An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions amongst employees at selected paint manufacturing industries within eThekwini, KwaZulu-Natal, South Africa

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DECLARATION

I, Michael Brendan Kinsey, hereby declare the content of this research project is the author’s own unaided original work, except where specific indication is given to the contrary (by reference). This work has not been previously submitted to the Durban University of Technology (DUT) or any other University.

________ ________ ________11/04/2023________

M. B Kinsey (Student number: 21015825) Date

DEDICATION

I dedicate my thesis to my loving God Jehovah for guiding, blessing and providing me with the opportunity to reach this level of education. I also dedicate my thesis to the following special people:

My late grandmother (Mrs Reshinmathie Singh)

My parents (Shanthie and Kenneth Balland)

My daughter (Skylar Liana Kinsey)

and my siblings (Michelline, Meshan, Mishael and Daniel)

I would like to thank you all for the love, encouragement, support and motivation you have shown me throughout this journey.

"Trust in Jehovah with your whole heart."

(Proverbs 3: 5)

ABSTRACT

Introduction: Diesel engines have high efficiency, durability, and reliability, together with their low-operating cost. These important features make them the most preferred engines for heavy-duty applications in agriculture, construction and industry. However, diesel engines are combustion engines and emit combustion products in their exhaust gas. Pollution emitted from diesel-operated vehicles are one of the largest preventable contributors to pollution caused by exhaust emissions, which are responsible for several health problems. The pollution produced by diesel-powered vehicles occurs significantly during idling and in the process of acceleration. Diesel particulate matter (DPM) is one of the concerning pollutants created from the combustion of diesel fuel due to the size of the particles and impacts they have on the respiratory system. Epidemiological studies have provided strong evidence for associations of DPM inhalation with inflammatory lung and cardiovascular diseases. In addition, DPM is classified as a human carcinogen by the International Agency for Research on Cancer.

Methodology: The relationship between an employee's upper respiratory symptoms and diesel exhaust emitted from forklift trucks was studied in two paint manufacturing companies located in eThekwini, KwaZulu-Natal, South Africa. The study population comprised 120 employees from both paint manufacturing companies. Data collection was conducted in two phases. The first phase entailed using a questionnaire as a data collection tool to establish Objective One of the research. The questionnaire was adapted to determine if there were any existing upper respiratory symptoms related to diesel exhaust emissions (DEE) being experienced amongst the exposed group of employees. The questionnaire consisted of three sections. Section A captured the participants' biographical information such as name, age, gender, race, residential address, contact information and spoken home languages. Section B of the questionnaire captured the employees' work history information. Section C captured information related to health issues of the employees.

The second phase of the research entailed conducting personal air sampling. The purpose of the personal air sampling was to meet Objective 2 of the research, namely to quantify the level of diesel particulate matter employees were exposed to. Twenty-four personal air samples in total were taken from both paint manufacturing companies. The personal air sampling was conducted and analysed in accordance with the National Institute for Occupational Safety and Health (NIOSH) method 5040. The selection process for employees for the personal air sampling were based on their job function, source of pollution and exposure duration. Diesel powered forklift truck drivers were identified as the most exposed group of employee's. Personal air sampling was conducted over an 8-hour period.

Results: The results of the questionnaire indicated that the ratio of males to females was approximately 4:1 (78.3%: 21.7%) ($p < 0.001$). None of the respondents indicated any shortness-of-breath issues. A small number (n = 2 or 1.7%) indicated that they sometimes experienced shortness of breath whilst doing work outside of their jobs ($p < 0.001$). However, some respondents did indicate that they coughed at their work stations ($p < 0.001$). Additionally, all of the respondents (n = 120) believed that exposure to diesel powered forklifts impacted their general health. According to the Hazardous Chemical Agents regulations of South Africa, an occupational exposure limit for DPM over an eight-hour time weighted average (TWA) of 0.16 mg/m^3 was legislated. Twenty-four personal air samples were taken from the most exposed group of employees. Results of the personal air sampling indicate that DPM, measured as elemental carbon (EC), were below the occupational exposure limit of 0.16 mg/m^3 for all samples taken. The results ranged between 0.004 mg/m^3 and 0.011 mg/m^3. The results established that the most exposed group of employees, being the diesel-powered forklift truck drivers, were exposed to relatively low quantities of DPM.

Conclusion: It was concluded that based on the results of the personal air sampling for DPM, the highest risk group of employees, namely the diesel-powered forklift truck drivers were exposed to relatively low levels of diesel particulate matter. This could be due to engineering controls in place such as the use of diesel particulate filters (DPF) on the diesel-powered forklift trucks, frequencies and duration of operating the diesel-powered forklift trucks and ventilation factors as the study setting was an above-ground study conducted in open warehouses. In addition, recommendations to further reduce the exposure to DPM were made in accordance with the hierarchy of control.

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ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AED	Aerodynamic Equivalent Diameter
AhR	Aryl Hydrocarbon Receptor
ANS	Autonomic Nervous System
AP-1	Activator Protein 1
Ca	Calcium
CAA	Clean Air Act
CI	Combustion Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
Cu	Copper
CRDI	Common Rail Direct Ignition
CRP	C-Reactive Protein
DEE	Diesel Exhaust Emission
DNA	Deoxyribonucleic Acid
DPF	Diesel Particulate Filter
DPM	Diesel Particulate Matter
EC	Elemental Carbon
EGR	Epidermal Growth Receptor
EPA	Environmental Protection Agency
Fe	Iron
FFP	Filtering face piece
G-CSF	Granulocyte Colony-Stimulating Factor

g/dm^3	Grams per Decimetre
HACs	Heterocyclic Aromatic Compounds
HC	Hydrocarbons
HELF	Human Embryo Lung Fibroblasts
HVO	Hydro-treated vegetable oil
HR	Hour
IARC	International Agency for Research on Cancer
ICAM-1	Inter Cellular Adhesion Molecule 1
IgE	Immunoglobulin E
IL-1	Interleukin-1
KG	Kilogram
Km	Kilometre
L	Litre
MAPK	Mitogen- Activated Protein Kinase
MCP	Monocyte Chemotactic Protein
Mg	Magnesium
mg/m^3	Milligrams per Cubic Meter
MIN	Minute
MIP	Macrophage Inflammatory Protein
MMP	Matrix Metalloproteinase
MSHA	Mine Safety and Health Administration
MyD88	Myeloid Differentiation response gene–88
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute for Occupational Safety and Health
NLRP3	NOD-Like Receptor–Related Protein 3

NMAM	NIOSH Manual of Analytical Methods
NO	Nitrogen Oxide
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxide
NPAHs	Nitrated Polycyclic Aromatic Hydrocarbons
OC	Organic Carbon
OECD	Organization for Economic Co-operation and Development
OEL	Occupational Exposure Limit
OHS Act	Occupational Health and Safety Act
OSHA	Occupational Safety and Health Administration
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PPM	Parts Per Million
RCD	Respirable Combustible Dust
ROS	Reactive Oxygen Species
SO_2	Sulphur Dioxide
STEL	Short-Term Exposure Limit
TC	Total Carbon
Th2	T-helper type 2
TLV	Threshold Limit Value
TNF-ά	Tumour Necrosis Factor Alpha
TRPV1	Transient Receptor Potential cation channel subfamily V member 1
TWA	Time Weighted Average
USEPA	United States Environmental Protection Agency
VCAM-1	Vascular Adhesion Molecule 1

WHO	World Health Organization
Zn	Zinc
μm	Micrometre
%	Percentage
°C	Degree Celsius

LIST OF DEFINITIONS

Carcinogen	Means any chemical agent or mixture which induces cancer or increases its incidence (South Africa 1993: 219).
Diesel engine	An internal combustion engine which draws air via the throttle into the combustion chamber where it is compressed to high temperatures and pressure, then the vehicles fuel injectors simultaneously spray finely atomized fuel into the compressed air at high velocity, causing the fuel to undergo a series of spontaneous chemical reactions that result in self-ignition (Four-stroke diesel engine 2020: 1).
Diesel exhaust emissions	A mixture of organic and inorganic compounds resulting from the combustion of diesel fuel. These compounds exit a vehicle's exhaust pipe as gases and solid particles (Ilar, Plato, Lewne, Pershagen and Gustavsson 2017: 1).
Diesel particulate matter	Diesel particulate matter (DPM) is a complex, multi-pollutant mixture of solid and liquid particles suspended in a gas, resulting from the combustion of diesel fuel. The particulate fraction of the diesel exhaust aerosol consists of a solid carbon phase and ultra-fine droplets of a complex mix of semi-volatile organic compounds (Jin, Qua, Liu, Gao, Wanga, Zhang, Bai and Xu 2013: 655).
Elemental carbon	Elemental carbons are the pure carbon particles that account for a greater fraction of DPM mass and hence

	are the basic building blocks of DPM (Apicella, Mancaruso, Russo, Tregrossi, Oliano, Ciajolo and Vaglieco 2020: 2).
Health	A state of complete physical, mental and social well-being and not merely the absence of disease or infirmity (The World Health Organization 2014:1).
Nano particles	Nano particles are particles smaller than 100 µm that can enter the bloodstream and which are potentially harmful to health (Kima, Kabir and Kabir 2015:2).
Occupational Exposure Limit (OEL)	A limit value set by the Minister, which represents the airborne concentrations of a hazardous chemical agent, where the standards of exposure may be an eight-hour time weighted average, a ceiling limit or a short- term exposure limit. (South Africa 1993: 219).
Occupational Ceiling Limit (CL)	A maximum or peak airborne concentration of a hazardous chemical agent over the shortest analytically practicable period of time, which does not exceed 15 minutes (South Africa 1993: 219).
Occupational eight-hour time weighted average (TWA)	The maximum average airborne concentration of a hazardous chemical agent when calculated over an eight-hour working day, for a five day working week (South Africa 1993: 219).
Occupational short-term exposure limit (STEL)	Means the time weighted average maximum airborne concentration of a hazardous chemical agent when

calculated over a 15-minute period (South Africa 1993: 219).

Organic carbon Organic carbon is the group of complex compounds found in DPM, including Hydrocarbons, such as aldehydes and higher concentrations of polycyclic aromatic hydrocarbons, but excludes inorganic substances such as sulphates and also elemental carbon (Apicella *et al*. 2020: 2).

Total carbon The carbon compound found in diesel emissions are known as total carbon (TC), which is a combination of organic carbon and elemental carbon and usually makes up to 85% of diesel particulate matter (Apicella *et al*. 2020: 2).

CHAPTER 1

INTRODUCTION

1.1 Introduction to the study

Particulate matter found to enter the respiratory system during breathing is divided into three groups, namely inhalable, thoracic and respirable particles, which are potentially harmful to health if deposited in the lungs or airways (Armah *et al.* 2021:2). Resitoglu, Altinisik and Keskin (2014: 15) stated that diesel engines have high efficiency, durability and reliability together with their low-operating cost. These important features make them the preferred combustion engine. In addition, Knothe, Gepen and Krahl (2005: 25) stated that diesel fuel's durability, high torque capacity and fuel efficiency ensured its role in the most demanding application and became the preferred choice of fuel to power diesel engines, which have been the engine of choice for heavy-duty applications in mining, agriculture, construction and industry.

However, diesel engines are considered one of the largest contributors to pollution caused by the exhaust emissions which are responsible for several health problems. Currie, Zivin, Mullins and Neidell (2014:16) stated that most of the pollution produced by diesel powered vehicles occurred during idling and in the process of acceleration. Furthermore, Chen *et al* (2017:2) stated that pollution emitted from diesel operated vehicles is one of the leading preventable threats to global health.

