPM measurement duration alternatives listed below, based on your preference/operational needs (1=lowest; 5=highest):
   a. Spot-check (short interval, typically 1-5 minutes)
   b. Short duration (less than one hour)
   c. Medium duration (full-shift 8 – 12 hours)
   d. Long duration (days or weeks)

18. Based on your perspective, rank the factors that will impact on the measuring of DEE and/or DPM at your operation? (1=lowest; 5=highest):
   a. Prevalence of occupational disease
   b. Employee health and safety
   c. Compliance to legislation
   d. Cost of measurement
   e. Production targets
   f. Employee wellness and working comfort

19. Rank the importance of the cost components associated with a DEE and/or DPM measurement methodology (1=lowest; 5=highest)
   a. Initial set-up cost (capital layout)
   b. Operational cost (day-to-day running and maintenance)
   c. Technology life cost (cost to replace or update methodology)
   d. Supporting costs (human resources, external laboratories etc.)

20. Rank the listed parameters based on the importance of each parameter when choosing a DEE methodology (1=lowest; 5=highest)
   a. Cost
   b. User-friendly
c. Lead-time of measurement results
d. Aligned with compliance
e. Duration of measurement
f. Quantity of data points obtained
g. Integration of measurement with other information (e.g. medical surveillance/personal exposure monitoring/engine maintenance)
h. Ease of integration of the methodology with underground communications network

21. Rank the listed parameters based on the importance of each parameter when choosing a DPM methodology (1=lowest; 5=highest)
   a. Cost
   b. User-friendly
c. Lead-time of measurement results
d. Aligned with compliance
e. Duration of measurement
f. Quantity of data points obtained
g. Integration of measurement with other information (e.g. medical surveillance/personal exposure monitoring/engine maintenance)

22. Rank the importance of mobility of the measurement methodology (1=lowest; 5=highest)
   a. Handheld (small and light weight)
b. Portable (medium in size and weight but still portable)
c. Benchtop (larger size but kept in one space)
d. Installed on machine

23. When legislation is passed on DEE and/or DPM, which department(s) will have the responsibility to measure DEE and/or DPM at your operation?
   i. Ventilation
   ii. Occupational Hygiene
   iii. Engineering
   iv. Supply Chain
   v. Health and Safety
   vi. Determined by the Inspectorate that passed the legislation
   vii. Combination of departments (please specify):
   viii. Other (please provide details):

24. What are the operational challenges with regard to the measurement of DEE and/or DPM at your mine? (select one or more)
   a. Lack of management support
   b. Lack of finances
c. Lack of employee support
d. Lack of legislative requirement
e. Other (please specify)

25. What other specific requirements would your operation have for DEE and/or DPM measurement methodologies?

26. If you feel there are other information that we need to take into consideration that have not been covered by this questionnaire, please provide the details:
   Contact person with whom we can verify or clarify information:
   a. Name:
   b. Email:

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c. Phone (landline/cellphone):
d. Designation:
e. Operation:

Annexure B: Electronic Database from Online Questionnaire

This electronic database contains the information that was obtained from the respondents in response to the online survey and questionnaire.

Complete responses were received from participants that represented the following:

- Provinces: Gauteng, Northern Cape, Limpopo, Free State, Mpumalanga, North West
- Commodities: Gold, Coal, Chrome, Platinum, Diamond, Manganese, Copper

Fleet population information was not received from all the online survey participants.

Refer to the electronic database of the questionnaire feedback.

Annexure C: Fleet Population

This electronic database contains the information that was obtained from the respondents to the online survey.

The information does not cover all underground mines. Efforts were made to obtain more comprehensive information from the original engine manufacturers; however, no information has been received to date.

Refer to electronic database that accompanies this report.
Annexure D: Evaluation and Selection Criteria

