

DEVELOPMENT OF A REGULATORY MECHANISM FOR THE CONTROL OF EXPOSURE TO DIESEL PARTICULATE MATTER (DPM) IN THE SOUTH AFRICAN MINING INDUSTRY

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partial fulfilment of the requirements for the degree of Master of Science in
Mining Engineering.

Johannesburg, August 2014

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DECLARATION

I, Anil Ramdev Nundlall declare that this research report is my own work. It is being submitted for the degree of Master of Science, Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at this or any other University.

_____ day of _____, 2014

To:

Kashmeera and Rahul Nundlall

For your patience and support

& Astro – for your evening companionship.

PUBLICATIONS AND PRESENTATIONS

Publications

- 1) Position Paper on Diesel Particulate Matter for the Group Environmental Engineers (GEE) – a standing committee of the Chamber of Mines South Africa.

Presentations

- 2) Mine Occupational Health Advisory Committee (MOHAC) – sub committee on Diesel Particulate regulation development.
- 3) Safety, Health, Environment and Quality (SHEQ) Board of Gold Fields Limited.

ABSTRACT

The International Agency for Research on Cancer (IARC) in June 2012 declared diesel exhaust to be a Group 1 Human carcinogen. Currently in South Africa there are no regulatory mechanism specifically to control exposure to diesel exhaust and particulate matter. The objective of this research report is to develop a regulatory mechanism for the control of exposure to Diesel Particulate Matter (DPM) in the South African Mining Industry

The primary methods used during this research were to establish a crude exposure baseline using the NIOSH 5040 method of sampling and analysis for personal exposure. The numbers of samples per occupation at the mines under study were done according to the Mandatory Code of Practice on Airborne Pollutants issued by the DME (now DMR); the sample results were also used to estimate the total carbon to elemental carbon (TC/EC) ratio.

The analysis of the development of Occupational Exposure Limits (OELs) and or tailpipe emissions standards was primarily literature based.

From the personal samples taken, there were a number of overexposures when compared to current international benchmarks such as the Mine Health and Safety Administration standards in the USA. The processes of developing occupational exposure limits are well defined internationally and the various health impact studies have provided adequate data for the exposure limits to be developed. Recommendations have been made for a phased-in approach to compliance with exposure limits that will be introduced through regulation.

Most of the health impact studies tend to indicate that the odds of developing lung cancer at much lower exposures are reduced. The time to lobby for an OEL for exposure to DPM and to introduce tailpipe emissions standards (as necessary e.g. in coalmines) has become urgent. This work concludes that as close to a

health based OEL would be Time Weighted Average (8hr) of 0.1 mg/m³ EC, as sampled and analysed through the NIOSH 5040 method.

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ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AEHS	Australian Environmental Health Services Pty Ltd
AIHA	American Industrial Hygiene Association
CANMET	Canada Centre for Mineral and Energy Technology
CFR	Code of Federal Regulations
CSIR	Council for Scientific and Industrial Research
DEEP	Diesel Emission Evaluation Programme
DME	Department of Minerals and Energy
HEPA	High Efficiency Particulate Air filter
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational Exposure Limit
OEM	Original Equipment Manufacturer
SAMRASS	South African Mines Reportable Accidents Statistical System
SANS (SABS)	South African National Standards previously known as the South African Bureau of Standards (SABS)
SIMRAC	Safety in Mines Research Advisory Committee
TLV	Threshold limit value
US DoH	United States Department of Health
US DoL	United States Department of Labour

GLOSSARY

Adsorb

The attachment of a substance to a surface. In the case of diesel particulate matter organic vapours condense as liquids and are adsorbed onto the solid carbon particles that form the core of diesel particulate matter.

Aerodynamic diameter

Diameter of a unit density sphere having the same gravitational settling velocity (terminal velocity) as the particle in question. (Online dictionary, reference 54, 2013)

Aerosols

Are an assembly of liquid or solid particles suspended in a gaseous medium long enough to be observed and measured, particle sizes generally range between 0.001 to 100 μm . (National Institute for Occupational Safety and Health, 2012)

Carcinogen, carcinogenicity:

A substance capable of causing cancer. Carcinogenicity, therefore, is a potential cancer-producing characteristic of a substance.

Case-control study

A case-control study is an epidemiological study that is often used to identify risk factors for a medical condition. This type of study compares a group of patients who have that condition with a group of patients that do not have it, and looks back in time to see how the characteristics of the two groups differ. (Attfield MD et al, 2012)

Catalyst

A substance that influences the rate of a chemical reaction but is not one of the original reactants or final products and is not consumed or altered in the reaction. Catalysts are used in many processes in the chemical and petroleum industries. Emission control catalysts are used to promote reactions that change exhaust pollutants from internal combustion engines into less harmful substances. (DEEP Technology Transfer, Glossary of terms, 2013)

Cohort study

This study identifies a group of people and follows them over a period of time to see how their exposures affect their outcomes. This type of study is normally used to look at the effect of suspected risk factors that cannot be controlled experimentally, for example the effect of smoking on lung cancer. (Attfield MD et al, 2012)

Diesel oxidation catalyst (DOC)

Catalyst promoting oxidation processes in diesel exhaust. Usually designed to reduce emissions of the organic fraction of diesel particulates, gas phase hydrocarbons, and carbon monoxide. (DEEP Technology Transfer, Glossary of terms, 2013)

Diesel particulate filter (DPF)

A device, which physically captures diesel particulates, preventing their discharge from the tailpipe. Collected particulates need to be removed from the filter, usually by continuous or periodic oxidation (“burning off”) in a process called *regeneration*. (DEEP Technology Transfer, Glossary of terms, 2013)

Diesel particulate matter (DPM)

Particles found in diesel exhaust. Most emission regulations specify DPM measurement methods in which particulates are sampled on filters from cooled exhaust gas. The cooling causes condensation of vapours in the gas sampling train. Thus, the DPM is composed of both solid and liquid particles and is generally classified into three fractions: (1) inorganic carbon (soot), (2) organic fraction (often referred to as the soluble organic fraction (SOF) or volatile organic fraction (VOF)) and (3) sulphate fraction. (DEEP Technology Transfer, Glossary of terms, 2013)

Elemental carbon (EC)

Inert graphitic carbon, as opposed to carbon in organic compounds, sometimes used as a surrogate measure for diesel particulate matter, especially in occupational health environments. Elemental carbon usually accounts for 40-60% of the total DPM mass. (DEEP Technology Transfer, Glossary of terms, 2013)

Epidemiology is the study of the distribution and patterns of health-events, health-characteristics and their causes or influences in well-defined populations. It is the cornerstone method of public health research, and helps inform policy decisions and evidence-based medicine by identifying risk factors for disease and targets for preventive medicine. (Online dictionary, reference 55, 2013)

Field blanks

Filter cassettes, used in quality control, that are identical to those used for sampling dust, except that these are not used in sampling. They are brought to the sampling site, handled as the regular sample cassettes would be and are sent back for analysis. It is expected that these cassettes will show little or no trace of contamination, otherwise, the results from exposure measurement using

the regular sampling cassettes could be questioned. (Mine Health and Safety Inspectorate – South Africa, 2009)

Homogeneous exposure group (HEG)

Means a group of employees who experience pollutant exposures similar enough that monitoring exposures of any representative sub group of employees in the group provides data useful for predicting exposures of the remaining employees. (Mine Health and Safety Inspectorate – South Africa, 2009)

The International Agency for Research on Cancer (IARC)

The International Agency for Research on Cancer (IARC) is part of the World Health Organization. Its mission is to coordinate and conduct research on the causes of human cancer, the mechanisms of carcinogenesis, and to develop scientific strategies for cancer control. The Agency is involved in both epidemiological and laboratory research and disseminates scientific information through publications, meetings, courses, and fellowships. (International Agency for Research on Cancer, 2012)

Indirect Injection (IDI)

In diesel engines with indirect injection, the fuel is injected into an auxiliary pre-chamber. Combustion starts in the pre-chamber and continues in the cylinder. (DEEP Technology Transfer, Glossary of terms, 2013)

Impactor

A component of the dust sampling train, which removes particles larger than a specified aerodynamic diameter. Diesel particulate is, for the most part, less than 0.8 micrometre in size. An impactor can be used for selective sampling of this fraction by removing particulates larger than the fraction of ultimate interest. (Mine Health and Safety Inspectorate – South Africa, 2009)

Interference

In diesel sampling, carbon substances or compounds from sources other than diesel exhaust that may cause the result of analysis to be over-or underestimated. (Watts WF, Ramachandran G, Diesel Particulate Matter Sampling Methods, 2000)

Inorganic Substances

Chemical compounds that, unlike organic compounds, do not contain carbon atoms combined with hydrogen. Inorganic substances include all non-carbon compounds, as well as some simple carbon compounds, such as carbon monoxide, carbon dioxide, carbonate salts, or forms of pure carbon itself (graphite, diamond). (ACGIH Diesel Exhaust, 2002)

Milligrams per cubic metre (mg/m³)

A measure of the airborne concentration of a substance. In the case of airborne DPM, the mass of diesel particulate in milligrams found in one cubic metre of sampled air (1000 litres) is used to calculate the concentration of DPM. If 0.34 milligrams of diesel particulate is measured in one cubic metre of air, then the concentration of DPM is 0.34 mg/m³.

Micrograms per cubic metre (µg/m³)

1 milligram=1,000 micrograms. For example, 0.34 mg/m³=340 µg/m³

Nanoparticles

Particles in the nanometre range, i.e. smaller than 1 µm (10⁻⁹ m or 10⁻³ µm)

Occupational exposure limit (OEL)

Has a similar definition to Threshold Limit Value (TLV).

Opacity

The extent to which a medium is opaque and able to block the transmission of light.

Organic carbon (OC)

The complex carbon compounds found in diesel particulate, including hydrocarbons such as aldehydes and polycyclic aromatic hydrocarbons (PAHs). Organic carbons do not include elemental carbon and inorganic substances such as sulphates. (DEEP Technology Transfer, Glossary of terms, 2013) (ACGIH Diesel Exhaust, 2002)

Pre-separator (Size selector)

In a sampling train, the pre-separator removes a portion of the airborne dust that does not need to be collected. In the case of respirable dust, a 10-mm nylon cyclone used as pre-separator removes the larger, non-respirable dust. (Mine Health and Safety Inspectorate – South Africa, 2009)

Respirable dust

Airborne dust that is capable of penetrating into the gas exchange region of the lungs. (ACGIH Diesel Exhaust, 2002)

Respirable combustible dust (RCD)

The portion of a respirable dust sample that can be burned off a silver membrane filter when exposed to a temperature of 400°C for two hours. In most Canadian provinces, RCD has been used as a measure of the exposure of miners to diesel particulate matter. (Watts WF, Ramachandran G, Diesel Particulate Matter Sampling Methods, 2000)

Sampling train (dust)

The complete assembly of what is required to perform dust sampling. It includes: a self-regulated pump, plastic/rubber tubing, lapel clips and a filtration medium in a sampling cassette to collect the dust sample. It may or may not include a pre-separator. In the case of respirable dust sampling, a nylon cyclone is used as a pre-separator to remove the coarse, non-respirable dust. (Watts WF, Ramachandran G, Diesel Particulate Matter Sampling Methods, 2000)

Size selective sampling (SSS)

A method of measuring airborne DPM exposures through a mechanical separation of particles into two size fractions: above and below (typically) 0.8 µm, followed by weighing of the smaller sized particles. (DieselNet Glossary of Terms, 2013)

Threshold limit value (TLV)

Time-weighted average concentration of an air pollutant at the workplace for a conventional 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed without adverse health effects (TLV Committee of the American Conference of Governmental Industrial Hygienists). (DieselNet, Glossary of Terms, 2013)

Total carbon (TC)

The sum of the elemental carbon and organic carbon associated with diesel particulates. Typically amounts to 80-85% of the total DPM mass. (DieselNet Glossary of Terms, 2013)

Volatile organic fraction (VOF)

The organic fraction of diesel particulate matter as determined by vacuum evaporation. It may or may not be equivalent to the SOF fraction. Depending on the exact analytical procedure, the VOF may include the organic material (SOF) as well as some of the sulphate particulates which, being composed primarily of sulphuric acid and water, are also volatile. (DEEP Technology Transfer, Glossary of terms, 2013)

Please note that in most cases the glossary of terms and explanations are used almost verbatim from their source.

PREFACE

This work prepared a crude baseline of personal exposure data from three mines to gauge the level of compliance when benchmarked against international standards. The latest epidemiologic studies were considered to provide guidance on recommending an exposure level for regulation. Tests were also conducted on selected diesel emissions technology to ascertain the technical feasibility of achieving the personal exposure or tailpipe emissions standards.

CHAPTER 1: INTRODUCTION

1.1 Background Information

The International Agency for Research on Cancer (IARC) is part of the World Health Organization and in June 2012 declared diesel exhaust to be a Group 1 Human carcinogen (IARC Press Release No.213, 2012), this category is used when there is sufficient evidence of carcinogenicity in humans. Diesel Particulate Matter (DPM) is a constituent of diesel exhaust.

“Diesel exhaust emissions have been found to contain many thousands of gaseous, liquid and particulate substances, some of which are known to exhibit some form of biological activity. While the major gaseous components (nitrogen, carbon dioxide, water vapour) comprise approximately 90 % of the mass of diesel exhaust, there are much smaller but more toxic quantities of carbon monoxide, nitric oxide, nitrogen dioxide, sulphur dioxide and hydrocarbons, all of which have been extensively studied. The information on the composition and health effects of the diesel particulate (soot) fraction is not as well understood”. (United States Department of Labour, 30 CFR Part 72, 2001).

Research into the sampling and analysis of DPM has been on-going by local and international occupational health and safety authorities and mining groups; their primary goal is to establish safe exposure levels by understanding the toxic effects and dose response relationships. These studies, exposure standards and regulated limits will be discussed in Chapter 4.

The flexibility, mobility, power and cheaper infrastructure costs afforded by the diesel engines have endeared them to a variety of uses in a many industrial applications, including mining, transport etc., although disadvantages such as diesel emissions are fast becoming a subject of huge concern regarding the health of operators of the diesel engines.

1.2 Objectives

To develop a regulatory mechanism for the control of exposure DPM in the South African Mining Industry.

1.3 Literature Survey

1.3.1 International Perspective

The attraction to the modern direct-injection diesel engines remains and it is evident by its widespread use, primarily due to its rugged, powerful, durable, and reliable design. The diesel engines tend to be workhorse engines. That is why they are found in heavy-duty trucks, tractors, buses and even trains, cranes, bulldozers, large cruisers, and other construction and mining equipment. Many international research organizations have conducted, and continue to conduct, research into the toxicity, carcinogenic attributes and other adverse health effects of exposure to DPM. The most prominent of these research reports has been the extensive 20 year scientific research study, the Diesel Exhaust in Miners Study (DEMS, 2012) release by the National Institute for Occupational Safety and Health (NIOSH) and the National Cancer Institute (NCI). The study, one of the most comprehensive in recent history, on the subject included 12,315 workers from eight non-metal mining facilities. This study provided further understanding on whether breathing in diesel exhaust fumes could lead to lung cancer and other health outcomes.

Diesel exhaust has also been classified by the International Agency for Research on Cancer (IARC) as a Group 1 human carcinogen in June 2012 (IARC Press Release No.213, 2012), and by the National Institute for Occupational Safety and Health (NIOSH) as a potential carcinogen (NIOSH,1988). Diesel exhaust is also considered to be detrimental to human health, with respect to its neoplastic and non-neoplastic effects, by the World Health Organisation (WHO, 1996). The National Toxicology Program has listed DPM as Reasonably Anticipated to be a Human Carcinogen (National Toxicology Program, December 2002).

The many in depth studies that have been conducted in various occupational (including mining) and environmental conditions have led many regulatory authorities to promulgating stringent threshold limit values (TLVs) or occupational exposure limits (OELs) with which the various users of diesel equipment must comply to safeguard the health of employees and the public. The NIOSH 5040 sampling and analytical method was developed to assist industry to comply with the regulated limits, see Appendix II.