Moreover, Wierzbicka, Nilsson, Rissler, Sallsten, Xu, Pagels, Albin, Osterberg, Strandberg, Eriksson, Bohgard, Rynell and Gudmundsson (2014:213) stated that levels of occupational exposure to diesel engine exhaust emissions, namely diesel particulate matter, are usually higher than the general population. In addition, Li, Yang, Xu, Xu and Hong (2015:1360) stated that occupational exposure to diesel particulate matter (DPM) may be higher when workers are close to the emissions source. Retrospective studies within South African mines have shown that employees are exposed to significantly high levels of diesel particulate matter emitted from the underground mining diesel powered machinery (Pretorius *et al.* 2017: 301).

Research on the above-ground occupational setting relating to DPM exposure is of vital importance as studies have shown that exposure to DPM had adverse effects on the respiratory health of employees (Ali, Liu, Yousaf, Ullah, Abbas and Munir 2018:3; Wu, Jin and Carlsten 2018: 834; Kima *et al.* 2015:136 and Ristovski, Milevic, Surawski, Morawska, Fong, Goh and Yang 2012: 204). The size of DPM particles had a direct link to their potential for causing respiratory health problems (Kima *et al.* 2015:136; Ristovski *et al.* 2012: 204; Dobrzynska, Szewczynska, Posniak, Szczotka, Puchalka and Woodburn 2019:1 and Ehsanifar, Azami, farzadki, Rezaei, Salami, Zavareh, Nikzaad and Jonidi 2019:338).

Anderson, Thundiyil and Stolbach (2012:166) stated that the World Health Organization (WHO) estimates that emitted particulate matter (PM) pollution contributes to approximately 800 000 premature deaths each year, ranking it as the 13th leading cause of mortality worldwide. Studies show that the relationship is deeper and far more complicated than originally thought. The United States Mine Safety and Health Administration (MSHA) issued a final ruling for US metal and non-metal mines. In this ruling, MSHA requires that mines meet a limit of exposure of 0.40 mg/m^3, although the American Conference of Governmental Industrial Hygienists (ACGIH) suggested a Threshold Limit Value (TLV) of 0.02 mg/m^3. According to the Hazardous Chemical Agents regulations of South Africa, an occupational exposure limit over an eight-hour time weighted average (TWA) of 0.16 mg/m^3 has been recommended (South Africa 1993: 236).

1.2 Background to the problem

The study was conducted at two paint manufacturing companies within the eThekwini Municipality, KwaZulu-Natal, South Africa. The research site provided employment to individuals from various surrounding communities such as Kingsburgh, Umbumbulu, Umlazi, Isipingo, Chatsworth, Durban, Pinetown and Phoenix. The first paint manufacturing plant was Company A, situated 24 kilometres (kms) south of the central business district (CBD) of eThekwini. The second paint manufacturing plant was Company B, situated 11 kms south of the CBD of eThekwini.

These paint manufacturing companies were selected as they operate and repair diesel-powered forklifts on site. Company A had 175 employees, while company B had 168 employees. The researcher identified the different work areas within each paint plant. The work areas identified were raw material stores, distribution warehouse and repairs workshop. Employees working within these areas were identified as the exposed group of employees and were included in the study. This group of employees make up the study population for the research. The researcher was motivated to pursue this study due to the retrospective research indicating that a correlation exists between diesel exhaust emissions and respiratory health effects thereof (Kima *et al.* 2015:136; Dobrzynska *et al*. 2019:1 and Ehsanifar *et al.* 2019:338). In addition, research related to diesel particulate matter is of vital importance due to diesel exhaust fumes being classified as a Group One carcinogen by the International Agency for Research on Cancer (IARC) (Wierzbicka *et al*. 2014:213). Figure 1 below depicts a map indicating the research sites within eThekwini.

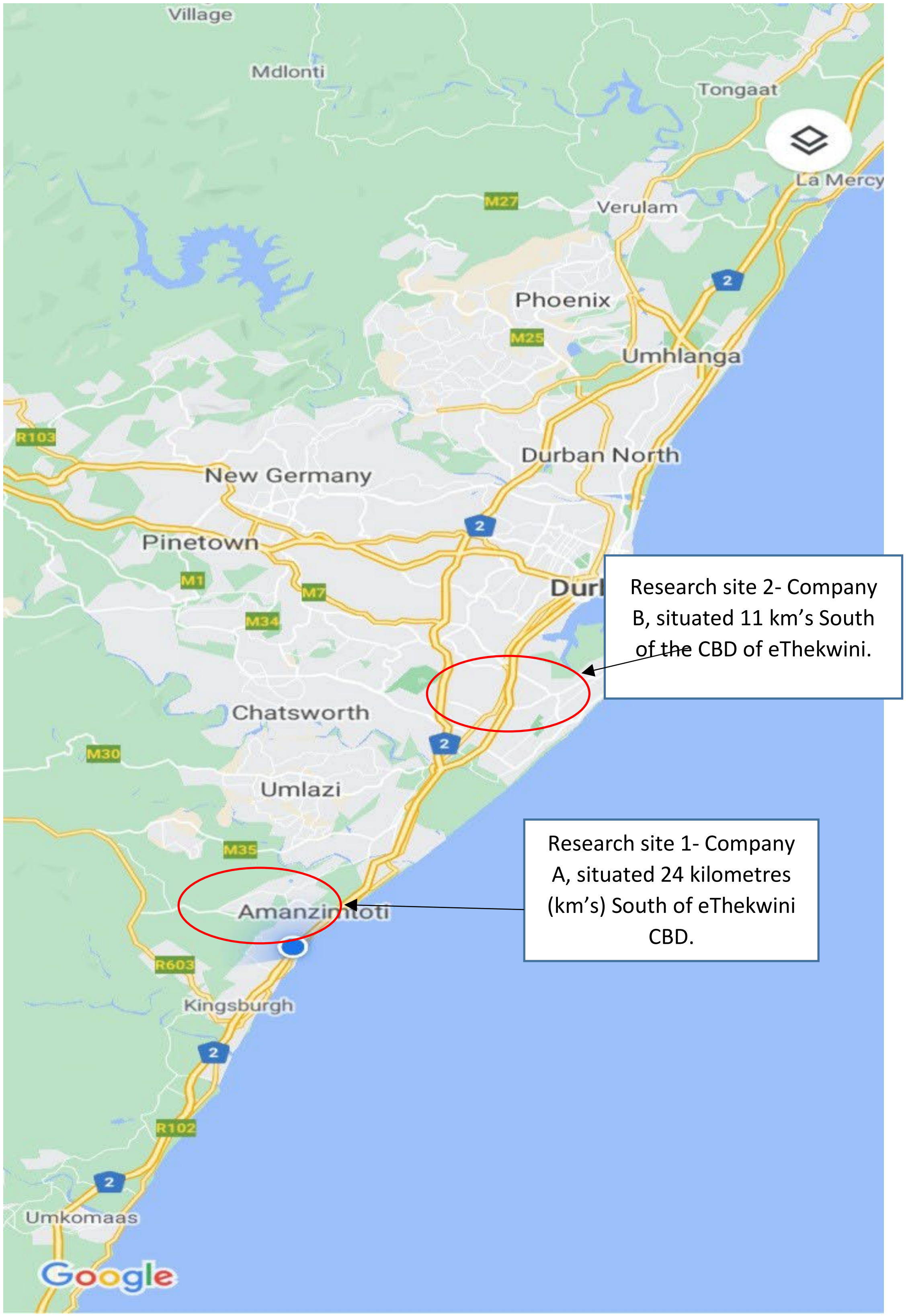

Figure 1: Map indicating research sites within eThekwini (World beach guide:1).

1.3 Rationale for the study

The research will benefit future employees exposed to diesel exhaust emissions in the different occupational setups where diesel powered machinery is utilized. According to the Hazardous Chemical Agents regulations of South Africa, an occupational exposure limit (OEL) for DPM over an eight-hour time weighted average (TWA) of 0.16 mg/m^3 was recommended. This study hopes to shed light on the negative health impacts associated with exposure to diesel particulate matter and the importance of having more stringent regulatory measures in place in South Africa to lower the current OEL limit for DPM. In addition, this study aims to determine current and new measures for the reduction and control of DPM. This study further aims to establish new themes for further research on exposure to DPM.

1.4 Significance of the study

According to CAREX Canada (2017:1), occupations that may be exposed to diesel exhaust from the use of on-road engines include bus and subway drivers, bus garage workers, trucking company workers, forklift operators, fire-fighters, lumberjacks, toll-booth operators and parking garage attendants. In addition, Dobrzynska *et al* (2019:1) stated that with prolonged exposure to diesel engine exhaust fumes, the risk to human health increases and can have a negative impact on the development and functioning of the nervous system, and can lead to asthma, respiratory and cardiovascular diseases or even cancer.

According to Wu, Jin and Carlsten (2018: 834), epidemiological studies have provided strong evidence for associations of DPM inhalation with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence of the adverse effects related to short-term exposure, whereas fewer studies have addressed the longer-term health effects. Short-term exposure to DPM has been associated with significant increases in hospitalizations, emergency department visits or home medical visits, mainly for chronic obstructive pulmonary disease (COPD), asthma and pneumonia.

1.5 Research problem

The prolonged and continuous operation of diesel-powered forklift trucks within the paint manufacturing industry, along with poor maintenance, ventilation, age of the vehicle and few to no exposure reduction measures in place, have a direct impact on the respiratory health of the exposed and most exposed group of employees. Exposure to DPM could potentially contribute to the prevalence of upper respiratory symptoms associated with DPM and ultimately impact on the health and well-being of the exposed.

1.6 Purpose of the study

The purpose of the study was to establish the existence of a co-relation between the data obtained in the health questionnaire on DPM associated respiratory symptoms and the quantified emissions obtained from personal air sampling of the most exposed group of employees. In addition, the study aims to identify regulatory and mitigating measures for the reduction of exposure to DPM.

1.7 Aim and Objectives

1.7.1 Aim

To investigate the upper respiratory symptoms and exposure to diesel particulate matter amongst employees.

1.7.2 Objectives

In order to achieve the aim of the study, the following objectives were identified:

I. To determine the existence of upper respiratory symptoms related to DPM exposure amongst the selected group of employees;

II. To quantify the level of DPM the selected group of employees were subjected too; and

III. To make recommendations to mitigate DPM exposure in the workplace.

1.8 Limitations

a) The study was carried out at one point in time and gives no indication of the sequence of events, whether exposure occurred before, after or during the onset of the outcome of the study.
b) The study investigated the current respiratory health of employees. It is not the intention to infer causality.
c) The studies scope did not include analysing exposed employee's medical files to validate answers received within the health questionnaire.

1.9 Exclusion

The study population has excluded all security, visitors and administrative support employees due to their functions and site situation from sources of DPM.

1.10 Conclusion

This chapter has introduced the study, its background and aims and objectives. It created the context within which the researcher conducted the investigation. The next chapter reviews current and retrospective literature on DPM, the various emissions emitted from diesel engine exhausts and the related health effects to the upper and lower respiratory system due to DPM exposure.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Diesel engines are widely used in transport and power supply, making occupational exposure to diesel exhaust common. Both human and animal studies associate exposure to diesel exhaust with inflammatory lung effects, cardiovascular effects, and an increased risk of lung cancer (Taxell and Santonen 2017: 243). A study in the United States in 2015 found that some 385 000 people have died prematurely from air pollution related to vehicle exhaust emissions. Diesel vehicles were responsible for 47% of those deaths, and the figure increased as high as 66% in France, Germany, Italy and India where diesel- powered engines make up a large proportion of engines used (Anenberg, Miller, Henze, Minjarese and Achakulwisut 2019:2). Research from a study carried out by Harvard University in collaboration with the University of Birmingham, the University of Leicester and University College London found that more than 8 million people died in 2018 from fossil fuel pollution, significantly higher than previous research suggested, meaning that air pollution from burning fossil fuels like coal and diesel was responsible for about 1 in 5 deaths worldwide (Vohra, Vodonos, Schwartz, Marais, Sulprizio and Mickley 2021: 2).