<table>
<thead>
<tr>
<th>No.</th>
<th>Criteria</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Instrument information:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Name, make and model</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Manufacturer, country</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Supplier, country</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Criteria for DEE measurement methodology</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Type of measurement instrument</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gas meter</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Gravimetric sampling</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Particle size meter</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Opacity meter</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>DPM instrument</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>This instrument can be applied to the following methodology:</td>
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</tr>
<tr>
<td></td>
<td>Exhaust monitoring</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>Area monitoring</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Personal monitoring</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>This instrument can be used by the following departments to measure DEE:</td>
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</tr>
<tr>
<td></td>
<td>Ventilation</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Occupational Hygiene</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Engineering</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Environmental</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>The instrument addresses the following technological challenges:</td>
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</tr>
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<td></td>
<td>Monitoring equipment and related consumables are locally available</td>
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</tr>
<tr>
<td></td>
<td>Selective for specified DEE constituents (e.g. CO, NOx, SOx)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Time between measurement and reporting of results is not too long</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Technology would be reliable enough in the applied conditions</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>User-friendly</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Portable enough for operational requirements</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Sensitive for required concentration levels</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>This instrument measures the following constituents of DEE:</td>
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<td></td>
<td>Gases (CO, NOx, SOx)</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Particulate matter below 10 micron</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Hydrocarbons (volatile and semi-volatile)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Particulate matter above 10 micron</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>Measurement duration</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spot-measurement (short interval, typically 1-5 minutes)</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Medium duration (full-shift 8 to 12 hours)</td>
<td>30</td>
</tr>
<tr>
<td>No.</td>
<td>Criteria</td>
<td>Weighting</td>
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<tr>
<td>-----</td>
<td>--------------------------------------------------------------------------</td>
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</tr>
<tr>
<td></td>
<td>Short duration (less than one hour)</td>
<td>20</td>
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<tr>
<td></td>
<td>Long duration (days or weeks)</td>
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<tr>
<td>7</td>
<td>Instrument complies with the following important factors:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Integration of measurement with other information (e.g. medical</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>surveillance/personal exposure monitoring/engine maintenance)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>User-friendly</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Duration of measurement</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Quantity of data points obtained</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>Lead-time between the measurement and reporting of results</td>
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</tr>
<tr>
<td></td>
<td>Cost</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>This instrument can withstand the conditions of the measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat resistant (&gt; 100 °C)</td>
<td>Temp</td>
</tr>
<tr>
<td></td>
<td>Resistant to excessive moisture</td>
<td>Moisture</td>
</tr>
<tr>
<td></td>
<td>Drop test</td>
<td>Height</td>
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<td></td>
<td><strong>Criteria for DPM measurement methodology</strong></td>
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</tr>
<tr>
<td>9</td>
<td>Type of methodology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gravimetric sampling according to NIOSH 5040</td>
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<tr>
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<td>Real-time DPM monitor</td>
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<tr>
<td>10</td>
<td>This instrument measures the following parameters:</td>
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<tr>
<td></td>
<td>EC, OC and TC</td>
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<tr>
<td></td>
<td>Total Carbon (TC)</td>
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</tr>
<tr>
<td></td>
<td>Elemental Carbon (EC)</td>
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<tr>
<td></td>
<td>Organic Carbon (OC)</td>
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<td>11</td>
<td>The instrument addresses the following technological challenges:</td>
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<tr>
<td></td>
<td>Monitoring equipment and related consumables are available locally</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Time between measurement and reporting of results is not too long</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Technology would be reliable enough in the applied conditions</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>User-friendly</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Selective for specified DPM constituents (e.g. EC, OC, TC)</td>
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<tr>
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<td>Sensitive for required concentration levels</td>
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<tr>
<td>12</td>
<td>Measurement duration</td>
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<td>Medium duration (full-shift 8 to 12 hours)</td>
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</tr>
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<td></td>
<td>Spot-measurement (short interval, typically 1-5 minutes)</td>
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</tr>
<tr>
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<td>Short duration (less than one hour)</td>
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</tr>
<tr>
<td></td>
<td>Long duration (days or weeks)</td>
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</tr>
<tr>
<td>13</td>
<td>Instrument complies with the following important factors:</td>
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</tr>
<tr>
<td></td>
<td>Integration of measurement with other information (e.g. medical</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>surveillance/personal exposure monitoring/engine maintenance)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>User-friendly</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Quantity of data points obtained</td>
<td>20</td>
</tr>
<tr>
<td>No.</td>
<td>Criteria</td>
<td>Weighting</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------------------------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td></td>
<td>Lead-time between the measurement and reporting of results</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Duration of measurement</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Aligned with legislation</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Cost</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td><strong>Overall criteria for DEE and DPM methodologies</strong></td>
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</tr>
<tr>
<td>14</td>
<td>Lead time for methodology</td>
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</tr>
<tr>
<td></td>
<td>Real-time / immediate</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>End of shift (8 to 12 hours)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>One to five hours</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Five to ten days</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Two to three weeks</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>This instrument can be applied to the following methodology:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exhaust monitoring</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Area monitoring</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Personal monitoring</td>
<td>20</td>
</tr>
<tr>
<td>16</td>
<td>Skills level required</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High level of skills to do extensive data evaluation and interpretation</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Moderate level of skills to do some form of data evaluation</td>
<td>40</td>
</tr>
<tr>
<td>17</td>
<td>Cost component of methodology</td>
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</tr>
<tr>
<td></td>
<td>Initial set-up cost (capital layout)</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Supporting costs (human resources, external laboratories etc.)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Operational cost (day-to-day running and maintenance)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Technology life cost (cost to replace or update methodology)</td>
<td>10</td>
</tr>
<tr>
<td>18</td>
<td>Mobility of methodology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Handheld (small and light weight)</td>
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</tr>
<tr>
<td></td>
<td>Installed on machine</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Portable (medium in size and weight but still portable)</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Bench-top (larger size but kept in one space)</td>
<td>10</td>
</tr>
</tbody>
</table>
Annexure E: Guidance Note and SOP for the Measurement of DEE and DPM

1 Introduction

Project SIM 150601 set out to "develop methodologies for the measurement of diesel exhaust emissions (DEE) and diesel particulate matter (DPM)". At the start of the project a questionnaire was designed and administered to assess the end-user needs and requirements in relation to the measurement of DEE and DPM. This information was used to develop evaluation criteria for selecting methodologies to measure DEE and DPM. The selected methodologies were evaluated and the outcomes were used to develop a Guidance Note and a Standard Operating Procedure (SOP).

The measurement of DEE and DPM concentrations is not an isolated aspect in the management and control of DEE and DPM exposure. Measurements are taken within a specific context; and taking these measurements requires a holistic approach and the support of various disciplines within the organisation such as Engineers, Occupational Hygienists, Ventilation Officers, Supply Chain Managers, Financial Managers, and Mining Personnel. Without this context, approach and the necessary support, the measurement of DEE and DPM is effectively meaningless.

2 Objective of the Guidance Note

- The objective of the Guidance Note is to assist the end-user in planning and carrying out meaningful DEE and DPM measurement in the South African Mining Industry (SAMI).
- The purpose of DEE and DPM measurements is to monitor personal exposure and the effectiveness of DEE and DPM control measures. In addition, DEE and DPM measurements are used to monitor the condition and the health of diesel-powered engines, as they relate to employee exposure.
- This Guidance Note and SOP are not mandatory in themselves. However, they should be used in conjunction with the "DMR 16/3/2/4-A1 Guideline for the compilation of a mandatory Code of Practice (COP) for an occupational health programme on personal exposure to Airborne Pollutants" (referred to in this Guidance Note as the “DMR 16/3/2/4-A1”).

3 Responsibilities

DEE is classified as a Class 1 Human Carcinogen and, in a mining context, originates from a variety of diesel-powered equipment involved in a mining operation. In view of this, the responsibility to manage DEE and DPM concentration levels is integrated within different departments of a mining operation.

- The measurement of DEE and DPM is the responsibility of multiple disciplines at a mining operation. The responsible person or function in each department should be clearly defined.
- The monitoring of DEE and DPM in relation to personal exposure may be the responsibility of the Occupational Hygienist.
- The monitoring of DEE and DPM in the working environment may be conducted by the Ventilation and/or Environmental Engineer.
- The monitoring of DEE and DPM emissions at the source (i.e. diesel-powered equipment) with a view to assessing the health and prognostic maintenance of diesel-powered equipment may be the responsibility of the Engineering Department.

