# Diesel Vehicle Emissions in Underground Mines: The South African Perspective

**Nardus Potgieter**
INFOTOX (Pty) Ltd.
PO Box 98092, Waterkloof Heights, 0065, South Africa

## Abstract

In South Africa the mining sector is one of the primary contributors to the economy and as such is one of the largest employers in the country. South Africa has a long history of mining commodities such as base metals, gold and coal, and the mining methods are traditionally labour intensive. The use of diesel-powered vehicles for mining and materials handling underground is however becoming more widespread. Concerns regarding the exposure of mine employees to the emissions from diesel powered vehicles underground have, as in other countries, become an issue of concern for occupational health authorities.

Regulatory mechanisms for controlling occupational exposure to vehicle emissions are not currently prescribed in South Africa. Research is however underway to establish an occupational exposure limit for diesel particulates. In the South African context this presents a number of interesting challenges. The effects of chronic exposure to diesel particulates on the respiratory and cardio-vascular systems are well documented, but the immunological response as a result of acute exposure has received less attention.

In South Africa, the geographic mining areas also support other heavy industries and activities such as coal-fired electricity generation. Mining and industrial areas are often characterised by large communities of a lower socio-economic status living in informal settlements where coal- or wood-fired energy is utilised on a daily basis, especially during winter. The industrial and domestic emissions generated in and around these settlements result in exposure to poor air quality outside the working environment. Establishing an occupational exposure limit for diesel vehicle emissions in an underground mining scenario would therefore require consideration of this residential exposure outside the working environment, as well as the poor socio-economic status of workers which is a predisposing factor for a poor health status.

This presentation qualitatively highlights the concerns about health impacts associated with combined residential and occupational exposure to airborne particulates, as it pertains to South African mines. The dilemma that these concurrent exposures create in formulating criteria for setting an occupational exposure to diesel particulate matter, will be discussed.

# 1 Introduction

The mining sector is one of the primary contributors to the South Africa economy and as such is one of the largest employers in the country. South Africa has a long history of mining and the mining methods are traditionally labour intensive. Approximately half a million people are currently directly employed in mining and mining-related activities, and thus represent a large population at risk of exposure to the associated occupational health hazards.

Mechanised methods of mining and materials handling are well established in South Africa and are becoming more widespread to reduce the cost of production. Diesel engines in particular are used in some underground mining operations and as such, the exposure of mine employees working underground to the emissions from diesel-powered vehicles has become an issue of concern.

As is the case in other countries that utilise diesel powered vehicles for mining, the South African occupational health authorities are investigating strategies and technologies for controlling the exposure to diesel exhaust emissions. A number of European countries, the USA and Canada have adopted regulations that limit exposure levels of diesel exhaust in the workplace.

Since no regulatory basis for controlling occupational exposure to vehicle emissions yet exists in South Africa, research has thus far primarily focused on quantitatively establishing the risk posed to human health by these emissions. The health effects of diesel exhaust emissions, in particular in underground mining environments, have been thoroughly researched and discussed in the open literature. However, findings with regard to the immunological response as a result of acute exposure have highlighted concerns specific to the South African context.

This paper explores some of the aspects considered in the current research initiative for the establishment of an occupational exposure limit for diesel emissions in South African underground mines. In the South African situation, the influence of additional exposures outside the working environment, as well as the poor socio-economic status of workers, on the health effects observed from particulate emissions are highlighted. These concurrent exposures complicate the formulation of criteria for setting an occupational exposure limit to diesel particulate matter in underground mines.

# 2 Emission components and regulation

The composition of diesel exhaust is well known and the components are generally divided into two categories, namely gaseous and particulate emissions (Schnakenberg 2002). In many countries the gaseous component, which comprises mainly oxides of carbon, nitrogen and in some instances sulphur, is strictly controlled for road-going vehicles. In the occupational environment however, the focus is on the regulation of diesel particulate matter (DPM) (Eastwood 2001). DPM is generally regulated through either tailpipe emission standards which regulate the actual production of emissions, or occupational exposure standards that regulate the quantity of an emission component that a worker can repeatedly be exposed to over a set time period without sustaining adverse health effects (Infotox 2005).