Employees are exposed daily to unknown quantities of diesel exhaust emissions from diesel powered forklift trucks. These emissions are composed of various gases and particulate matter which are toxic and have an adverse impact on the health and well-being of those being exposed. In addition, diesel engine emissions are shown to be a respiratory irritant, aggravate asthma in patients suffering from asthma and could cause chronic obstructive pulmonary disease (COPD). In addition, Dobrzynska *et al* (2019:1) and Ehsanifar *et al* (2019:338) stated that prolonged exposure to diesel exhaust fumes can impact on the development and function of the nervous system.

A literature review was completed to substantiate the potential respiratory effects of diesel engine exhaust emissions exposure within the above-ground occupational environment. The literature review established all emissions emitted from diesel engine exhausts and the health effects associated with the upper and lower respiratory system. However, the review focused more on determining diesel engine exhaust emissions, namely diesel particulate matter (DPM) and the health effect it had on the upper respiratory system. DPM is a measurable indicator for diesel exhaust emissions. In addition, this chapter aimed to review retrospective and current studies within this field of research, national and international research, exposure limits and to establish mitigating measures of reducing occupational exposure to diesel particulate matter respectively.

2.2 THE INTERNAL COMBUSTION ENGINE

2.2.1 Invention of the diesel engine

It is to a large part the invention of thermal engines, first the steam engine in the eighteenth century, then the internal combustion engines in the nineteenth century that made globalization possible and the economic, social and governmental structures one lives in cannot be imagined without the engine-driven industry and transportation (Steiner *et al*. 2016: 1541).

Mirriahi (2017: 1) stated that prior to 1894, diesel fuel was regarded as an unwanted by-product of the crude oil refining process. According to Mollenhauer and Tschoeke (2010: 3) Rudolph Diesel, a young German student who studied at the Polytechnikum München, a university in Nuremberg, Germany, later re-named the Technische Hochschule, where he graduated in 1880 as the best examinee ever up to that time, discovered that the steam engine which was the dominant heat engine of the day, wastes a tremendous amount of energy.

In addition, the steam engine had been discovered to produce vast amounts of smoke which polluted the air and environment when measured against the ideal energy conversion cycle formulated by Carnot in 1824. Rudolph Diesel later designed the very first combustion engine which required only compressed air and a highly combustible fuel, namely the distillate or the once wasted by-product of the crude oil refining process (Tschoeke 2010: 3). Early diesel engines were large and operated at low speeds due to the limitations of their compressed air-assisted fuel injection systems.

In its early years, the diesel engine was competing with another heavy fuel oil engine concept- the hot-bulb engine invented by Akroyd-Stuart. High-speed diesel engines were introduced in the 1920s for commercial vehicles such as submarines and ships applications and in the 1930s the use in locomotives, trucks, heavy equipment and electricity generation plants followed. Thereafter, the use of off-road diesel engines became widespread between the 1930s and 1950s (Dieselnet 2018: 1).

Of all existing internal combustion engines, the diesel engine is amongst the most popular and is therefore of great concern with respect to the environment and public health. After its invention in the late 1890s, the diesel engine rapidly evolved into a prominent technology for heavy-duty applications in the stationary, marine, railroad and military sectors, but at first did not feature heavily in the private transportation sector (Steiner *et al*. 2016: 1542).

However, it was in the late 1980s, with the adaptation of turbochargers and the development of a common rail direct injection systems that diesel engines were made feasible for the light-duty and the private transportation sectors. Since then, diesel engines' popularity has continuously increased, to a large part certainly due to obvious reasons such as their higher durability and higher fuel efficiency compared to petrol cars (Steiner *et al*. 2016: 1542). Off-road applications of diesel engines usage included diesel powered heavy equipment, locomotives, tractors, forklift trucks and generators in the mining industry (Pronk, Coble and Stewart 2009: 445).

Resitoglu *et al* (2014: 15) stated that diesel engines have high efficiency, durability and reliability together with their low-operating cost. These important features make them the most preferred engines. In addition, Knothe *et al* (2005: 25) stated that diesel's durability, high torque capacity and fuel efficiency ensured its role in the most demanding applications and became the preferred choice of fuel to power diesel engines, which have been the engines of choice for heavy-duty applications in the agriculture, construction and industry environments.

However, diesel engines are considered as one of the largest contributors to pollution caused by exhaust emissions, which is responsible for several health problems (Mohankumar and Senthilkumar 2017:1228, Wierzbicka *et al.* 2014:213 and Armah *et al.* 2021:2). In addition, Steiner *et al* (2016: 1541) highlighted in their research that despite all the great advantages of diesel engines, the downside of these internal combustion engines is evident, i.e. their iniquitousness has created one of the major challenges for the environment and the effect on human health due to emissions on a regional scale and the earth's climate on a larger global scale.

2.2.2 Operating principal of a diesel engine

Combustion ignition (CI) or diesel engines operate on the principle of internal mixture preparation, whereby fuel is injected into the combustion chamber and subsequently has to mix with an oxidant (i.e. intake air) before combustion can commence. As a result, the CI engine combustion process is characterized by a great degree of heterogeneity, a process that is described as diffusion flame combustion due to the requirement of this air fuel mixing process. Diffusion flame combustion is the primary cause of particulate emissions in a CI engine (Ristovski *et al.* 2012: 201, Mohankumar and Senthilkumar 2017:1228 and Steiner *et al.* 2016: 1542).

Knothe *et al* (2005:26) highlighted that the operating principles of diesel engines are significantly different from those of the spark-ignited engines. In a spark-ignited engine, fuel and air that are close to the chemically correct or stoichiometric mixture are inducted into the engine cylinder, compressed, and then ignited by a spark. The power of the engine is controlled by limiting the quantity of fuel to air mixture that enters the cylinder using a flow-restricting valve called a throttle.

However, in diesel engines, also known as compression-ignited engines, only air enters the cylinder through the intake system (Four-stroke diesel engine 2020: 1). This air is compressed to a high temperature and pressure, and then finely atomized fuel is sprayed into the air at high velocity. When it contacts the high-temperature air, the fuel vaporizes quickly, mixes with the air and then undergoes a series of spontaneous chemical reactions that result in a self-ignition or auto ignition. In addition, Knothe *et al* (2005:26) stated that when auto ignition occurs, the portion of the fuel that had been prepared for combustion burns very rapidly during a period known as premixed combustion. Figure 2 below depicts the basic operating principal of a diesel-powered engine.

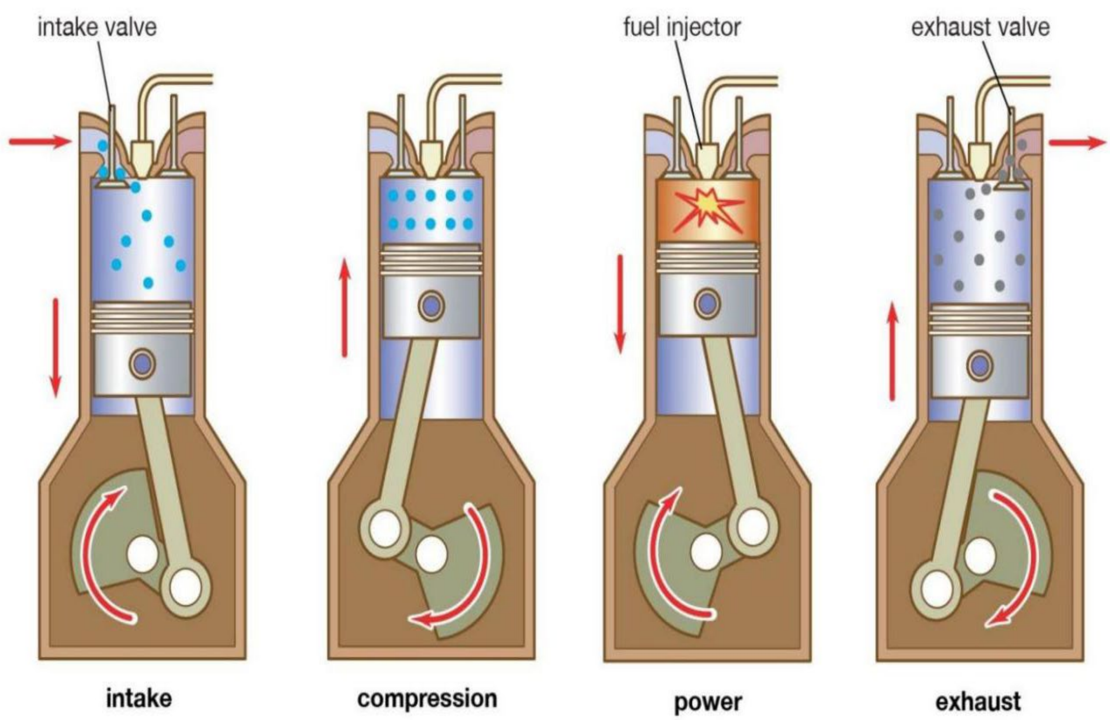

Figure 2: The operating principle of a diesel (combustion) engine (Four-stroke diesel engine 2020: 1).

2.2.3 Diesel exhaust process

Once the fuel that had been prepared during the ignition delay is exhausted, the remaining fuel burns at a rate determined by the mixing of the fuel and air. This period is known as mixing-controlled combustion. The heterogeneous fuel to air mixture in the cylinder during the diesel combustion process contributes to the formation of soot particles, technically known as diesel particulate matter (Guild, Ehrlich and Johnston 2001: 90).

In addition, Ilar *et al* (2017: 1) stated that emissions from diesel fuelled vehicles constitute a mixture of organic and inorganic compounds, occurring as gases as well as solid particles. Although Sydbom, Blomberg, Parnia, Stenfors, Sandstrom and Dahlen (2001: 733) stated that complete combustion of diesel fuel produces water and carbon dioxide, the use of diesel fuel within a diesel motor normally results in incomplete combustion and the formation of various gases, liquids and solid particles.

2.2.4 Diesel exhaust gaseous composition

Steiner *et al* (2016: 1543) and Taxell and Santonen (2017:243) stated that the gaseous exhaust fraction of diesel exhaust consists of approximately 99% by volume of non-toxic inorganic gases such as nitrogen, water and oxygen. Toxic inorganic gases such as carbon dioxide (CO_2), carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO_2) and a complex mixture of organic compounds account for the remaining percentage.

The organic fraction consists of small molecules such as methanol, ethylene or formaldehyde but mainly of larger aliphatic compounds and more complex molecules such as benzene, naphthalene, pyrene, anthracene and their various functionalised derivatives, collectively referred to as polycyclic aromatic hydrocarbons (PAHs), nitrated polycyclic aromatic hydrocarbons (NPAHs) and heterocyclic aromatic compounds (HACs). In addition, it has been estimated that diesel engine exhaust emissions contain approximately 20000 different chemical compounds (USEPA. 2017:1).

2.2.4.1 Carbon monoxide

According to Sydbom *et al* (2001: 734), diesel exhaust emissions contain a complex mixture of gases such as carbon monoxide (CO). CO is a result of the incomplete combustion of natural gas and any other material containing carbon such as gasoline, kerosene, oil, diesel fuels, coal or wood (Zhong *et al.* 2017: 864 and Guild *et al*. 2001: 93). Carbon monoxide is emitted from all transportation sources including passenger cars, trucks, buses, motorcycles and industrial driven vehicles (WHO 2018: 38).

According to OHSA (2018: 1), CO is a poisonous, colorless, odorless and tasteless gas. In addition, Guild *et al* (2001: 93) stated that one of the main reasons CO is so dangerous is due to its ability to interfere with the blood's ability to transport oxygen. Although it has no detectable odor, CO is often mixed with other gases that do have an odor. In addition, one can inhale carbon monoxide right along with gases that one can smell and not even know that CO is present (Carbon monoxide poisoning 2018:1).

