Establishing a baseline diesel particulate matter (DPM) exposure profile for an underground mechanized platinum mine.

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Author's Contribution

This study was planned and executed by a team of researchers. Each member's contribution played a pivotal role to the success and completion of this study. The contribution of each member is summarised in Table 1.

Table 1: The contribution of each team member.

Name	**Contribution**
Mrs. M.M.M. Liebenberg	• Planning and conducting of personal sampling underground. • Literature study research and statistical analysis. • Writing of article.
Mr. M.N. van Aarde	• Supervisor • Approval of protocol. • Assisted with planning of study. • Reviewing of dissertation. • Interpretation of the results.
Mr. J.J van Staden	• Assistant-supervisor • Planning and coordinating of research study. • Supplying of equipment required for sampling. • Interpretation of the results. • Reviewing of documentation

The following is a statement from the supervisors each individual's role in this study:

I declare that I have approved the article and that my role in the study as indicated above is a true representation of my actual contribution and that I hereby give my consent that it may be published as part of Marilize Liebenberg's M.Sc (Occupational Hygiene) dissertation.

Mr. M.N. van Aarde

Mr. J.J. van Staden

List of Abbreviations

%:	Percent
℃:	Degree celcius
ACGIH:	American Conference of Governmental Hygienists
AQI:	Air quality index
Ar:	Argon
BHP Billiton:	Broken Hill Proprietary billiton Company
CH_4:	Methane
CO:	Carbon monoxide
CO_2:	Carbon dioxide
CSIR:	Council for Scientific and Industrial Research
cSt:	Centistokes
DE:	Diesel exhaust
DEP:	Diesel exhaust particles
DOC:	Diesel oxidation catalyst
DPF:	Diesel particulate filter
DPM:	Diesel particulate matter
EC:	Elemental carbon
FBC:	Fuel-borne catalyst
H:	Hydrogen
HC:	Hydrocarbon
H_2SO_4:	Sulphuric acid
IARC:	International Agency for Research on Cancer
IgE:	Immunoglobulin-E
INP:	Intranasal pressure
kg/l:	Kilogram per litre
kg:	Kilogram
kW:	Kilowatt
LHD:	Load Haulage Dumper Operator
L/min:	Liters per minute.
Ltd:	Limited
m^3/s/kW:	Cubic meters per second per kilowatt
m^3/s:	Cubic meters per second
Max:	Maximum
MHSA:	Mine Health and Safety Act
Min:	Minimum
MSHA:	Mine Safety and Health Administration

NIOSH:	National Institute for Occupational Safety and Health
NO:	Nitrogen monoxide
NO_2:	Nitrogen dioxide
NO_x:	Nitrogen oxides
N_2:	Nitrogen
O_2:	Oxygen
OC:	Organic carbon
OEL:	Occupational exposure limit
OEM:	Original equipment manufacturer
PAH:	Polycyclic aromatic hydrocarbons
PM:	Particulate matter
PPE:	Personal protective equipment
ppm:	Particles per million
RPE:	Respiratory protective equipment
RPM:	Resolutions per minute
SANS:	South African National Standard
Sasol:	South African Synthetic Oil Limited
SO_2:	Sulphur dioxide
$SO_{3:}$	Sulphate
TC:	Total carbon
TWA:	Time weighted average
ULSD:	Ultra-low sulphur diesel
USA:	United States of America
USEPA:	United States Environmental Protection Agency
µm:	Micrometer
µg/m^3:	Micrograms per cubic meter of air

Abstract

Title: Establishing a baseline diesel particulate matter (DPM) exposure profile for an underground mechanized platinum mine.

Background: Workers are daily exposed to diesel exhaust (DE) and DPM due to the continuous increase of diesel-powered vehicles in the underground mining environment. The National Institute for Occupational Safety and Health (NIOSH) recommends that DE be regarded as a "potential occupational carcinogen". A great concern in the South African mining industry is that there is currently no existing occupational exposure limits (OEL) for DPM.

Aim: To quantify the exposure of workers to DPM (that consists out of total carbon (TC): which is a combination of elemental carbon (EC) and organic carbon (OC)) in the ambient air of underground working environments. Also to compare different occupations exposure levels to an international standard (the Mine Safety and Health Administration's (MSHA) OEL for TC) as South Africa has no proposed guideline or standard for occupational exposure to DPM and finally to determine whether or not occupations working at mines with different mining methods have different exposure levels to DPM.

Methodology: Workers personal exposure to DPM was monitored using the NIOSH 5040 method. A DPM sampler that consisted of a cyclone, a pre-packed SKC filter cassette (37 mm) with impactor, tubing, label clips and a sampling pump was used. The flow rate was calibrated at 2.0 litres per minute (L/min) for the sampling of sub-micrometer particles. The personal sampler device was attached to the employee's breathing zone for the duration of the work shift (normal eight-hour time-weighted average (TWA) standard). A high risk group (workers operating diesel-powered vehicles), a low risk group (workers working in the same mine, sharing the same supplied air, but not operating these vehicles) and a control group (workers working at a different mine with a different mining method) was monitored. The exposure levels were evaluated and compared with the specific OEL mentioned previously.

Results: For the purpose of this study, TC exposure results were evaluated and not EC or OC. All the occupations within their specific exposure group was exposed to TC. When the control group's exposures were compared with the high and low risk group exposures, a significant difference was recorded (p-value = 0.0001). However when the high and low risk exposures were compared with each other, no difference was recorded (p-value = 0.4405). When the results of the various groups were compared with the MSHA OEL all the occupations from the high and low risk group's results were above the OEL, but only one occupation from the control group exceeded the OEL.

Conclusion: It should be noted that all the occupations no matter the mining method / mine was exposed to TC. The high and low risk exposure groups was however much higher than the control group and a continues monitoring programme should be implemented for these exposure groups. Their results exceeded the OEL, where the control group had much lower exposure levels and only one occupation exceeded the OEL. Greater focus should be given to the mechanized mining occupations since diesel-powered vehicles are used to perform their core mining needs whereas at the conventional mine the use of these vehicles are limited.

Recommendation: Depending on the different occupations sampled various engineering controls can be considered. Some include diesel oxidation catalysts (DOC), diesel particulate filters (DPF) and diesel disposable exhaust filters (DEF) or also known as disposable diesel exhaust filters (DDEF) which is very effective in removing DPM from the exhaust of diesel-powered equipment. Education and training are also critical components to the success of a diesel emission management programme and the last resort to be considered is the appropriate personal protective equipment (PPE). South Africa should consider the implementation of national standards in order to monitor the progress and success of the diesel emission management programme implemented.

Keywords: Diesel particulate matter, diesel exhaust, exposure level, occupational exposure level, total carbon.

Opsomming

Agtergrond: Werkers word daagliks blootgestel aan dieseluitlaat (DE: diesel exhaust) en dieselstofdeeltjies (DPM: diesel particulate matter) as gevolg van die veeleisende en toenemende gebruik van dieselaangedrewe voertuie in die ondergrondse mynomgewing. Die Nasionale Instituut vir Beroepsveiligheid en Gesondheid (NIOSH) beveel aan dat dieseluitlaat (DE) as 'n potensiële beroepskarsinogeen beskou word. 'n Groot bekommernis in die Suid-Afrikaanse mynbou-industrie is dat daar tans geen beroepsblootstellinglimiete (OEL: occupational exposure limits) vir dieselstofdeeltjies (DPM) bestaan.

Doelstelling: Om die blootstelling van werkers aan dieselstofdeeltjies (bestaande uit totale koolstof: 'n kombinasie van elementale koolstof en organiese koolstof) in die omgewende lug van die ondergrondse werksomgewing (veral waar gemeganiseerde myntoerusting gebruik word) te kwantifiseer ten einde 'n blootstellingsprofiel vir hierdie werkers daar te stel.

Metode: Werkers se persoonlike blootstelling aan DPM is met gebruik van die NIOSH 5040-metode gemonitor. 'n DPM-monsternemer wat bestaan het uit 'n sikloon, 'n pre-verpakte SKC-filterkasette (37 mm) met impaktor, buise, etiketklampe en 'n monsternemingpomp is gebruik. Die vloeitempo is gekalibreer teen 2,0 liter per minuut (L/min) vir monsterneming van submikrometer deeltjies. Die persoonlike monsternemingtoestel is aan die werknemer se asemhalingsone gekoppel vir die duur van die werkskof (normale agt-uur tydsweging gemiddelde standaard (TWA: time-weighted average standard). 'n Hoë risiko (werkers wat dieselaangedrewe voertuie beheer), lae risiko (werkers wat in dieselfde myn werk, wat dieselfde lugtoevoer deel, maar nie naby die dieselaangedrewe toerusting werk nie) en 'n kontrolegroep (werkers wat in 'n ander myn met 'n ander mynmetode werk) is gemonitor. Die OEL van hierdie werknemers is met mekaar vergelyk, en ook met die blootstellinglimiete wat gestel is deur die Myn Veiligheid en Gesondheid Administrasie (MSHA) of OEL.

Resultate: Vergelyking van die kontrolegroep se blootstellings met die hoërisiko- en laerisikogroepe het 'n betekenisvolle verskil aangedui. Die hoërisiko- en laerisikoblootstellings is met mekaar vergelyk, maar geen verskil is aangeteken nie. Die resultate van die verskillende groepe is vergelyk met die MSHA OEL; slegs die hoërisiko- en laerisikogroepe se resultate was hoër as die OEL.