4 **Contextual Information**

DEE is a pollutant that has a complex and inconsistent composition every time it is formed by a diesel-powered engine. Different factors have an influence on the formation of DEE such as engine condition, temperature, driving style, fuel composition or even mitigating technologies (exhaust after-treatment type and condition). For meaningful observations it is important to have a good understanding of the context of the mining operation in which the DEE and DPM measurements are undertaken as this informs the choice of DEE and DPM measurement methodologies. Without the contextual information, the DEE and DPM measurements are likely to be less than optimal.

The contextual information is dynamic and changes as circumstances change at the mining operation. Some of the information can be captured prior to or after the Baseline Risk Assessment (BRA). In order to assist with the gathering of contextual information an inventory should be compiled, and the factors listed in Figure 20A should be documented (the list of factors is not exhaustive).
The contextual information factors that should be documented are briefly discussed below.

4.1 **Legislative framework in which the mine operates**
Mining operations have to comply with specified national and international regulations, standards and/or occupational exposure limits (OELs). The prevailing standards for the relevant DEE components and DPM in each type of environment (i.e. OEL vs raw exhaust vs workplace atmospheres) need to be documented.

4.2 **Specific health and safety requirements of the mining operation**
The mining operation may have specific health and safety requirements that may apply to DEE and DPM measurements. For example, measuring equipment that is used in potentially explosive atmospheres has to comply with national standards (e.g. SANS 60079-0:2012).

4.3 **Characteristics of the workplaces affected by diesel emissions**
The workplaces that are affected by DEE need to be documented. The high-risk areas in which the diesel-powered equipment operates or idles for prolonged periods of time are usually easy to identify and document. However, care should be taken not to overlook the apparent low-risk workplaces such as those that are far from but still downstream of the diesel sections. For example, light duty vehicles (e.g. people
carriers) moving around in the upstream sections may create exposure for workers that are upstream of the diesel sections, or significantly contribute to the exposure in diesel sections.

4.4 Characteristics of the diesel-powered equipment fleet
Information regarding the fleet needs to be captured and documented. This information includes age of fleet, engine technology, exhaust after-treatment, type of machine and engine hours, type of fuel used and certified emission standard (Tier 0 – 4), among other features. This information is usually captured and maintained by the Engineering Department. As machines and engines are replaced and refurbished, this will impact on the monitoring strategy.

4.5 The current DEE and DPM concentrations for the entire fleet
The diesel-powered equipment (i.e. sources) varies and as controls are implemented and maintenance practices improve, the emission concentrations are reduced. The reduction will not necessarily be to the same extent on all equipment. The frequency of measurement is discussed in Section 5.

Note: The Occupational Safety and Health Administration (OSHA) in the USA has set limits for the DPM concentrations emitted by diesel-powered equipment in underground coal mines that range between 2.5 and 5.0 g/hr. These limits can be used as a guideline when monitoring the emissions of the fleet.

4.6 Diesel-powered equipment maintenance regime
The maintenance regime of the diesel-powered equipment at the mining operation needs to be documented. Record the following aspects of the maintenance regime (the list is not exhaustive):

- The frequency or schedule of maintenance;
- Pre- and post-shift inspections;
- Replacements or repairs carried out during scheduled maintenance;
- Effectiveness of maintenance; and
- Original equipment manufacturer (OEM) risk assessments.

The maintenance regime is usually captured and maintained by the Engineering Department. However, the documentation of the maintenance regime should be reviewed and updated as changes are made as this may impact on the monitoring strategy.

The effective maintenance of diesel-powered equipment has been shown to reduce DPM significantly (Waytulonis, 1992). It is important that this part of the contextual information is well documented as it will be referenced during the evaluation of the measurement data.

4.7 Inventory of the DEE and DPM controls in place
An inventory must be made of the DEE and DPM controls that are already in place and updated as progress on the reduction of emissions is made. Controls to be implemented are:

- Controls implemented on the machines (i.e. at the source): document the type and nature of exhaust after-treatment, catalytic converters, purifiers and
diesel particulate filters, for example. Information about the controls may inform the choice of measurement parameter.

- Ventilation in underground mining operations: document the ventilation design, whether the design can accommodate diesel-powered equipment in an underground mine, the volume of air that is produced, and whether it is sufficient for the DEE and DPM concentrations anticipated and/or measured;
- The administrative controls in place: document the number of diesel-powered vehicles and equipment allowed in a workplace;
- The personal protective equipment (PPE): document the PPE that can be used as a last resort. PPE relates to the protection required and may change as engineering controls become more (or less) effective. Retain evidence that the PPE of choice complies with the requirements of SANS 50149 (SABS, 2003).

Note: The type of PPE can be determined by calculating the Assigned Protection Factor (APF) that will ensure sufficient protection to an employee in relation to an OEL (or in-house limit value). Protection factor = DEE or DPM concentration ÷ OEL (refer to Table 1A).

Table 5A: Type of PPE required for the calculated protection level (HSA, 2010)

<table>
<thead>
<tr>
<th>Protection Level</th>
<th>OEL Protection</th>
<th>APF Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFP1*</td>
<td>4x</td>
<td>4x</td>
</tr>
<tr>
<td>FFP2</td>
<td>12x</td>
<td>10x</td>
</tr>
<tr>
<td>FFP3</td>
<td>50x</td>
<td>20x</td>
</tr>
</tbody>
</table>

*Filtering face pieces

- And any other relevant controls.

4.8 Personal exposure to DEE and DPM

The current personal exposure of mine employees to DEE and DPM should be assessed and documented by undertaking a BRA according to DMR 16/3/2/4-A1.

Useful resources for risk assessments are:

- SIMRAC Handbook Chapter 3: Hazard Identification and Risk Assessment (Guild and Marais, 2001); and

Keep a record of the employees in the high-risk occupations of the mine. Take care not to overlook the employees in apparent low-risk occupations, such as roving employees, office staff in close proximity to machine workshops and those that take DEE and DPM measurements periodically. The employees in these occupations may be at risk of short-term high exposure concentrations.

4.9 Organisational policies and procedures

The organisational policies and procedures that may have a direct and indirect impact on the effective control of personal exposure to DEE and DPM should be documented. Examples include the supply chain policies and procedures for the procurement of the type of fuel (e.g. 10 ppm, 50 ppm or 500 ppm sulphur), engine technology procured (Tier 1, 2, 3 or 4) and new or retrofitted after-treatments on the vehicle (e.g. catalytic converters or DPM filters). Other relevant examples may be the Human Resources policies and procedures for the development and retention of skills to ensure the
effective maintenance of the diesel-powered equipment used by the mine. Another matter to consider is conflicting priorities across different departments, such as machine maintenance vs production pressures vs personal exposure to harmful pollutants.