Sandilands and Bateman (2016: 151) stated that engine exhaust fumes, in the absence of a catalytic converter, is a common source of CO emissions. In addition, the World Health Organization's (WHO) guidelines for carbon monoxide exposure are expressed at four averaging times, as follows: 100 mg/m^3 for 15 minutes (min), 60 mg/m^3 for 30 min, 30 mg/m^3 for 1 hour (hr) and 10 mg/m^3 for 8 hrs (WHO 2018: 70). According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:233), the OEL for CO over an 8 hr TWA is set at 50ppm.

2.2.4.2 Carbon dioxide

Carbon dioxide (CO_2) is a colorless, odorless, nonflammable gas that is soluble in water, with a molecular weight of 44 Da and density of 1.977 g/dm^3, and is a byproduct of the combustion and fermentation of organic matter (Podlewski *et al.* 2017:135). According to Guild *et al* (2001: 93), beside CO_2 being odourless and colourless, it is said to have a slightly acidic taste when in contact with the mouth. In addition, it was found that the occupational exposure to CO_2 is very common due to diesel exhaust fumes in heavy-duty vehicles such as forklift trucks found within factories (Podlewski *et al*. 2017:135).

CO_2 levels are of importance as research and evidence by Kirikkaleli and Adebayo (2021:30139) indicate that CO_2 emissions globally are rising to alarming levels. According to Ram (2019: 231), CO_2 is neither a direct nor indirect health hazard in normal concentrations of 500-1200 ppm. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:233), the OEL for CO_2 over an 8hr TWA is set at 10000ppm.

2.2.4.3 Sulphur dioxide

Sulphur dioxide (SO_2) is a gas primarily emitted from fossil fuel combustion at power plants and other industrial facilities, as well as fuel combustion in mobile sources such as locomotives, ships, and other diesel powered equipment. Guild *et al* (2001: 95). According to Miller (2017: 107), SO_2 tends to occur in the same kinds of atmospheres as particulate matter and high humidity such as emissions from diesel engines. Scientific evidence links SO_2 exposure with adverse impacts on the respiratory system (Sulphur dioxide 2018:1). In addition, Guild *et al* (2001: 95) stated that SO_2 gas is dangerous to the eyes as it causes irritation and inflammation of the conjunctivae.

In recent reviews of the standard, EPA has determined that even short-term exposure to high levels of SO_2 can have a detrimental effect on breathing function, particularly for those that suffer from asthma (Geravandi *et al.* 2015: 1 and Gorguner and Akgun 2010: 31). SO_2 also reacts with other chemicals in the air to form tiny sulphate particles, contributing to levels of particulate matter with a micrometre size of 2.5 ($PM_{2.5}$) (Sulphur dioxide 2018:1). According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:249), the OEL-STEL/C is set at 0.5 ppm.

2.2.4.4 Oxides of Nitrogen exposure

Gorguner and Akgun (2010: 31) highlighted that the oxides of nitrogen, i.e. nitrogen oxides, are composed of a mixture of nitrogen and oxygen types of gases. The most toxicological nitrogen oxides are nitrogen monoxide (NO) and nitrogen dioxide (NO_2), both of which are non-flammable and colourless to brown at room temperature. In addition, these gases are present in the exhaust of diesel-powered engines and these fumes cause irritation to the nose, throat and windpipe (Guild *et al.* 2001: 95).

However, when this gas is inhaled, it mixes with moisture in the lungs and damages the tissue which results in bleeding and an accumulation of fluid in the lungs (Guild *et al.* 2001: 95). Millions of workers face fatal respiratory injury when they are exposed to NO_x or any of these gases. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:245), the OEL- over an 8hr TWA for NO and NO_2 are set 50 ppm and 0.4 ppm.

2.2.4.5 Polycyclic Aromatic Hydrocarbons exposure

Polycyclic aromatic hydrocarbons (PAHs) particulate emissions originate from high temperature combustion of fossil fuels (pyro synthesis of aromatic compounds), unburned fuel and lubricating oil (Alves *et al*. 2015: 11535). Although PAHs in diesel engine exhaust emissions are not currently regulated, they are considered to be amongst the greatest threats to human health since many are known to cause cancer, DNA damage and genetic mutations (Xiangzhi *et al*. 2015: 1360). In addition, Guild *et al* (2001: 90) stated that included amongst the PAH in DPM, is benzo-a-pyrene, which is one of the most powerful carcinogens known to man.

2.2.4.6 Diesel particulate matter

Anderson, Thundiyil and Stolbach (2012:167) stated that the sources of man-made diesel particulate matter (DPM) include combustion in mechanical and industrial processes and vehicle emissions. Furthermore, Ristovski *et al* (2012: 201) critiqued that vehicle emissions are the predominant source of DPM emissions and diesel engines, in contrast to petrol engines, emit a larger mass of DPM and number of particles, typically by factors of 10–100. However, Jin *et al* (2013: 655) stated that diesel engines emit up to 100-150 times more particulates and up to two to twenty times more oxides of nitrogen than petrol-driven engines.

According to Armah *et al* (2021:2), Mensah *et al* (2020:2) and Ristovski *et al* (2012: 200), diesel particulate matter consists of carbon monoxide, carbon dioxide, hydrocarbons, oxides of nitrogen, ash, metallic abrasion particles, sulphates and silicates. Traditional diesel exhaust systems are the main source of exposure due to partial combustion, with a minimal fraction of DPM from gaseous condensation within the exhausts.

According to Jin *et al* (2013: 655) and Wheatley and Sadhra (2004:369), DPM is a complex, multi-pollutant mixture of solid and liquid particles suspended in a gas. The particulate fraction of the diesel exhaust aerosol consists of a solid carbon phase and ultra-fine droplets of a complex mix of semi-volatile organic compounds. In addition, Ristovski *et al* (2012: 203) stated that diesel particles consist of many primary carbonaceous particles that agglomerate together to produce a complex, fractal-like morphology.

Moreover, Anderson, Thundiyil and Stolbach (2012:167) argued that DPM can be described by its aerodynamic equivalent diameter (AED). Particles of the same AED will tend to have the same settling velocity. Researchers traditionally sub-divide particles into AED fractions based on how the particles are generated and where they deposit in human airways: <10, <2.5, and <0.1 micrometer (µm) (PM_{10}, $PM_{2.5}$, and $PM_{0.1}$, respectively).

Particles with a diameter greater than 10 µm have a relatively small suspension half-life and are largely filtered out by the nose and upper airway. DPM with a diameter between 2.5 and 10 µm ($PM_{2.5–10}$) is defined as coarse particles, less than 2.5 µm as fine particles and less than 0.1 µm as ultrafine particles (Anderson, Thundiyil and Stolbach 2012:167). Figure 3 below illustrates the size of diesel particulate matter in contrast to other materials.

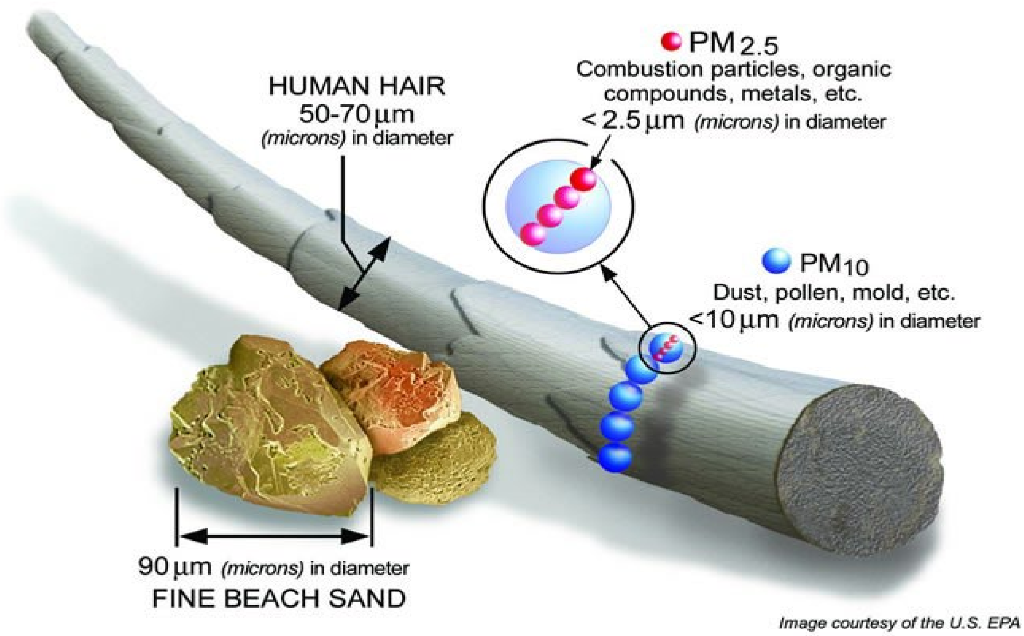

Figure 3: The size of diesel particles that are 10 µm and 2.5 µm in contrast to human hair and fine beach sand size (What is particle pollution 2018:1).

Ristovski *et al* (2012: 201) indicated that besides diesel exhaust particles being a complex, multi pollutant mixture of solid and liquid particles suspended in a gas, it is also a very dynamic physical and chemical system that exhibits very strong spatial and temporal dependency in terms of its composition. In addition, Liebenberg *et al* (2011: 20) stated that DPM is the portion of diesel engine exhaust emissions that is made up of solid carbon particles and has a surface that attacks and absorbs organic chemicals such as PAHs; condensed liquid hydrocarbons (HC); and inorganic compounds such as sulphate compounds.

The composition of diesel exhaust particles depends on many factors, namely the level of dilution and its subsequent atmospheric processing after being emitted from the tailpipe; the engine operating condition (e.g. speed/load, injection timing and strategy); the presence of after-treatment devices such as a diesel particle filters; the maintenance status of the engine; and the type of fuel and lubricants used (Ristovski *et al.* 2012: 201).

2.2.4.6.1 Elemental carbon

Pronk *et al* (2009: 443) explained that the particulate fraction is primarily in the sub-micron range and consists of an insoluble elemental carbon (EC) core and an absorbed surface coating of relatively soluble organic carbon (OC). EC is a primary pollutant directly emitted from combustion processes, such as biomass burning and fossil fuel combustion. EC consists of the refractive carbon content of the graphite like material. Furthermore, EC is commonly used as a surrogate of black carbon even though the two are typically defined quite differently by measurement methods. EC is operationally defined by different thermal or thermal/ optical measurement methods based on the thermal properties, while black carbon is often characterized or measured based on light absorbing properties (Wang, Zhang, Yao, Cheng and Zlotorzynska 2022: 2).

2.2.4.6.2 Organic carbon

Organic carbon is a collection of different non-refractive materials (Wang *et al*. 2022: 2). OC can also be emitted from primary emissions and produced from secondary organic aerosol formation (Pronk *et al.* 2009: 443). The EC and OC typically constitute 33-90% and 7-49%, respectively of the particulate mass. The opposite roles on radiative forcing between OC and EC suggest that the relative magnitudes between OC and EC (or the OC/EC ratio) have important implications for investigating climate-related aerosol effects. OC/EC ratio could provide some insights into source contributions, with a lower ratio indicating primary combustion sources and higher ratio indicating secondary organic aerosol formation (Wang *et al*. 2022: 2).

2.2.4.6.3 Total carbon

According to Pronk *et al* (2009: 443), the carbon compound found in diesel emissions, also known as total carbon (TC), is a combination of OC and EC and usually makes up almost 85% of diesel particulate matter. Elemental carbon is the pure carbon particles that account for a greater fraction of DPM mass and hence are the basic building block of DPM. Organic carbon is the group of complex compounds found in DPM, including HC s such as aldehydes and higher concentrations of PAH s, but excludes inorganic substances such as sulphates and also EC (Liebenberg *et al.* 2011: 20).