At present the research initiative focuses on the latter and is therefore aimed at establishing what these levels of exposure are. This presents a number of interesting challenges in South Africa. The geographic mining areas often also support other heavy industries and activities such as coal fired electricity generation. As is the case with mining, these operations also employ large numbers of labourers. Mining areas as a result are often characterised by large communities of a lower socio-economic status living in informal settlements where coal- or wood-fired energy is utilised on a daily basis. The industrial and domestic emissions generated in and around these settlements result in exposure to poor air quality outside the working environment. Establishing an occupational exposure limit for diesel vehicle emissions in an underground mining scenario would therefore require consideration of these residential exposures, as well as the poor socio-economic status of workers, which is a predisposing factor for a poor health status.

### 2.1 Particulate matter characteristics

Diesel engines, similar to many other combustion processes, produce large numbers of sub-micron soot particles that are believed to cause several of the adverse health effects observed from exposure to combustion emissions. Over 80 per cent of diesel exhaust particles are smaller than 0.1 µm in diameter (Salvi and Holgate 1999) and therefore can remain airborne for long periods of time after emission into the atmosphere (Editorial 1999). The total mass of airborne ultrafine particles (< 0.1 µm ∅) and nanoparticles (< 0.050 µm ∅) are insignificant in comparison with larger (i.e. PM10 and PM2.5) particles that contribute most of the mass of airborne particulates. However in terms of numbers, the vast majority of airborne particles are in the ultrafine range and larger particles make a small contribution to total numbers (Morawska et al 2004).

Such ultrafine particles are easily inhaled and are readily deposited in the lungs, from where the toxicological effects associated with both the particulates, and the compounds adsorbed onto the surface of these particles, originate (Siegel et al 2004). Consequently, although the specific contribution of the ultrafine particle component of particulates to the associated toxicity (regardless of the chemical composition of those particles) has often not been realised in the past, its importance is being increasingly recognised and studied in the more recent scientific literature.

It is estimated that as many as 18 000 different high molecular weight organic compounds can be adsorbed onto the carbonaceous core of a particle (Salvi and Holgate 1999). These adsorbed compounds are commonly referred to as the soluble organic fraction (SOF), and the type and number of these compounds adsorbed depend on the composition of the particle core. Both nitrates and sulphates may be included in the core, depending on factors such as temperature of the combustion process and composition of the fuel. Sulphates in particular have been shown to be responsible for hydrocarbon retention on particulates, especially polynuclear aromatic hydrocarbons (PAHs) that are products of incomplete combustion (Duran et al. 2003).

For this reason the response of humans to diesel exhaust may vary, depending on the constituent components of the exhaust emissions (Takizawa 2004). As a result of compound-specific health effects, an occupational exposure limit surely has to focus not only on regulating the total amount of particles emitted, but has to consider the composition of these particles. By regulating exposure to particulates however, exposure to adsorbed substances would also be reduced.

### 2.2 Health effects of particulate exposure

Diesel exhaust in general has been classified as a "suspected occupational carcinogen" (NIOSH 1988) and as "likely to be carcinogenic" (National Toxicology Program (US) 2002). Previous studies focused primarily on this suspected carcinogenic nature of DPMs for setting chronic occupational exposure limits. Acute exposure to DPM, the topic of more recent studies, has been shown to affect the nose, eyes, lungs and cause symptoms such as headache, fatigue and nausea. Exposure studies in healthy humans have documented a number of changes in the airways. In many experimental systems, diesel exhaust particles were shown to increase the sensitisation and therefore the response to common allergens (Takizawa et al. 2004).

It is precisely these effects of exposure to particulates that pose a problem for setting of an occupational exposure limit in the South African context. Factors such as advanced age, specific disease status (e.g. tuberculosis and HIV), pre-existing inflammation in the lungs and sensitisation due to pre-exposures to sensitising agents, would influence the susceptibility of individuals to the health effects of ultrafine particles. Individuals with chronic respiratory diseases or asthma may be at risk of further complications induced by occupational or environmental exposure to particulates (Dick et al. 2003).

## 3 Setting an occupational exposure limit

Possible health effects form the primary basis for establishing of an occupational exposure limit for diesel particulate emissions in underground working environments, and the information presented earlier is consequently a crucial point for consideration. It is clear that several factors have to be taken into account. Occupational exposure limits apply to the workforce, which in general is considered to be healthier than the general public. The mining industry would exclude the very young and very old, and those with infirmities and physical impairment. Occupational exposure limits therefore cannot be developed on the same basis as health regulations for the general public.

Increased participation of South Africa in the global market is likely to lead to a framework for consistent occupational exposure limits spanning international borders. One of the reasons for this harmonisation is that differing national requirements for occupational health and safety levels in the mining industry may affect the cost of producing commodities. Factors of sustainable development then come into account.