Note: Employees may be exposed to the fumes of diesel and this may have an impact on how measurement data is evaluated. Although there are similarities between diesel fumes and DEE, it should be noted that DEE and DPM are combusted, partially combusted, and unburnt diesel products. As a practical example, a workshop employee’s measured Total Carbon (TC) may be high where no Elemental Carbon (EC) is present. In this case it is possible that the employee has washed the engine with diesel. Review the policies and procedures regarding the use, storage and transfer of diesel fuel.

4.10 Requirements for medical surveillance
The Occupational Medical Doctor at the mining operation should be consulted about the requirements for a DEE and DPM medical surveillance programme relevant to the DEE and DPM exposure management programme. These requirements should then be documented. For example, 3-hydroxybenzo[a]pyrene (3OH-BaP) is a biomarker in urine that is used for the biological monitoring of employee exposure to benzo[a]pyrene (BaP), a polycyclic aromatic hydrocarbon (PAH) that is classified as a human carcinogen (Boogaard, 2008). BaP is one of the many PAHs that are found in DEE and, owing to its carcinogenicity, it is used as a marker for most toxic PAHs.

4.11 Any other relevant contextual information
The monitoring of DEE and DPM is a dynamic process. As relevant information becomes available, it should be documented.

5 Frequency of Measurement
The measurement of DEE and DPM is conducted over different periods as follows:

- **During the initial BRA of the personal exposure of employees**: During the fleet inventory it is recommended that baseline measurements of personal exposure be taken in parallel to the engine emissions. The personal exposure measurements apply to the high-risk employees, machine operators and roving employees. In addition, care should be taken not to exclude employees in workplaces that are in close proximity to the high-risk areas, such as administrative offices at the workshops and rest areas downstream from diesel sections.
- **Issue Based Risk Assessment (IBRA)**: High-priority risks to employees that were identified during the BRA are evaluated in detail and an in-depth IBRA is conducted. The purpose of the IBRA is to design suitable control strategies to reduce the risk.
- **Continuous monitoring in line with the DMR 16/3/2/4-A1**: Continuous monitoring aims to assess the personal exposure of employees to DEE and DPM, to assess the effectiveness of control measures and to monitor the condition of the diesel-powered equipment.
- **Intermittent monitoring when changes in the documented contextual information occur**: Examples include changes in the type of fuel procured, engine technology procured and new after-treatments on the vehicle.
6 Type of DEE and DPM Measurement

As with any airborne pollutant, DEE and DPM can be measured in different places to assess the risk of personal exposure to the pollutant. The following types of measurement can be taken:

- **Personal exposure monitoring of employees at risk**: This type of DEE and DPM measurement should be taken in line with the mine’s DMR 16/3/2/4-A1.
- **Environmental or area monitoring in the workplace**: This monitoring is carried out to assess the concentrations of DEE and DPM in the workplace atmosphere. Environmental measurements assess the effectiveness of the ventilation but also the effectiveness of the controls that are fitted on the engine itself for reducing DEE.
- **Tailpipe and raw exhaust measurements**: These measurements are used to assess the engine condition and controls that are fitted on the engine itself for reducing DEE.

7 DEE and DPM Measurement Methodologies

DEE is a complex mixture of gases, vapours and particulates, with DPM established as a marker for DEE. During the evaluation of various methodologies, it was found that no one methodology was able to measure all the components of DEE and DPM in personal exposure, environmental conditions and raw exhaust emissions. And there is not one methodology that can be recommended per commodity. One or more technologies can be applied as a methodology in the SAMI. The following methodologies are recommended, based on the feedback from the SAMI end-users and the current availability of methodologies to the SAMI:

- NIOSH 5040 (DPM measured as Elemental Carbon (EC));
- FLIR Airtec Real-time DPM;
- Sub-micron Particle Mass Concentration Analysis;
- Electrochemical gas sensors; and
- Denuder tubes.

Refer to Annexure E1 for the SOPs and additional information for each of the recommended methodologies.

7.1 Factors to consider when deciding on a methodology

Certain factors need to be considered when establishing a DEE and DPM methodology for a mining operation:

- **Choice of methodology**: It is very important to choose the correct methodology that is fit for purpose at the mining operation. This is why contextual information is so important; e.g. the legislative framework or the controls that are in place.
- **Understanding and documenting the methodology**: Once a methodology has been chosen, the reasons for this choice should be documented as it may have been informed by the contextual information regarding the mining operation. The documentation of these reasons is important for institutional memory, as new developments are made and new instrumentation comes onto the market.
- **Choosing a methodology that is sufficiently selective and specific to the chosen parameter**: It is necessary to confirm that the methodology actually measures the DEE and/or DPM parameter of choice (e.g. carbon-monoxide (CO) vs DPM). It is
important to document how the parameter is measured and what the limitations of
the methodology are. The limitations should include the instrument-specific (e.g.
temperature and humidity) and the environmental-condition limitations (e.g. will the
instrument still operate effectively in an ultra-deep mine). Be aware of terminology
that is used in marketing material that may be misleading (not necessarily with
malicious intent). This is especially important when new technologies come onto
the market. If the parameter of choice is DPM, the end-user should confirm that
DPM is actually measured according to the definition of DPM. If the parameter of
choice is one of the DEE gases (e.g. CO), the methodology should be sufficiently
selective and specific for that gas.

- **Choice of marker for DEE:** EC is an established marker for DEE and DPM (Birch,
2003b). Research has shown that there is a strong, positive correlation between
EC and CO (Vermeulen et al, 2010). However, end-users should be aware that
engine-based controls (such as after-treatments or fuel additives) may skew this
relationship. For example, a catalytic converter has been designed to reduce CO
emissions but not necessarily DPM emissions. End-users are urged to document
the evidence of a positive relationship between the different components of DEE
before deciding on one marker or surrogate. This relationship should be verified
periodically to confirm that the relationship still holds true.