Gevolgtrekking: Die hoërisiko- en laerisikogroepe is die beroepe wat in ag geneem moet word, veral waar dit om die gesondheid van die werknemers gaan. Ongeag hierdie blootstellingswaardes behoort al die beroepe wat ondergronds werk deel te vorm van 'n

voortgesette moniteringsprogram om die blootstelling aan DPM as gevolg van die hoë blootstellingsresultate te evalueer, veral in die gemeganiseerde mynindustrie.

Aanbeveling: Afhangende van die verskillende beroepe wat gemonitor is, kan verskillende bedryfskontroles oorweeg word. Party daarvan sluit in dieseloksidasiekataliste (DOC: diesel oxydation catalysts), dieselstofdeeltjiefilters (DPF: diesel particulate filters) en wegdoenbare dieseluitlaatgasfilters (DDEF: diesel disposable exhaust filters), wat besonder effektief is in die verwydering van DPM uit die uitlaat van dieselaangedrewe toerusting. Opvoeding en opleiding is ook krities-belangrike komponente vir die sukses van 'n dieselemissiebeheerprogram. Laastens behoort die beskikbaarstelling van toepaslike persoonlike beskermingstoerusting oorweeg te word. Suid-Afrika behoort die implementering van nasionale standaarde te oorweeg om die vooruitgang en sukses van die dieselemissiebeheerprogram wat in werking gestel is, te monitor.

Sleutelwoorde: Dieselstofdeeltjies, dieseluitlaat, blootstellinglimiet, beroepsblootstellinglimiet, totale koolstof.

Preface

This mini-dissertation was written according to an article format. Chapter 1, 2 and 4 was written according to the Manual for Postgraduate Studies of the North-West University (Potchefstroom campus) and the references were conducted according to the Harvard style. Chapter 3 was written according to the guidelines of "The Occupational Health Southern Africa". The relevant references are provided according to the author's instructions as recommended by the specific journal (Vancouver style).

Chapter 1

General

Introduction

General Introduction

1.1 Introduction

Diesel-powered mining equipment has allowed the industry to achieve tremendous improvements in productivity over the past 30 to 50 years, leaving more and more workers exposed to exhaust emissions (Grenier et al. 2001; Stanton, Unsted & Belle 2007). The widespread use of diesel equipment has generated concern about occupational exposures to diesel engine exhaust, which has been classified as a probable human carcinogen. The National Institute for Occupational Safety and Health (NIOSH) considers diesel exhaust (DE) as a "potential occupational carcinogen" and also recommends that the workers exposure be reduced (Birch & Cary 1996). A great concern in South African mining is that there is no existing occupational exposure limits (OEL) for diesel particulate matter (DPM). However measurements has been undertaken to develop national standards and guidelines that will assist in the monitoring and the control of exposure to DPM (Van Niekerk et al. 2005). Table 1 illustrates the current limits used by various countries, institutions or agencies to monitor / evaluate the exposure of DPM and also to control the exposures.

Table 1: Substance specific limits that is set by the various countries, institutions or agencies

Country/Institution/Agency	Exposure/Guideline limit	Substance Measured
Canada	1.5 mg/m^3	RCD
Mine Safety and Health Adminstration (MSHA)	0.4 mg/m^3 – 0.16 mg/m^3	TC
Switzerland (road tunnels)	0.1 mg/m^3	TC
Germany (underground no-coal mining)	0.1 mg/m^3	EC
American Conference of Governmental Hygienists (ACGIH)	0.2 mg/m^3	EC
South Africa	No guideline	No guideline

RCD: Respirable Combustible Dust; TC: Total Carbon; EC: Elemental Carbon ; mg/m^3: miligram per cubic meter (Grenier et al. 2001 ; Van Niekerk 2005).

The exhaust fumes of diesel-powered vehicles are a complex mixture of noxious gases and DPM, which have particulate and gas phase pollutants (Wheatley & Sadhra 2004; Van Niekerk et al. 2005; Bagley et al. 2002). The gaseous phase consist largely of gases such as nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), sulphur dioxide (SO_2), various hydrocarbons (HCs), aldehydes and water vapour. Other gaseous exhaust components are low-relative-molecular-mass polycylic aromatic hydrocarbons (PAHs) (Nikasinovic, Momas & Just 2004).

DPM is defined as a sub-micron (smaller than 1 micrometer (µm)) physical aerosol component of DE, which is made up of solid carbon particles which attract and absorb organic chemicals such as PAH, condensed liquid HC and inorganic compounds such as sulphates compounds (Belle 2008). Over 80 percent (%) of diesel exhaust particles (DEP) are smaller than 0.1 µm in diameter, thus meaning that they remain airborne for long periods of time and when inhaled, are readily deposited into the lung. The United States Environmental Protection Agency (USEPA) regards DPM as a danger to the environment and claims it to be one of the top twenty air pollutants (Van Niekerk et al. 2005).

The particulate phase is composed of EC, absorbed or condensed HCs referred to as organic carbon (OC) sulphates and traces of metallic components (Nikasinovic, Momas & Just 2004; Bagley et al. 2002). The carbon compound found in diesel emissions, known as TC is a combination of OC and EC and usually makes up to 85% of DPM. EC is the pure carbon particles that account for a greater fraction of DPM mass and hence are the basic building block of DPM. OC is the group of complex compounds found in DPM including HC such as aldehydes and PAHs but excluding inorganic substances such as sulphates (Belle 2008).

The specific composition of the DE and the particulate fraction varies depending on the engine type, the maintenance, operator habits, the type of fuel, and the exhaust treatment device (Monforton 2006). Thus the critical issues that needs more emphasis are: DPM monitoring programme; a better understanding of after-treatment technologies which can improve engine selection and usage; the importance of diesel fuel properties; and improved education, training and awareness of diesel emissions (Van Dyk & Naidoo 2007).

1.2 Aim and Objective

To quantify the exposure of workers to DPM (specifically TC levels) in the ambient air of underground working environments. Also to compare different occupations exposure levels to the MSHA OEL for TC, as South Africa has no proposed guideline or standard for occupational exposure to DPM and finally to determine whether or not occupations working at mines with different mining methods play any role in the exposure levels.

1.3 Basic Hypothesis

The hypothesis of this project is that:

- Only the high and low risk exposure group are exposed to DPM.
- The high and low risk exposure levels exceed the MSHA OEL for TC.
- There is a significant difference between the exposure levels of the various groups.

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Chapter 2

Literature Study

Literature Study

Workers are daily exposed to the underground emissions of diesel driven vehicles, which have the potential to be an "occupational carcinogen". Thus a literature review was completed to investigate the potential exposure to diesel particulate matter in the underground mining environment.

2.1 Diesel exhaust (DE) and diesel particulate matter (DPM)

The use of diesel-powered vehicles has continuously increased in the underground mining environment, leaving more workers exposed to diesel emissions (Van Niekerk et al. 2005; Stanton, Unsted & Belle 2007). These diesel-powered vehicles are very flexible, mobile, they have a high power output and are widely used in mining operations (Stanton, Unsted & Belle 2007; Van Dyk & Naidoo 2007). Besides the advantages of these vehicles they result in incomplete combustion and the formation of various liquid and solids particles in sometimes very confined spaces underground (Belle 2008; Stanton, Unsted & Belle 2007; Sydbom et al. 2001). The exhaust emissions of diesel-powered vehicles are a complex mixture of compounds that contains a gaseous and particulate phase originated from unburned fuel, lubricant oil and combustion products (Monforton 2006; Ono-Ogasawara & Smith 2004).

2.1.1 Gaseous phase

The gaseous phase consist largely of gases such as nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), sulphur dioxide (SO_2), various hydrocarbons (HC), aldehydes and water vapour (Van Niekerk et al. 2005; Sydbom et al. 2001; Nikasinovic, Momas & Just 2004). This phase consist of many irritants and toxic chemicals (Van Dyk & Naidoo 2007).

Although the major portion of DE consist of Nitrogen (N_2), O_2, water and CO_2, it also contains potentially harmful substances such as particulate matter (PM), HC, which are the main source of the unpleasant odour associated with burning diesel fuel, NO, NO_2, CO and sulphur oxides (Van Dyk & Naidoo 2007).

2.1.2 Particulate phase

Diesel particulate matter is the portion of DE that is made up of solid carbon particles and has a surface that attack and absorb organic chemical such as polycyclic aromatic hydrocarbons (PAH), condensed liquid HC and inorganic compounds such as sulphate compounds (Grenier et al. 2001). Diesel particulate matter is defined as a sub-micron (smaller than 1 micrometer (µm)) physical aerosol component of DE (Belle 2008; Monforton 2006). Over 80 percent (%) of diesel exhaust particles (DEP) are smaller than 0.1 µm in diameter and thus remain airborne for long periods of time, meaning that they are respirable and are deposited into the lung (Van Niekerk et al. 2005; Monforton 2006). Diesel particulate matter has the potential to induce adverse health effects and is also regarded as a danger to the environment by the United States Environmental Protection Agency (USEPA), who claims it to be one of the top twenty air pollutants (Belle 2008; Van Niekerk et al. 2005).

The particulate phase is composed of elemental carbon (EC), organic carbon (OC) absorbed form fuel oils, sulphates from fuel sulphur and traces of metallic components (Nikasinovic, Momas & Just 2005). The carbon compound found in diesel emissions, known as total carbon (TC) is a combination of OC and EC and usually makes up to 85% of DPM (Belle 2008). Elemental carbon is the pure carbon particles that account for a greater fraction of DPM mass and hence are the basic building block of DPM (Grenier et al. 2001; Belle 2008). Organic carbon is the group of complex compounds found in DPM, including HC such as aldehydes and higher concentrations of PAHs but excludes inorganic substances such as sulphates and also EC (Belle 2008; Ono-Ogasawara & Smith 2004).