The DEMS project (Attfield *et al*, 2012)³ identified more than 35 cohort and case-control studies that have been done on the potential health impact of exposure to diesel exhaust, especially with respect to lung cancer, most of these studies have found an increased risk of lung cancer with increased exposure to diesel exhaust.

Arising from the many health impact studies that have been done internationally, many regulatory authorities have regulated exposure to diesel exhaust and diesel particulate matter; this will be further expanded upon in section 1.3.6.

1.3.2 South African Mining Perspective

In 2008 there were 1241 operational mines employing just over 512 000 employees (DMR 2009) which in 2011 accounted for 8.8% of the GDP and if the induced effects are taken into account this contribution to the GDP is closer to 18% (COM 2011), thus signifying the importance of the mining industry to the South African economy in terms of contribution to the fiscus and direct employment.

To date there have been no regulatory mechanisms (e.g. OELs) that specifically address DPM. No mention is made of DPM in the regulations of either the Mine Health and Safety Act (Act 29 of 1996) (MHS Act) or the Occupational Health and Safety Act (Act 85 of 1993) (OHS Act), although employers are obliged to

conduct risk assessments on all hazards that may affect the health and safety of their employees and initiate appropriate risk mitigation measures.

The Mine Ventilation Society recommended the use of a minimum of 0.1 m³/s of diluting air per rated kW power of the diesel engine at the point of application for indirect injection diesel engines using low emission fuel (MVSSA, November 1999)³³ to dilute the diesel exhaust, primarily the gases produced, diesel particulate matter was not the main consideration. There are no specific OELs for DPM in the South African mining industry, although a value of 2 mg/m³ has been generally accepted as being appropriate (Unsted, 2002).

Research into exposure to Diesel engine emissions has been primarily through the Mine Health and Safety Council (MHSC); a statutory body created by the Mine Health and Safety Act (Act 29 of 1996), through the Chamber of Mines Research Organisation (COMRO) and privately funded in-house (mining houses) research into exposure levels (base lining) and control methods. The few reports that are available will be discussed briefly here:

In The SIMRAC Project Gen 010 the authors (Haase H, et al, March 1995) concluded that the critical components of diesel exhaust emissions were NO₂ (peak exposures) and DPM (time averaged exposures). In a later publication (Unsted, 2002) the author conceded that DPM was to be considered more critical in the light of the stringent TLV that had been announced at the time by the American Conference of Governmental Industrial Hygienists (ACGIH). They also found that DPM emissions were sensitive to engine maintenance and it could be conveniently measured with gravimetric dust samplers. Also of note was that operators of diesel-powered vehicles and persons in headings with low or no ventilation experienced the highest exposure levels.

In SIMRAC Project Gen 208 the author concluded that (Unsted AD, April 1996) size selective sampling would not be appropriate due to the large fraction of sub-micrometre particulates that would conceal any DPM emissions, which are mainly sub-micrometre in size. The project also concluded that there was no technical justification to advocate the use of low emissions diesel fuel, as emissions levels could be better and more effectively controlled by an engine maintenance programme than by a change in fuel formulation.

In SIMRAC Project Health 824 (Kay SA, Ross M. 2002) the urine 1-hydroxypyrene level was determined in two separate groups of workers, one group based in the surface plant and the second, exposed to diesel emissions. The results indicated no statistically significant difference in the exposure to Polycyclic Aromatic Hydrocarbons (PAHs) between the two groups. However results from two workers (both diesel bus drivers) exceeded the reference limit for industrial exposure. The industrial exposure reference limit for 1-hydroxypyrene (a biological indicator of exposure to PAHs) is 2.34 [mol/mol creatinine] and the two drivers had 1-hydroxypyrene levels of 2.4 and 2.8 [mol/mol creatinine], respectively, a possible reason cited for the high exposure was their proximity of the drivers cab to the exhaust tailpipe.

One of the larger MHSC studies into diesel emissions was conducted in 2002 in selected gold, coal and platinum mines, indicated that workers were exposed to mean EC concentrations that exceeded the ACGIH guidelines of 0.02 mg/m³ (the ACGIH has subsequently withdrawn is recommended TLV on DPM), and some samples exceeded the MSHA guidelines of 0.160 mg/m³ total carbon. The highest EC measured was 4.58 mg/m³, while the lowest exposure was 0.012 mg/m³. A number of samples from the South African mines were ten times higher than the MSHA limits (Van Niekerk et al, 2002).

The author (Van Niekerk et al. 2002) further stated that the South African mining industry shares the same global concern regarding occupational exposure to DPM and its associated health effects, yet there is no OEL or guidelines regarding DPM in the working environment. Belle (Belle BK, 2008) revealed that TC versus EC (TC/EC) ratios measured in South African mines have shown the limitations associated with the adoption of international standards because the median TC/EC ratio for underground platinum mines in South Africa is 1.8, with a range of 1.2 to 5.8; coal mines have a median ratio of 1.44, with a range of 1.25 to 2.13, both of which differ from the international ratios (at MSHA in the USA, a TC:EC ratio of 1.3 is used), which makes it difficult to rely on the international OELs to regulate DPM.

In the recommendation from his work, Nundlall (Nundlall, 2004) indicated that the Department of Minerals and Energy should convene the Occupational Hygiene working group to consider amending the regulated list of Occupational Exposure Limits (OELs) to include an OEL for exposure to DPM. A phased approach was suggested to allow the mining industry to comply with the OEL whilst improving its control measures and upgrading its diesel engine technology i.e. starting at 1.5 mg/m^3 (total carbon – using the RCD method) and allowing a 2 year compliance period, then lowering the OEL to $400 \text{ }\mu\text{g/m}^3$ (total carbon), and after a further negotiated compliance period, finally to converge with the MSHA regulated OEL, to bring South African legislation in line with international standards on occupational exposure to DPM.

Further to the adoption of an appropriate OEL, it was also recommended that the Department of Minerals and Energy compile a guideline for the preparation of a mandatory code of practice or guidance note on the use of diesel engines in mines to address the health aspects (occupational exposure to diesel emissions) and safety aspects (explosion and fire prevention etc.).

This report further amplifies the research recommendations from the initial work done in 2003/2004, (Nundlall, 2004).

1.3.3 Diesel Engines in the Mining Industry

The petrol (gasoline) engine was invented and patented in 1876 by Nikolaus August Otto, the principle of the 4 stroke engine is still used today. Both the petrol and steam engines of the time were fairly inefficient, utilising about 10 per cent of their fuel to move the vehicle and the remainder produced heat (Brain, 2013). This inefficiency prompted the German Scientist Dr Rudolf Diesel to direct his efforts to design an engine with a higher efficiency and in 1892 he obtained a patent for what is now known as the Diesel engine.

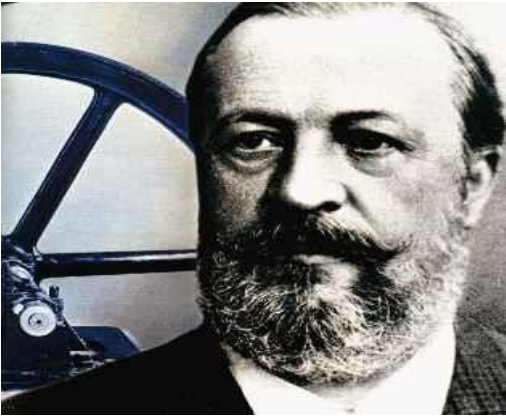
Key personalities in the development of modern petrol and diesel engines	
	
Nikolaus August Otto – patented the petrol engine in 1876	Rudolf Diesel – patented the diesel engine in 1892

Figure 1.1 Nikolaus August Otto and Rudolf Diesel - developers of modern automotive engines

The first successful engine, a single cylinder – 25 horsepower unit, was built in 1897. The first diesel engine locomotive was placed in service in the Ruhr coal-

mining district of Germany in or about 1927. From the years 1931 to 1934, the number of diesel engines in use at underground mines in Germany increased from 57 to 189 units, (Harrington D and East J H, 1947).

The use of this diesel technology rapidly spread after its success in the German mines was demonstrated to mines in France, Belgium and the British coalmines in 1939 and the American coalmines in 1946.

Diesel engines have been in use in South African mines for approximately 85 years, amongst the first users being traced as far back as 1928 at the Van Dyk Consolidated Mines Ltd on the Witwatersrand gold mines as a replacement for battery locomotives (Belle BK, 2008). Although the use of diesel equipment in our mines has boosted the productivity levels, it may have also had negative health effects on the employees due to their exposure to the pollutants produced by the diesel engine.

Unfortunately, in South Africa, these or any adverse health effects due to exposure to DPM have not been quantified as a direct causal agent.

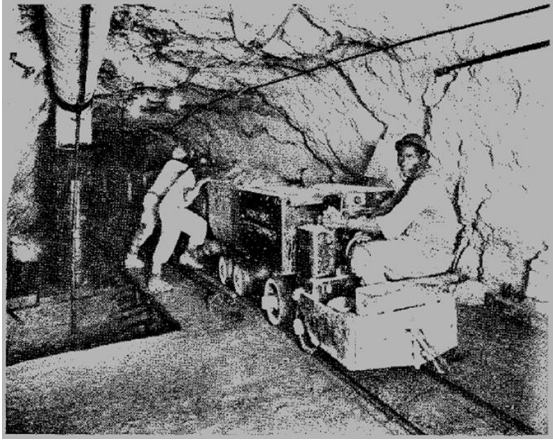
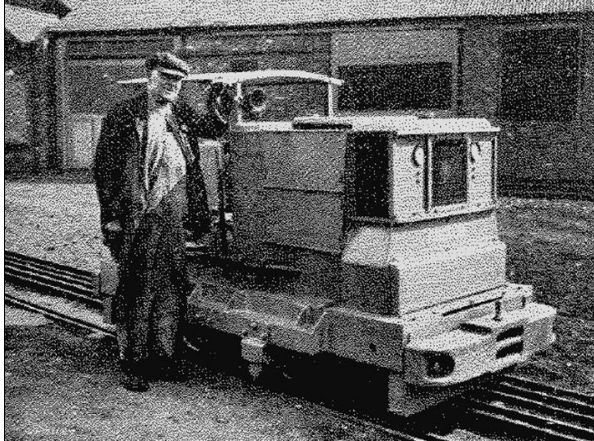
Locomotives used in mines in the early 1930's	
	
Battery locomotives, were being replaced by diesel locomotives	Early diesel locomotive used in mines.

Figure 1.2 Early Battery and Diesel locomotives



Figure 1.3 Typical sources of current DPM exposures.

1.3.4 Properties and Measurement of Diesel Engine Emissions

Diesel operated engines function by facilitating the combustion of liquid fuel without spark ignition. This is achieved by compressing the air alone in the combustion chamber and the heat of compression accomplishes the ignition when the fuel is introduced into the chamber (US DoH, 1988).

The diesel exhaust emission is a complex mixture of compounds containing both particulate and gaseous fractions. The composition will vary greatly with the operating conditions viz. 1) Type of fuel and engine (e.g. low sulphur fuel, power rating of diesel engine). 2) The load cycle (e.g. idling, acceleration, deceleration or full load). 3) Engine maintenance (e.g. mechanical wear, engine fatigue). 4) Tuning (e.g. optimum performance of fuel and air ratios). 5) Exhaust gas treatment (water baths, filtration etc.). 6) The varying environmental settings in which these diesel engines operate also add to the complexity of the emission (ACGIH 2002, US DoH 1988, Worksafe Australia,1994).

The gaseous constituents include carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, sulphur dioxide and hydrocarbons (e.g. ethylene, methane, benzene, formaldehyde and polycyclic aromatic hydrocarbons (PAHs).

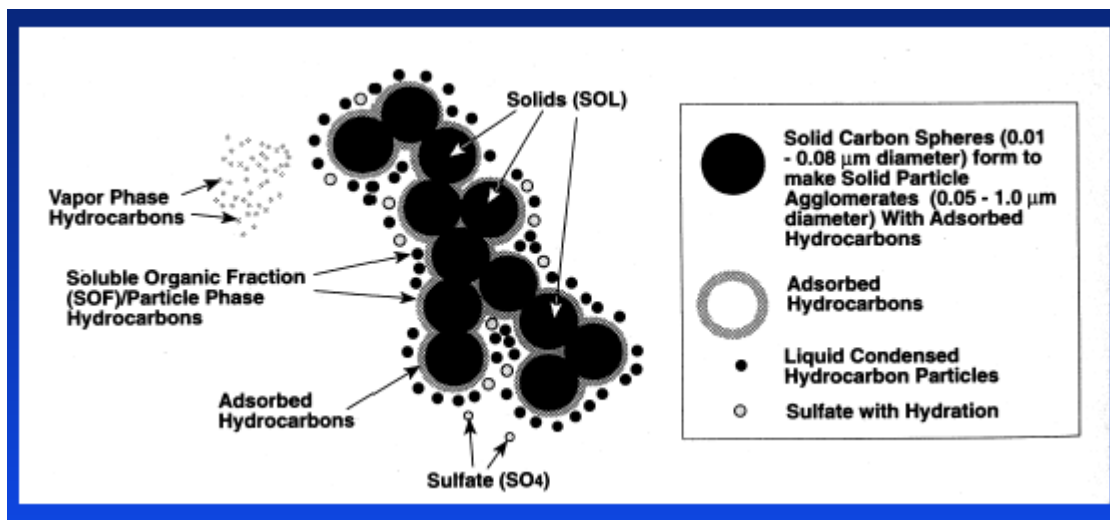


Figure 1.4 Composition of DPM (Reproduced from DEEP, October 2001)

The particulates are composed of a solid carbon core (consisting mainly of elemental carbon), see figure 1.4, that are produced during combustion and when released into the atmosphere they tend to form chains or aggregates (US DoL, 30 CFR Part 72 January, 2001).

The particulate size fraction that most diesel particulates are found in is the less than 1 μm range and thus comprise of fine, ultrafine and nanoparticles. (See Figure 1.5 -logarithmic scale is used for particle aerodynamic diameter). Due to their small size, DPM aerosols behave similarly to the surrounding gases. They have much longer residence times in a mine atmosphere than larger mechanically generated particles, which are removed from the atmosphere quite quickly by gravitational settling. In addition, a large portion of diesel particles is deposited in the human respiratory tract in comparison to larger aerosols. These

small diesel aerosols will penetrate deeply into regions of the human lung where gas exchange occurs, potentially increasing the health risks associated with long-term exposure to diesel aerosols (NIOSH, 2011). This means that persons who are not in close proximity to a diesel engine could also be exposed to diluted DPM. It is estimated that approximately 1800 different substances of smaller diameter from the combustion process can be adsorbed onto the diesel exhaust particulate and these constitute approximately 15 per cent to 65 per cent of the particulate mass, (DieselNet, 2013).

Sampling techniques for particulate matter includes the solids and liquids in the diluted exhaust, the solids generally comprise of elemental carbon and ash, and the liquid components are condensed hydrocarbons, water, and sulfuric acid. Particulates are formed when smaller particulates gather and solidify around a central core (in this case carbon), through a process called nucleation which is followed by clustering of the nuclei particles into DPM. This process of DPM development occurs in the diesel engine and in the dilution chamber. (DieselNet, 2013).