2.2.4.6.4 Metals in DPM

Furthermore, Mohankumar and Senthilkumar (2017:1228) indicated that the particulate matter in diesel exhaust emissions also contains some other metals like calcium (Ca), iron (Fe), magnesium (Mg), copper (Cu) and zinc (Zn) in their composition, which leads to several other adverse health effects. Another study indicated that the deposition of metals like iron could lead to the production of free radicals and finally cause both acute and chronic lung injuries.

Steiner *et al* (2016: 1542) stated that the exact mechanisms underlying the formation of soot are complex and only partly understood. The main pathway appears to be pyrolyzation of unburnt fuel and lubrication oil, mainly to ethyne, followed by polymerization reactions, ring closure and stacking of the resulting polycyclic, graphite-like sheets in a turbo-striated structure. In addition to the elemental carbon in the soot particles, the solid fraction of diesel exhaust contains metal and metal-oxides originating from lubrication and fuel additives and from engine wear.

2.2.4.6.5 Source of DPM

Ristovski *et al* (2012: 201) argued that the primary cause of DPM emissions is the presence of a fuel-rich mixture, characterized by a high equivalence ratio (i.e. the fuel-air ratio). Although diesel motors produce a lesser quantity of carbon monoxide than petrol motors, they release ten times the amount of nitric oxide, aldehydes and particulate matter compared to unleaded petrol engines, and over one hundred-fold more than catalysed unleaded petrol engines (Mazzarella, Ferraraccio, Prati, Annunziata, Bianco, Mezzogiorno, Liguori, Angelillo and Cazzola 2007:1156).

Chen *et al* (2017:2) found that pollution emitted from diesel operated vehicles is one of the leading preventable threats to global health. In addition, Currie *et al* (2014:16) stated that most of the pollution produced by diesel powered vehicles occurred during idling and in the process of acceleration. Moreover, Wierzbicka *et al* (2014:213) stated that levels of occupational exposure to diesel engine exhaust emissions, namely diesel particulate matter, are usually higher than the general population.

In addition, Li, *et al* (2015:1361) stated that occupational exposure to diesel particulate matter may be higher when workers are close to the emission sources. In studies by Dobrzynska *et al* (2019:2) and Karthikeyan and Prathima (2016: 3674), the authors stated that the risks associated with global warming and climate change should also be stressed. Black carbon, the major component of fine particulate matter and carbon dioxide that can be emitted in diesel exhausts, has a significant role to play in global warming (Armah *et al.* 2021:2).

Hodas, Loh, Shin, Li, Bennett, McKone, Jolliet, Weschehler, Jantunen, Lioy and Fantke (2016: 837) stated that the indoor occupational environment is of particular importance when considering the health effects associated with diesel particulate matter exposures because employees who spend the majority of their time indoors are exposed to two to three orders of the magnitude larger than exposures to outdoor emissions. According to CAREX Canada

(2017:1), occupations that may be exposed to diesel exhaust from the use of on-road engines include bus and subway drivers, bus garage workers, trucking company workers, forklift operators, fire-fighters, lumberjacks, toll-booth operators and parking garage attendants.

Pronk *et al* (2009: 443) stated that the National Institute of Occupational Safety and Health estimated that approximately 1.4 million employees in the United States were occupationally exposed to diesel exhaust between 1981 and 1983 and following a second study, it was estimated that 3 million workers were exposed to diesel exhaust emissions in 15 countries of the European Union between 1990 and 1993. Taxell and Santonen (2017:244) found that over 3.6 million workers alone are exposed to diesel engine exhaust in Europe in 2017. Occupational exposure occurs in mining, construction work, professional driving, agriculture and other activities that apply diesel-powered vehicles and tools.

Grahame, Klemm and Schlesinger (2014:627) stated that oxidative stress levels in workers at a bus depot were elevated after a workday compared to before work, and were more highly elevated at the end of a second consecutive workday than after the first workday. Relative to the general U.S. population, workers in the trucking industry most consistently exposed to higher levels of diesel exhaust had significantly elevated rates of both lung cancer and ischemic heart disease.

Pronk *et al* (2009: 454) stated that EC levels in forklift drivers at a dockyard were found between the range of 4 and 36 mg/m^3, except for one study which reported levels of 122 mg/m^3. Significantly lower EC exposure levels in dockyard forklift drivers were reported when exhaust filters were used compared with levels when no exhaust filters were used. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:236), the OEL for over an 8-hr period was set at 0.16 ppm. However, DPM is not regarded as a notation carcinogen in SA (South Africa 1993:236).

2.3 THE HUMAN RESPIRATORY SYSTEM

According to Lonescu (2013:13), respiration is the act of breathing, namely inhaling (inspiration) oxygen from the atmosphere into the lungs and exhaling waste carbon dioxide from the blood (expiration) into the atmosphere. Breathing is controlled by the autonomic nervous system (ANS), the part of the nervous system that acts automatically or outside of one's conscious control (Respiratory health 2017:1). The respiratory system comprises organs involved in breathing and consists of the nose, pharynx, larynx, trachea, bronchi and lungs.

Air is taken in by the lungs, or inhaled, for the purpose of extracting oxygen from the air. Oxygen passes through tiny vessels in the lungs called alveoli. The alveoli allow oxygen molecules to pass into the bloodstream. The oxygen molecule is then distributed to all cells in the body. When oxygen is metabolized by the body, carbon dioxide is released into the blood. The carbon dioxide waste is carried back to the lungs where it is exhaled back into the air (Respiratory health 2017:1).

Shusterman (2011: 104) stated that the nose, paranasal sinuses, Eustachian tubes and larynx form part of the upper airway structures and these structures are especially vulnerable to occupational diesel particulate matter insult and injury. In addition, the nose and upper airway play a sentinel role in the respiratory tract, alerting an individual to the qualities of the inspired atmosphere. The upper airway also clears contaminants from the inspired airstream and physically conditions inspired air before its entry into the lower respiratory tract (Shusterman 2011: 101).

In addition, Lonescu (2013: 13) stated that the respiratory system consists of two major parts, namely the upper respiratory tract and the lower respiratory tract. The upper respiratory tract consists of the nasal cavity, frontal sinuses, maxillary sinus, larynx and trachea. The lower respiratory tract consists of the bronchi, alveoli and lungs. Upon a person taking a breath, air enters the body through the mouth or nasal passage. It travels through the sinuses that help regulate the temperature and humidity of the air which flows down the throat through the larynx and trachea, and enters the lungs via tubes called main-stem bronchi.

One main-stem bronchus leads to the right lung and the other to the left lung. Within the lungs, the bronchi divide into smaller tubes called the bronchioles, which finally end in tiny air sacs called alveoli. At this level, diffusion occurs, allowing for oxygen from the alveoli to pass through the alveoli walls into the blood and for carbon dioxide to pass through the capillary walls of the alveoli for expiration. From the lungs, the bloodstream delivers oxygen to all the organs and other tissues (Lonescu 2013: 13). Figure 4 below depicts the movement of DPM from an emission source into the human body.

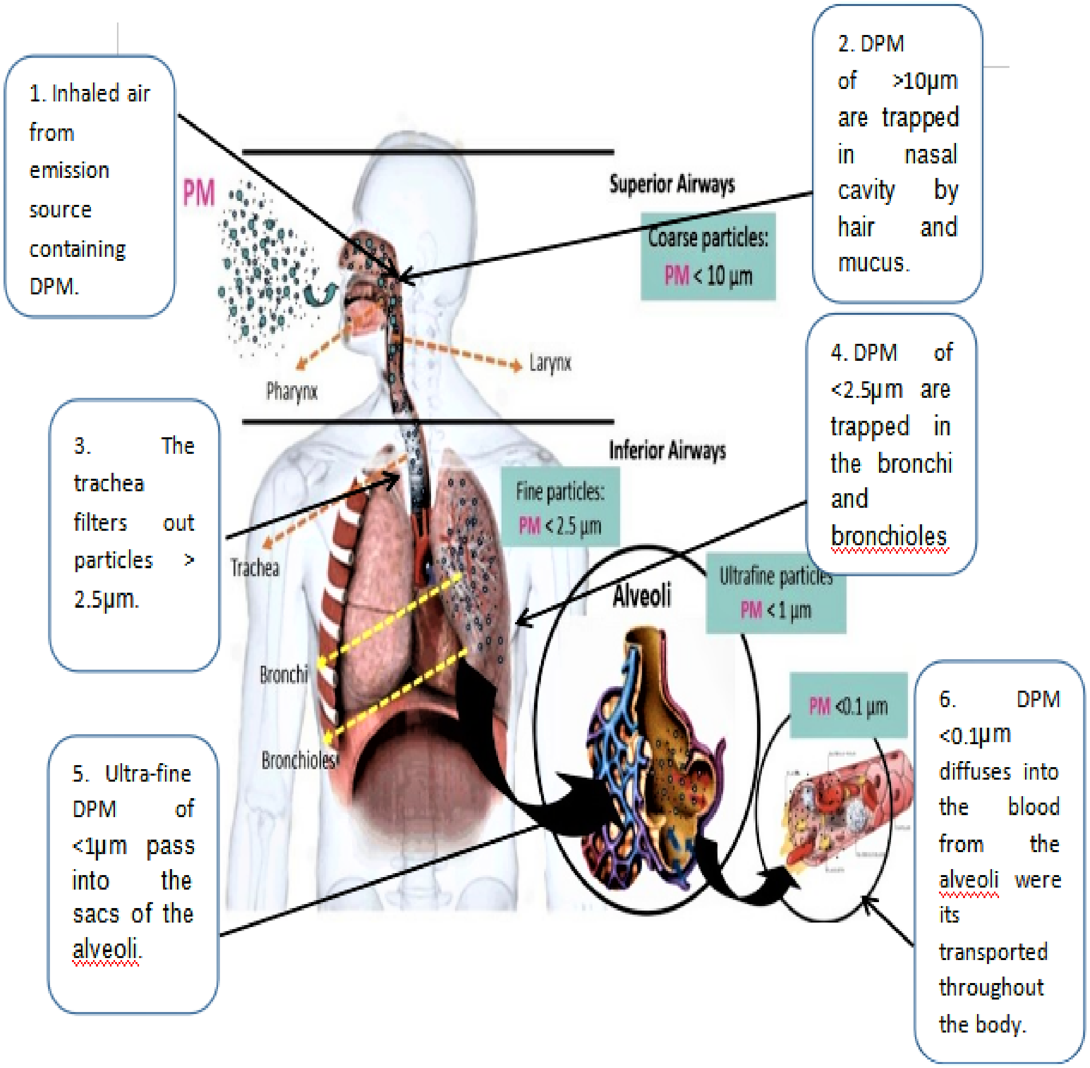

Figure 4: The movement of DPM from emission source to various parts of the respiratory system (Respiratory tract and particulate matter (PM) size classification 2017:1).

2.4 HEALTH EFFECTS

2.4.1 Diesel engine exhaust emissions exposure

Particulates found to enter the respiratory system during breathing are divided into inhalable, thoracic and respirable particles, which are potentially harmful to health if deposited in the lungs or airways (Armah *et al.* 2021:2). While the air one breathes is comprised mainly of gaseous compounds (i.e. 78% N_2, and 21% O_2), trace amounts of suspended particles (i.e. aerosols) that are present in air have a profound impact on human respiratory health.

There are a variety of anthropogenic and natural particle sources present in ambient air. Examples of natural particle sources found in air include sea spray and particles produced by marine biota, terrestrial dust, volcanoes, forests and bio-aerosols (such as fungi and pollens), whereas anthropogenic particle sources include nano-materials production, industrial processes, environmental tobacco smoke and most notably, vehicle emissions (Ristovski *et al*. 2012: 201).