Because the National Institute for Occupational Safety and Health (NIOSH) regards DPM as a "potential occupational carcinogen" much attention has been focused on the particulate phase components due to the acute and chronic respiratory health effect (Bagley et al. 2002; Birch & Cary 1996; Wheatley & Sadhra 2004).

2.2 Health effects

The health effects caused by over-exposure to DE emissions are both acute and chronic, thus action is required to minimise the employee's exposure to these emissions. The health risks and their severity will depend on the amount of chemicals that individuals have been exposed to, as well as the duration of exposure (Van Dyk & Naidoo 2007). Individuals can react differently to the same type of exposure due to differences in metabolism, or the capacity to repair tissue damage (Van Dyk & Naidoo 2007; Scheepers et al. 2002).

In the past 3-5 years an overall consensus has been establish about the adverse health effects caused by the exposure to diesel particulate (Perkins 2005). Acute health effects of DE exposure include symptoms such as eye, throat and bronchial irritation, fatigue, light-headaches, nausea, lung function changes and coughing (Van Niekerk et al. 2005). Chronic exposure to diesel emissions can have more severe effects on human health and is likely to occure when a person is repeatedly exposed to diesel fuel over a prolonged period. There is evidence that prolonged exposure may increase the risk of lung cancer due to the very fine particles associated with DE (Van Dyk & Naidoo 2007). Diesel particulate matter has also been associated with a variety of adverse health outcomes involving potential immune mechanisms which includes acute pulmonary inflammation, altered allergic sensitisation, and exacerbation of asthma and respiratory infections (Siegel et al. 2004).

2.2.1 Acute health effects

Respirable particles generally enter the human airways via nasal passages. The nose plays an important role in the defense mechanism of the respiratory apparatus, and are both the first target of inhaled toxicants and the first shield protecting the more sensitive lower airways (Nikasinovic, Momas & Just 2004).

2.2.1.1 Nasal effects

As mentioned above the first target organ affected by the exposure to DE is the nose. It plays a pivotal role in the defense mechanisms of the respiratory asparatus, and nasal diseases are often associated with lung diseases which suggest that there might be a link between the upper and lower airways. Many authors report this association, especially respiratory diseases such as nasal allergy and asthma (Van Niekerk et al. 2005).

2.2.1.2 Nasal inflammatory response

The nasal inflammatory response is a non-specific biochemical and cellular response of which the purpose is to protect the epithelium and underlying tissue from the irritant effects of DPM. It is observed as an inflammatory cell influx in the mucosa, and an alteration in the cytokine patterns of the epithelium lining fluid measured in the nasal fluid (Van Niekerk et al. 2005). In-vitro studies conducted by Nikasinovic, Momas & Just (2004) as well as Deveouassouz et al. (2002) demonstrate that DPM extract induces cytokine production from allergic and non-allergic subjects.

2.2.1.3 Nasal hyperresponsiveness

The effect of DEP on nasal airway resistance produces a dose-dependent increase in intranasal pressure (INP) and in vascular permeability assessed on the skin. Nikasinovic, Momas & Just (2004) also reported that DEP increases sneezing frequency. However short-term exposure to DE also induces nasal hyperresponsiveness to histamine as demonstrated by change in sneezing frequency and nasal secretion.

2.2.1.4 Humoral response in the nasal epithelium

The humoral (antibody-mediated) response is a specific way of protecting the nasal epithelium from subsequent injury. Nasal DPM-induced inflammatory reaction leads to enhanced local total Immunoglobulin-E (IgE) production. Enchanced IgE production is an important observation related to allergic responses, since IgE plays a central role in eliciting the release of biochemical mediators of immunological inflammation, which is important in allergic diseases. Allergic hypersensitivity results from the inappropriate production of IgE in response to allergens (Van Niekerk et al. 2005). Exposure to DEP alone leads to increased production of total IgE. IgE augmentation corresponds to an increase only in the number of IgE-secreting cells, suggesting that DEP acts selectively on pre-existing IgE committed cells (Nikasinovic, Momas & Just 2004).

2.2.1.5 Adjuvant-like effects in the nasal epithelium

IgE plays a pivotal role in the pathophysiology of allergic diseases in humans (Nikasinovic, Momas & Just 2004). Other investigations have focused on the ability of DPM to enhance epithelium allergic response to allergen challenge in previously sensitised individuals. Data suggest that exposure to DE may aggravate nasal allergic reactions by enhancing nasal hyperresponsiveness. Several authors have published results suggesting a significant effect of both fine particles and gas components from DE in the adjuvant-like effect (Van Niekerk et al. 2005).

2.2.2 Chronic health effects

Chronic exposures are associated with cough, sputum production and lung function decrements (Sydbom et al. 2001). Chronic exposure have more severe effects on human health and is likely to occure when a person is repeatedly exposed to diesel fuel over a prolonged period. There is evidence that prolonged exposure to diesel emissions may increase the risk of lung cancer due to the very fine particles associated with diesel emissions (Van Dyk & Naidoo 2007).

2.3 Diesel fuel

During the development of cleaner diesel engine technologies, attention was given to the requirements for diesel fuel quality. Research has shown that fuel properties such as sulphur content, density, cetane number, O_2 and aromatic content can all influence particulate and gaseous emissions.

The majority of diesel fuel used in the mining industry is a mixture of HC obtained from the distillation of crude oil, and this mixture will determine the quality of fuel. The critical properties of the fuel will depend on the type of crude oil and the distillation process used for the crude oil that will refine the diesel fuel down to meet the various diesel fuel specifications and standards (Perkins 2005; Van Dyk & Naidoo 2007).

2.3.1 Main components in fuel standards

2.3.1.1 Cetane number

The cetane number of diesel fuel defines the ignitability of the fuel (its warm-up characteristics). A higher cetane number is desirable and indicates a fuel that will ignite easier inside the combustion chamber. Although a cetane number of 40 is normally accepted, modern engines will operate better at a cetane number of above 50. A higher cetane number will reduce particulate emissions and combustion noise (Perkins 2005; Van Dyk & Naidoo 2007).

For low cetane number fuels (with too long an ignition delay), most of the fuel is injected before ignition occurs, which results in extremely rapid burning rates once combustion starts with high rates of pressure rise and high peak pressures. Ignition may occur sufficiently late in the expansion process for the burning process to be quenched, resulting in incomplete combustion, excessive NO_x formation and **PM** emissions (Van Niekerk et al 2005).

2.3.1.2 Viscosity

The viscosity of fuel is an indication of the fluid's resistance to flow. A higher viscosity will indicate a higher resistance to flow. Viscosity affects injector lubrication and atomisation, which means that low-viscosity fuel, may not provide sufficient lubrication for the precision fit of fuel-injection pumps or injector plungers, resulting in leakage or increased wear. High-viscosity fuels, on the other hand, can form large droplets on injection, which can end up in the combustion chamber. The fuel inside the combustion chamber can then cause excessive exhaust smoke and emissions. Both extremes, viscosities that are too high and to low, should be avoided (Van Dyk & Naidoo 2007).

2.3.1.3 Cold behaviour

The cold behaviour of fuel relates to the geographic areas where cold weather affects the fuel. It also relates to the clouding point and the pouring point of fuel. Evidence that the clouding and pouring points of fuel have been reached is when the wax in the fuel becomes visible and physically changes state. Crystals of paraffin wax appear which can cause the filters to plug. Fuel additives can be used to guarantee resistance to these properties (Van Dyk & Naidoo 2007).

2.3.1.4 Flash point

The flash point of fuel is the minimum temperature required for ignition of the fuel. This is critical for mining operations for safe handling and to contain the risk of flammability. The minimum (min) flash point temperature is therefore required for safety purposes. The flash point of diesel fuel does not affect engine performance or combustion, and therefore does not have an influence on emission levels. A min flash point of 52 degree Celsius (℃) is generally accepted (Van Dyk & Naidoo 2007).

2.3.1.5 Lubricity

The lubricity of the fuel is critical to the wear of components in the fuel-injection system and is basically the ability of the fluid to minimise friction between components. This is especially a concern when lower-sulphur fuels are used. Fuel suppliers often include lubricity additive packages when supplying low-sulphur fuels. The recommended lubricity value for fuel is 3.1 kilogram (kg) (Van Dyk & Naidoo 2007).

2.3.1.6 Sulphur content

Sulphur in diesel fuel occurs naturally and relates primarily to the quality of the crude oil used in the refining process and the only real benefit of sulphur in fuel is that it provides lubricity (Van Dyk & Naidoo 2007; Perkins 2005). The main negative effect of fuel with high sulphur content is the direct effect that the sulphur content has on the DPM emissions (Van Dyk & Naidoo 2007). SO_2 is the gaseous component and the sulphates is the solid particulate component to diesel emissions that are derived entirely from fuel sulphur (Perkins 2005). Sulphates (as SO_3) are a fraction in total DPM which will in turn create sulphuric acid (H_2SO_4) in combination with moisture. SO_3 particles act as nuclei and are a precursor for the growth of DPM hence less sulphur in the fuel results in lower diesel particulate emissions. When exhaust after-treatment technologies including oxidation catalysts and catalysed particulate filter are used the conversion of SO_2 to SO_3 is greatly increased and thus DPM emissions are increased as a result (Van Dyk & Naidoo 2007).