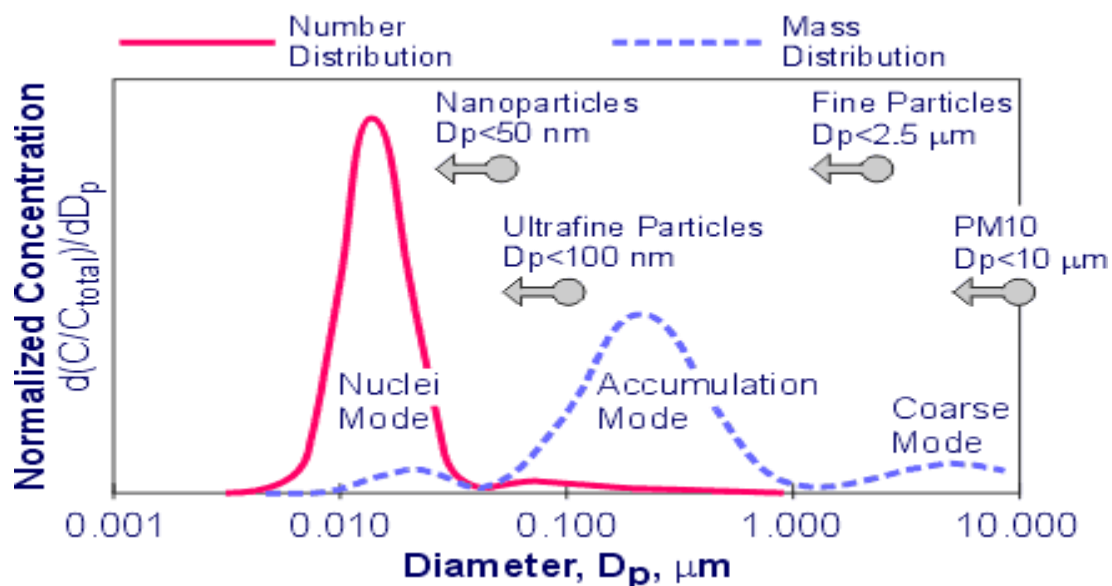


Figure 1.5 Diesel Particulate Size Distribution, (DieselNet, 2013)

Size distributions of diesel particulates are divided into the nuclei mode and accumulation mode (see figure 1.5 above) the nuclei mode contains the majority of particles and are much smaller, generally less than 1 μ m. In mass distributions, the majority of the particulates (i.e., the particulate mass) are found in the accumulation mode. In number distributions most particles are found in the nuclei mode. This means that diesel particulate matter is composed of numerous small particles holding very little mass, mixed with relatively few larger particles which contain most of the total mass. A small fraction of diesel particulates resides in a third, coarse mode.

It is important to note that in the Nucleic mode, the particles are composed mostly of volatile condensates (hydrocarbons and sulfuric acid), with little mass. Up to 10 % of the particulate mass is in the nucleic mode with about 90% of the total particle count, thus most of the particles are in the nanoparticle range (primarily in the 10-20 nm range), (DieselNet, 2013).

In the accumulation mode most the particles are made of solids (carbon, metallic ash) intermixed with condensates and adsorbed material (heavy hydrocarbons, sulfur species), and range in size from 30 to 500nm (0.03 to 0.5 μ m). The particle sizes above 1 μ m are found in the coarse mode and have little or no particle numbers and are not formed during the combustion process but are formed by deposition or particulate material from walls of the engine cylinder. (DieselNet, 2013).

“Although measurement of specific organic compounds, particularly genotoxins, may be relevant in characterizing the potential toxicity of diesel exhaust, a single compound or compound class would not reflect exposure to the particulate fraction—even if unique markers are found—because the composition of the

exhaust is highly variable. Carbon is a logical exposure surrogate to monitor because diesel particulate matter is predominantly (typically more than 80%) carbon, but carbon in the organic fraction (i.e., *organic carbon*, or OC) of diesel particulate matter is not a selective measure because other sources of OC (e.g. cigarette smoke and other combustion aerosols, asphalt fumes) are present in many workplaces.” (Birch, 2003, p.231).

Elemental Carbon (EC)

Elemental carbon (i.e., carbon in the soot particle core, or EC) is the recommended portion of the diesel exhaust to monitor because it is a more selective measure of particulate diesel exhaust and make up 30%–90% of the particulate mass of diesel exhaust (Birch, 2003). Diesel engines function by allowing a mixture of fuel and intake air, which includes oxygen (O₂), nitrogen (N₂), and carbon dioxide (CO₂), to ignite under high temperatures and pressures formed by compression. If temperatures are hot enough, fuel will burn without the presence of oxygen within these regions, creating solid carbon soot. Another term for this soot is elemental carbon (EC). Once the EC is formed, most of it will combine with oxygen and burn during later stages of the combustion process. However, the remainder will be emitted from the engine exhaust as solid particulate matter or DPM (NIOSH, 2011).

Organic Carbon (OC)

On a mass basis, EC is the largest contributor to particulate matter (PM) emissions produced by a diesel engine, but another large contributor is organic carbon (OC), or compounds that form when hydrocarbons, in fuel and lubricating oil, are consumed but not fully oxidized during the combustion process. Sources of OC emissions include fuel that is post-injected (“leaked”) into the chamber too late during the combustion process or lubrication oil that is scraped from cylinder walls or introduced into the combustion chamber from other sources. OC

compounds are partially composed of volatile material, and contribute to total DPM mass (NIOSH, 2011). In occupational settings, where diesel equipment is used in relatively close proximity to workers, the contribution of OC is normally negligible, especially when EC levels are well above background (Birch, 2003).

Ash

Fuel and lubricating oil often contain a number of additives (detergents, dispersants, etc.), which are composed of metallic elements. When these fluids are consumed during combustion, these metallic elements can form inorganic solids known as ash. Normal wear of metallic engine components are another, though less substantial, source of ash generation. Ash's contribution to DPM mass is often lower in comparison with other forms of particulate matter emissions (NIOSH, 2011).

Sulphuric Compounds

Sulfur containing compounds are another contributor to DPM emissions. Sulfur dioxide forms when sulfur in the fuel and lubrication oil oxidizes during the combustion process. During the emissions process, sulfur dioxide can react with other compounds in the exhaust and form solid sulfates, which contribute to overall DPM emissions (NIOSH, 2011).

Total Carbon and EC: TC Ratio

Total carbon (TC) is a term used to describe the sum of the EC and OC fractions of DPM ($TC = EC + OC$). The EC:TC ratio defines the fraction of EC in TC. The relationship between EC and OC fractions depends on engine operating conditions, engine type, fuel type, and a number of other parameters. EC and OC make up over 80% of total DPM mass (NIOSH, 2011).

Methods that are available for measurement of DPM in coal and non-coal are (US DoL, 30 CFR Part 57, 1998.Watts and Ramachandran, 2000.DEEP, October 2001).

- a) respirable combustible dust (RCD)
- b) size selective (SS) sampling
- c) elemental carbon (EC) analysis

Although each method provides information concerning DPM, none measures DPM directly. Thus, the NIOSH 5040 (Appendix II) method was developed to evaluate EC as a surrogate for estimating DPM exposure.

The RCD method is used for measuring the exposure of workers to DPM and is based on the principle of ashing or “burning” of the combustible, carbon-based components of the respirable dust sample. This approach yields the mass of respirable combustible dust. A key disadvantage of this method is that oxidation of the mineral portion of the dust sample is believed to interfere with the analysis to the point that significant overall mass increases may result. The interference of oil mists and efficiency of the cyclones were also amongst concerns noted by regulators at the US Department of Labor when considering this method for evaluation of DPM. Due to the carbon in coal dust, this method is not suitable for measurement of DPM in coal mines. This method was developed by CANMET and specifically uses a silver membrane filter. (US DoL, 30 CFR Part 57, 1998, p.58129; DEEP, October 2001, p.13-16).

“With the SS approach, the samples are obtained using equipment similar to the RCD method as sampling pumps and cyclone pre-separators are used. The respirable portion of the dust then passes through a single-stage impactor. The impactor jets and flow rate were designed and chosen to provide a cut size of 0.8 micron. This means that particles greater than 0.8 micron in size (coal dust

portion) would, for the most part, be removed from the air stream by impaction on the substrate which follows the jets. Particles less than 0.8 micron in diameter will continue on to be captured by a filter which follows the impactor portion of the sampler. Weighing that filter yields the estimated mass of diesel particulate matter”(DEEP, October 2001, p.4). However the mass value could be affected by any other type of airborne dust, vapour or particulate small enough in size to reach the final filter (US DoL, 30 CFR Part 57, 1998, p.58129; DEEP, October 2001, p.4). This method was developed initially for coal mines, where it is supposed that DPM and coal dust exhibit a bimodal distribution, with coal dust being larger than 0.8 micrometre and DPM smaller than 0.8 micrometre. In a metal mine, the method works reasonably well as long as concentrations of mineral dust are low.

Elemental Carbon is a product of combustion in diesel engines and is composed of inert graphitic carbon; it is a specific marker of diesel exhaust in many occupational settings where other combustion aerosols are not present. However, the organic carbon (OC) portion of the collected sample is subject to interferences from other organic aerosols not directly connected with diesel exhaust, such as drill oil mist, hydraulic fluids, coal dust, cigarette smoke and other organic materials. Elemental carbon constitutes a large fraction of the diesel particulate mass and it can be used as a measure of diesel particulate emissions. This method allows quantification of organic and elemental carbon at low levels utilising the Thermal Optical Method, the basis of the NIOSH 5040 analytical method. (US DoL, 30 CFR Part 57, 1998, p.58128).

In South Africa, currently, there is only one accredited laboratory that has the facilities or equipment to conduct this type of analysis. The samples obtained for this research report was analysed at this accredited laboratory.

Sampling of DPM directly in the engine exhaust involves complex equipment and procedures. Tailpipe measurements of DPM and gaseous emissions may be required to assess compliance to tailpipe emission standards, the state of health of an engine, the need for maintenance and is also the best way to determine the impact of exhaust cleaning equipment (e.g. diesel particulate filters). Currently the market has a variety of direct reading, real-time monitors that allows for the measurement of particulate matter and the various gasses produced at the tailpipe.

Opacity meters, also known as smoke meters do not accurately measure DPM concentrations, but are a quick and easy-to-use tool to evaluate the condition of an engine or gross malfunctions of DPM control technologies such as ceramic or other high efficiency filtration units.

Exposure monitoring for DPM in mines has undergone significant enhancements in the recent past with improved sampling and analytical technology in the market place enabling more accurate analysis of personal samples and real-time monitoring to trouble shoot problems with engine maintenance or efficiency of control devices such as diesel oxidation catalysts or filters. These tools enable the operators and regulators to reduce the health impact of DPM to employees and check compliance to regulated limits.

1.3.5 Health Effects of exposure to Diesel Particulate Matter

The International Agency for Research on Cancer (IARC), which is part of the World Health Organization (WHO), classified diesel engine exhaust as carcinogenic to humans (Group 1) in June 2012, based on sufficient evidence that exposure is associated with an increased risk for lung cancer. IARC also

found that there was a positive association (*limited evidence*) with an increased risk of bladder cancer (Group 1) (IARC Press Release No.213,2012).

The Diesel Exhaust in Miners Study (DEMS project (Attfield *et al*, 2012)³, is the most recent of over 35 studies into the health impact of diesel emissions, and is probably one of the most comprehensive having concluded a cohort study of 12 315 workers exposed to diesel exhaust in eight mining facilities. The results from this study indicated a higher lung cancer mortality risk associated with the highest diesel emission exposed workers, primarily underground workers, and also some evidence of lung cancer on surface-only workers from diesel emission exposure.

In a companion study to the one discussed above, a nested case-control study in the cohort of 12 315 miners in the eight mining facilities was done, yielding further evidence that reinforced a causal effect of exposure to diesel exhaust on lung cancer mortality. A statistically significant exposure-response relationship was observed after controlling for confounders such as smoking and other lung cancer risks. The exposure-response curve indicated a steep increase in lung cancer risk with increasing exposure in the low to moderate exposure range followed by a levelling out and then a decrease in risk amongst the heavily exposed subjects, this levelling out could possibly be biological action due to saturation of metabolic activation and enhanced detoxification or greater DNA repair efficiency at higher exposure levels. (Attfield *et al*, 2012)⁵.

In both studies, the exposure lagged 15 years, lagging is an analytic technique that removes from consideration exposures in the year's just preceding death which are likely to be too recent to be responsible for cancer. It is generally accepted that approximately 15 to 20 or more year's exposure is required to

develop lung cancer. The strongest associations in this study were observed when exposures lagged for 15 years. (Attfield *et al*, 2012)³, (Attfield *et al*, 2012)⁵.

Some of the other health effects include headaches, eye and nose irritation, asthma, nausea, lung inflammation, cardiopulmonary disease, cardiovascular disease and cancer (as detailed above). The majority of these effects are acute and dependant on high exposure levels over short duration, the chronic issues are the diseases. (Department of Mines and Petroleum – Western Australia, 2013. New South Wales Department of Primary Industries – Australia, 2008).

What is believed to be a precedent setting court decision was made by Superior Court of Quebec (Canada) on the 24th January 2013, where the court granted compensation to the widow of a mine electrician who contracted lung cancer after long term exposure to diesel exhaust, he was not a smoker. The Superior Court reviewed several decisions made in lower courts, Compensation and Occupational Health commissions, in coming to its conclusion. (Quebec Superior Court Judgment, December 2012).

1.3.6 Regulations and Standards for Emission and Exposure Control

(DieselNet,2013)

Internationally, DPM is regulated via two mechanisms i.e. Occupational Health and Safety Standards and Tailpipe Emission Standards. Where diesel engines are used in confined spaces, their operation is regulated by occupational health standards in addition to tailpipe emissions. These standards are called Permissible Exposure Limits (PELs), Threshold Limit Values (TLVs) or Occupational Exposure Limits (OELs) or other similar descriptors and represent values of exposure that most workers can be repeatedly exposed to over a 40-hour week (8 hours a day) without sustaining any adverse health effects.

Tailpipe emission standards specify the maximum concentration of pollutants in diesel exhaust that may be discharged from a diesel engine. Regulatory authorities responsible for the protection of the environment usually implement these standards. The duty to comply with these tailpipe emission standards normally rests with the original equipment manufacturer (OEM) and diesel engines would have to be certified for emissions by an accredited testing facility before being sold.

In South Africa, the regulatory authority (Department of Minerals Resources) for Mine Health and Safety would normally promulgate regulations controlling the exposure of the workforce to below a specified Occupational Exposure Limit (OEL), which has a similar definition to a TLV. Under the Mine Health and Safety Act (Act 29 of 1996) a Guideline for a Mandatory Code of Practice on the use of diesel engines should also be considered from a health and explosion prevention perspective. The South African National Standards (SANS) also publishes engine performance standards that can be made legally binding to OEMs and industry when referred to in legislation.

Currently in South Africa there are no occupational exposure limits or legally binding tailpipe emissions standards in place for DPM. Mining companies are however obliged to conduct risk assessments in terms of Section 11 of the Mine Health and Safety Act (Act 29 of 1996) on all factors that could adversely affect the health and safety of the workforce and institute appropriate mitigation measures, where no local regulations exist, international best practice should be utilised. OEMs are also required to provide a full disclosure, in terms of Section 21 of the Mine Health and Safety Act (Act 29 of 1996) of the health and safety impact of the equipment being sold to a mining company and advise on appropriate measures that can be taken to eliminate or reduce the risk. (Nundlall, 2004, p36).

Table 1.1 provides some guidance on exposure levels that are currently used internationally (DieselNet, 2013):

Regulator/Agency	Date Submitted	Exposure Guideline/ Limit	Substance Measured
Canada (Ontario)	2011	0.4 mg/m ³	TC
Swiss MAK Exposure Limit	2001	0.1 mg/m ³	EC
MSHA	2008	0.16 mg/m ³ TC, 0.123 mg/m ³ EC	TC and EC
Germany (tunnelling & non-coal mining)	1996	0.3 mg/m ³	EC
Germany (other applications)	1996	0.1 mg/m ³	EC
Australia	2012	0.2 mg/m ³ TC, 0.1 mg/m ³ EC	TC and EC

Table 1.1 International exposure guidelines/limits

The German TRK Values are the ambient concentrations that can be achieved using technically available measures. Legend for substances measured is: EC- Elemental carbon, TC-Total carbon, MAK – Maximum concentration in ambient air.