2.4.1.1 Carbon monoxide

Hu *et al* (2012: 146) stated that exposure to carbon monoxide could result in upper respiratory irritation, coughing, chronic respiratory disease, acute respiratory infections and chronic bronchitis. Carbon monoxide is very harmful when inhaled due to the fact that it displaces oxygen in the blood and deprives the heart, brain and other vital organs of oxygen. Without warning, large amounts of CO can overcome a person in minutes, causing them to lose consciousness and suffocate (OSHA 2018: 2).

Besides tightness across the chest, initial symptoms of CO poisoning may include headache, fatigue, dizziness, drowsiness, general malaise, flu-like symptoms and nausea (Sandilands and Bateman 2016: 151). People suffering with angina may experience sudden chest pains. During prolonged or high exposures, symptoms may worsen and include vomiting, confusion and collapse, in addition to loss of consciousness and muscle weakness.

Symptoms vary widely from person to person (OSHA 2018: 2). CO poisoning may occur sooner in those most susceptible: young children, elderly people, people with lung or heart disease, people at high altitudes, or those who already have elevated CO blood levels, such as smokers. Furthermore, CO poisoning poses a special risk to foetuses. Carbon monoxide poisoning can be reversed if caught in time. However, even if one recovers, acute poisoning may result in permanent damage to the parts of the body that require a lot of oxygen, such as the heart and brain. Significant reproductive risk is also linked to CO. According to Sandilands and Bateman (2016: 151), rapid removal of the patient from the source of exposure is the most important aspect of reducing exposure and the effects caused.

2.4.1.2 Carbon dioxide

According to Podlewski *et al* (2017:136), the symptoms and signs of CO_2 intoxication are primarily neurological. Poisoning with carbon dioxide is usually a combination of life-threatening hypoxia and hypercapnia, which leads to impairment in the level of consciousness ranging from drowsiness and confusion to even deep coma and respiratory acidosis. Intense hypercapnia may lead to cerebral edema and paralysis of the respiratory center. In concentrations of up to

1% of total volume of air aspirated, it will make some people feel drowsy. When breathing air containing CO_2 at concentrations exceeding 5% total volume, the gas causes shortness of breath, anxiety and stimulation of the respiratory center.

Concentrations of 7–10% of total volume of aspired air may cause dizziness, headache, visual and hearing dysfunction and unconsciousness within a few minutes to an hour. Concentrations exceeding 10% total volume of air causes hallucinations and impaired consciousness, including coma and convulsions. Concentrations of more than 20% of total volume of air aspired causes death within several minutes, whereas concentrations exceeding 30% cause instantaneous death (Podlewski *et al.* 2017:136).

2.4.1.3 Sulphur dioxide

Geravandi *et al* (2015: 1) stated that SO_2 has been shown to have harmful effects on human health due to its ability to penetrate deep into sensitive parts of the upper and lower respiratory system and cause or worsen chronic obstructive pulmonary disease, bronchitis, emphysema and other respiratory diseases, leading to increased hospital admissions and premature death. In addition, Gorguner and Akgun (2010: 31) stated that SO_2 contributes to respiratory illness and aggravates pre-existing heart and lung diseases, especially asthma.

Sulphur dioxide contributes towards injury to the upper respiratory tract, including the larynx, trachea and lower respiratory tract such as the bronchi and alveoli, which occur with high exposures above 50 parts per million (ppm). Response to this substance varies in a wide range, with atopic and asthmatic subjects being the most susceptible.

Classical signs include the rapid onset of a burning of the eyes, nose and throat with associated cough, chest pain, chest tightness, dyspnea, accompanied by conjunctivitis, corneal burns and pharyngeal edema, which may be followed hours later by pulmonary edema. Bronchiolitis obliterans can develop 2 to 3 weeks after exposure (Gorguner and Akgun 2010: 31). Furthermore, Geravandi *et al* (2015: 1) stated that SO_2 exposure leads to irritation of the eyes.

2.4.1.4 Oxides of nitrogen

Breathing air with a high concentration of nitrogen oxides can irritate the airways in the human respiratory system. Such exposure over short periods can aggravate respiratory diseases, particularly asthma, leading to respiratory symptoms such as coughing, wheezing or breathing difficulties. This results in hospital admissions and visits to emergency rooms. Longer exposures to elevated concentrations of nitrogen oxides may contribute to the development of asthma and potentially increase susceptibility to respiratory infections. People with asthma including children and the elderly, are generally at a greater risk for the health effects of nitrogen oxides (EPA: United States Environmental Protection Agency 2016:1).

2.4.1.5 Polycyclic aromatic hydrocarbons

Polycyclic aromatic hydrocarbons (PAHs) are believed to cause cancer in humans (Xiangzhi *et al*. 2015: 1360). PAHs are mainly emitted from automobile exhausts. Furthermore, Xiangzhi *et al* (2015: 1365) stated that exposure to PAHs findings indicate that DNA damage is induced. However, the DNA damage was dependant on the dose and exposure period. Low concentration exposure can also damage the DNA of human embryo lung fibroblasts (HELF) cells.

2.4.1.6 Diesel particulate matter

According to Ristovski *et al* (2012: 204), the primary exposure mechanism to DPM is through inhalation. DPM is responsible for the development of upper and lower respiratory disease. In particular, a study conducted by Ristovski *et al* (2012: 201) showed that the DPM surface area and adsorbed organic compounds play a significant role in manifesting chemical and cellular processes that, if sustained, can lead to the development of adverse respiratory health effects.

The size of particles has been directly linked to their potential for causing respiratory health problems (Kima *et al.* 2015:136 and Ristovski *et al.* 2012: 204). Anderson, Thundiyil and Stolbach (2012:166) stated that the World Health Organization (WHO) estimates that emitted particulate matter (PM) pollution contributes to approximately 800 000 premature deaths each year, ranking it as the 13th leading cause of mortality worldwide. Studies show that the relationship is deeper and far more complicated than originally thought.

Kim *et al* (2017: 6) stated that DPM within the range of 10 μm leads to physical damage to the upper respiratory system such as the alveolus and larynx, and can induce oxidative stress and inflammation on respiratory organ tissue. DPM triggers pulmonary oxidative stress and inflammation. Furthermore, Anderson, Thundiyil and Stolbach (2012:166) highlighted that human airway epithelial cells exposed to DPM express inflammatory cytokines. According to Taxell and Stantonen (2017:246), recent epidemiological studies link exposure to DE to an increased lung cancer risk at relatively low (occupationally relevant) cumulative exposures. A large cohort study and a nested case control study amongst US non-metal miners demonstrated an association between retrospective estimates of cumulative respirable EC exposure and lung cancer mortality (Taxell and Stantonen. 2017:246).

According to Anderson, Thundiyil and Stolbach (2012:170), alveolar macrophages exhibit respiratory burst activity, producing reactive oxygen species, nitrogen species, and release tumour necrosis factor alpha (TNF-ά) and interleukin-1 (IL-1) after exposure. Additionally, oxidative stress generated from activation of inflammatory cells, reactive oxygen species may be directly generated from the surface of particles. These responses were shown to cause measurable pulmonary damage after only a single exposure in mice.

According to Wu, Jin and Carlsten (2018: 834), epidemiological studies have provided strong evidence for associations of DPM inhalation with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence of the adverse effects related to short-term exposure, whereas fewer studies have addressed the longer-term health effects. Short-term exposure to DPM has been associated with significant increases in hospitalizations, emergency department visits or home medical visits, mainly for chronic obstructive pulmonary disease (COPD), asthma and pneumonia (Taxell and Stantonen 2017:246).

Furthermore, Ali *et al* (2018:3) stated that studies have revealed that concentrations of DPM exceeding air quality guidelines can lead to a variety of human health problems, mostly including respiratory disorders, lungs disease, rhinitis, pulmonary diseases and heart problems. In addition, various studies conducted thus far pointed out that diesel exhaust exposure could lead to several other problems like acute eye infections, bronchial irritation, nausea, light headiness, phlegm and cough (Mohankumar and Senthilkumar 2017:1228).

2.4.1.6.1 Chronic obstructive pulmonary disorder

Chronic and continuous exposure to increased levels of air containing DPM has been related to the incidence of chronic obstructive pulmonary disorder, chronic bronchitis, asthma and emphysema (Wu, Jin and Carlsten 2018: 834, Iheanacho, Zhang, King, Rizzo and Ismaila 2020: 439 and Riley and Sciurba 2019: 786). Chronic obstructive pulmonary disease (COPD) is defined as incompletely reversible airflow obstruction associated with persistent respiratory symptoms, including dyspnea, cough and excessive sputum production (Riley and Sciurba 2019: 786).

Although more than 75% of COPD diagnoses in the United States are related to tobacco smoke, other occupational or environmental particles, or gas exposures such as diesel exhaust and smoke from indoor cooking contribute to the development of COPD. Chronic obstructive pulmonary disease is a heterogeneous syndrome caused by mechanistically distinct pathophysiological processes including innate and adaptive TH1 type immune response to toxins, microbes or autoimmunity; persistent TH2 inflammation; antiprotease deficiency; and other mechanisms affecting the airways, alveoli, or both, resulting in diverse clinical presentations, responses to treatment and patterns of progression (Riley and Sciurba 2019: 786).

A very large study in 10 US cities showed a 2.5% increase in COPD- related admissions occurs for each 10 mg/m^3 increase in PM_{10} exposure. Another US study showed that a sudden increase in $PM_{2.5}$ is associated with an increased risk by approximately 0.9% for COPD-related hospitalizations. Furthermore, a recent population-based cohort study from Canada confirms that ambient air pollution, including traffic related $PM_{2.5}$ pollution, is a risk factor for COPD-related hospitalization (Wu, Jin and Carlsten 2018: 834).

2.4.1.6.2 Health effects of metals in diesel particulate matter

Advanced research carried out to estimate the various toxic metals concentration of diesel particles indicated that these metals activated the epidermal growth receptor (EGFR) and led to increasing the levels of guanosine triphosphate bound in human lung cells. Iron and other metals like such as Cu and Zn present in particulate also leads to several problems. This metal usually occurs due to excessive wear of engine components due to improper lubrication. These metals have a great tendency to cause major injury to macromolecules by undergoing a redox-cycle, which will lead to the generation of hydroxyl radicals (Mohankumar and Senthilkumar 2017:1231).

Figure 5 below depicts the inflammatory response occurring during the inhalation of DPM. Within the figure, A elaborates the potential immuno-inflammatory and cellular interactions contribute to DPM exposure–induced inflammation. Innate cells are the first line of defence against these particles. DPM from various combustion sources causes injury in airway epithelial cells, monocytes and macrophages accompanied by TNF-α, IL-8, IL-6, IL-1β, granulocyte colony-stimulating factor (G-CSF), macrophage inflammatory protein (MIP) 3α, and monocyte chemotactic protein (MCP) 1 release, and matrix metalloproteinase (MMP) activation. These mediators can recruit neutrophils, monocytes and macrophages to the damaged tissue (Wu, Jin and Carlsten 2018: 836).

In addition, IL-4, IFN-γ induction TH1 cells, and IL-4 from the TH2 response can recruit the pathogenicity of innate immune cells and cause local inflammation. Serum levels of TNF-α, IL-8, IL-6, C-reactive protein (CRP), E-selectin, intercellular adhesion molecule 1 (ICAM-1), and vascular adhesion molecule 1 (VCAM-1) are known to cause vascular endothelial injury and further participate in CVD development. B, TLR-mediated myeloid differentiation response gene–88 (MyD88) signalling, aryl hydrocarbon receptor (AhR), and IL-1 receptor activation are associated with inflammatory cytokines generated from airway epithelial cells after combustion-derived particle exposure. DPM is known to cause airway epithelial injury through oxidative stress, and endogenous reactive oxygen species (ROS) production induces cytokines release through activating NOD-like receptor–related protein 3 (NLRP3) inflammasome, activator protein 1 (AP-1) and mitogen-activated protein kinase (MAPK) signalling (Wu, Jin and Carlsten 2018: 836).