- **Concentration of parameter:** The chosen methodology should be able to measure
the anticipated concentrations. The DEE and DPM concentrations measured in
raw exhaust far exceed those of personal exposure and workplace atmospheres.
Historical data or initial screening measurements during the risk assessments may
provide an indication of the estimated concentration ranges.

Note: Concentration ranges depend on various factors, such as engine performance, engine mode
tested, workplace ventilation and employee time spent in close proximity to the source. The
instrument suppliers should be able to provide information on the tolerance of the equipment in the
planned application.

- **Comparative parameter:** Where possible and for ease of comparison, choose a
parameter that can be measured in the raw exhaust (i.e. at the source), in the
workplace atmosphere and for personal exposure.

### 7.2 Implementation of the methodology

There are a number of aspects to consider when implementing the chosen methodology,
as follows:

- **Consistency:** Whichever methodology is implemented, it should be executed
consistently or in the same manner. The type of methodology may not always
provide absolute measurements. Initial measurements may be indicative until
such time as the accuracy of the measurement can be improved. Record information that will provide the background of the measurement (e.g. date, time, shift and purpose of measurement). In order to obtain reliable trends, the measurements need to be taken consistently and recorded. It will also be beneficial to the user if they are presented graphically.

- **Personal exposure measurements:** These measurements should be conducted
according to documented methodologies and best practice procedures for
personal exposure monitoring. Various methodologies are available for personal exposure to gases, vapours, particulates and fumes (e.g. NIOSH, OSHA and Health and Safety Executive (HSE)). As methods are revised, it is important to ensure that the latest version of the method is used. Within the scope of this project the most appropriate recommended methodologies were evaluated and are discussed in Annexure E1.

- **Environmental and workplace atmosphere measurements**: These measurements depend on the choice of methodology and can be taken in a similar way to the personal exposure measurements. Refer to Annexure E1 for further detail.

- **Raw exhaust measurements**: The implementation of a DEE and DPM measurement methodology for raw exhaust can become a challenge. In order to obtain representative emissions, a diesel-powered machine has to operate under circumstances and loads that are typical of its normal operation. Unfortunately, this does not necessarily present a safe environment or consistent condition for taking DEE and DPM measurements.

  Note: “Normal operation” under typical engine load will result in “worst case scenario” emissions. It is not “normal operation” to operate an engine under 100% load for a full shift. Although the highest emission concentrations will be obtained, operating the engine under 100% load for a full shift may not be supported by management as this will result in increased wear and tear and an increase in the running cost of the engine.

The following procedures are recommended when taking raw exhaust measurements:

- Establish different engine operation modes. This is machine specific as not all machines can necessarily be operated in the same way when DEE and DPM measurements are taken. When taking raw exhaust measurements, the engine can be operated on idle, high idle, full stall and/or full load. The recommended mode is high idle as the engine can operate in a stationary position with a small load on the engine. Find an operating mode that can be implemented in such a way as to provide the most consistent and reproducible measurements.

- When taking raw exhaust measurements try to meet the following conditions:
  
  o Operate the engine at the desired mode until the engine temperature has stabilised before taking a measurement. Oil or coolant temperature can be used as an indicator of engine temperature.
  
  o Maintain a consistent engine speed between measurements.
  
  o It may not be practical to measure or quantify the actual load on the engine but exhaust temperature can be used as an indicator. Maintain a consistent exhaust temperature between measurements.
  
  o Try to take multiple raw exhaust measurements (e.g. three), keep sampling times consistent (i.e. minimum of 30 seconds) and record the average result.

- Alternatively, take an area measurement in one spot in each workplace where a single machine will pass by multiple times during a shift. These measurements will be of the diluted raw emissions, but they will represent the
actual operating emissions of one machine under typical loads. These measurements can be taken at a safe distance. It is recommended that these measurements are taken under supervision during short periods within the shift so that optimum readings are taken, and machine down-time is not considered (i.e. lunch breaks). Record the contextual information of the measurement (such as shift, time (hours), machine(s) operating, and the workplace (e.g. level, shaft, area) and any other relevant information).

Note: Multiple passes by multiple vehicles will prevent identification of the problematic source, and prevent the development of trends for each respective vehicle. However, area measurements where multiple vehicles pass may provide information on the effectiveness of the ventilation in that area.

- Put in place the necessary health and safety precautions for the technician taking the measurements of DEE and DPM. Taking measurements at the tailpipe of an engine exposes the technician to excessive concentrations of DEE and DPM. The technician can be fitted with a personal gas-detection system to determine the personal exposure to harmful gases such as CO against the short-term exposure limit (STEL) and the ceiling limit (CL). In the event that warning limits are exceeded, an alarm will sound so that the technician can be removed from the source of exposure.

- Document the raw exhaust measurements of each machine in relation to the controls that are implemented on the diesel-powered equipment. The measurements will change as improvements are made, scheduled maintenance is carried out or deterioration of the engine performance occurs.

Technical details on how to execute the recommended DEE and DPM measurements are given in the SOPs in Annexure E1.
Annexure E1: Standard Operating Procedures (SOPs)

The standard operating procedures (SOPs) for different methodologies are explained below. **There is not one methodology that is specific to a commodity or a machine.** One or more methodologies can be combined to obtain a good understanding of the diesel exhaust emissions (DEE) and diesel particulate matter (DPM) concentrations in the employees’ breathing zone, the workplace or the raw exhaust of a machine. The methodologies are based on the feedback obtained from the South African Mining Industry (SAMI) and the current methodologies available in South Africa.

Where referring to international standards, always refer to the latest version of the standard. The latest versions of equivalent standards to those that are referenced may also be used. These include ISO, NIOSH, HSE or European Union (EU) standards.

A.1 NIOSH 5040

The measurement of Elemental Carbon (EC) using the NIOSH 5040 (Birch, 2003a) method was developed by NIOSH in the United States of America (USA). The method was developed to assess the personal exposure of employees to DPM, with EC used as the marker for DPM. The method involves sampling DPM onto a tissue quartz filter and subsequently conducting a laboratory analysis of the filter using a thermal optical method.

Note: NIOSH 5040 is available from the following site: https://www.cdc.gov/niosh/docs/2003-154/pdfs/5040.pdf. At the time of publishing this document, no other equivalent standards were available for this method. The ISO standards referenced here can be purchased directly from the ISO or via the SABS.