Table 1.2 provides some guidance on Tailpipe emissions standards for diesel engines that are currently used internationally (DieselNet, 2013):

Regulator/Agency	Date Submitted	Exposure Guideline/ Limit	Substance Measured
Argentina (Euro 2 standard)	2000	0.15 g/kWh	DPM
Australia (Euro 4 standard)	2003	0.4 g/kWh	DPM
Brazil (Euro 3 standard)	2011	0.2 to 0.6 g/kWh	DPM
Japan, Vehicle (depending on engine size)	2008	0.17 to 0.4 g/kWh	DPM
United States (MSHA - Coal)	2001	2.5 g/h	DPM

Table 1.2 International tailpipe emissions standards

Country	Year Introduced	Fuel quality (Sulphur content)	Engine standard available
United States	2010	15 ppm	US EPA Tier 4
Canada	2010	15 ppm	US EPA Tier 4
Australia	2009	10 ppm	Euro V (from 2003)
Germany	2002	20 ppm	Euro 5/6
Brazil	2011	10 ppm	US EPA Tier III/Euro IIIA
India	2010	350 ppm nationwide, 50 ppm selected areas	Euro III nationwide, Euro IV selected areas
South Africa	2006	500 ppm nationwide, 50 ppm selected outlets, and less than 10 ppm by July 2017	Euro 2, Planned to be at Euro 4 by 2010 and Euro 5 by 2017. (DoE 2011) ²²

Table 1.3 Engine certification and fuel quality available locally and internationally (DieselNet, 2013)

CHAPTER 2: MATERIALS AND METHODS

2.1 Introduction

In 1989 the Department of Minerals and Energy, through the Mining Inspectorate, introduced the Gravimetric Dust Sampling system which changed the way sampling for dust exposure was done from a snapshot (konimeter) based to full shift sampling using a dust sampling train consisting of a sampling pump, filter media and cyclone and collecting the sample in an employee's breathing zone. This system was further refined in 2002 with the introduction of the Mandatory Guideline for a Code of Practice on Airborne pollutants which brought in the concept of the homogeneous groups for ease of sampling and analysis, and also set out a detailed methodology for scheduling, sampling, analysis and reporting of airborne pollutant exposure. Mine employees have thus been sensitised and have been using dust sampling trains for about 24 years in the mining industry.

The collection of samples for this project utilised the same equipment used for the dust sampling programme, with specialised DPM pre-prepared filters obtained from the accredited laboratory.

Some of the information shared with the operators of the diesel engines and instructions given to them were:

- a) A brief explanation of the objectives, the operation of sampling devices, and the reason for the sampling (i.e. measurement of Diesel Exhaust emissions).
- b) The operator was requested not to obstruct the operation of any component of the sampling train in any way i.e. crimping the tubing or inverting the filter holder etc.

- c) The need for the operator to continue to work in a routine manner and to report any unusual occurrences or problems encountered during the sampling period to the investigator.
- d) The operator was also informed as to when and how the sampling train would be retrieved.

After the explanation and instructions were given, the sampling train was attached to the operator in a manner that did not constitute a safety hazard, i.e. all parts of the sampling train were neatly tucked away or taped out of the way, as was reasonably practicable, so as not to interfere with his duties. The sampling head was situated in the operator's breathing zone.

2.2 Case Study Setting & Design (Crude baseline)

The study was conducted at three underground gold mines. One is deep level, fully mechanised mine with a large diesel engine fleet, and the other two mines are conventional deep level gold mines using diesel locomotives to transport broken rock.

The design was to obtain a crude baseline of DPM exposure amongst directly exposed (diesel engine operators and attendants), potentially the highest exposed and those who were considered not to be directly exposed (in-stope workers, rock drillers etc.), the aim being to attempt to distinguish the level of exposure closest to the source and the diluted exposure level.

The data will also be used to determine the Total carbon to Elemental carbon ratio (TC: EC), which will be used in the discussion on the development and recommendation of occupational exposure limits.

2.3 Study Population & Sample

The South African mining population in 2011 was as follows:

Commodity	Average Number Employed
Gold	145 561
Platinum Group Metals	194 929
Coal	78 580
Other (including small scale mining and Diamond)	40 968
Total	513 211

Table 2.1 Average Mining population 2011, (COM, 2011)

Of this study population, this research report focused on the diesel engine operators on the gold mines selected, data was also obtained from other sources to provide an indicative or comparative range of exposures.

The study sample was a random selection of operators of mobile diesel powered equipment and employees not directly exposed to diesel exhaust for personal exposure measurement, for the purpose of this study these groups were regarded as a homogeneous exposure groups (HEGs) as per current Department of Minerals and Energy guidelines on Occupational Hygiene.

2.4 Measurement Methods

The mine's Code of Practice on Airborne Pollutants (i.e. the mines being studied) was the basis of the sampling, which has been established as a routine process for many years. The measurement and analysis of personal exposure on the diesel equipment operators were carried out according to the NIOSH 5040 method (see Appendix II NIOSH 5040 Sampling and Analytical Method for Diesel Particulates). This method essentially specifies the type of sampling equipment, sampling media and analysis technique best suited to obtain the elemental carbon (DPM) concentration.

A standard sampling pump was used, set to a sampling flow rate of 2.0 l/min, using standard calibration methods.

The sampling medium used was the SKC DPM Cassette, which was specially designed for sampling of DPM.

2.5 Analysis of Personal Samples

The personal samples that were collected in the breathing zone of the diesel engine operators, were analysed according to the NIOSH 5040 method at an accredited laboratory; one of the result reports is attached as Appendix III

2.6 Quality Assurance in Sampling and Analysis

A quality assurance programme is included in the Code of Practice on Airborne Pollutants, one of them being the use of Field Blanks to ensure accuracy of analysed results.

The collection of the personal sample in the breathing zone of the diesel engine operators was carried out according to the established NIOSH 5040 method, and the calibration and quality control as required by this method were observed i.e. the calibration of the sampling pumps (pre and post sampling checks), checks on the sampling train integrity, and the use of field blanks.

2.7 Analysis of Data

The data were double punched into a personal computer and utilising the Microsoft Excel package to capture and analyse the data to obtain:

- a) The mean personal exposure of diesel equipment operators (directly exposed) and those considered not directly exposed to DPM in the selected mines.
- b) The TC: EC ratios were also calculated

2.8 Limitations

Limitations of the study design were:

- a) This study was at best able to provide a crude baseline of exposure to DPM on the selected mines and occupations. The results cannot be generalised within the mines studied or within the industry as a whole.
- b) It was not able to cover all exposure scenarios e.g. different vehicle types, vehicle maintenance levels, fuel type etc.

This study attempted to look at the occupational exposure of mine employees to DPM under prevailing conditions; various management, ventilation systems and states of engine maintenance were not studied in depth, whilst their influence on DPM exposure is recognised.

2.9 Sources and Selection of Literature

Literature research was primarily focussed on credible information sources such as the World Health Organisation (WHO), The International Council on Mining and Metals (ICMM), The National Institute for Occupational Safety and Health (NIOSH), Mine Health and Safety Administration (MHSA) etc.

A full list of literature consulted is included in the Reference section, Section 7. Also a fair amount of personal consultation occurred with technical and policy specialists that are not referenced.

CHAPTER 3: RESULTS

3.1 Introduction

The results are presented in tables, graphically and literature (e.g. process of developing standards) where appropriate. The results of personal exposure are in mg/m³. No attempt has been made to correlate the results with prevailing environmental conditions, as the samples taken were full shift samples and employees who were being sampled operated in varying environmental conditions.

3.2 Exclusions

Personal samples were excluded if the post measurement sampling train did not compare favourably to the pre measurement checks i.e. flow rate, leakage into tubing, battery life etc.

3.3 Personal Exposure Results

Gold Mine 1 (Mechanised Mining)	Occupation	No. of employees sampled
	LHD Operator	47
	Locomotive Operators	25
	Drill Rig Operators	31
	Artisan	46
	Artisan Aides	16
	Utility Vehicle Operators	17
	Charmec Operators (Blasting Assist)	9
	Total number of Personal Samples	191

Gold Mine 2 (Conventional mining)	Locomotive Operators	51
	Artisan Aides	5
	Artisans	2
	Battery Bay Attendant	3
	Shaft Employees	4
	Pump Attendants	3
	Construction Team members	1
	Stope employees (production zone)	2
	Total number of Personal Samples	71
Gold Mine 3 (Conventional Mining)	Locomotive Drivers – directly exposed only.	14

Table 3.1 Number of personal samples taken and analysed.

The tables and graphs below present the results from the selected mines that were used for the crude base lining.

Gold Mine 1 – Deep Level mechanised mining, large diesel fleet.				
Occupations Directly exposed to diesel emissions	Average Total Carbon (TC) Max/Min mg/m ³	Average Elemental Carbon (EC) Max/Min mg/m ³	Average Organic Carbon (OC) Max/Min mg/m ³	Diesel Fuel Specification High – 500ppm Sulphur Low - <50ppm Sulphur
LHD Operator	0.33 0.71 / 0.04	0.09 0.28 / 0.005	0.24 0.54 / 0.03	High
	0.32 0.85 / 56	0.12 0.31 / 0.003	0.20 0.56 / 0.04	Low

Loco Drivers	0.15 0.27 / 0.10	0.02 0.09 / 0.004	0.13 0.20 / 0.09	High
	0.13 0.28 / 0.06	0.02 0.05 / 0.004	0.11 0.23 / 0.05	Low
Utility Vehicle Driver	0.41 0.67 / 0.27	0.08 0.15 / 0.04	0.33 0.62 / 0.19	High
	0.26 0.73 / 0.13	0.09 0.30 / 0.01	0.16 0.44 / 0.11	Low
Drill Rig Operator	0.26 0.57 / 0.04	0.07 0.18 / 0.00	0.19 0.39 / 0.04	High
	0.33 0.79 / 0.03	0.11 0.34 / 0.001	0.21 0.69 / 0.02	Low
Artisan	0.26 0.87 / 0.03	0.06 0.24 / 0.001	0.20 0.76 / 0.03	Mixed
Artisan Aides	0.19 0.4 / 0.11	0.04 0.19 / 0.003	0.15 0.25 / 0.07	Mixed
Charmec Operator (Blasting Assistant)	0.11 0.16 / 0.06	0.04 0.08 / 0.001	0.07 0.08 / 0.06	High
	0.25 0.44 / 0.16	0.09 0.11 / 0.05	0.16 0.34 / 0.11	Low

Table 3.2 Personal sample results taken at Gold Mine 1

Gold Mine 1												
	OEL	Mean	Standard Error	Median	Standard Deviation	Sample Variance	Kurtosis	Skewness	Range	Minimum	Maximum	Count
LHD Operator	0.16	0.3287	0.0294	0.3115	0.2012	0.0405	-0.4623	0.5676	0.8094	0.0406	0.8500	47
Drillrig Operator	0.16	0.3052	0.0381	0.2448	0.2119	0.0449	0.1364	0.9098	0.7646	0.0250	0.7896	31
Artisan Assistant	0.16	0.1864	0.0199	0.1724	0.0794	0.0063	2.3887	1.4443	0.2948	0.1063	0.4010	16
Artisan	0.16	0.2585	0.0285	0.2001	0.1930	0.0372	1.8497	1.4107	0.8396	0.0333	0.8729	46
UV Operator	0.16	0.3005	0.0434	0.2292	0.1789	0.0320	1.4255	1.4531	0.6000	0.1344	0.7344	17
Loco Driver	0.16	0.1393	0.0109	0.1240	0.0547	0.0030	1.4385	1.3863	0.2219	0.0573	0.2792	25
Charmec Operator	0.16	0.2199	0.0351	0.1948	0.1054	0.0111	2.2768	0.8927	0.3841	0.0576	0.4417	9

Table 3.3 Statistical analysis of data from Gold Mine 1

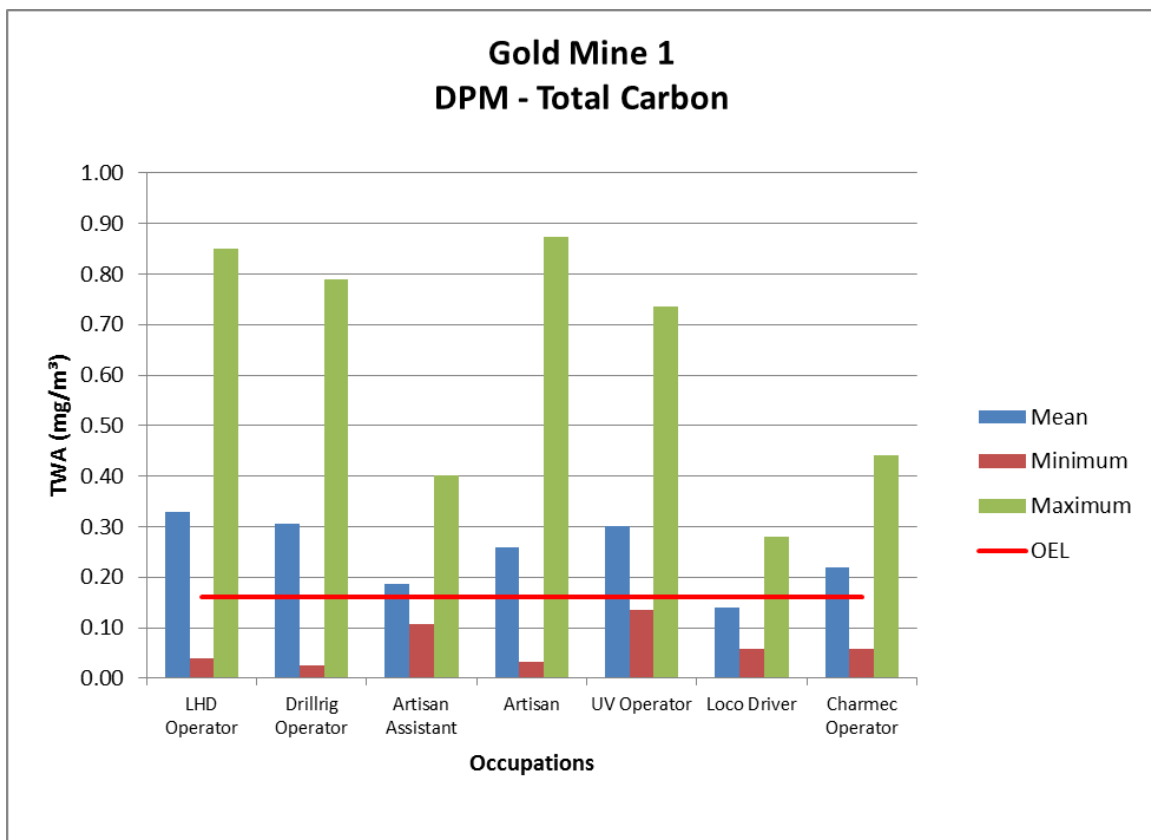


Figure 3.1 Graphical representation of data from Gold Mine 1

Gold Mine 2 – Conventional Mining, Diesel Locomotive Fleet				
Occupations Directly exposed to diesel emissions	Average Total Carbon (TC) Max/Min mg/m ³	Average Elemental Carbon (EC) Max/Min mg/m ³	Average Organic Carbon (OC) Max/Min mg/m ³	Diesel Fuel Specification High – 500ppm Sulphur
Locomotive Operators	0.06 0.54 / 0.02	0.005 0.11 / 0.00	0.056 0.43 / 0.02	High
Artisan Aides	0.05 0.1 / 0.03	0.001 0.007 / 0.00	0.05 0.09 / 0.03	High
Artisans	0.13 0.22 / 0.04	0.01 0.03 / 0.000	0.12 0.19 / 0.04	High
Battery Bay Attendant	0.13 0.22 / 0.04	0.01 0.03 / 0.000	0.12 0.19 / 0.04	High
Shaft Employees	0.05 0.06 / 0.03	0.001 0.002 / 0.000	0.05 0.06 / 0.03	High
Pump Attendants	0.03 0.04 / 0.03	0.000 0.001 / 0.00	0.03 0.04 / 0.03	High
Construction Team	0.04	0.00	0.04	High
Stope employees (production zone)	0.04 0.05 / 0.03	0.00 0.00	0.04 0.05 / 0.03	High

Artisan Aides	0.05 0.1 / 0.03	0.001 0.007 / 0.00	0.05 0.09 / 0.03	High
Artisans	0.12 0.22 / 0.04	0.01 0.03 / 0.00	0.11 0.19 / 0.04	High