2.3.2 Diesel fuel supply

Fuel cleanliness is one of the most important factors in correct injection equipment operations. In summary, the following factors should be considered when reviewing the quality of a diesel fuel supply:

a. A higher cetane number will improve ignition and reduce particulate emissions and noise.
b. Viscosity affects the fuel injection system performance and metering – a narrower min/maximum (max) span rating is best.
c. Cold behaviour characteristics apply to winter fuels in colder geographic regions with lower 90% distillation point.
d. Flash point does not affect engine performance and emissions but is critical for safe handling and flammability concerns.
e. Lubricity is largely related to reduction in fuel sulphur levels and has been compensated by additives in the refining process and modifications, and engineering in fuel injection systems.
f. Sulphur in diesel fuel produces SO_2 gaseous and SO_3 sulphate particulate emissions. The move to ultra low sulphur fuel smaller than 0.0015% or 15 parts per million (ppm) will minimise these sulphur emissions and also reduce overall diesel particulate emissions. More significant is the ability to use catalysed diesel particulate filter technologies with ultra-low sulphur diesel (ULSD) (Perkins 2005).

2.3.3 Diesel fuel specifications

In South Africa there are currently no requirements specified for diesel fuel used in underground mining operations. However, the South African National Standard (SANS) for automotive diesel fuel used in general is specified in SANS 342:2005; Automotive Diesel Fuel. Some of the diesel fuel specifications as per SANS 342:2005 are given in Tabel 1 (SANS 342:2005; Edition 3.3)

Tabel 1: South Africa diesel fuel specifications

Fuel Property	Standard grade fuel	Low sulphur diesel
Flash Point (°C)	55 (min)	55 (min)
Sulphur content (ppm)	3000 (max)	500 (max)
Cetane number	45 (min)	45 (min)
Viscosity (cSt)	2.2 – 5.3	2.2 – 5.3
Density (kg/l)	0.80 (min)	0.80 (min)

*cSt: centistokes; kg/l: kilogram per litre.

The South African authorities have proposed a 50 ppm ULSD voluntary limit in 2006, which will be mandatory by 2010 (Van Dyk & Naidoo 2007).

2.3.4 Storage and handling

Fuel contaminants can be divided in three general categories:

a. Those originating from foreign materials entering the fuel as dust, dirt, rust or water.
b. Those produced in the fuel through the biological activity of bacteria, yeast and fungi.
c. Those produced by fuel degradation such as sediments.

Contamination by dust, dirt and rust can be controlled by enforcing standards for fuel storage, transport and handling. It is important that fuel lines and fuel tanks be cleaned regular to minimise contamination.

Water can cause corrosion of storage tanks and other fuel components, which can contribute to fuel degradation and microbial growth. When water cannot be removed from the fuel, the fuel should be treated with a biocide. An additional danger when diesel becomes contaminated with water is that it is flammable. Water often enters fuel tanks by means of condensation of moisture and should be removed regular. The supplier of fuel products will be able to assist with the removal of water from diesel.

When diesel fuel is subjected to high temperatures for prolonged periods, it can undergo chemical changes that can result in the fuel changing colour from light yellow to dark brown or black. This process is called degradation.

To maintain integrity of low-sulphur fuels, it is important that they be stored and handled in the appropriate manner. The contamination of fuel by water and dirt may influence the diesel engine's performance. Contamination should be prevented by keeping fuel-tank caps, dispensing nozzles and hoses clean. In case studies it is often found that fuel tanks do not have gauges and operators then use dirty rods to measure fuel levels, which can cause contamination of the fuel. It is also especially important not to store low-sulphur fuels in old, dirty containers that were once used for other products or even for diesel of different grade (Van Dyk & Naidoo 2007; Perkins 2005).

2.3.5. Typical problems encountered when changing from a higher- to lower emission fuel

Historically when sites have changed from high sulphur, high aromatic fuels to low emissions fuels, a number of issues have arisen. Typically these include leaking fuel pump seals and loss of power as a result of the lower aromatic content of the low-emission fuel, which results in the swelling of the seals being reduced when there is a sudden change in aromatics. This problem is very common with older engines and can be prevented by introducing the lower-emissions fuel in stages by mixing the low-emission fuel with new fuel percentage-wise until 100% low-emission fuel is in use (Van Dyk & Naidoo 2007, Perkins 2005).

The loss in power relates to the lower density of some low emission fuels. Recalibration of fuel pumps may be necessary to overcome this problem. Care should be exercised when sending machines off site for maintenance to ensure only the fuel used on site is also used by the repair company. In some cases it may be necessary to send fuel with the engine to the repair company (Perkins 2005).

2.3.6 Fuel additives, synthetics and emulsions

Fuel additives or fuel-borne catalysts (FBC's) are products used for lowering the regeneration temperatures in diesel particulate filters (DPF) systems. Regeneration is the process whereby a sufficient temperature is reached inside a DPF to ignite the build-up or combust the soot on the filter to prevent the soot from plugging the filter. Fuel additives commonly used are metals and materials such as platinum, cerium, iron, strontium and copper. Additive blended fuels should only be used together with DPF systems so that the additives can be captured by the filters. If vehicles are using fuels with additives, it should be ensured that their DPF systems are working properly and that no exhaust leaks are present which would allow the additives to escape into the atmosphere (Van Dyk & Naidoo 2007).

Synthetic diesel fuel is produced by the gas-to-liquid conversion of CO and hydrogen (H) to HC. The process is called the Fischer-Tropsch process and is normally followed when a limited supply of crude oil is available for the production of petrodiesel.

Properties of Fischer-Tropsch synthetic fuel are:

a. Higher cetane number (up to 70).
b. Ultra low sulphur content (smaller than 10 ppm).
c. Low aromatic content (smaller than 3%).

The leading company in the world for the commercialization of synthetic fuels is South African Synthetic Oil Limited (SASOL), based in Secunda, South Africa. Synthetic fuels also have the potential to significantly reduce exhaust emissions because of their higher cetane number, ultra low-sulphur content and low aromatic content.

Fuel-water emulsions are produced by adding water to the diesel fuel during combustion in order to reduce the combustion temperature which, as a result also reduce the NO_x emissions. Particulate emissions are also reduced by improved atomisation and spray pattern and more complete combustion. CO and HC emissions are increased. The emulsion should be blended in a separate unit that will allow the water droplets and the fuel to mix first before it is used. The water droplets will be surrounded by the fuel so that no water will actually come into contact with the engine surface. A 30% reduction in NO_x and a 50% reduction in particulate emissions have been reported. The major disadvantages experienced with fuel-water emulsions are a reported 10-15% rated power loss and the indication by some users of fuel-injection failures with some of the older types engines. It is also noted that when operating in cold geographic climates, these emulsions can exhibit cold behaviour properties (Van Dyk & Naidoo 2007; Perkins 2005).

2.4 Biodiesel / Biofuels

The use of plant oils as fuels in the compression ignition engine is as old as the engine itself. Although vegetable oil alone proved too viscous for continuous use in the diesel engine, plant oil-based fuels were developed during the early part of the twentieth century. Biodiesel today describes an alkyl ester, mainly methyl esters of fatty acids of the oils that can be used in an unmodified diesel engine. Although animal oils can be used to produce biodiesel, plant oils are more abundant (Swanson, Madden & Ghio 2007; Van Dyk & Naidoo 2007).

Relative to petroleum diesel emissions, biodiesel emissions have been shown to contain less PM, CO and PAH. Furthermore, sulfur-containing compounds appear to be undetectable. However, the combustion of biodiesel in a diesel engine typically does increase the release in

NO_x, which, in addition to inducing potential health effects, have been identified as an ozone precursor (Swanson, Madden & Ghio 2007).

Biodiesel can be mixed with petroleum diesel to create a blend, but it can also be used neat without any blending being done.

2.4.1 The advantages of biodiesels

a. Little or no sulphur content.
b. Little or no toxicity.
c. A higher cetane number than diesel, which will improve ignition.
d. No aromatics and PAH's.
e. A higher flash point, which is critical for safe handling and flammability.
f. Better lubricity.
g. Reduced PM, CO and HC emissions (Perkins 2005).

2.4.2 The disadvantages of biodiesel

a. Increased NO_x emissions as a result of the higher O_2 content of biodiesel.
b. A lower heating value than petrodiesel.
c. High cost.
d. Potential to cause degradation of rubber seals and gaskets in certain fuel-injection systems.
e. Emissions have a different odour from petroleum fuels which results in complaints (Perkins 2005).

Although currently accounting for a small fraction of diesel use, biodiesel is a fuel alternative that has shown potential for becoming a commercially accepted part of this nation's energy infrastructure (Swanson, Madden & Ghio 2007).

2.5 Ventilation requirements

Ventilation is one of the main requirements for providing acceptable environmental conditions in underground operations. Its main purposes are to supply air for human respiration, to dilute and remove contaminants resulting from the mine production processes i.e. dust, products of combustion, etc., and to provide a suitable working climate with respect to heat.

The ventilation requirements of the diesel fleet often dictate the volume of airflow employed in underground mines, however the actual volume required depends upon the basis with which dilution requirements were derived (Van Dyk & Naidoo 2007; Perkins 2005).

The dilution of seam gases such as methane (CH_4) or the control of radioactive gases sometimes overrides the diesel-based volume requirements, but in the case of mechanized sections the removal or dilution of diesel contaminants can typically be the demanding air volume requirements. In the past, ventilation was the most obvious method for controlling diesel emission exposure in the underground environment. Today, however, there is a better understanding of diesel emission control and it is realised that a multi-faceted approach to controlling diesel exposure underground is needed. Dilution and removal of diesel contaminants is a major factor in ventilation system design and operation. The actual air volume flow required in the underground environment depends on the base dilution requirements determined.