There is however a strong argument that employees that are exposed to similar agents in the workplace under similar conditions would react similarly and thus, are in need of similar protection. Specifically, it is inappropriate to provide two levels of occupational health protection: one for first-world nations and another for developing countries. In formulating an appropriate limit for exposure to diesel particulates in South African mines, it is consequently important to consider guidelines and standards in other countries.

It should be noted however, that the scientific basis for a guideline is not always clear and many countries simply adopt guidelines developed by the most prominent agencies in the world. A disadvantage of this basic approach to adopting guidelines lies in the practical application. In certain cases the mining industry may not have the resources and infrastructure to immediately afford the worker protection by introducing international exposure limits. Development of an occupational exposure limit is therefore a process that takes into account health effects data, sampling and analytical feasibility, technological feasibility, political and economic factors.

## 4 Establishing a routine sampling and analysis method for occupational exposure assessment

It may be concluded that exposure to diesel exhaust emissions and diesel particulates in the workplace can no longer be regulated in isolation from the non-occupational environment, since workplace exposure has the potential to enhance inflammatory reactions (including allergic reactions) to other contaminants and allergens encountered outside the working environment.

Considering the known potential health risks and the implication thereof for setting regulatory exposure levels, it is necessary to quantify these risks in the occupational environment by measuring the levels of emissions to which workers are exposed to on a daily basis. The method selected for this should distinguish DPM from other particulate matter commonly found in underground working environments. Furthermore, the selected method should differentiate and quantify the different components of DPM (i.e. particle cores and SOF) so as to correctly assess the risks associated with the exposure.

Three methods of sampling and analysis are used in underground mines in various parts of the world for diesel particulate matter samples (Watts and Ramachandran 2000).

- *The respirable combustible dust method (RCD) was developed in Canada to determine diesel particulates in non-coalmines (DEEP, 2001). RCD involves the collection of airborne matter on a sample filter, which is then weighed. The collected sample includes inorganic particulates, drill oil mist, the soluble fraction of diesel exhaust adsorbed onto the particulate matter, elemental carbon and other combustible material such as carbonaceous material that may be present in the ore dust. After combustion, the sample is again weighed and the combustible fraction is quantified.*

- *NIOSH (1998) developed a sensitive measure of the elemental carbon part of diesel particulate matter (Method 5040). The method also determines soluble organic carbon (i.e. SOF) and by summation of the elemental carbon and SOF the total carbon (TC) can be determined. In general, elemental carbon accounts for approximately 50 per cent of the mass of diesel particulate matter. Since elemental carbon is a product of combustion and consists of inert graphitic carbon it is a specific marker of diesel exhaust aerosol where other combustion aerosols are not present. The SOF portion, on the other hand, is subject to interferences from other organic aerosols not associated with diesel exhaust (such as drill oil mist).*

- *Size selective (SS) sampling (Watts and Ramachandran 2000) is based on observations that sub-micrometer aerosols found in coalmines are primarily diesel in origin (NIOSH, 2002; Cantrell et al., 1993). The difference in the aerodynamic diameter particle size between combustion and mechanically generated aerosols (e.g. coal dust in coal mines and inorganic carbonaceous materials) can be used to separate diesel particulates from non-combustion aerosols. The SS sampler can be used in conjunction with the method for determining* *elemental carbon for quantification of diesel particulates in coalmines. Size selective (SS) sampling utilises an additional size separation over and above the conventional cyclone size pre-classifier.*

Gravimetric-based methods such as the *respirable combustible dust method* are inadequate at moderately low workplace concentrations because so little mass is collected that the weighing error becomes very large. Furthermore, these methods are not selective enough because all combustible substances are measured, including those of non-diesel origin.

Methods based on evolved gas analysis, such as the NIOSH Method 5040, are much more sensitive to diesel particulate matter and exploit the unique and strong correlation between elemental carbon and diesel particulate matter. This measurement uses the carbonaceous cores of the particulates, consisting of elemental carbon, to quantify airborne DPM concentrations.

Considering the current South African situation, the NIOSH method may not be selective enough to accurately quantify the risks. In South Africa the fuel used by mines is of a lower grade than that commercially available to on-road vehicles. This so-called "mining diesel" is supplied at lower cost to mines and is therefore not refined to such high grades as commercial fuel. The specification for mining diesel stipulates a maximum sulphur content of 0.15 per cent. Sulphate-based particles and the associated adsorbed SOF, thus pose an increased risk to the South African underground workforce, and as such should be quantified. A method which allows for the measurement of both carbon- and sulphur-based particulates and distinguishes between the particle cores and adsorbed compounds (SOF) would be required, especially during the research stage.