Table 3.4 Personal sample results taken at Gold Mine 2

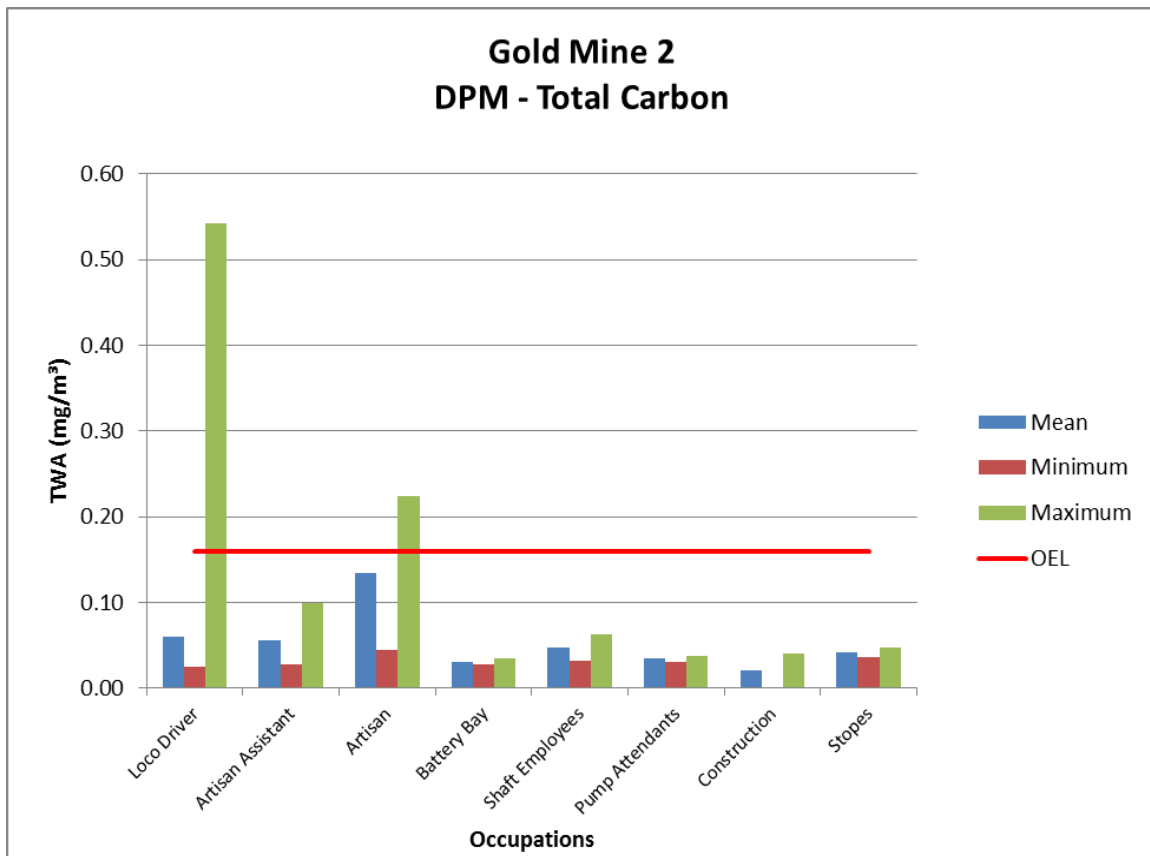


Figure 3.2 Graphical Representation of data from Gold Mine 2

Gold Mine 3 – Conventional Mining, Diesel Locomotive Fleet				
Occupations Directly exposed to diesel emissions	Average Total Carbon (TC) Max/Min mg/m ³	Average Elemental Carbon (EC) Max/Min mg/m ³	Average Organic Carbon (OC) Max/Min mg/m ³	Diesel Fuel Specification High – 500ppm Sulphur
Locomotive drivers	0.17 0.30 / 0.06	0.04 0.09 / 0.004	0.13 0.24 / 0.06	High

Table 3.5 Personal sample results taken at Gold Mine 3

3.4 Testing of a sample of Diesel Emission controls

A suite of tests were done to compare the effectiveness of various technologies in reducing Diesel Particulate Matter (DPM) in internal combustion engines used at the selected mines. These tests were conducted at a testing facility in Pretoria with the selected equipment manufacturers and technical guidance from the CSIR Natural Resources and Environment. Some of the results are discussed here as it relates to the development and introduction of a regulatory mechanism to control occupational exposure to diesel exhaust emissions, in particular, diesel particulate matter (DPM). The reports themselves are not referenced as they remain internal confidential documents.

Tests were conducted using a 5 cylinder Deutz engine, commonly used to power diesel locomotives and primarily used in the conventional mines (gold mines 2 and 3); these are considered tier 0 engines. A 6 cylinder air cooled Duetz engine was also used to compare the effects on a more modern in engine (tier 2), primarily used in the mechanised mine (gold mine 1).

Engines on the Test Bench

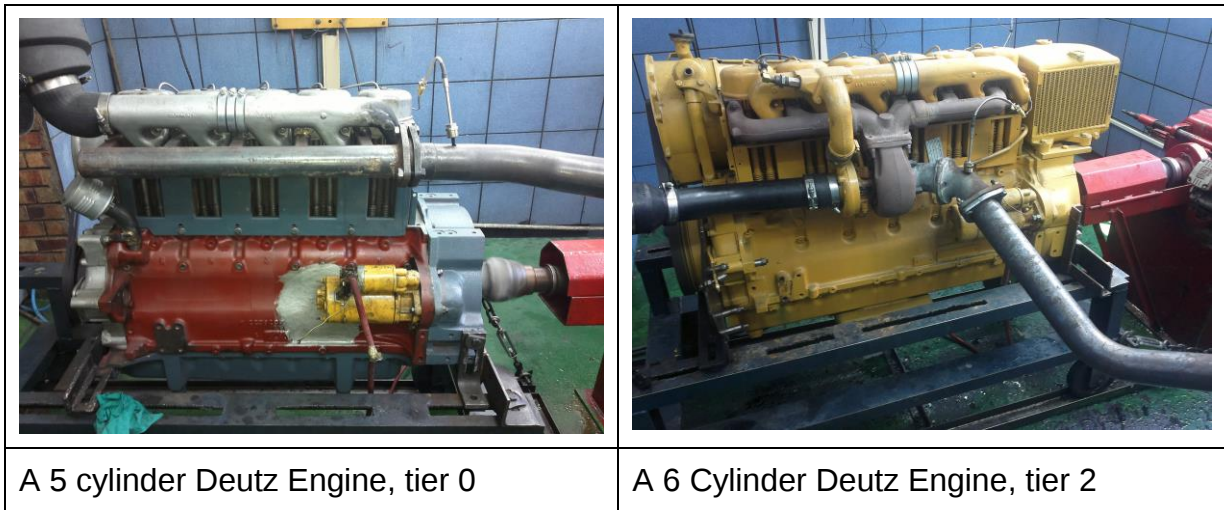


Figure 3.3 Diesel engines on a test bench

Some of the control measures tested, using both the 5 and 6 cylinder engines were:

- 50 ppm sulphur diesel
- 500ppm sulphur diesel
- Bio-diesel
- A fuel additive
- Catalytical convertors
- Diesel particulate filters (DPF)
- Combination DPF and Catalytical convertors
- Waterbox

The main aim of these tests was to get an indication of the reduction in DPM production.

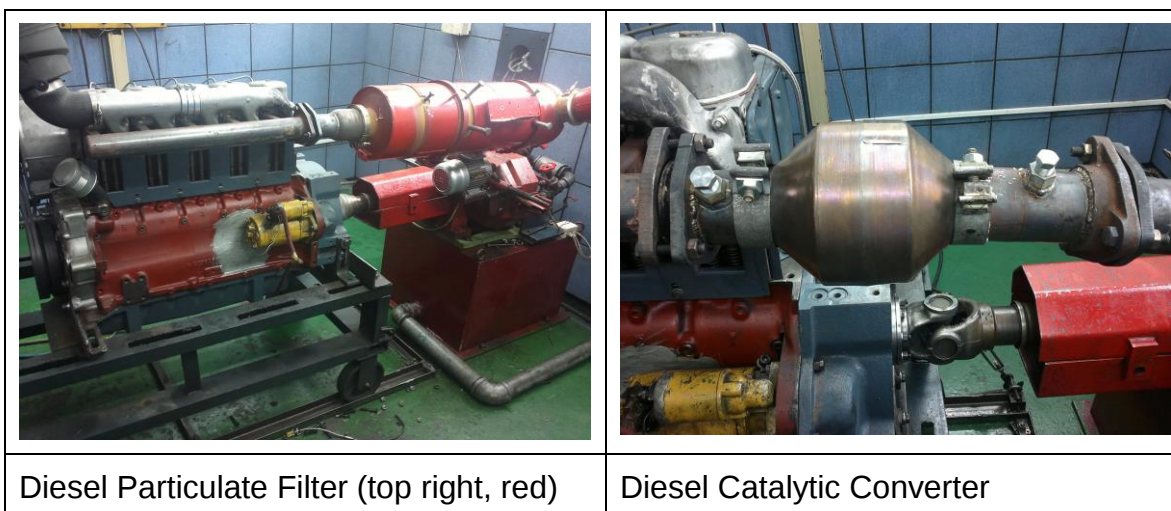


Figure 3.4 Emissions Control tests

Results of the tests as compared the use of 500 ppm sulphur diesel is represented in the figures below:

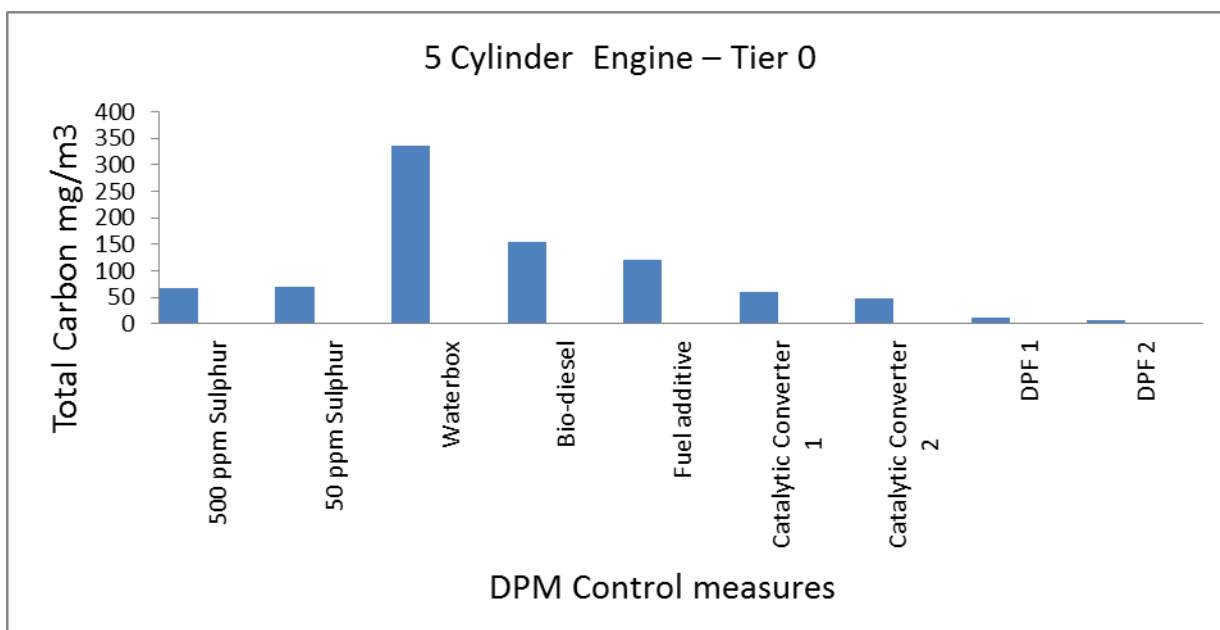


Figure 3.5 Results of control measures tested on the 5 cylinder diesel engine

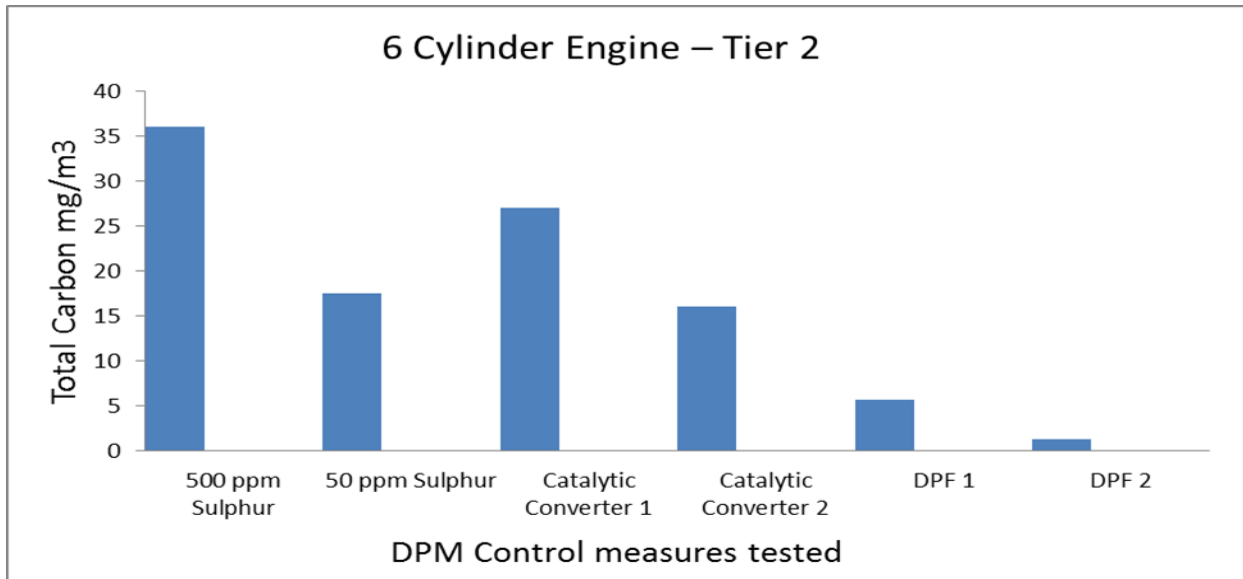


Figure 3.6 Results of control measures tested on the 6 cylinder diesel engine

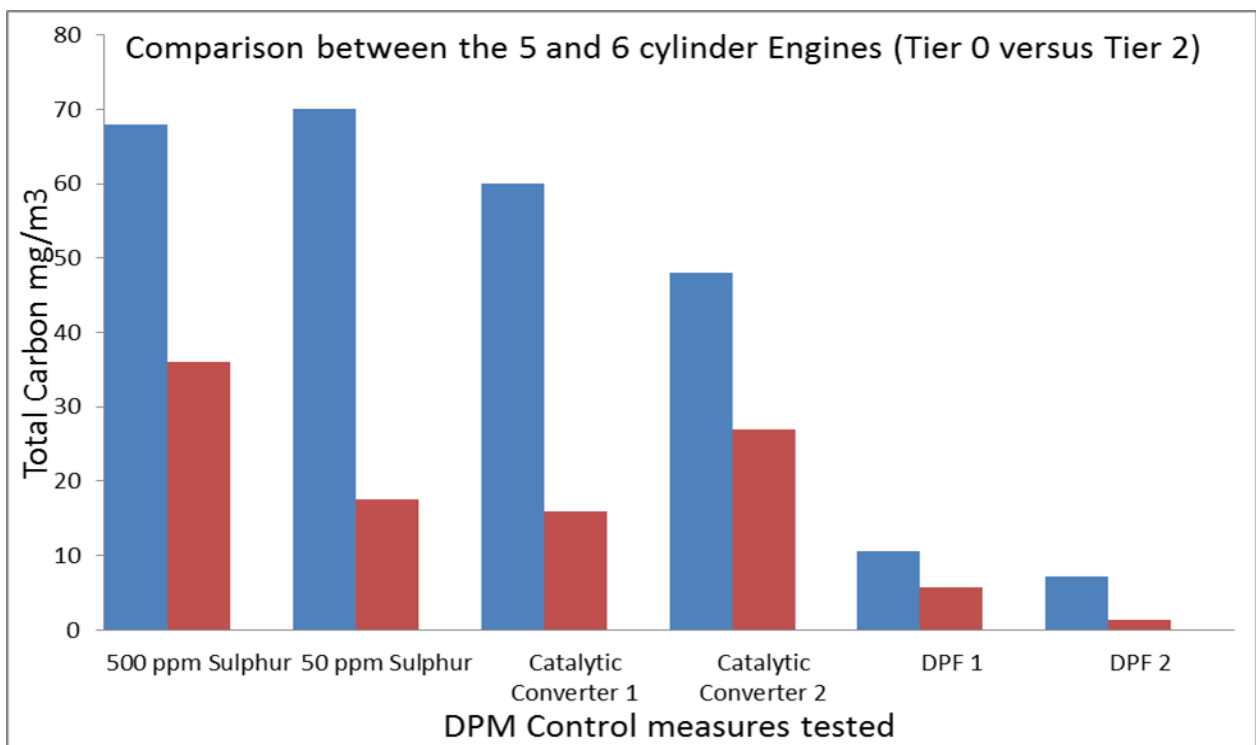


Figure 3.7 Comparison control measures tested on the 5 and 6 cylinder diesel engines (■ - 6 cylinder engine, Tier 2, ■ - 5 cylinder engine, Tier 0)

- All measurements quoted are for Total carbon except where otherwise stated.