Canada provides an example of the three basic types of regulation that specify the ventilation requirements for diesel-powered equipment:

a. A 0.063 cubic meters per second (m^3/s) ventilation requirements per kilowatt (kW) of rated engine power.
b. A specified dilution volume based on the quality of the engine exhaust as determined by the certification process. The method recognizes cleaner engines and fuels with a lower ventilation requirement.
c. A 100%, 75%, 50% rule for the prescribe ventilation flow requirement for the first, second and third pieces of diesel equipment in an area (this still applies in one Canadian jurisdiction).

During the certification process, the prescribed ventilation flow rates for an engine can vary depending on the testing body. The Canadian jurisdiction determine a dilution volume according to the gases and particulates generated by the engine, by using an air quality index (AQI), whereas the Mine Safety and Health Administration (MSHA) gives independent ventilation requirement based on both the gas emissions and the particulate dilution requirements. In the United States of America (USA), however, greater emphasis is put on monitoring and compliance with occupational exposure limits (OEL). In Australia ventilation requirements for diesel equipment underground are based on the ventilation flow rate per kW of engine power. These regulations state that the air volume should not be less than 0.06 m^3/s per kW ($m^3/s/kW$) of engine power or 3.5 m^3/s, whichever is the greatest (Van Dyk & Naidoo 2007; Perkins 2005).

In South Africa there are currently no legal ventilation requirements for diesel equipment in underground mining operations. However, the standard historically adopted by the mines was 0.06 – 0.065 $m^3/s/kW$ of engine power at the point of operation. This was found to be adequate in terms of diluting CO and nitrogen monoxide (NO) concentrations to meet the South African legal concentration limits for CO and NO, as stipulated in the Mine Health and Safety Act (MHSA) of 1996. For planning purposes, however, it was found that these ventilation requirements would probably have to be increases to at least 0.08 m^3/s at the point of operation. It should however, be noted that OEL's for CO and NO were reduced during October 2006. The table on "Occupational Exposures Limits for Airborne Pollutants" under Regulation 22.9(2) (a) was substituted by revised OEL schedule. In this revised schedule the OEL for CO has been reduced from 50 ppm to 30 ppm and the OEL for NO from 100 ppm to 20. It may therefore be necessary to reconsider the adopted ventilation standard of 0.06 – 0.065 $m^3/s/kW$ of engine power to take into account the changes in OEL's for DE emission gases.

Although there is a lot of variation in ventilation requirements between countries, local regulations laying down compliance to meet OEL for DE emissions will override any of the general regulations or guidelines mentioned (Van Dyk & Naidoo 2007; Perkins 2005).

It should also be kept in mind that some of the gases commonly associated with diesel emissions can also be generated from other processes in the underground environment. These processes will have to be taken into account when determining the diesel-based ventilation requirements. Examples of some of these processes are:

1. CO_2 emission can be a result of oxidation of organic material, rotting timber, heating or combustion, etc.
2. NO_x can result from either diesel engines or blasting.
3. SO_2 emissions are mainly the result of diesel engines, oxidation and blasting of sulphide-containing ores and sulphide dust.

Ventilation will continue to play an important part in controlling diesel emissions underground, and should be considered together with engineering control measures as it would be unrealistic to attempt to control emissions purely by means of ventilation (Van Dyk & Naidoo 2007; Perkins 2005).

2.6 Vehicle movement and ventilation control (automation)

The ventilation supplied to a specific section will determine the number of vehicles that can safely operate in that location at the same time in order to limit exposure to diesel emissions. This applies especially if the vehicles operate on the intake-air side of the ventilation system. Where ventilation resources are limited for all the potential activity, a "tag-in" and "tag-out" boards are used to control access to these sections. Since the introduction of tag boards more planning is incorporated into vehicle movements resulting in lower emissions.

Due to the potentially significant operating cost of a ventilation system, it should be borne in mind that it is also possible to “ventilate-on-demand” by simply activating ventilation controls (fans for example) to a specific area. In this way ventilation is only activated when it is required. In such systems, local ventilation could be initiated by a vehicle operator on entering a particular section (Van Dyk & Naidoo 2007; Perkins 2005).

2.6.1 Summary

Ventilation has been and will continue to be an important part of mine’s diesel emissions control strategy. Historically it has been the primary method through simple dilution; today combined engineering solutions are required as it would be unrealistic to control emissions purely with ventilation. Hence the movement towards cleaner engines and fuels exhaust conditioning and better maintenance.

With the introduction of ever-clean diesel systems, or alternate power engines, with potentially low ventilation dilution requirements, it must be remembered that ventilation serves numerous other functions that can become more demanding that any diesel design based criteria.

2.7 Diesel engine basics

The idea of the diesel engine was develop by Rudolf Diesel who obtained a German patent for it in 1892. The use of diesel engine locomotives in South African mines can be traced back to Van Dyk Consolidated Mines Limited (Ltd) on the Witwatersrand gold mines in 1928 as a replacement for battery locomotives. The advantages and disadvantages were recognised in those days, and surprisingly, there are no significant additions to this list, but only refinements. The recognised advantages were, no installation cost, high mobility, greater power. The disadvantages were, heat input into the air, noxious gases exhausted into the air, danger of explosions (in coal mines) or fires (Belle n.d.).

The diesel engine is today still the subject of intensive development and is definitely one of the most efficient liquid-fuel-burning prime movers yet achieved.

2.8 Diesel engine maintenance issues

Maintaining diesel powered mine mobile equipment is not simply the act of repairing breakdowns and regular service routines as is done in much of the mining industry. Maintaining mobile equipment in a mine should include a combination of preventive predictive, planned and reactive activities. This rule of good maintenance holds particularly true for diesel engines (Perkins 2005).

Diesel engines maintenance is an important component in reducing workers' exposure to diesel emissions. Poor maintenance practices and deviation from the specific requirements for the maintenance of diesel equipment negatively affect the effectiveness of all other control technologies that have been implemented to improve emissions.

The maintenance of diesel-powered mining equipment must always follow a systems-based process and should incorporate a combination of preventive, predictive, planned and reactive/proactive activities.

Figure 1 summarises the meaning of these subsidiary maintenance terms.

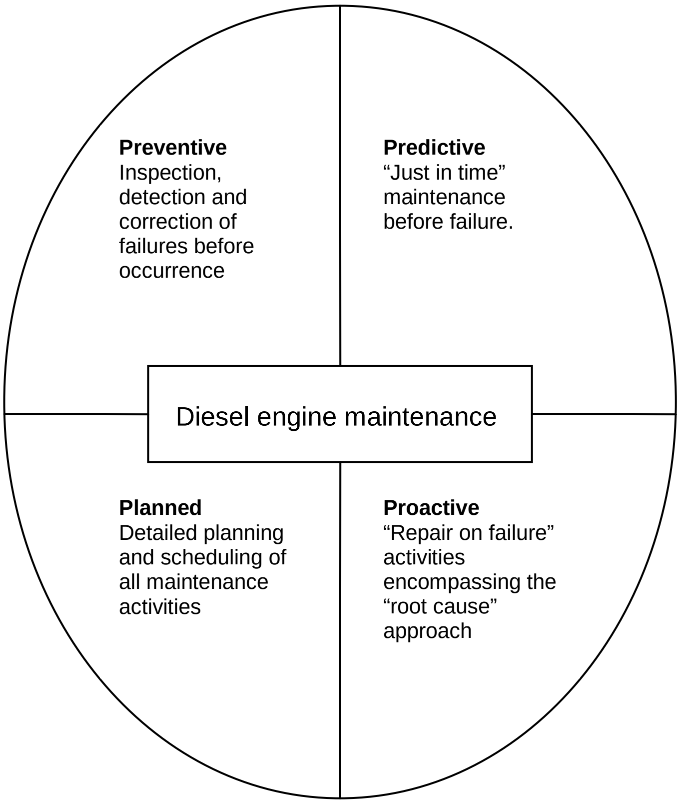

Figure 1: Collaborative activities for diesel engine maintenance

From previous studies it has been determined that a good diesel emissions management plan is centered on a good engine maintenance plan. The Mine Safety and Health Administration (1995) held a series of workshops to obtain input from the mining community on methodologies to reduce mine worker exposure to DPM from diesel engines. Some of the comments from key people in the mining industry that highlighted the importance of having a good maintenance plan were the following:

"To control DPM, we've got a good strong preventive maintenance program. We bring equipment in on a regular basis on 50, 250 and 1000-hour intervals and do the recommended filter checks and changes as recommended by the manufacturers".

"I just want to stress the importance of a good maintenance programme. We have a very good maintenance programme in that it's preventive maintenance, as well as involving fixing problems that arise on the job".

"A well-conceived maintenance programme strives to maintain optimum engine performance and thereby control DE emissions. The maintenance programme consists of regular scheduled replacements of fluid and filters, operating performance evaluations and additional weekly permissibility inspections, and a training programme to educate maintenance personnel in the engine operating recommendations and requirements". (Van Dyk & Naidoo 2007).

2.9 Solutions / Control measurements

2.9.1 Allied emission controls

Allied emission controls are engineered supplementary systems that control DE after it leaves the engine's exhaust, and can include systems such as in-line exhaust emission control systems, air-conditioning cabins and extraction ventilation systems in underground maintenance workshops.

In-line exhaust emission controls are basically after-treatment devices used to control DE. Examples of after-treatment devices include:

2.9.1.1 Diesel oxidation catalysts (DOC)

Diesel oxidation catalysts is also known as and can be correctly referred to as catalytic converters although the former is the proper reference. Diesel oxidation catalysts normally of a stainless steel canister, that typically contains a honeycomb-like structure called a "catalyst support". The precious metals used are most often platinum or palladium which is exposed to the flow of exhaust gas.