The sampling train consists of the following:

- Gravimetric sampling pump that complies with the requirements of ISO 13137 (ISO, 2013) and has a flow rate that is suitable for low volume sampling (typically between 1 and 5 L/min). The required flow rate is determined by the size-selective sampler (please consult with the manufacturer). Typical flow rates are 2.2 L/min. Flow meters that are used to verify the flow rate of the pump also have to comply with the requirements of ISO 13137.
- 37 mm diameter cassette and tissue quartz filter.
  - Non-coal mines: Use a 3-piece styrene cassette with filter and cellulose backing pad. The filter does not require weighing prior to cassette assembly. Alternatively, use the SKC DPM cassette.
  - Coal mines: Only use the **SKC DPM cassette** that was developed by NIOSH for sampling DPM in coal mines. The cassette contains a tissue quartz filter, backing pad and an impactor that will separate the fine coal dust from the DPM to prevent interference with the analysis result.
Note: The SKC DPM cassette is commercially available from SKC Inc. and no similar product is currently available from another manufacturer.

- Size-selective sampler (i.e. cyclone) with a particle size-selection performance that matches the criteria for respirable dust as described in ISO 7708 (ISO, 1995). The SKC DPM cassette requires the use of the SKC GS1 cyclone. Please confirm the required flow rate of the sampler with the supplier.

Note: The SKC GS1 cyclone fits onto the 3-piece cassette.

The sampled filter is submitted to an analytical laboratory that can analyse DPM according to NIOSH 5040.

Note: Visit the South African National Accreditation System (SANAS) website for a list of accredited service providers.

This methodology can be implemented in the following ways:

- **Personal exposure measurements**: These are taken via full-shift sampling to assess personal exposure in accordance with DMR 16/3/2/4-A1.

- **Environmental or area monitoring**: This monitoring involves full-shift sampling in one spot in a workplace with diesel-powered equipment and roving employees moving around. In addition, measurements can be taken upstream and downstream from workplaces to assess cumulative effects of the pollutants. The effectiveness of the ventilation in workplaces is assessed.

- **Raw and dilute exhaust measurements**: These can be taken in different ways:
  - Only short sampling periods of 5 to 10 minutes can be accommodated with this methodology as the emission load is fairly high. Start with shorter sampling periods and only increase the sampling time when the emissions improve; i.e. the DPM concentrations decrease.
  - **Raw exhaust sampling**: The standard NIOSH 5040 methodology has to be modified to protect the sampling pump, cassette and cyclone against high temperatures and high levels of moisture. The sampling train consists of a metal probe (typically used for raw exhaust measurements), a length of tubing connected directly to an SKC DPM cassette with a 1.0 micron impactor, with a tissue quartz filter, and a sampling pump. The probe is fixed to the tailpipe of the exhaust. Where possible, ensure that the probe can be positioned in the middle of the tailpipe and is of sufficient length to sample at a depth of approximately 20 cm inside the tailpipe (Davies, 2013). When taking measurements in the tailpipe of diesel-powered equipment that has a waterbox fitted, ensure that the probe is positioned sufficiently away from the water outlet to prevent water from running into the probe.
Dilute exhaust sampling: This is short-term sampling in close proximity to the tailpipe of the diesel-powered equipment. The recommended distance is approximately 1 m away from the opening of the tailpipe when sampling on high-idle engine mode. The distance can be extended; however, this will mean that the DEE will become increasingly diluted and this will result in lower concentrations being measured. It is important that the distance remains consistent between measurements in order to obtain reliable trends. Make use of a bracket or spacer to ensure consistent distances between measurements.

Note: Please be aware that the sampling pump, cassette and size-selective samplers were not designed to withstand high temperatures and may melt when the distance is decreased or the engine is operated at a higher load mode (e.g. full load). Please confirm the maximum allowable temperature for the sampling equipment with the respective manufacturers. Take the necessary health and safety precautions for the technician.

A.2 Airtec Real-time DPM
This instrument was originally developed by NIOSH (USA) for the real-time personal monitoring of DPM exposure. This methodology was also validated and compared to the laboratory method NIOSH 5040 (Noll et al, 2013). After sampling, the data can be downloaded from the instrument so that the information can be evaluated for trends and spikes during the sampling period.

Note: The instrument is commercially manufactured by FLIR (USA) and at the time of publishing this document, there were no other commercial manufacturers of a similar instrument. The instrument can be purchased through a number of suppliers in South Africa.

The sampling train consists of the following:

- The Airtec instrument;
- A cassette with an impactor (similar to the SKC DPM cassette but without the filter);
- A GS1 cyclone fitted to the impactor; and
- A 3-piece cassette inside the Airtec with a tissue quartz filter.

Note 1: The Airtec methodology was originally designed to use a Teflon filter in the cassette. The direct readings from the instrument were then calibrated against the laboratory method NIOSH 5040. By using a tissue quartz filter instead, the filter can be analysed after sampling according to NIOSH 5040. A slight difference between the real-time readings and the laboratory results can be expected. It is possible to validate the real-time readings of the Airtec instrument using the tissue quartz filter with the results from the laboratory analysis.

Note 2: The total carbon (TC) on the instrument is based on a built-in factor that converts the measured EC to a calculated, interference-free TC. This factor was established according to conditions in the USA but can be amended once the ratio between EC and TC has been determined for the mining operation in which testing will
take place. This factor will have to be reviewed periodically and updated when new engine technology or after-treatment systems are introduced or if there is a significant change in fuel properties.

Note 3: Speak to the manufacturer for instructions on how to change some of the factory settings on the instrument. This is a relatively simple procedure but requires assistance from the supplier. Some of the settings can be amended to:

- Reduce the difference between the real-time readings and the laboratory analysis; and
- Amend the factor for the EC to TC conversion for your mining operation.