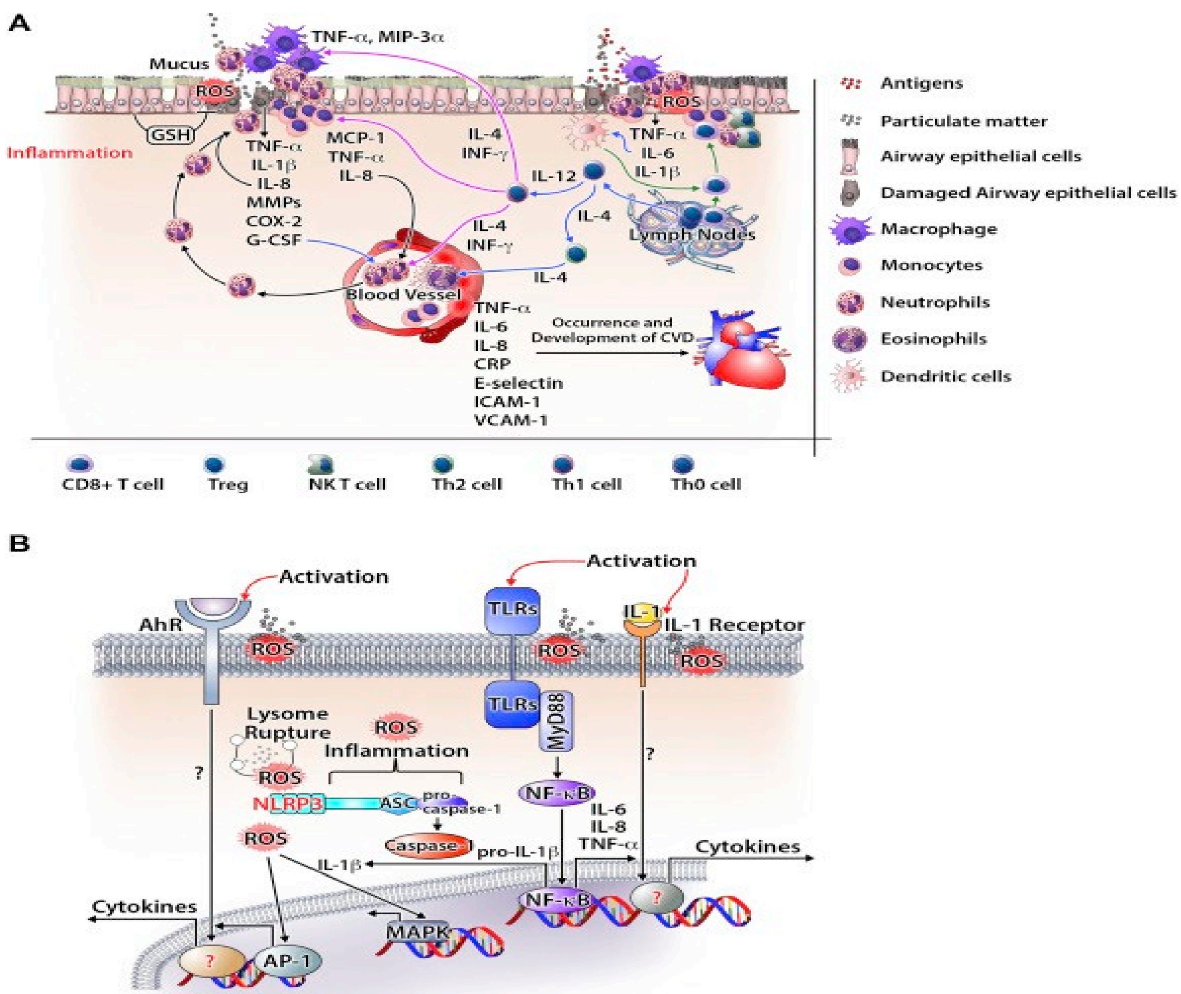

Figure 5: Cellular pathways of inflammatory effects caused by combustion-derived DPM exposure (Wu, Jin and Carlsten 2018: 836).

Moreover, this oxidative damage is associated with the primary development of occupational asthma and chronic obstructive pulmonary disease (COPD). Long-term exposure to DPM results in airway remodeling and chronic inflammation. DPM may also contribute to asthma development by enhancing atopy and Immunoglobulin E (IgE) responses. Several controlled human experiments have demonstrated adverse effects on the pulmonary system (Anderson, Thundiyil and Stolbach 2012:170). In addition, continuous and chronic exposure to diesel particulate matter contributes to the risk of developing respiratory inflammation and possibly respiratory diseases, as well as lung cancer (World Health Organization 2016:1).

According to Ping and Guang (2017: 836), animal and epidemiological studies have shown that both short-term and long-term exposure to DPM could pose a risk to health. From the animal studies, it is suspected that long-term DPM exposure can increase the risk of lung tumours. It was noted that the occupational environmental DPM concentrations are usually lower than the animal experimental DPM concentration. However, Ping and Guang (2017: 836) further indicated that long-term exposure to DPM resulted in a higher risk of lung cancer. The epidemiological studies included miners, construction, truckers and railroad workers. The relative risk of lung cancer ranged from 1.13 to 5.10 under different DPM exposure conditions.

Mazzarella *et al* (2007:1156) stated that inhaled diesel particulate matter can easily reach even the lower respiratory tract. Particles bigger than 5 μm and lower than 10μm normally do not reach the alveoli and are most likely to be wiped away by mucociliary clearance within the nasal passage and bronchial tube. To explain the acute respiratory effects caused by inhaled diesel particulate matter, the same authors suggest that transition metals (iron in particular) present in particulate matter emitted from the exhaust of diesel powered vehicles would damage airways through the induction of increased free radical's formation, which would then determine adverse respiratory effects. Diesel exhaust emission, namely diesel particulate matter, acts particularly through PAHs which deposit on the mucosa.

In addition, Bonatesta, Chiappetta and LaRocca (2014: 366) stated that pulmonary inflammation, asthma and cardiovascular conditions are some of the forty-four problems associated with the deposition of soot in the respiratory tracts. Moreover, Kumar, shadie, Buknal, Rutlighe, Garthwaite, Herbert, Halliburton, Parsons and Wark (2015:73) found that diesel particulate matter with a range of 2.5μm to 10μm coarse particles which have a higher metal content and may have a greater potential to cause injury to the airway epithelial cells of the respiratory system. It can be concluded from the various studies that DPM has the potential to cause damage to the upper and lower respiratory tract. In addition, continuous and chronic exposure to DPM could lead to one developing COPD, occupational asthma and lung cancer (Kumar *et al.* 2015:73, Wu, Jin and Carlsten 2018: 836, Anderson, Thundiyil and Stolbach 2012:170 and Armah *et al.* 2021:2).

2.4.2 Deposition of diesel particulate matter into the lower respiratory system

According to Grahame *et al* (2014:627), exhaust emissions from diesel engines are especially rich in ultra-fine particles and therefore may contribute greatly to health effects. Ultra-fine particles (particles with a diameter of less than $PM_{0.1}$) are of specific concern because their small size engenders them with a large reactive surface area and allows them to penetrate deep into the respiratory tract. Furthermore, Ali *et al* (2018:3) stated that ultra-fine particles have the ability to penetrate deep into lungs, thereby posing a high health risk, and they are more toxic as compared to other particles. In addition to a possible affection of lung cancer, diesel particulates have also been found to increase the risk of bladder cancer (Mohankumar and Senthilkumar 2017:1228).

Moreover, Niekerk, Simpson and Fourie (2002:5) stated that over 80% of diesel exhaust particles are between 0.1 and 0.2µm in diameter and thus remain airborne for long periods of time and when inhaled, they are readily deposited in the lungs. Following inhalation and deposition of the ultra-fine particulates in the lungs, macrophages in the alveoli rapidly phagocytise the particulates using scavenger-type receptors, and migrate towards the bronco-alveolar junction. Large numbers of ultra-fine particulates seem to pose a burden on the macrophage-phagocytose system, thus resulting in an increased number of particles coming into contact with the respiratory epithelium.

According to Hosseini *et al* (2016: 2), exposure to DPM can trigger T-helper type 2 (Th2) immune responses which are directly associated with the development and exacerbation of allergic asthma. Furthermore, reported effects of inhaled diesel particles on the airways of healthy human subjects after exposure to diesel exhaust particulate for one hour included increased numbers of alveolar macrophages, T-lymphocytes and neutrophils in the broncho-alveolar lavage fluid, as well as an acute inflammatory response in the peripheral blood and airway tissue. The inflammatory indices involved peripheral blood neutrophilia, thrombocytosis, increased histamine, fibronectin, neutrophils and B-lymphocytes in the airway lumen and increased numbers of inflammatory cells in the bronchial tissue, which include neutrophils, lymphocytes and mast cells (Niekerk *et al*. 2002:5).

Additionally, Robertson, Thomson, Carter, Stott, Shaw, Hadoke, Newby, Miller and Gray (2014:12) stated that pulmonary diesel exhaust particulate increases blood pressure and has a profound adverse effect on the myocardium, resulting in tissue damage, but also increases vulnerability to ischemia-associated arrhythmia and reperfusion injury. These effects are mediated through the activation of pulmonary transient receptor potential cation channel sub-family V member 1 (TRPV1), the sympathetic nervous system and locally generated oxidative stress. Ristovski *et al* (2012: 205) stated that upon deposition of DPM in the lungs, inflammation in the lungs occurs and involves a complex set of molecular and cellular responses. The pathways associated with acute inflammation in response to particle exposure involve a carefully orchestrated sequence of events, mediated in part by chemotactic molecules (chemokines).

Upon deposition of DPM in the lungs, phagocytic cells such as neutrophils and macrophages are recruited to the foreign particle by chemokines. These particles, after being engulfed, are transported by the mucociliary escalator for removal to the gastrointestinal tract. DPM induces the release of inflammatory cytokines, such as IL-6, IL-8, granulocyte-macrophage colony stimulating factor and tumor TNF-a form immune cells (e.g. macrophages), as well as structural airway cells (e.g. bronchial epithelial cells) (Ristovski *et al.* 2012: 205).

A study concluded that long-term employment in jobs with substantial exposure to diesel exhaust could be associated with a 20–50% increase in the risk of getting lung cancer (Mohankumar and Senthilkumar 2017:1228). In addition, Taxell and Santonen (2017:247) stated that based on the available epidemiological studies that provide dose response data, the relationship between the risk ratio (RR) of lung cancer mortality and cumulative EC exposure was RR = 0.00098x µgEC/m^3-year, corresponding to 200 extra lung cancer deaths per 10 000 for career-long occupational exposure at 10 mg EC/m^3. However, other authors have shown that even short-term exposure has adverse effects on the respiratory system (Wu, Jin and Carlsten. 2018: 834, Iheanacho *et al*. 2020: 439 and Riley and Sciurba 2019: 786) and an OEL of 0.16 mg/m^3 was recommended to prevent adverse health effects (Kim *et al.* 2017: 6, Ping and Guang 2017: 836 and Armah *et al.* 2021:2).

2.4.3 Carcinogenic effects due to diesel emissions

In 1988, the National Institute for Occupational Safety and Health (NIOSH) recommended that diesel exhaust emissions maybe regarded as a potential occupational carcinogen and stated that reductions in workplace exposure would reduce the risks of cancer. However, Grahame *et* *al* (2014:620) stated that the World Health Organization has classified diesel engine emissions as carcinogenic in 2012. In addition, Wierzbicka *et al* (2014:213), Taxell and Santonen (2017: 243) and Armah *et al* (2021:2) stated that recently, diesel exhaust was classified as a group one carcinogen by the International Agency for Research on Cancer (IARC). The unique nature of diesel particulates, which have a large surface area able to further absorb toxins and include mutagenic and carcinogenic compounds such as polyaromatic hydrocarbons (PAHs), increases the likelihood of carcinogenesis (Armah *et al.* 2021:2).