# 5 Implementing an OEL

Once the current situation has been assessed, the information reviewed and an occupational exposure limit has been set, the question of implementation remains. Considering the health effects, the regulatory limits introduced would be very precautionary and limit workplace exposures to allow for the contribution of extraneous exposures. Since the effects of all exposures would impact on general health and productivity, the ideal situation would be to limit diesel particulate concentrations in the work environment to the lowest level that can be achieved in practice. However, this cannot be done without balancing costs and benefits and there is often no clear distinction between safe and hazardous exposures.

Amongst the various strategies that could be employed for the reduction of underground emission concentrations, those that offer the highest reductions with the lowest cost would obviously be preferred. The effects of engine maintenance, fuel quality and the use of low emission engines on exposure levels will consequently have to be quantitatively assessed in South African mines, as these are the strategies which may be more acceptable to the broader national mining community.

## 5.1 Fuel quality and maintenance

As described earlier, fuel quality is an issue in South Africa because of sulphur levels in the fuel and the effects that sulphur has on particulate formation. Fuel quality may also influence the feasibility of some post combustion control technologies, such as particulate filters. The feasibility and effect of low sulphur diesel fuel for use by the mining industry will have to be assessed. Such an initiative would also help to generate awareness in the mining sector with regard to fuel quality and its importance in emission control.

Several studies have indicated that proper maintenance is the cornerstone of any emission reduction program (Schnakenberg & Bugarski 2002; McGinn 2000). It is one of the simplest methods of reducing harmful emissions and the added benefits that maintenance has for cost-effective operation of diesel equipment, makes it an attractive control option. The level of maintenance provided to an underground diesel vehicle fleet is one of the aspects that is being evaluated in the current initiative to establish the levels of exposure in South African mines.

### 5.2 Engine certification

Selecting clean engine technology to replace engines that have reached the end of their operational life is a very effective means of improving underground air quality. Unfortunately, a large percentage of the vehicles currently being operated in South African mines are older technology, which in some cases are being maintained and operated far beyond their intended operational life.

In South Africa there are no criteria for the approval of diesel engines in terms of emissions, and currently there is limited control over the types of engines that are introduced into South African mines. The United States' engine certification programme run by the Mine Safety and Health Administration (MSHA) appears to be a model on which to base an engine replacement programme.

Thus, in addition to establishing the levels of occupational exposure to diesel particulates, it would also be necessary to evaluate tailpipe emissions. This would form an important basis for setting guidelines for government approval of engines, to assess the effectiveness of engine maintenance programmes and to assess the effectiveness of post-combustion control devices.

### 5.3 Diesel emission control technologies

In the underground mining environment, the traditional strategy for controlling exposure to airborne pollutants is to use mine ventilation to increase the airflow and so dilute the pollutants in the air. The concept of dilution is utilised in some technologies used for the control of exposures. These methods and devices are very effective for reducing exposures by minimising occurrences of undiluted pockets of pollutants. Dispersion is however not considered as an emission control strategy in itself, because it does not necessarily remove exhaust pollutants. It also has a limit to its effectiveness and the benefit-to-cost ratio may soon become unfavourable once multiple vehicles are deployed in a confined area. This is clearly a problem where exhaust emissions are not controlled.

Subsequently alternative control technologies such as filters, scrubbers and catalysts should be considered. Various "add-on" post combustion devices such as these, are available and have been shown to be effective for reducing diesel particulate emissions. Unfortunately, these technologies are expensive and may not be as effective in the South African mines if the questions of fuel quality and proper maintenance are not addressed.

# 6 Conclusion

South African occupational health authorities are faced with a multitude of challenges for setting exposure guidelines in the workplace. The foremost being the poor health status of workers, particularly with regard to HIV/AIDS and the diseases and increased susceptibilities related thereto. This is a factor of great concern, also in the underground mining environment.

Setting an occupational exposure limit for diesel particulates in underground mines therefore not only has to consider the increased risks due to exposure to diesel particulates, but also has to take into account the impacts of additional residential exposures. The effects of chronic exposure to diesel particulates combined with residential exposure to particulates from coal burning on the respiratory and cardio-vascular systems, as well as the associated immunological responses, have to be recognised. In addition, the poor socio-economic status of workers is already a pre-disposing factor for a poor health status.

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