The Airtec methodology can be implemented in the following ways:

- **Personal exposure measurements**: These measurements are taken with full-shift sampling to assess personal exposure in accordance with DMR 16/3/2/4-A1.
- **Environmental or area monitoring**: This can be achieved in a similar way to using the NIOSH 5040 methodology. Multiple short-term readings can be taken by using the same filter inside the instrument. After each sampling period (e.g. 10 min or 2 hours), it is only necessary to reset the running time to zero. It is possible to see the different sampling periods when the data is downloaded. Although the tissue quartz filter can be analysed, the measured concentration will be the cumulative result for all the areas that were measured on the same filter.
- **Raw exhaust measurements**: The same approach can be used as for the NIOSH 5040 methodology. Remove the cyclone from the train and connect the tubing from the metal probe directly to the empty cassette with an impactor. The impactor without the filter can be used multiple times for short-term readings. Short-term sampling times are recommended as well.

Note 1: Please note that the instrument will give an alarm at elevated readings owing to preset factory settings. These settings can be adjusted to a different setting if the user so chooses.

Note 2: The increased exhaust back pressure may have an effect on the actual sampling flow of the instrument when sampling directly from the exhaust. Adjust the measurement position accordingly.

Note 3: To prevent possible contamination on personal/area measurements, it is recommended that one instrument is dedicated to raw exhaust measurements. Where possible do not switch between personal/area measurement and raw exhaust measurements. If only one instrument is available, start with the lower concentrations (i.e. personal/area) and then measure the higher concentrations (i.e. raw exhaust).

### A.3. Sub-micron particle mass concentration analyser (PMC)

This methodology measures the particle mass concentration of fine particulates in raw exhaust with the use of laser light scattering. The instrument comes with a heated metal probe for placement inside the tailpipe of the diesel-powered equipment.
Note: At the time that the methodology evaluations were carried out, only two instruments were evaluated from local suppliers in South Africa:

- The Saxon Junkalor SMG200M (which superseded the DPM 1.0 model); and
- The DPM-RT instrument.

Methodologies that use the photo-acoustic principle are available; however, the laser light scattering instruments are more practical and cost effective.

It is recommended that the connecting tubing of the instrument is heated to reduce the moisture content as this may interfere with the laser.

Note: Make sure that the whole length of the probe is heated to avoid cooling, especially inside the instrument.

Ensure that the instrument has a size-selection functionality so that only particulates of the respirable fraction are measured. Typical size ranges are between approximately 100 nm and 10 micron.

Select a probe that can be fitted inside the tailpipe so that the technician can step away from the raw exhaust that is emitted.

Sampling times are determined by the instrument’s sampling programme but are typically 5 to 10 minutes once the engine temperature has stabilised (oil temperature is often used to check for stability).

This methodology is currently only available for the measurement of fine particulates in raw exhaust and is not designed for personal or area measurements. Fine dust and water vapour in the workplace atmosphere will interfere with the readings.

### A.4 Electrochemical gas sensors

This methodology is used for measuring multiple gases in raw exhaust and uses electrochemical gas sensors to measure CO, NO, NO₂ and NOₓ. Suppliers and manufacturers of these instruments can fit other sensors for gases such as sulphur dioxide (SO₂).

Note: There are a variety of multi-gas analysis instruments available from local suppliers to the SAMI that make use of electrochemical gas sensors. The instrument that was used in this project was the Dräger MSI EM200-E Multi-gas analysis instrument.

These instruments are fitted with a metal probe for placement in the tailpipe. Where possible, select a probe that can be fitted inside the tailpipe so that the technician can step away from the raw exhaust that is emitted. The instrument has a heated sensing chamber to reduce the
relative humidity and a filter to remove all particulates. Only gases are allowed through to the gas sensors.

Sampling times are determined by the instrument's sampling programme but are typically 5 to 10 minutes.

This methodology is currently only available for the measurement of gases in raw exhaust. For personal or area measurements the standard occupational exposure methodologies such as sorbent tubes should be used.

A.5 Denuder tubes

The denuder tubes evaluated in this project were developed by the University of Pretoria to sample semi-volatile organic compounds in the gas- and particle-associated phases separately (Geldenhuys, 2015). The denuder consists of two multi-channel silicone rubber traps that contain 22 parallel polydimethylsiloxane (PDMS) rubber tubes to capture gaseous compounds. The two traps are separated by a quartz fibre filter that is held in position by a Teflon connector. The particles are captured in the quartz fibre filter. Both the filter and the PDMS traps are analysed after sampling using thermal desorption gas chromatography-mass spectrometry (TD-GC-MS), or preferably thermal desorption with two-dimensional gas chromatography-mass spectrometry (TD-GCXGC-MS). The laboratory analysis provides a list of PAHs, one of them being BaP.

Note: At the time of publishing this document, the University of Pretoria was the only supplier of the Denuder tubes. The contact person is Prof. Patricia Forbes: patricia.forbes@up.ac.za. No commercial supplier is currently available.

The sampling train consists of the following:

- Gravimetric sampling pump as described for the NIOSH 5040 methodology. The recommended flow rate is approximately 0.5 L/min;
  Note: Please confirm the flow rate for your application when the Denuder tubes are acquired
- Denuder tubes with quartz fibre filter; and
- Flexible tubing.

Only short sampling times (typically 10 to 30 minutes) can be accommodated by the methodology, as excessive sampling volumes reduce sampling efficiency. For this reason, the Denuder methodology is not recommended for full-shift sampling.

The methodology can be implemented in the following ways:

- **Personal exposure measurements**: It is not recommended that this methodology is used for personal exposure measurements.
• *Environmental or area monitoring*: The sampling train can be set up in a stationary position in a workplace and sampling can be conducted for short sampling times (typically 10 to 30 min).

• *Dilute exhaust measurements*: Take the measurement at a distance from the tailpipe (e.g. 1 m away) but not from the inside of the tailpipe as the sampling equipment will not withstand the high temperatures and the excessive concentrations. The methodology does not allow for the technician to insert the tube and step away from the raw exhaust.
References


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Annexure F: Additional outputs from SIM 150601

This Annexure contains additional outcomes from this project as conference presentations. The outputs in this section were made available to conference delegates in the form of a book of abstracts and are in the public domain. Please note that conference organisers do not allow acknowledgements in conference abstracts.