Diesel oxidation catalysts performs two primary functions in terms of emissions reduction. Diesel oxidation catalysts are known to be efficient at reducing CO and HC emissions by converting them into CO_2 and water . The catalyst oxidizes the CO, the gaseous HC and the liquid HC absorbed on the carbon particles. By reducing HC, they also reduce aldehydes, aromatics and PAHs, as well as the foul odour and burning of the eyes sensed by humans. The soluble organic fraction of total DPM is also converted in the same reaction that occurs with HC. For the effective conversion of CO and HC, the exhaust temperature needs to reach at least

250℃ and it is therefore important to have a good knowledge of the cycle duties of the vehicles involved.

2.9.1.2 Scrubber tanks (water-based conditioning systems)

Water scrubbers were one of the first emissions control technologies employed on diesel engines. The system is basically a tank filled of water through which the DE is routed before they are emitted into the atmosphere. Water scrubbers are used today mainly for safety purposes and are not considered as an emission control system.

As a safety control they perform three functions:

1. Cool exhaust gases and related surfaces to safe temperatures.
2. It prevents sparks.
3. It prevents flames.

These functions are critical in gassy mines. In some cases water scrubbers are also used to cool down exhaust gases when used in conjunction with DPF's to prevent the filter from becoming a fire hazard. When scrubber tanks are used, maintenance is very important. Water levels have to be maintained at all times. It should also be noted that in some cases condensation can cause ambient humidity and heat effects to increase (Van Dyk & Naidoo 2007; Perkins 2005; Van Niekerk et al 2005).

2.9.1.3 Exhaust fume diluters

Fume diluters are primarily used to dilute raw exhaust with ambient air by directing them away from the operator when they exit from the tailpipe. Secondarily it is used to lower exhaust temperatures. The construction is a circular manifold with an annular gap around the circumference. As the exhaust gas passes through the annular gap and across an aerofoil surface a low pressure is created at the throat of the circular manifold and fresh air is drawn in to it.

It is important to note that diesel emission testing should be done upstream of the diluter in order to obtain a true measurement of the exhaust gas emissions (Van Dyk & Naidoo 2007; Perkins 2005).

2.9.1.4 Redirection of exhaust

In any diesel emissions control strategy considerations, attention should be given to the direction of the exhaust tailpipe. The circumstances will determine the best way of positioning the tailpipe. Although there is no absolute right or wrong way when positioning the tailpipe, the following general considerations can be kept in mind:

1. Direct the exhaust as far away from the operator as possible.
2. For side-operated vehicles, direct the exhaust to the opposite side from where the operator sits.
3. Direct the exhaust to minimise the agitation of dirty road surfaces and walls.
4. Ensure that the exhaust tailpipe is not restricting the exhaust flow, to prevent elevation of the exhaust back-pressure (Van Dyk & Naidoo 2007; Perkins 2005).

2.9.1.5 Myths surrounding the idling of vehicles

Idling means that the engine is in operating mode but is not engaged in a gear, or when the accelerator is released and there is no load on the engine. Apart from the increase in diesel emissions during idling, engine operating and maintenance costs will also increase and idling will shorten the life of the engine.

In general, there are a few myths surrounding the idling of diesel engines:

1. Operators often believe that a diesel engine needs to be warmed up for long periods, but today's modern engines usually require a warm-up period of less than 5 minutes.
2. It is also believed that idling saves fuel, but it is said that if an engine idles for longer than 10 seconds, then it uses more fuel than restarting the engine would do.
3. Operators often believe that idling causes less wear and tear on the engine. Idling for extended periods, however, causes wear and tear on the internal parts of the engine than running the engine (Van Dyk & Naidoo 2007; Perkins 2005).

2.9.1.6 Air-conditioning cabins

Enclosed operator cabins are successfully used in underground mining operations to control operator exposure to DE. A research study indicated that an adequately designed and maintained cabin can reduce personnel exposure to DPM by as much as 80%. Cabins should be air-conditioned and filtered air should provide for a positive pressure inside the cabin to prevent contaminants from entering.

When considering the use of enclosed cabins, maintenance will be important to ensure a contaminant-free environment inside the cabin. Maintenance will typically include schedules to ensure leak-free doors and windows, filter maintenance, open windows, air-conditioning breakdowns, pressure loss inside cabin etc. However, maintaining a good environment for the operator inside the cabin does not mean that the employee's who share the same working environment has the same luxury. It is important that all control measures be considered to benefit the whole workforce and not a selected portion thereof. Operating best practices should be enforced in order to provide acceptable environment conditions for all. For example, operators should not be allowed to idle engines for extended periods just to keep the air-conditioning running. Informing the operator about the effects of idling on fuel consumption, exhaust emissions; associated health effects, etc. will be an important part of their education. A proper education and training programme will play an important role in implementing best practices for the control of diesel emissions (Van Dyk & Naidoo 2007).

2.9.1.7 Workshop extraction systems

Diesel engines can spend considerable amounts of time being operated in workshops and garage areas. The two main modes of operation while in a workshop are at idle while setting up for repairs, running diagnostic routines or assembly and disassembly. The main mode of operation of a diesel engine will be the idling mode, which is the worst mode in which to be in terms of emissions and is the highest contributors to HC emissions. The other mode of operation in workshops is during emissions testing and engine diagnostics in which case extended periods at full throttle stall condition are common. This mode also produces high emissions.

Regardless the maintenance and repair workshops located underground or on surface, extraction ventilation inside them is critical and should be enforced. Workshops and garages often have insufficient ventilation flows and velocities to support extended operation of diesel engines and their emissions.

The most common are suction fan systems with networked flexible exhaust pick-up horses, which can be modified for use in the underground workshop environment where diesel equipment is worked on. These are very common to most welding shop setups and can also be used for extracting diesel fumes. For use with underground mining equipment the suction boot at the end of the flexible pick-up needs to be modified so that it can fit over top of the various types of tailpipes and exhaust deflectors. To work effectively for extracting DE this type of system must:

1. Ensure that the system has sufficient fan volume to accommodate the number of engines and extraction pick-ups in the shop.
2. Make sure that there are proper adapters for the suction boots to fit all types of tailpipe and exhaust deflectors in the mobile fleet.
3. Have a sufficient network of ventilation ducting and flexible pick-ups to cover the entire workshop so that no diesel engine is run without an extraction pick-up.
4. Ensure that the exhaust end of the extraction system is routed directly into the exhaust ventilation raise for underground shops or well away and downwind of surface shop areas.

2.9.2 Operating practices

The culture and attitudes of the workers will determine how management will promote and enforce operating practices. Operators of diesel-powered equipment need to know everything about that piece of equipment since most of the equipment has become very expensive, as well as sophisticated. It is the responsibility of management to ensure the implementation and enforcement of the required training on best practices and standard operating procedures.

Education and training will form part of a diesel emission management programme. Training should be regarded as an activity that adds value to both production and the health and safety of the employees. Proper training on diesel emissions is critical for all mine site operations, and regular follow-up training should be provided. Specific training should be given to the different levels of operations, which could include operators, maintenance personnel, ventilation personnel, etc. The following aspects can be included in a basic programme:

1. General information on emission components.
2. Health effects associated with diesel emissions.
3. Statutory requirements or exposure standards for individual components.
4. Sources of diesel emissions underground.
5. Factors influencing emissions levels.
6. Measurements of emission levels.
7. Risk control measures to control emissions.
8. Procedures for the monitoring and review of control measures.

Specific training will be required for specialists, who include mainly the operators of the equipment, as well as the mechanics who work on the equipment. For these two groups the following training considerations can be kept in mind:

a. A good knowledge of both the practical and theoretical aspects of the subject is a requirement (classroom and hands-on experience).
b. Keep the group that is being educated to a manageable size so that all can participate.
c. Choose people who like to communicate with others, both formally and informally, so that they can teach others who are not involved in the formal training process.
d. Do the training in stages so that expertise is acquired over time.
e. Implement a skills competency system (Van Dyk & Naidoo 2007).

2.9.3 Personal protective equipment (PPE)

Personal protective equipment is always the last resort if all other attempts to control fail. It acts only as an interim control while other control methods are being considered. In the case of diesel emissions, the only PPE considered will be respiratory protective equipment (RPE).

Where RPE is used, a respiratory protection programme needs to be in place and should include at least the following:

1. Procedures for selecting RPE.
2. Procedures for the proper use of RPE.
3. Training on the hazards they are exposed to.
4. Training of employees in applying RPE.
5. Suitable resting procedures.
6. Procedures for cleaning, storing, handling etc. of RPE.
7. Medical evaluations and surveillance of workers using RPE.
8. Procedures for evaluating the effectiveness of the programme.

Suitable gloves should be provided for when hot or cold diesel fuel is handled. The same principle will apply when hot oil is handled (Van Dyk & Naidoo 2007). Please note however, that PPE should always be considered as the last resort and the hierarchy of control should be kept in mind when corrective steps are taken to reduce exposure of DE and DPM.

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Include an abstract of less than 150 words.

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This should clearly indicate the nature of data gathering, the main issues to be covered, definition and delimitation of the problem, the importance of the paper and the purpose of the research or review. The date when the research was conducted must be provided. The cited literature (which may be part of the introduction or a separate section) must be relevant and correctly acknowledged.

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Chapter 3

Article

Establishing a baseline diesel particulate matter (DPM) exposure profile for an underground mechanized platinum mine.