- Results indicated an average TC/EC ratio of 0.60 or 60% EC, when elevated levels of TC were experienced the elevation appeared more on the Organic Carbon side.

3.5 Total Carbon to Elemental Carbon Ratios

Belle (Belle BK, 2008) revealed that TC versus EC (TC/EC) ratios measured in South African mines have shown the limitations associated with the adoption of international standards because the median TC/EC ratio for underground platinum mines in South Africa is 1.8, with a range of 1.2 to 5.8; coal mines have a median ratio of 1.44, with a range of 1.25 to 2.13, both of which differ from the international ratios, which makes it difficult to rely on the international OELs (see table 1.1) to regulate DPM.

The calculated TC: EC ratios from the three mines under study, using diesel locomotive drivers as the case for all operations, the study indicated that for Gold Mine 1 a TC: EC ratio of 7.7 (low sulphur fuel used) and TC: EC ratio of 8.1 (high sulphur fuel used). For Gold mines 2 and 3 the TC: EC ratio was 7.2 and 7.5 respectively (both operations using high sulphur).

The TC/EC ratio seems to be widely variable as indicated in figure 3.8 below, in the USA, a default TC/EC ratio has been established at 1.3, based on studies at a number of mines (MSHA, 2003). The OEL in the USA is based on a TC: EC ratio of 1.3, the regulated limit being 0.16 mg/m^3 TC, and through the use of the TC: EC ratio the EC is calculated to check if the limit for EC is exceeded. This process is explained further below. In Australia a TC: EC ratio of 2.0 has been accepted and limits are based on both TC (0.2 mg/m^3) and EC (0.1 mg/m^3), these are not legislated. Due the Australian accepted limits not being legal limits they are not enforced by the mining inspectorate but are rather self-enforced by the employers and overseen by the trade unions. Confusion could arise in this scenario if an exposure level exceeds the EC and not the TC as an example; no explanations are provided as to how that will be resolved.

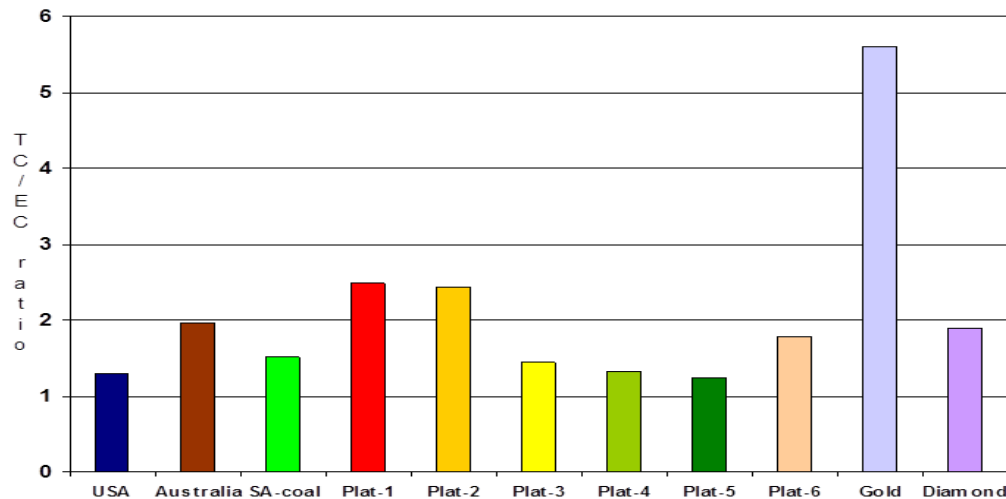


Figure 3.8 Wide variability in TC: EC ratios in South Africa, Belle (Belle BK, 2008)

Enforcement of the OEL in the USA based on their TC: EC ratio's and error factors can be a complex set of calculations before a citation (fine or administration penalty) can be issued. The following set of calculations is reproduced from the MSHA's document on the "Use of Error Factors in Determining a Miner's Overexposure to DPM" (MSHA, 2013), the document itself is undated.

"The DPM permissible exposure limit (PEL) is 160 micrograms of total carbon (TC) per cubic meter of air ($160_{TC} \mu\text{g}/\text{m}^3$)."(MHSA, 2013).

"1. TC from a personal sample **must exceed** $160 \mu\text{g}/\text{m}^3$ times the error factor (EF) for TC to result in a miner's overexposure to DPM. The EF for TC is 1.192. Thus, it follows that the miner **is not overexposed** to DPM when TC from the miner's personal sample **is less than or equal to** $160 \mu\text{g}/\text{m}^3$ times the EF for TC as demonstrated below:

$$TC \leq 160 \times [\text{EF for TC}]$$

$$TC \leq 160 \times 1.192$$

$$TC \leq 190.72$$

Per MSHA's practice to round up to the next higher integer, 190.72 is rounded to 191. Therefore, a miner **is not overexposed** to DPM when $TC < 191$ ($\leq$ changed to $<$ because 191 is greater than 190.72)

2. When TC from a full-shift personal sample **is equal to or greater** than $191 \mu\text{g}/\text{m}^3$, MSHA will evaluate the EC content of the personal sample as follows to confirm that the TC exposure is not the result of organic carbon interferences:

The miner **is overexposed** to DPM when EC on the miner's personal sample for TC is greater than 160 times the EF for EC. The EF for EC is 1.095. This relationship may be expressed mathematically as:

$$EC > 160 \times [\text{EF for EC}]$$

$$EC > 160 \times 1.095$$

$$EC > 175.2$$

175.2 is rounded up to next higher integer = 176

$EC \geq 176$ ($>$ changed to $\geq$ because 176 is already higher than 175.2)

Therefore, a miner is overexposed to DPM when EC on the personal sample equals or is greater than $176 \mu\text{g}/\text{m}^3$. (MHSA, 2013).

The enforcement action is based on a single shift personal sample. Area samples are also taken to provide an adjustment factor to the personal samples if necessary.

A flow chart of the MHSA Enforcement Process is depicted in Figure 3.9 below (on the next page).

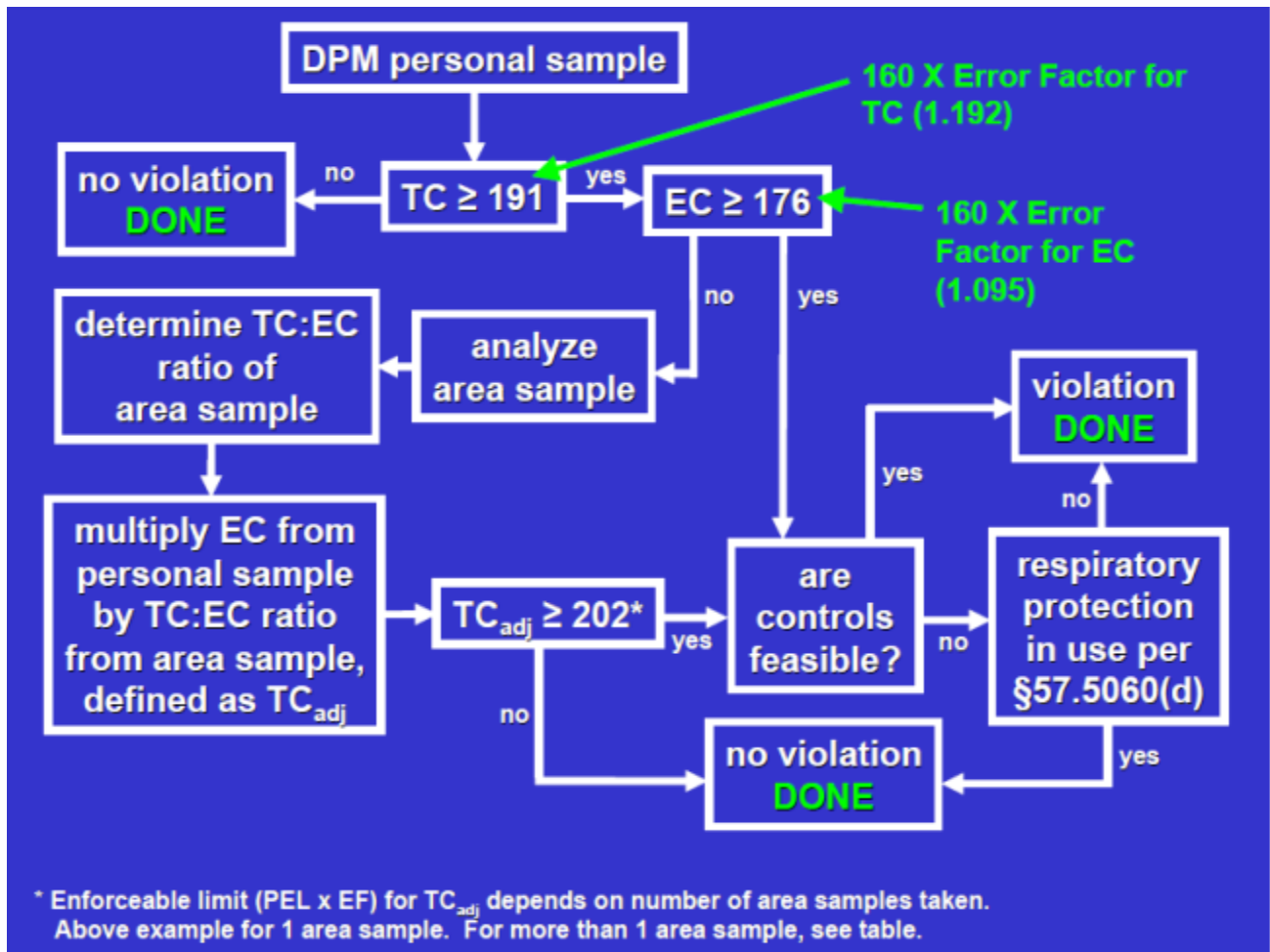


Figure 3.9 Flow Chart of the MSHA Enforcement Process (MSHA, 2013)

3.6 Development of Occupational Exposure Limits (OELs)

An Occupational Exposure Limit (as a generic term) is defined as a Time-weighted average concentration of an air pollutant at the workplace for a conventional 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed without adverse health effects.

Any OEL is not an absolute value that defines a safe or unsafe condition and is often, to the untrained, treated as an absolute value. To this end one of the global organisations that studies and develops OELs (or Threshold Limit Values), The American Conference of Governmental Industrial Hygienists (ACGIH),

makes the following statement on their publications such as the TLV Book (ACGIH, 2013).

“ACGIH® TLVs® and BEIs® are health-based values. ACGIH® TLVs® and BEIs® are established by committees that review existing published and peer-reviewed literature in various scientific disciplines (e.g., industrial hygiene, toxicology, occupational medicine, and epidemiology). Based on the available information, ACGIH® formulates a conclusion on the level of exposure that the typical worker can experience without adverse health effects. The TLVs® and BEIs® represent conditions under which ACGIH® believes that nearly all workers may be repeatedly exposed without adverse health effects. They are not fine lines between safe and dangerous exposures, nor are they a relative index of toxicology. The TLVs® and BEIs® are not quantitative estimates of risk at different exposure levels or by different routes of exposure.

Since ACGIH® TLVs® and BEIs® are based solely on health factors, there is no consideration given to economic or technical feasibility. Regulatory agencies should not assume that it is economically or technically feasible for an industry or employer to meet TLVs® or BEIs®.”

Most organizations that conduct epidemiological or toxicological studies on the human health impact of exposure to a harmful agent will invariably provide guidance for protection based solely on health considerations, the Diesel Emissions in Miners study conducted their studies on the same basis, and their finding will be expanded on further in this section.

The ACGIH follows a defined system to develop their TLVs with committee and Board Approval required at critical steps. The flow chart below will be used to briefly describe the process.

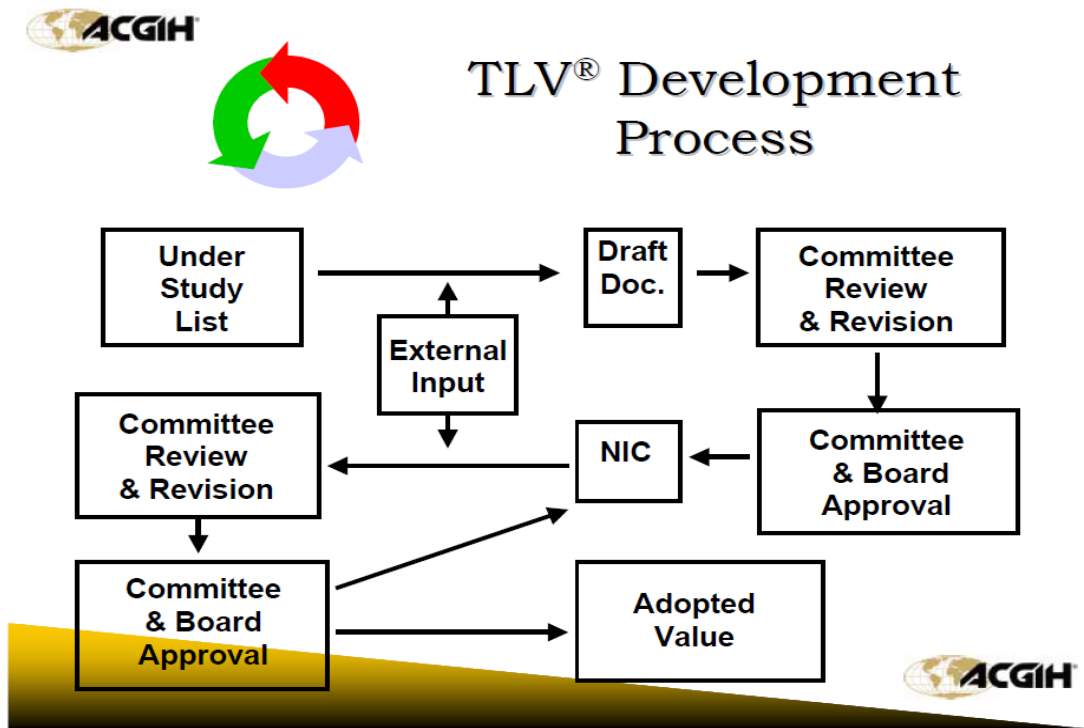


Figure 3.10 ACGIH - TLV Development Process

The ACGIH creates various committees focusing on various health risks (biological, airborne, chemical substances or physical agents etc.), these committees will decide on what they wish to focus on based on the availability of scientific data, number of workers exposed or the existence of a TLV, once agreed the substance will appear in the Under Study list.

Through a consultation process including external parties, a draft document is drawn up and after the committee reviews the draft document is sent for Board approval to be published as a notice for intended change. The committee will then further consult and obtain external input, revise and review all inputs and obtain Board approval to publish as adopted values in the TLV and BEI book.

There are a few organisations, worldwide, that independently set OELs; many countries substantially follow the methodology and guidelines from the EU SCOEL, German DFG, UK HSE, US ACGIH or US OSHA.

A practical issue is discussed on the issue of contribution of politics, economics and toxicology in the setting of consensual exposure limits (Dieter et al, 2001). The authors describe a process where after the scientists have determined what the maximum safe limits are that society still has the option to freely decide on what the limit should be i.e. between the maximum safe limit as proposed by the scientist and the minimum concentrations that will be guided by the economics and technology. In any event, the ALARA (as low as reasonably achievable) principle is advocated to ensure all factors are considered.