Application of a multi-channel polydimethylsiloxane denuder device for the determination of PAHs in diesel exhaust emissions

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Occupational exposure of underground miners to PAHs, arising from diesel emissions, is of great concern due to their toxicity [1]. The volatility range of these compounds and their partitioning between gaseous and particulate phases make them a challenge to sample and analyse, especially in unforgiving mining environments. A denuder consisting of a quartz fibre filter sandwiched between two multi-channel polydimethylsiloxane traps was first tested in the sampling of PAHs in diesel engine exhaust at a controlled engine test cell facility at a sampling flow rate of 500 mL/min for 10 min. The test engine was operated in five different modes: idle, high idle, 25, 50 and 100% torque. 10 priority PAHs were detected and quantified in the gas phase and 4 in the particulate phase by TD-GCxGC-ToFMS. PAHs were found predominantly in the gas phase with naphthalene having the highest concentrations during all modes of operation except idling. Total PAH concentrations ranged from 6.28–237.58 μg/m³ for the samples that were taken at the tailpipe of which 97% were found in the gas phase. The higher load modes showed elevated particulate concentrations which correlated to elevated soot emissions in the test cell. The denuders were then successfully used in a real-world coal mining application, where the total PAH concentrations ranged from 15.76–187.90 μg/m³ for idle engine mode and 50% torque mode, respectively, of which only 8% was in the particulate phase. The higher concentrations for the same engine mode in the coal mine as compared to the test cell could be attributed to factors such as the age and maintenance of the engine as well as the diesel fuel quality.

A computerized breath analyser device based on a micro-nano-chip of VO2 nanoparticles for personal pain-free determination of blood glucose levels in a type 1 diabetes mellitus patient and diesel engine emissions analysis

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The present technology proposes a competitive solution in diagnosis of diabetes mellitus through exhaled breath as well as analysing gases in the environment. In humans, it is well known that acetone in human breath can be a biomarker and indicator of fasting and/or lack of insulin in the blood. In the environment where there are exhausts from diesel engines, there are mixtures of air gases with noxious gases such as NO2, H2S, CO etc. In the present technology, a micro-nano-chip is packaged around the pertinent electronics in order to present a complete device for diagnosis and routine monitoring glucose levels. The new solution is non-invasive and hence alleviates pain as well as opportunistic infection which lead to currently more than 2 million amputations per year worldwide. From the tests conducted on one patient for many months, the present technology has been used to correlate its responses to human breath to the many parameters found in blood of such a patient. There is a positive correlation of between 94% to about 97% depending on whether the readings were taken in the afternoon or morning and whether it is pre-fasting or post-fasting period.

The technology trademarked here as MAL4NanoSnifferTM can be presented as an alternative solution, among a few competitors, to the diagnosis of glucose levels in diabetes patients. The technology can easily be extended to diagnosis of other diseases such as lung cancer and renal failure. We also show that the technology can be employed in monitoring the concentrations of noxious gases in diesel exhaust emissions. Various gases and potentially, ultrafine particulates are detected by the sensor. However, the individual compounds still require identification and quantification. These sensors still require development for application on diesel engine exhaust emissions and for this reason it is not in a format to be implemented yet.

Keywords: Breath Analysis, Nanotechnology, Diabetes, diesel engine exhaust
Multi-channel polydimethylsiloxane denuder devices for the determination of gas and particulate phase polycyclic aromatic hydrocarbons in underground mines

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Diesel exhaust emissions (DEE) contribute to ambient particulate and gaseous air pollutant levels, including those of polycyclic aromatic hydrocarbons (PAHs). Occupational exposure of underground miners to PAHs released from diesel powered engines is of great concern due to their carcinogenic and mutagenic properties. The volatility range of these compounds and their partitioning between gaseous and particulate phases make them a challenge to sample and analyse, especially in unforgiving mining environments. A denuder consisting of a quartz fibre filter sandwiched between two multi-channel polydimethylsiloxane traps was used to sample PAHs in trackless and conventional underground mining environments, in a platinum mine, at a sampling flow rate of 500 mL/min for 10 min. The samples were then thermally desorbed and subsequently analysed by two dimensional gas chromatography with mass spectrometric detection. Ambient and source samples in the trackless sections revealed that PAHs were predominantly found in the gas phase with 2-3 ringed PAHs, mostly naphthalene and its mono-methylated derivatives, being detected at the highest concentrations. Particle associated PAH concentrations were found in the µg/m\textsuperscript{3} range and included primarily 4-6 ringed PAHs with a predominance of fluoranthen and pyrene. The ventilation air inlet and outlet samples were used to assess ambient air quality underground with respect to PAHs and assisted in confirming that DEE were the main source of PAHs underground. Air samples taken at both an open air coal mine workshop and an underground platinum mine workshop were compared with respect to PAH profiles. Similarly, idle load haul dump (LHD) vehicle tailpipe emissions in both platinum and coal mines were compared to measurements at a controlled engine testing facility, where the higher concentrations of PAHs found in the mining samples could be attributed to factors such as diesel fuel quality and the age and maintenance of the engine. This work demonstrated that these small, portable, intrinsically safe denuder devices are suitable for assessing occupational exposure to gas and particulate phase PAHs in underground mining environments.
Annexure G: Presentations and publications

This annexure contains the presentations and publications of additional outcomes from this project, where due acknowledgement is given to the MSHC. Please note that it is the policy of the conference organisers not to distribute presentations. We request that MHSC members respect this arrangement and not make these presentations public without formal written consent from the organisers.

1. Poster Presentation by Genna-Leigh Schoonraad at the 42nd International Symposium on Capillary Chromatography and 15th GCxGC Symposium, May 13 – 18 2018 in the Congress Centre, Riva del Garda, Italy.

   Application of a multi-channel polydimethylsiloxane denuder device for the determination of PAHs in diesel exhaust emissions

   ![Poster Application of denuder - Schoonraad](double click to open)


   Multi-channel polydimethylsiloxane denuder devices for the determination of gas and particulate phase polycyclic aromatic hydrocarbons in underground mines

   ![Oral presentation - Multichannel.pdf](double click to open)

3. Journal publication: A computerized breath analyser device based on a micro-nano-chip of VO2 nanoparticles for personal pain-free determination of blood glucose levels in a type 1 diabetes mellitus patient and diesel engine emissions analysis. Please note that this article is in draft form and comments from the journal reviewer are due. This article has not yet been published.

   ![DRAFT A computerized breath 2](double click to open)