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ABSTRACT

The use of diesel-powered vehicles has continuously increased in the mining environment, leaving more workers exposed to diesel emissions.[1-2] Diesel particulate matter (DPM) mainly consists out of elemental carbon (EC) and organic carbon (OC) which combines to form total carbon (TC).[3] In this study the only focus was on the TC results due to the fact that it could be compared with the Mine Health and Safety Administrations (MSHA) occupational exposure limit (OEL) for TC, since South Africa has no set OEL for DPM. This study focused on the exposure of certain occupations to DPM employed at a conventional and mechanized platinum mine. Personal monitoring using the National Institute for Occupational Safety and Health (NIOSH) 5040 method was conducted on a high risk (workers operating diesel driven vehicles), low risk exposure group (workers working in the same mine but not in close proximity to the diesel driven vehicles) and a control group. The high and low risk exposure group was workers performing their daily task at a mechanized mine; whereas the control group was workers working at a conventional mine. The three groups TC exposures were evaluated and compared with each other. The only significant difference (p-value = 0.0001) was recorded when the control group exposures were compared with both the high and low risk group. Both the high risk and low risk occupations TC exposures exceeded the MSHA OEL of 160 micrograms per cubic meter ($\mu g/m^3$), whereas only one occupation exposure of the control group exceeded this OEL.

INTRODUCTION

In many underground mines, the equipment required to extract the ore, is powered by diesel driven vehicles.[4] These diesel-powered vehicles are very flexible, mobile, they have a high power output and are widely used underground. Besides the advantages of these vehicles they result in incomplete combustion and forms various liquid and solid particles in sometimes very confined spaces underground.[1,5]

NIOSH considers the exhaust emissions from the vehicles as a “potential occupational carcinogen” due to the widespread use of these vehicles, and recommends that the workers exposures be reduced.[2,4] The exhaust emissions of the vehicles are a complex mixture of compounds that contains both a gaseous and particulate phase.[4,6]

Gaseous phase

The gaseous phase consist largely of gases such as nitrogen oxides (NO_x), carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), sulphur dioxide (SO_2), various hydrocarbons (HCs), aldehydes and water vapour.[5,7] Other gaseous exhaust components are low-relative-molecular-mass polycylic aromatic hydrocarbons (PAHs).[7] Diesel engines produces less CO, but give rise to greater amounts of NO_x and aldehydes, which are particularly prone to cause irritation of the upper respiratory tract.[8]

Particulate phase

Diesel particulate matter is defined as a sub-micron (smaller than 1 micrometer (µm)) physical aerosol component of diesel exhaust (DE), which is made up of solid carbon particles which attract and absorb organic chemicals such as PAH, condensed liquid HC and inorganic compounds such as sulphates compounds.[9] Over 80 percent (%) of diesel exhaust particles (DEP) are smaller than 0.1 µm in diameter, thus meaning that they remain airborne for long periods of time and when inhaled, are readily deposited into the lung. The United States Environmental Protection Agency (USEPA) regards DPM as a danger to the environment and claims it to be one of the top twenty air pollutants.[8]

The particulate phase is composed of EC, absorbed or condensed HCs referred to as OC sulphates and traces of metallic components[,7,10] The carbon compound found in diesel emissions, known as TC is a combination of OC and EC and usually makes up to 85% of DPM. EC is the pure carbon particles that account for a greater fraction of DPM mass and hence are the basic building block of DPM. OC is the group of complex compounds found in DPM including HC such as aldehydes and PAHs but excluding inorganic substances such as sulphates.[9]

Currently South Africa has no set OEL for TC as well as EC or OC. However the United States Department of Labour' Mine Safety and Health Administration (MSHA) promulgated an interim DPM limit of 400 µg/m^3 TC. Since the 20 May 2008 the final rule of 160 µg/m^3 TC came into effect.[9,10]

METHODOLOGY

Personal monitoring was conducted in underground conventional and mechanized platinum mine with a target population of fifty seven workers. The workers were equally divided in a high risk, low risk and control group depending on their occupations and the specific mining method involved. The high risk exposure group was workers that actually use diesel vehicles to fulfill their daily tasks. The low risk exposure group was workers whose duties take place in an environment where diesel vehicles are routinely used but not driven by the workers. The high and low risk exposure group was workers that work at a mechanized mine. The control group workers were workers working at a conventional mine where the use of diesel driven vehicles was limited.

Personal monitoring was conducted for the duration of an eight hour morning shift by following / using the NOISH 5040 method and subsequent analysis by an accredited laboratory. A quartz-fiber filter (SKC International, product code: 225-317) was used in a 3-piece cassette that is designed for only one-time purpose. This SKC DPM cassette contains an impactor with a 0.8µm cut-point. The impactor's basic function was to remove respirable particles greater than 0.8 µm. It segregated most of the DPM from most of the ore dust and permitted only DPM to be collected, as the aerodynamic diameter of most DPM is less than 0.8 µm. A cyclone (SKC International, product code: 225-105) was attached to the DPM cassette for an extra sample cleanup in order to reduce loadings of inorganic dusts. A personal sampling pump with a flow rate of 2.0 liters per minute (L/min) with flexible tubing was attached to the sampler outlet.[11] The personal exposure was measured in the breathing zone of all the workers while performing their daily tasks.

Statistical analysis

Data was analyised by using the statistical software packages Microsoft excel and Statistica 8. The statistical analysis included basic statistics (mean). All differences were considered as statistically significant at a level of $p \leq 0.05$.

RESULTS AND DISCUSSION

In table 1 the mean duration values, the mean time weighted average (TWA) of TC was presented including the specific occupation and the total samples taken of each occupations.

Table 1: The specific occupations, the total samples taken of each occupation, the mean duration and the TWA of TC are indicated.

Occupation	n	Mean duration (min)	Mean TC (ug/m^3)
High risk exposure group			
Load haulage dumper (LHD) operator	9	393	499
Drill rig operator	5	413	398
Roofbolt operator	4	407	369
Developing machine operator	1	381	246
Low risk exposure group			
Sweeper	12	431	394
Belt attendant	7	406	399
Control group			
Developing machine operator	2	374	149
Fitter surface	1	127	162
Cheesa	1	320	37
Shaft timber	1	366	53
Haulage Construction Aid	3	313	33
Pipe tracks and salvage	4	318	75
Winch transport erector assistant	1	298	45
Loco crew	2	445	81
Loco team supervisor	3	369	41
Tip attendant	1	483	88

The high, low risk exposure group as well as the control group consisted of a total of 19 workers. For the purpose of this study only TC was discussed. Although EC is often used as a marker for particulate DE in the atmosphere this may not be appropriate for assessing the overall carbon contribution (EC and OC).[8]

In the table above the high risk group worker's mean TC TWA ranged from a maximum of 499 µg/m^3 to a minimum of 246 µg/m^3. As represented by the results of the high risk workers the LHD operators have the greatest exposure whereas the development machine operators have the smallest exposure. However it should be noted that more LHD operators were sampled compared to the one developing machine operator that was sampled. The belt attendants grouped under low risk workers have the greatest exposure result (399 µg/m^3 TC) and the sweepers have the smallest exposure of 394 µg/m^3 TC. Although the belt attendants have the greatest mean result, the variation between the two occupations is shown to be not that significant. The control group has a maximum result of 162 µg/m^3 TC and has a minimum TWA of 33 µg/m^3 TC. When the three groups are compared with each other the high risk workers appear to have the greatest mean results.

By comparing the results in Table 1 to the OEL implemented by the MSHA of 160 µg/m^3 TC every occupation grouped in the high and low risk groups are well above the OEL. The only occupation exposure above the OEL in the control group was a fitter working on surface.

The figure below illustrates the individual TC results for the different occupations. As noted and previously mentioned 19 personal samples of each exposure group was taken.

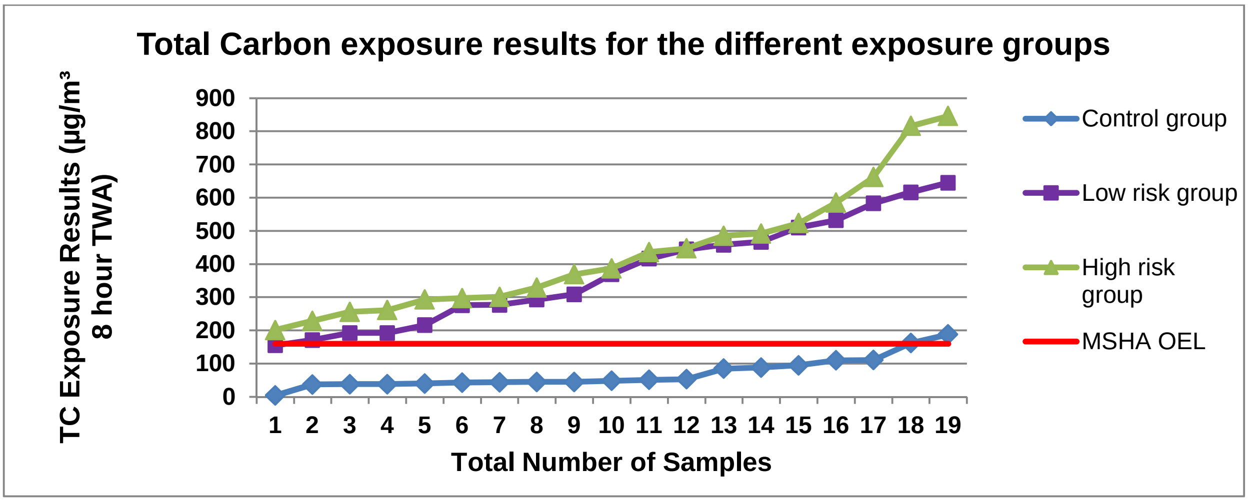

Figure 1: The personal TC TWA results for each individual as monitored in the specific exposure group

The highest TC result was presented by sample no. 19 of the high risk group with an exposure of 846 µg/m^3. The low risk exposure group's highest result was 645 µg/m^3. When comparing the control groups TC results with the other exposure groups there was a clear indication that these results differ severely from each other. The highest TC exposure result of the control group was indicated by sample no. 19 with a result of 188 µg/m^3. As indicated by the above figure the majority of the results are above the MSHA OEL.