The International Council on Mining and Metals provides guidance to the mining and metals companies on the setting and use of OELs (ICMM 2007, p.4). Their guidance is based on the goal of being able to achieve a global harmonised approach to setting OELs which would ensure that sound reasoning considers scientific, socioeconomic and technical issues in the OEL setting and adoption process.

The ICMM's proposal for harmonised setting of OELs has the following core deliberations:

- “• Literature review of relevant scientific data according to standardized criteria
- Evaluation of literature review according to standardized criteria
- Selection of critical health endpoint(s)
- Determination of whether critical effects are threshold/non-threshold
- Selection of key studies for OEL
- Selection of point of departure
- Selection of factors influencing uncertainty

- Application of individual uncertainty factors to each such influencing factor
- Determination of composite uncertainty factor
- Identification of non-scientific influences on development of OEL
- OEL
- Discussion on the availability and accuracy of sampling technology
- Documentation and publication of all key steps, above”

These steps indicate the OEL setting process is thorough to ensure that transparency is maintained and the end goal of protecting workers health is achieved when the derived OELs are implemented.

Of critical importance is an understanding of the dose-response relationship, which many of the epidemiologic studies attempt to establish. These studies are then further evaluated by organisations like the ACGIH who then recommend exposure levels.

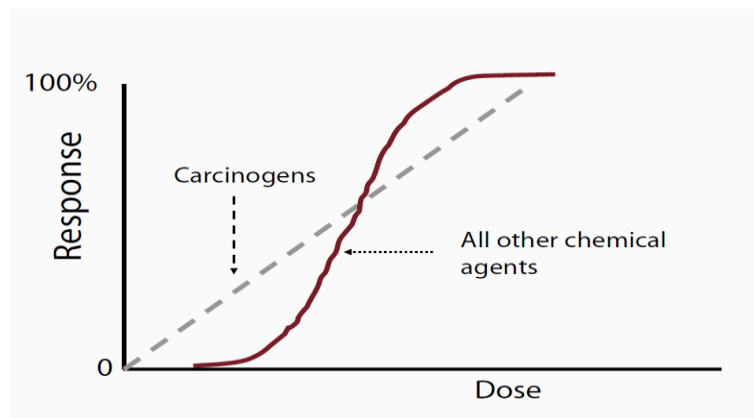


Figure 3.11 Typical Dose–Response relationships for chemical substances.

With the dose–response relationship it must be noted that with all other chemical agents there is a “safe” dose before the chemical effect causes harm whereas with carcinogens any dose will increase the risk and the greater the dose the greater the risk (Links JM, 2006).

It is worthy of repeating at this point that the International Agency for Research on Cancer (IARC) in June 2012 declared diesel exhaust to be a Group 1 Human carcinogen (IARC Press Release No.213, 2012), this category is used when there is sufficient evidence of carcinogenicity in humans. Diesel Particulate Matter (DPM) is a constituent of diesel exhaust.

The Diesel Exhaust in Miners Study (DEMS project Attfield *et al*)^{3,5}, comprises of many parts, the key studies for consideration here are the cohort and nested case control study within the 12 315 workers exposed to diesel exhaust in eight mining facilities. The cohort study indicated a higher lung cancer mortality risk associated with the highest diesel emission exposed workers, primarily underground workers, and also some evidence of lung cancer on surface-only workers from diesel emission exposure. The nested case-control study found a statistically significant exposure–response relationship demonstrating a steep increase in lung cancer risk with increasing exposure in the low to moderate exposure range followed by a levelling out and then a decrease in risk amongst the heavily exposed subjects.

In both studies, the exposure lagged 15 years, lagging is an analytic technique that removes from consideration exposures in the year's just preceding death which are likely to be too recent to be responsible for cancer. It is generally accepted that approximately 15 to 20 or more year's exposure is required to develop lung cancer. The strongest associations in this study were observed when exposures lagged for 15 years. Table 3.6 below provides a comparison between Cohort and Case-control study results in the diesel exhaust in miners study using hazard and odd ratios.

“An odds ratio (OR) is a measure of association between an exposure and an outcome. The OR represents the odds that an outcome will occur given a particular exposure, compared to the odds of the outcome occurring in the absence of that exposure.” (US National Library of Medicine, 2013)⁵⁶

Odds ratios are used to compare the relative odds of the occurrence of the outcome of interest (e.g. lung cancer), given exposure to the variable of interest (e.g. diesel particulate matter). “The odds ratio can also be used to determine whether a particular exposure is a risk factor for a particular outcome, and to compare the magnitude of various risk factors for that outcome.

- OR=1 Exposure does not affect odds of outcome
- OR>1 Exposure associated with higher odds of outcome
- OR<1 Exposure associated with lower odds of outcome”

The Hazard Ratio or relative risk (RR) is the risk of an event (e.g. developing lung cancer) relative to exposure and is a ratio of the probability of the event occurring in the exposed group versus a non-exposed group. (US National Library of Medicine, 2013).

Cumulative REC mg/m ³ -y quartiles.	Hazard Ratio, based on 15 year lagged REC cumulative exposure (DEMS Cohort Study)	Odds Ratio (OR), based on 15 year lagged REC cumulative exposure (DEMS Nested Case- control study)	Odds Ratio (OR), based on 15 year lagged REC cumulative exposure (DEMS Nested Case-control study) – After smoking removed from model.
<0.108	1.0	1.0	1.0
0.108 to < 0.445	1.50	2.11	1.94
0.445 to <0.946	2.17	3.48	2.42
≥ 0.946	2.21	5.90	3.75

Table 3.6 DEMS Comparison between Cohort and Case-control results

Table 3.7 below is reproduced from the United States Federal register on the regulations relating to DPM exposure of underground metal and non-metals

miners, it compares from various studies, the excess lung cancer death per 1000 exposed workers at various exposure levels of total carbon (US Federal Register 2001)⁴⁷. These studies were based on a 45 year occupational exposure (starting work at age 20 and ending at age 65), the lifetime risk was adjusted for other risks of death and calculated through to 85 years of age.

Study and Statistical Model	Excess Lung Cancer Deaths per 1000 Occupationally Exposed Workers ¹			
	200 µg/m ³	500 µg/m ³	644 µg/m ³	808 µg/m ³
Säverin et al. (1999)				
Poisson, full cohort	15	44	61	83
Cox, full cohort	70	280	422	577
Poisson, subcohort	93	391	563	693
Cox, subcohort	182	677	761	802
Steenland et al. (1998)				
5-year lag, log of cumulative exposure	67	89	95	101
5-year lag, simple cumulative exposure	159	620	721	771
Johnston et al. (1997)				
15-year lag, mine-adjusted	313	724	770	800
15-year lag, mine-unadjusted	513	783	811	830

¹ Assumes 45-year occupational exposure at 1920 hours per year from age 20 to retirement at age 65. Lifetime risk of lung cancer adjusted for competing risk of death from other causes and calculated through age 85. Baseline lung cancer and overall mortality rates from NCHS (1996).

Table 3.7 Lifetime excess risk of lung cancer at specific DPM exposure levels

In South Africa, the Leon Commission of Inquiry of 1994 examined occupational health and safety in the South African mining industry. The main focus of occupational health activity on the mines prior to the Leon Commission was on compensation for disease rather than prevention. (Hermanus, 2005). The applicable mining law, namely the Minerals Act concentrated predominantly on the safety issues in the mining industry with no specific provisions for promoting

occupational health. These deficiencies in the Minerals Act provided the impetus for the Commission to recommend the following:

- drafting of a new Mine Health and Safety Act (MHSA, 1996) to provide the comprehensive legal framework for creating a healthy and safe working environment;
- restructuring of the enforcement agency;
- promulgating of regulations and protective measures to protect the health of workers including occupational hygiene and medical surveillance programmes with specific reference to tuberculosis;
- restructuring of research institutions and health information systems; and
- ensuring appropriate training and certification of all workers in the industry.

The Mine Health and Safety Act (MHSA) came into effect on 15 January 1997 replacing the Minerals Act 50 of 1991 as the legal basis for regulating occupational health and safety and has established a number of tri-partite institutions for on-going consultation between the employers, employees and the government. The Mine Health and Safety Council (MHSC) was established to advise the Minister of Minerals and Energy on all aspects of safety and health in the mines. (Hermanus, 2005)

The Act requires the Council to establish and co-ordinate the activities of the three permanent tripartite committees. These are the Mining Regulation Advisory Committee (MRAC); the Mine Occupational Health Advisory Committee (MOHAC); and the Safety and Mines Research Advisory Committee (SIMRAC).

It is within these permanent tri-partite committees that the various new policies and regulations are developed, stakeholders consulted with and the Minister advised on policy and regulation. The Mine Health and Safety Inspectorate (MHSI) does have a Policy Unit which prepares the initial research or discussion document (through internal consultation) which then is discussed at the MOHAC, MRAC and then through the Legal Drafting Committee (LDC), gets approved by

the MHSC and then the Minister of Minerals Resources is advised for regulation promulgation. It must be noted that the Chief Inspector of Mines is also the chairperson of the MHSC.

The MHSI uses a four step approach in developing policy, which generally follows the accepted public policy development pattern of collection of evidence, research, analysis, consultation and creation of policy options. The MHSI's four step process is summarised in the table below:

Step in Process	Key activities
1 – Issue Identification	Defining the problem or issue. Confirming the problem definition and risks of inaccuracies. In the case of diesel exhaust this would mean defining the risks associated with exposure to diesel exhaust and DPM, also that diesel exhaust is now declared a carcinogen.
2- Issue Analysis	Understanding the problem, comparative data analysis, type of comparative data. In the current context this would mean conducting similar research that has been done in the report, using local and international relevant data and experience.
3- Generating Solutions and Policy Options	Creating a conceptual framework identifying expected outcomes and solutions, separating policy option from policy implementation options, and generating general assessment criteria. With regard to DPM this could mean the difference between setting and OEL (policy option) to prescribing or advising on minimum standards to control exposure such as use of diesel particulate filters (policy implementation).
4 – Performance Monitoring	Measuring the performance of a policy, selecting performance indicators. Again with DPM this could mean setting up systems to monitor exposure levels or the reduction in the number of cases of lung cancer of time (after expected lag periods)

Table 3.8 MHSI four-step approach in developing policy (MHSI, July 2009)²⁹

This process has begun, with a draft position paper on Diesel Particulate Matter being developed and circulated to the MHSC; the input was largely based on the document developed by the Chamber of Mines, Group Environmental Engineers representatives on MOHAC.

Table 1.1 provides some guidance on exposure levels that are currently used internationally, the sampling and analysis of DPM is now established and routine, the issue that persists is the few accredited laboratories that are able to analyse for DPM according to the NIOSH 5040 method. Of importance in setting an OEL for compliance is the ability to measure against the set OEL, the limit of detection on this analytical method is 0.003 mg/m^3 , the range that was studied in developing the standard varied between 0.023 mg/m^3 and 0.24 mg/m^3 elemental carbon, total carbon is derived.

3.7 Development of Tailpipe emission standard

(DieselNet, 2013)

As mentioned previously, DPM is regulated via two mechanisms i.e. occupational health and safety standards and tailpipe emission standards. The development of OELs has been discussed at length in the previous section and is normally the primary regulated control measure.

Tailpipe emission standards specify the maximum concentration of pollutants in diesel exhaust that may be discharged from a diesel engine. The duty to comply with these tailpipe emission standards normally rests with the original equipment manufacturer (OEM) and diesel engines would have to be certified for emissions by an accredited testing facility before being sold.

The Mine Safety and Health Administration (USA) and Natural Resources Canada have a diesel engine testing and approval process for use in mines. The Canadians approve their engines in accordance with the appropriate CSA standards:

- CAN/CSA-M424.2-M90 for non-gassy underground mines, or
- CAN/CSA-M424.1-88 for coal and other gassy mines.

Engine exhaust emissions are determined in the same manner for both standards, including the effect of any after-treatment devices on emissions.

MSHA also follows a regulated process in testing and approval of diesel engines for uses in mines and both the US and Canada publishes lists of approved engines.



Figure 3.12 MSHA Diesel engine testing facility

Once an engine is tested and approved a nameplate is affixed onto the engine stating the following:

- The engine approval number
- The required ventilation flow rate
- Engine rated power

- Rated speed
- High idle speed
- Maximum altitude before fuel deration
- Engine model number

Of importance is that the required ventilation flow rate is determined by the DPM emission rate and the minimum air volume required to dilute to an acceptable level.

The trade off-between having a diesel engine that has high emission levels and one that has substantially reduced emissions (through other control measures such as diesel particulate filters) is in the volume of ventilation air required to dilute the tailpipe DPM emission to accepted or regulated exposure levels. It has been recommended that diesel engines in coal mines do not exceed an DPM emission rate of 2.5 g/h. Should all diesel engines be able to meet this stringent standard of 2.5 g/h, the dilution ventilation requirements could be substantially reduced i.e. $2.5 \text{ g/h} = 20\,000 \text{ mg per 8 hours}$ and based on an OEL of 0.4 mg/m^3 (OELs are based on time weighted averages over 8 hours), the mine ventilation required to dilute the 20 000 mg down to $0.4 \text{ mg/m}^3 = 20\,000 / 0.4 = 50\,000 \text{ m}^3 / 8 \text{ hours}$ or $1.7 \text{ m}^3/\text{s}$. To dilute the 20 000 mg to 0.16 mg/m^3 would require $4.3 \text{ m}^3/\text{s}$ of mine ventilating air.

Table 1.4 provides some guidance on tailpipe emissions standards for diesel engines that are currently used internationally (DieselNet,2013).

3.8 Evaluation of dilution ventilation recommendations

Diesel exhaust emissions are produced at different levels due to varying load and idle conditions, equipment age and condition, state of maintenance and operator factors such as driving style.

A summary of dilution ventilation requirements is provided in the table 3.9 below.

Country	Type of Mine	Minimum dilution ventilation m ³ /s per kW	Other comments
Australia			
New South Wales	Coal	0.1 (all emissions)	0.06 m ³ /s/kW or 3.5 m ³ /s for gaseous emissions
Queensland	Coal	0.040	Minimum airflow 2.5 m ³ /s
South Australia	All mines	0.032	Minimum airflow 2.4 - 4.7 m ³ /s
Victoria	All mines	0.031	Minimum airflow 2.4 - 4.7 m ³ /s
Western Australia	All mines	0.063	Minimum airflow 2.4 - 4.7 m ³ /s
Canada			
Manitoba	Not specified	0.047	
Newfoundland	Not specified	0.050	
Ontario	Not specified	0.060	
Quebec	Not specified	0.092	
Saskatchewan		0.063	
Yukon Territory		0.047	0.05 m ³ /s per person and max velocity 2.5 m/s
Chile	Not specified	0.134	For 0.08% < CO < 0.12%
Columbia	Not specified	0.089	For CO<0.08%
Germany			
Lower Saxony	Coal	0.057	
North Rhine-Westphalia		0.068	CO <0.06%
	Non gassy	0.092	For 0.06% < CO < 0.08%
	Hard coal	0.137	For 0.08% < CO < 0.12%
Ireland	Non hard coal	0.063	
India	Hard coal		Min airflow 2.83 m ³ /s
Korea	Coal		0.05 m ³ /s per person
Mexico	Coal	0.268	0.05 m ³ /s per person
New Zealand	Coal		Min airflow 4.7 m ³ /s

Philippines	Not specified	0.047	Min airflow 0.33 m ³ /s
Romania	Coal Coal Coal		CO < 0.06%, min airflow 0.05m ³ /s For 0.06% < CO < 0.08%, min airflow 0.067 m ³ /s For 0.08% < CO < 0.12%, min airflow 0.100 m ³ /s
South Africa	All mines	0.06 to 0.1	Recommended by the Mine Ventilation Society of South Africa(MVSSA, November 1999) ¹⁹
Spain	Not specified	0.240	
Sweden	Not specified	0.034 to 0.169	Depends on fuel and airway size
United States	All mines		Equipment tested for minimum air quality to reduce the highest gaseous emission [CO, NO, NO ₂ , or CO ₂] to its safe level for 8 hour exposure [ACGIH]. Defined as 'nameplate' quantity to be delivered to operating equipment. Nameplate quantities for approved equipment range from 0.02m ³ /kW to 0.07m ³ /s
Zambia	All mines	0.05	

Table 3.9 Minimum recommended dilution ventilation rates m³/s/kW

Source: (DEEP) Diesel Emissions Evaluation Program, DieselNet, 2013 (www.dieselnet.com), (Department of Mines and Petroleum, Western Australia 2013), (New South Wales Department of Primary Industries, NSW, 2008) and personal contacts.

MHSA also specifies minimum air quantity to achieve Diesel Particulate Matter [DPM] level of 1.0 mg/m³[range is from 0.01 m³/s/kW to 0.18 m³/s/kW]. Current proposal relates to DPM level of 0.16 mg/m³. As a general reference, about 16.6 m³/s of air is required to dilute one gram per minute of DPM to 1,000 µg/m³ (MSHA 1997)³².

Canada has similar certification rules but generally higher than MHSA [e.g. Deutz BF6M 1013: MHSA – 0.29 m³/kW Canmet – 0.059 m³/kW].

Other countries [e.g. Germany, Austria] specify DPM levels; these have to be complied with by ventilation and filtration.

South Africa has legislation for gases at present but no legislation for DPM. The legislated gas limits are listed in table 3.10 below.

Substance	OEL	OEL-STEL/OEL-C
CO	30 ppm	100 ppm [OEL-C]
CO ₂	5000 ppm	30 000 ppm [OEL-C]
NO _x	25 ppm	35 ppm [OEL-STEL]
So ₂	2 ppm	5 ppm [OEL-STEL]

Table 3.10 South African regulated exposure limits for gases

Research in Australia (Davies B, 1998 and 2003) has indicated that thermal stratification can occur where large vehicles are operating; DPM levels from many vehicles in a heading (an area being mined) appear to be more than the sum of each engine (i.e. act synergistically) and the use of diesel engines should be based on the available ventilation at the sites of operation to reduce exposure.

The exhaust location on the diesel vehicle also plays a major role in reducing an employee's exposure to DPM. The location could be such that exhaust is directed away from the vehicle operator (MSHA, 1997) and this is in line with the observation made by Kay in SIMRAC Study Health 824 (Kay SA, 2002).

Therefore, to reduce DPM concentrations significantly in underground mines through ventilation, it may be necessary to supply air quantities in excess of those currently being used.

CHAPTER 4: DISCUSSION

4.1 Significance of IARC Declaration – Diesel Exhaust carcinogen

The International Agency for Research on Cancer (IARC), made the declaration regarding the carcinogenicity of exposure to diesel exhaust (including DPM) in June last year, has confirmed what many organisations, including IARC, had suspected for decades. Organisations such as the American Conference of Governmental Industrial Hygienists (ACGIH), the National Institute for Occupational Safety and Health and many other have over time rated diesel exhaust as a suspected or probable human carcinogen.

This declaration forces many countries and employers globally where the possibility of exposure to diesel exhaust and DPM exist to take measures to inform affected persons (employees or members of the public), control exposure by setting standards for exposure, implementing engineering controls and monitoring exposure levels. Alternatively, to change their modes of transport from diesel based to electric.

In South Africa, this declaration will place additional pressure on diesel engine manufacturers to ensure that they, with respect to the mining industry, comply with section 21 of the Mine Health and Safety Act (Act 29 of 1996 – MHSA) by engineering their products to be safe and without risk to the health and safety of employees.

Employees also, once informed, could utilise section 23 of the MHSA to withdraw from working in dangerous conditions as prolonged exposure to diesel exhaust could lead to lung cancer.

4.2 Significance of DPM Personal exposure results

In the absence of a local OEL for exposure to DPM, the exposure results for this study from the 276 samples analysed, indicates a fair degree of overexposure when compared the MSHA regulated exposure limit of 0.16 mg/m³ TC or 0.123

mg/m³ EC (based on the TC: EC ratio of 1.3) and the ACGIH recommended value of 0.02 mg/m³ EC. At Goldmine 1 the population identified as directly exposed such as diesel vehicle operators (locomotive, LHD drivers,) were mostly over-exposed on TC and to the ACGIH recommended EC limit. This mine also has a mixture (in transition) of high and low sulphur fuel. At gold mine 2, there were no average over-exposures to the MSHA standard; however the two maximum exposures were significant. This mine has only high sulphur diesel and older diesel locomotives (considered as tier 0). Gold Mine 3 only sampled diesel locomotive drivers and returned average overexposures to the MSHA and ACGIH standards.

At the mines studied and the many other mines, technical papers studied provides an indication of overexposure and clear evidence of action being taken to control exposure in that absence of any specific regulation to do so. Since about 2002 the MHSI had been engaging the mining industry on setting a regulatory mechanism for exposure to DPM, the convening of the DPM Task team was one of those initiatives at the time.

When these exposure measurement are viewed against the findings of some of the epidemiological studies, the DEMS table 3.6 and excess lung cancer deaths/1000 in table 3.7 , even at 0.2 mg/m³TC , a range of 15/1000 to 513/1000 excess lung cancer deaths were observed.

These personal sampling results and risks highlighted in the epidemiological studies clearly indicate the necessity to regulate and control exposures to diesel exhaust and DPM in South Africa.

4.3 Significance of diesel emission control testing.

One of the key issues in regulation is the technical feasibility of being able to achieve the standard OEL or tailpipe emission. The testing of some of the available diesel emission control technology was to have confidence that

equipment obtainable in South Africa could be used to reduce diesel emissions and thereby lower exposure. It was also done to compare results between technologies. It became clear that with the older engines (tier 0) that the use of lower sulphur fuel made little difference in terms of particulate emissions, however the use of diesel particulate filters did reduce the DPM emission rate. With the newer engine (tier 2), most of the technologies tested did have a positive impact on reducing diesel emissions. It must be noted that the choice of control technologies combined with adequate dilution ventilation will assist in reducing personal exposure to below OELs.

In the US and Canada there are lists of approved engines for use in mines which also specify a minimum ventilation requirement where the engine will be used, this is based on emissions testing and dilution ventilation calculations.

All emission control technologies are based on the diesel fuel and combustion process, ranging from the type of fuel to engine maintenance and exhaust after treatment devices such as water scrubbers. Some of the control technologies tested and that are available to the South African mining industry are low emissions engines, low sulphur fuel, fuel additives and alternate fuels (such as biodiesel), after treatment devices (such as diesel oxidation catalysts and particulate filters), mine ventilation, enclosed cabs in vehicles, routine and preventative maintenance on diesel engines and training as a vital part of the whole process of preventing exposure. As a last resort respiratory protective equipment could be used, the use of personal protective equipment which is low on the hierarchy of controls, the highest being elimination of the risk.

4.4 Regulatory trends on Diesel exhaust and DPM

The ACGIH withdrew its Notice of Intended changes on DPM exposure levels. The initial proposal was to reduce the TLV for DPM exposure to 0.02 mg/m³ (Elemental carbon), noting that the ACGIH focuses only on health based

standards, and currently the global mining communities are following the MSHA trends.

A listing of OELs is provided in table 1.1 with values ranging from 0.16 mg/m³TC to 0.4 mg/m³TC and 0.1 mg/m³EC to 0.3 mg/m³EC. In the USA the exposure limit for EC is based on a TC: EC ratio of 1.3, hence their EC exposure limit is 0.123 mg/m³ EC. These ratios have been studied and have been found to vary widely in many countries including South Africa. This will have an impact on directly adopting an international ratio based exposure level. These ratios for the South African context is discussed in section 3.5 and presented in figure 3.8, in this study the TC:EC ratios ranged from 7.2 to 8.1, which does not compare well with the USA.

Of importance in setting an OEL for compliance is the ability to measure to the set OEL, the limit of detection on this analytical method is 0.003 mg/m³, the range that was studied in developing the standard varied between 0.023 mg/m³ and 0.24 mg/m³ elemental carbon, total carbon is derived. This covers the full range of OELs mentioned above.

The process of setting OELs seems fairly well defined through the agencies such as the ACGIH that will review literature and consult before adopting TLV's. The ICMM has also weighed in with a detailed process of developing OELs with a view to harmonising the process across many countries. The Department of Minerals Resources has a four-step process that it used to develop policy and regulation and together with the MHSC, they inform the Minister of Minerals Resources on issues for regulation.

Tailpipe emissions standards are recommended and regulated in certain countries, The USA and Canada have diesel engine approval programs which test diesel engine and affix a nameplate on the engine which amongst other information, include a minimum dilution ventilation quantity. Table 1.2 provides

some guidance on tailpipe emissions standards for DPM from 0.05 to 0.4g/kWh, and include MSHA's coal mine standard of 2.5 g/hr. If engines are able to meet these stringent standards, air quantities for dilution can be reduced e.g. for an engine to meet the OEL of 0.16 mg/m³TC and produces 2.5 g/hr/8hr of DPM, it would require 4.3 m³/s of air to dilute. If the same engine could be controlled better to produce 2.0g/hr/8hr –then it would require 3.4 m³/s of air to dilute, a saving of about 1 m³/s – and ventilation is expensive.

The companion information to tailpipe emissions standards would be the minimum ventilation quantity to dilute exhaust gas and DPM. Table 3.9 provides guidance on this in terms of quantity of air per kW rating of that diesel engine, these values range from 0.034 to 0.24 (on the high side), most of the values recommended did not previously cater for DPM.

The ease of enforcement of and compliance to regulatory standards is a key ingredient in ensuring the reduction of exposure and thereby protecting employees, the process by MSHA was discussed in fair detail. They have a system of taking as single shift personal sample and then through series of calculations using TC: EC ratios and error factors will decide if an overexposure has occurred before writing out a citation. This process seems fair but onerous.

4.5 Significance of Epidemiological studies

Epidemiology, as indicated in the glossary, is the study of the distribution and patterns of health-events, health-characteristics and their causes or influences in well-defined populations. It is the cornerstone method of public health research, and helps inform policy decisions and evidence-based medicine by identifying risk factors for disease and targets for preventive medicine. Over 35 epidemiological studies have been identified by the researchers on the Diesel Emission in Miners Study and have themselves produced excellent work in studying the exposure history of over 12 000 mineworkers over 15 years to

reveal strong links between exposure to diesel emissions and developing lung cancer.

The work done by epidemiologists and toxicologist provides the necessary guidance to industrial/occupational hygienists and engineers to what are possibly safe or unsafe exposures through the development of dose-response curves. These relationships also assist in setting occupational exposure limits, as in the case of DPM the DEMS (see table 3.6) study indicated a very low exposure of $<0.108 \text{ mg/m}^3\text{-y}$ EC would not produce an excess lung cancer risk. However as the cumulative exposure increased beyond $0.108 \text{ mg/m}^3\text{-y}$ the exposures were beginning to be associated with a higher odds of the disease outcome i.e. lung cancer. Further studies indicated an excess risk of death per 1000 even at the lowest DPM, total carbon exposure of 0.2 mg/m^3 of between 15 to 513 cancer deaths per 1000, (US Federal Register 2001)⁴⁷ also see table 3.7.

The dose-response curve for carcinogen indicates that there is no “safe” exposure or dose before the effects begins; a single exposure could initiate the health impact.

CHAPTER 5: CONCLUSION

Diesel exhaust emissions are carcinogenic as has been demonstrated by numerous health impact studies and the declaration by the World Health Organisation. A wealth of information exists internationally on this subject so it is easier now for South African to access this knowledge and use it to evaluate and control exposure to DPM.

Most of the health impact studies tend to indicate that the odds of developing lung cancer at much lower exposures are reduced. The methods to sample and analyse for elemental carbon (the surrogate for DPM), the NIOSH 5040 method is available and is being used at one of the accredited laboratories and by focussing on a single pollutant such as elemental carbon that is derived directly from the combustion process in a diesel engine, we could avoid the onerous enforcement methods employed in the USA and set an OEL that could be complied with and easily enforced.

The few control measures that have been tested also indicate that the technology exists to be able to meet the new OELs when proposed, although some of the older engines will need more control technology in addition to low sulphur fuel, which only becomes a standard in July 2017, as indicated by the Department of Energy. While low sulphur diesel is a control measure, a combination of control measures will be required to effectively reduce exposure to employees which ranges from exhaust filtration to provision of ventilation for dilution.

The testing of diesel engines and specifying a minimum air quantity at the point of application of the diesel engine is a good idea and could be emulated in South Africa as well, this would require industry commitment to building the test facilities and then applying the results to further reduce exposure.

The time to lobby for an OEL for exposure to DPM and to introduce tailpipe emissions standards (as necessary e.g. in coal mines) has become urgent. This

work concludes that as close to a health based OEL would be Time Weighted Average (8hr) of 0.1 mg/m³ EC, as sampled and analysed through the NIOSH 5040 method.

CHAPTER 6: RECOMMENDATIONS

6.1 Occupational Exposure Limits for Diesel Particulate Matter (DPM)

It is recommended that the Department of Minerals Resources in conjunction with the Mine Health and Safety Council give consideration to a phased approach to allow the mining industry to comply with the recommended OEL whilst improving its control measures and upgrading its diesel engine technology.

The recommendation is as follows:

- a. An OEL of 0.25 mg/m^3 TC until December 2015.
- b. An OEL of 0.20 mg/m^3 TC until December 2016
- c. From the 1st of July 2017, 0.1 mg/m^3 EC

The recommendations are designed to allow the mining industry to prepare for the stringent standard also to make use of the introduction of the low sulphur fuel specification that is expected in July 2017.

6.2 Personal Protective Equipment

The use of respiratory protection should not be seen as the final mitigation of the exposure to DPM but as an intermediate step until the appropriate engineering control has been fully implemented and is effective. It is recommended that all diesel engine operators who are not in air-conditioned (with appropriate filtration) enclosed cabs use respiratory protection, such as a FFP3 masks that provide the highest level of protection for fine particulate matter. FFP2 is the current standard for dusts in mines.

6.3 Medical Surveillance of Workers Exposed to DPM

It is recommended that baseline medical surveillance is conducted on all employees to determine the levels of the urinary metabolite 1-hydroxypyrene, as an indicator of exposure to polycyclic aromatic hydrocarbons (PAHs - a

component of DPM). 1-hydroxypyrene is a specific and sensitive indicator of exposure and is associated with high exposure. The industrial exposure reference limit for 1-hydroxypyrene is 2.34 [mol/mol creatinine]. More frequent medical surveillance should be conducted on higher exposed groups, which would possibly be the diesel engine operators and their aides. Cognisance must be taken of the synergistic effects of multiple occupational and other exposures i.e. silica, radiation, solvents etc. One method of achieving this would be to ensure a linkage exists between an employee's medical surveillance and occupational exposure records.

6.4 Future Research Needs

In conducting this research and the literature review on DPM, the following areas are highlighted for further research:

- a) Further study needs to be conducted into TC: EC ratio in the South African context under varying load cycles, fuel types and states of maintenance etc., and to see how this information can be further used to reduce exposure to employees.
- b) Investigation of the synergy of multiple exposures e.g. silica dust, DPM and Radon.
- c) Further study needs to be done on the cost of compliance to any new legislated OEL and/or tailpipe emission standard with respect to retrofitting existing fleets with control technology, replacing existing fleets with more efficient engines (higher tier rating – engine certification) or electric fleets and trade off on saving in ventilation costs and most importantly the reduction of ill health amongst employee's (both acute and chronic).

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8. APPENDICES

Appendix I - IARC, Diesel engine exhaust carcinogenic. Press release no. 213

Appendix II NIOSH 5040 Sampling and Analytical Method for Diesel Particulates

Appendix III Position Paper on Diesel Particulate Matter for the Group

Environmental Engineers (GEE) –Chamber of Mines South Africa

Appendix IV – CSIR - DPM Analysis as per NIOSH 5040 result sheet

Appendix V Research Proposal, Development of a Regulatory Mechanism for the

control of Exposure to Diesel Particulate Matter (DPM) in the South African

Mining Industry, A.R Nundlall