Finally the true statistical difference came evident when comparing the control group with the high and low risk exposure groups. This will be illustrated by the tables below.

Table 2: The p-value, total samples and the mean TWA of TC of each exposure group are illustrated.

Group	n	Mean TC TWA	p-value
High risk group	19	434.8	0.4405
Low risk group	19	374.7	0.4405
Control group	19	75.6	0.0001

*p-value ≤ 0.05 regarded as significant

It is evident from table 2 that there is a significant difference when the control group is compared with the high and low risk exposure group (p = 0.0001). No significant difference was however documented when the high and low risk exposure groups were compared with each other (p = 0.4405). This significance could be due to the different occupations sampled or the fact that the control groups DPM samples were taken at a conventional mine whereas the high and low risk exposure group workers worked at a mechanized mining environment.

CONCLUSION AND RECOMMENDATIONS

The total samples exceeding the OEL supported by the MSHA are 68% of the total TC sample results recorded. The result also emphasis that there is a clear difference between the control group when compared with the results of the high and low risk exposure groups. The difference in exposure between the control, low and high risk exposure groups could well be the result of the different mining methods and the different occupations sampled.

This study led to valuable information provided to the mining environment being that set OEL is required for DPM (or TC as recommended by MSHA) because NIOSH regards DPM as a potential occupational carcinogen. Workers are clearly exposed to DPM mainly TC also indicated by the results and hence a diesel control management programme should be set in place in order to reduce these exposures.

The basic workforce exposed to DPM should receive general information on the components and suspected health effects of DPM. Measurement technologies that accommodate monitoring of DPM, the gaseous components as well as the temperatures should be implemented, maintained and other work shift should be included in the monitoring schedules. It is critical that all these points should be measured accurately and regularly by mine employees.

The mine should let operators continue to use engineering and administrative controls, but also supply these operators with the appropriate personal protective equipment (PPE) to reduce these employees' exposure to DPM. The employee should receive training and education on the correct use, maintenance and replacement of PPE.

Lessons Learned

From this study there was also limitation recorded.

1. Only one shift was recorded instead of taking all relevant shifts into consideration.
2. All occupations should have been sampled equaly to get a clear indication of the exposure levels.

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Chapter 4

Conclusion

Conclusion

The general aim of this study was to determine whether or not workers were exposed to DPM, more specific to TC. The specific aims were to: (1) compare different occupations exposure levels to an international standard (MSHA OEL) as South Africa has no proposed guideline or standard for occupational exposure to DPM (TC) and to (2) determine whether or not occupations working at mines with different mining method plays any role in the exposure levels.

The use of TC made it possible to compare the results against the MSHA OEL for TC and because it makes up 85% of DPM it indicated the overall carbon contribution (Belle 2008; Van Niekerk et al. 2005).

During the completion of this study there was an indication that when occupations were sampled individually, the greater portion of the exposure groups were exposed to TC well above the OEL when performing their day to day activities. The high and low risk exposure group all exceeded the OEL, keeping in mind that these occupations work at a mechanized mine. Only one occupation (fitter surface) from the control group's exposure result exceeded the OEL. These workers were from a conventional mine where the use of diesel-powered vehicles were limited. However the low exposure from the control group, no exposure to TC was actually anticipated except for workers working with these vehicles.

Comparing TC results within the exposure group, no significant difference could be recorded between the high and low risk exposure group. The workers results were similar to each other. The low risk exposure group were expected to have a lower exposure than the high risk group because these workers do not actually operate the diesel vehicles but only work in the same environment. The control group exposure was compared to the high and low risk group and a significant difference was recorded.

The mining method also plays a pivital role in the exposure and can be noted throughout the study. The control group working in a conventional mine had much lower exposure results than the workers from the mechanized mine that use diesel vehicles to perform their core mining needs.

Summary

- It can be noted that all the occupations are exposed to DPM no matter the result.
- The high and low risk group exposures differ significantly when compared with the control group, individually and when in a group.

- The high and low risk group exposures exceed the OEL when compared individually as well as in a group. Only one occupation from the control group exceed the OEL.
- Different mining methods play a pivital role in the workers exposures due to the nature of their duties. In the conventional mine the use of diesel-powered vehicles are limited whereas the mechanized mine use diesel vehicles to perform their core mining needs.

Limitations of this study

- It should be mentioned that during this study the vehicle maintenance was not checked and that these equipment varied from brand new to very old. No comparison between the exposure to TC, vehicle maintenance, type and year of purchase was made.
- This study indicated that when sampling the exposure of different occupations to TC the environmental conditions could provide additional information into the results of the study.
- The total amount of samples of each occupations varied and therefore a clear exposure profile for each occupation could not be identified.
- Only morning shift was monitored and no other shifts (afternoon and night) were sampled or compared with each other.

The objectives was achieved with the execution of this study. Employees working underground were evaluated based on personal monitoring for a full shift; and analysis was performed by an accredited laboratory. There is a clear indication that workers are exposed to DPM; significant difference was recorded when the exposure groups were compared with each other. The specific mining method also plays a role with regards to the exposure of workers to DPM.

The hypothesis that only the high and low risk group are exposed to DPM was partially accepted as the control group is also exposed to DPM.

The second hypothesis that the high and low risk exposure levels exceed the MSHA OEL was accepted. All the occupations from the high and low risk group exceeded the OEL.

The third hypothesis that there is a significant difference between the exposure groups was partially accepted. There was no significant difference between the high and low risk exposure group, but when compared with the control group a significant difference was recorded.

Recommendations

As mentioned throughout in the study, due to the lack of South African standard the following recommendations were based mostly on recommendations, guidelines and references provided by the Council for Scientific and Industrial Research (CSIR) and NIOSH. An overview of the strategies being utilized in the underground mining industry to reduce DPM will be discussed.

Recommendations for limiting TC exposures in underground mines:

- A successful monitoring programme needs to be in place, to sample personal and stationary (area) exposures. The continuous sampling will determine whether or not the controls that will be/was implemented by the mine is successful or whether another approach is required by the mining industry to lower the exposure levels to DPM.

- Good engineering controls should be applied before any other approaches are taken. The following engineering controls are recommended:
  - DOC, DPF and diesel disposable exhaust filters (DEF) are very effective in removing DPM from the exhaust of diesel-powered vehicles (Van Dyk & Naidoo 2007).
  - Diesel fuel quality shoud be considered if cleaner diesel engine technologies want to be achieved. Fuel properties such as sulphur content, density, cetane number, O_2 and aromatic content can all influence particulate and gaseous emissions.
  - A good maintenance programme needs to be implemented. The vehicles should be part of a maintenance schedule and the year of purchase should determine the frequency of maintenance. Excessive emissions from poorly maintained engines may jeopardize the performance of aftertreatment technologies example DOCs etc. (Mischler & Colinet n.d.).
  - Ventilation is one of the main requirements for providing acceptable environmental conditions in underground mines. Its main purposes are to supply air for human respiration, to dilute and remove contaminants resulting from the mine production processes such as dust and products of combusiton, and to provide a suitable working climate with respect to heat (Van Dyk & Naidoo 2007).
  - Enclosed operator cabins should be considered as it controls the operators exposure to DE (Van Dyk & Naidoo 2007).

- Operators of diesel-powered vehicles need to know everything about that piece of equipment since most of the equipment are very expensive, as well as sophisticated. It is the responsibility of management to ensure the implementation and enforcement of the required training on best practices and standard operating procedures (Van Dyk & Naidoo 2007).

Education and training are critical components to the success of a diesel emission management programme. Training is often difficult to sell at the operation level as a value added activity. Production and safety are always top priorities for mine operations so training needs to be seen as an activity that adds value to mine productivity as well as the health and safety of the employees. Proper training on diesel emissions is critical for all mine site operations, and regular follow-up training should be followed. Specific training will be required for specialists, who will include mainly the operators of the equipment as well as the mechanics who work on the equipment (Van Dyk & Naidoo 2007).

The following aspects can be included in a basic training programme:

- General information on emission components.
- Health effects associated with diesel emissions.
- Statutory requirements or exposure standards for individual components.
- Sources of diesel emissions underground.
- Factors influencing emission levels.
- Measurement of emission levels.
- Risk control measures to control emissions.
- Procedures for the monitoring and review of control measures.

- Personal Protective Equipment (PPE) is always the last resort if all other attempts to control fail. It only acts as an interim control while other control methods are being considered. In the case of diesel emissions, the only protective equipment considered will be respiratory protective equipment (RPE).

  Where RPE are to be issued to workers, site should develop a Respiratory Protection Programme needs to be in place and should include at least the following:

  - Procedures for selecting RPE.
  - Procedures for the proper use of RPE.
  - Training on the hazards they are exposed to.
  - Training of employees in applying RPE.
  - Suitable resting procedures.
  - Procedures for cleaning, storing, handling etc. of RPE.
  - Medical evaluations and surveillance of workers using RPE.
  - Procedures for evaluating the effectiveness of the programme (Van Dyk & Naidoo 2007).

Only the commitment and dedication of management to the health and safety of the workers will determine the successful of the diesel management programme. Every aspect should be considered and the advantages and disadvantages should be noted before any long term planning is implemented.

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