According to Moolgavkar, Chang, Luebeck, Lau, Watson, Crump, Boffetta and McClellan (2015: 664), the decision to change the classification of diesel exhaust by IARC in June 2012 was based on the results of a diesel exhaust in a miner's study and other studies, in which it was concluded that there was sufficient evidence of carcinogenicity for diesel exhaust in humans and upgraded its classification of diesel engine exhaust from probably carcinogenic (Group 2A) to carcinogenic to humans (Group 1).

2.5 FACTORS INFLUENCING GREATER DIESEL ENGINE EXHAUST EMISSION EXPOSURE

2.5.1 Mechanical factors

Diesel engine emissions can be significantly affected as the engine deteriorates due to normal wear or the lack of proper service. A number of studies carried out before the wide-spread application of technologies such as engine gas re-circulation (EGR) and NOx after treatment have shown that diesel engines usually deteriorate, emitting higher DPM, CO and HC emissions and lower NOx emissions. Fuel injection system faults are the most common reasons for increased DPM emissions. For older mechanical fuel injection systems, this includes problems with the fuel injection pump such as transient air/fuel ratio control and maximum fuel stop settings. Normal engine wear can result in decreased injection pressures and delayed fuel injection timing. A number of different engine malfunctions can cause retarded or delayed injection timing, which increases DPM emissions (Dieselnet 2018: 1).

, Alves *et al* (2015: 11530) stated that modern diesel engines have extremely low diesel particulate emissions, almost at the level of the measurement error of the existing gravimetric method. However, Alves *et al* (2015: 11537) also stated that based on a study on several diesel powered vehicles in Europe, it was found that due to inappropriate maintenance, repair or use and accelerated catalyst ageing may be pointed out as possible factors justifying higher emissions emitted from diesel engines.

Moreover, Lee, Jung, Park, Ryu, Kim, Ha, Kim, Yi and Yoon (2015: 17) stated that the composition and generation of diesel exhaust varies depending on the age of the diesel engine, type of engine, fuel characteristics, driving cycle, and whether the exhaust is filtered. In addition, Alves *et al* (2015: 11527) stated that amongst other factors, the composition of diesel exhaust emissions depends on driving conditions, vehicle age and category, fuel, lubricant and after-treatment technology.

2.5.2 Occupational setting

Pronk *et al* (2009: 454) stated that the enclosure of the worksite and type of diesel equipment used are the most important determinants affecting occupational diesel exhaust emission exposure. Pronk *et al* (2009: 445) further stated that in one study it was found that EC exposure were generally higher for mechanics in stand-alone workshops. This was due to a number of factors such as ventilation, size of the workshop and the number of workers within that workspace. Moreover, Mohner and Wendt (2016: 186) found that diesel exhaust exposure was also influenced by various factors such as weather conditions, type of vehicle and ventilation. Pronk *et al* (2009: 445) further stated that colder weather, compared to warmer weather, resulted in greater personal exposure levels for mechanics.

2.6 SAMPLING METHOD FOR DIESEL PARTICULATE MATTER

2.6.1 National Institute for Occupational Safety and Health (NIOSH) Method 5040

Birch (2010:1) stated that exposure to diesel exhaust particulates and other fine particle pollution are of concern due to studies indicating that a positive link exists between airborne levels and respiratory illness and mortality. A carbon analysis method based on a thermal-optical technique was evaluated and published as Method 5040 (Annexure F) in the NIOSH Manual of Analytical Methods (NMAM). The method was initially published in 1996 and was later updated. In addition, within sample analysis, total carbon (TC), organic carbon (OC) and elemental carbon (EC) are determined (Birch. 2010:1). In addition, McLaughlin, Parks, Grubb, Mason and Miller (2020:1) stated that the NIOSH method 5040 was designed to quantify the mass of EC and OC present, which in turn is used to determine the concentration of DPM in the sampled air.

Elemental carbon is a selective marker of exposure in workplaces were diesel powered equipment is operated. In addition, elemental carbon is accepted internationally as a surrogate measure of exposure to this industrial pollutant and the NIOSH method 5040 has been used in numerous industrial hygiene surveys. The thermal optical analyser design has improved, although the operation principal remains the same. The analyser is equipped with a pulse diode laser and photo-detector that permit continuous monitoring of the sample filter transmittance (Birch 2010:1).

The NIOSH method 5040 was used retrospectively in an underground mining study in South Africa to obtain elemental carbon, organic carbon and total carbon values. This method proved reliable when correctly set up and utilized for DPM sampling (Pretorius *et al.* 2017: 301). Li *et al* (2015: 1363) stated that occupational exposure to diesel particulate matter may be high when workers are close to the source of emission. In addition, Hodas *et al* (2016: 837) stated that the indoor occupational environment is of particular importance when considering the respiratory health effects associated with diesel particulate matter exposures because employees who spend the majority of their time indoors are exposed to two to three orders of the magnitude larger than exposures to outdoor emissions.

2.7 OCCUPATIONAL EXPOSURE LIMITS FOR DIESEL PARTICULATE MATTER

2.7.1 International exposure limits

According to Anderson, Thundiyil and Stolbach (2012:167) in 1970, the Clean Air Act (CAA) was the first major American regulatory effort aimed at both studying and setting limits on emissions and air pollution. The 1970 CAA defined the National Ambient Air Quality Standards (NAAQS). These standards set limits on six primary pollutants found in air: carbon monoxide, lead, nitrogen dioxide, ozone, sulphur dioxide and particulate matter (PM). Furthermore, the United States Environmental Protection Agency (USEPA) regards diesel particulate matter amongst the top twenty air pollutants of concern for occupational exposure (Niekerk *et al*. 2002:3).

Some European countries such as Germany and Switzerland, as well as Canada and the United States, have adopted regulations that limit the exposure levels of diesel particulate matter in the workplace. In the United Kingdom, there are at present no regulatory limits for diesel particulate matter. British Columbia, New Brunswick, Quebec and Ontario have adopted a level for respirable combustible dust (RCD) to represent exposure to diesel particulates (Niekerk *et al*. 2002:3). Furthermore, Niekerk *et al* (2002: 5) stated that in 1990, the Canadian *ad hoc* diesel committee published a guideline suggesting that exposure to diesel particulate matter should be measured using the RCD method and be limited to 1.5 mg/m^3 over a normal eight-hour shift.

In a study by Wheatley and Sadhra (2004:369), it was found that in the early 2000s, there were no OEL for diesel fumes in the United Kingdom. The guidance from HSE is that adverse health effects are unlikely if exposure to CO_2 from emissions is <1000 ppm. (HSE, 1999). In Germany, however, a limit of 100 µg/m^3 EC applied, except where OC > EC, when the limit is 150 µg/m^3 TC.

In January 2001, the United States Mine Safety and Health Administration (MSHA) issued a final ruling for US metal and non-metal mines. In this ruling, MSHA requires that mines meet a limit of exposure of 0.40 mg/m^3 within eighteen months after acceptance of the tabled document. Mines would thereafter be expected to reduce exposure in order to meet a 0.16 mg/m^3 limit of exposure by January 2006 (Niekerk *et al.* 2002: 5).

The exposure limit is based on the measurement of total carbon using the NIOSH 5040 Method. The American Conference of Governmental Industrial Hygienists (ACGIH) is the organization that publishes the well-known Threshold Limit Value (TLV) guidelines on an annual basis. In 1996, the ACGIH published a notice of intended change in which a diesel particulate matter TLV of 0.15 mg/m^3 was suggested. In 1998, the ACGIH further reduced this proposed TLV to 0.05 mg/m^3. However, in 2001, the ACGIH suggested a limit of 0.02 mg/m^3 (Niekerk *et al*. 2002: 5).

According to Ping and Guang (2017: 836), in the United States, the Mine Health and Safety Administration (MSHA) published final diesel regulations for underground metal/non-metal and for underground coal mines on 19 January 2001. The MSHA recommended an interim limit for DPM concentrations at 0.4 mg/m^3. However, in 2005 MSHA changed the interim exposure limit to a permissible exposure limit and regulated the new DPM standard at 0.308 mg/m^3. However, in Australia, the official limit for DPM exposure in underground mines was still not established and varies from state to state. New regulatory agencies in Australia have adopted 0.1 mg/m^3 for underground mines (Ping and Guang 2017: 836).

The underground metal/non-metal mine rule establishes a concentration limit for diesel particulate matter and requires mine operators to use engineering or work practice controls to reduce DPM exposure to that limit. The 2001 rule introduced two DPM limits: (1) an "interim" DPM concentration limit of 400 µg/m^3 effective July 19, 2002 and (2) a final DPM concentration limit of 160 µg/m^3 effective January 19, 2006 (Emission standards 2017:1).

For the purpose of ambient sampling (according to NIOSH method 5040), DPM was defined as total carbon (TC). This definition includes both elemental and organic (i.e., hydrocarbon derived) carbon, and excludes inorganic ash and sulfates from the TLV (Emission standards 2017:1). In addition, Taxell and Santonen (2017:245) stated that the European Union has significantly reduced the emission exposure of DPM over the last decade. This is depicted in Figure 6 below.

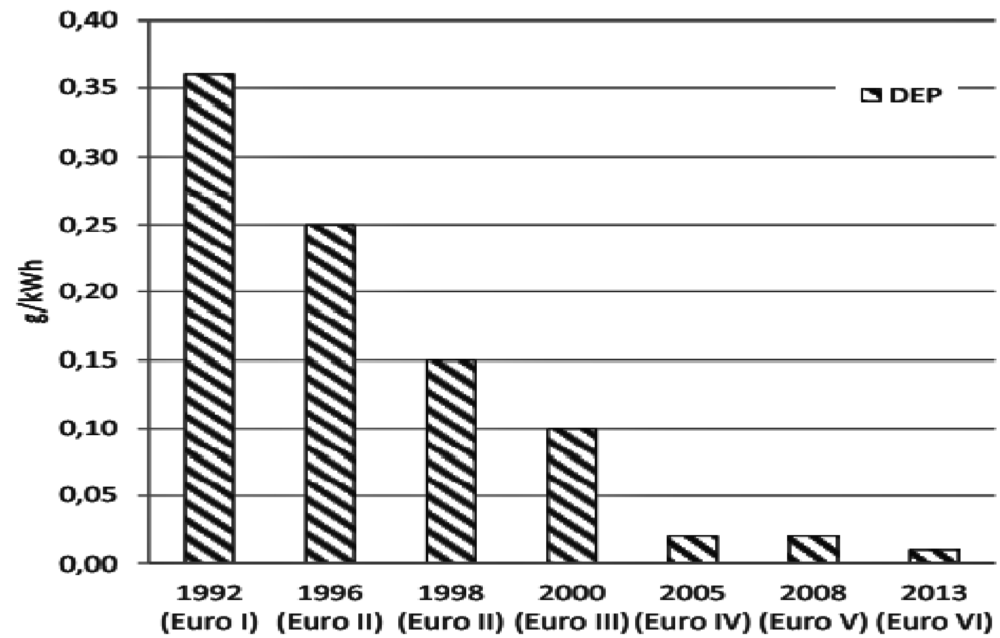

Figure 6: EU emission standards for heavy-duty diesel vehicle engines from 1992 to 2013, as an example of the significant evolution of the emission regulations seen in the last decades (Taxell and Santonen 2017:245).

Anderson, Thundiyil and Stolbach (2012:173) stated that although DPM exposure is ubiquitous, there is no defined and studied safe level. Patient education and behavioral modification strategies may contribute to better overall health. Additionally, this data can enable policy-makers, after weighing the economic impact, to enforce or strengthen existing legislation that limits DPM exposure. However, according to Armah *et al* (2021:2), adhering to the Occupational Safety and Health Administration's (OSHA) recommendations for DPM could assist in preventing occupational diseases due to exposures to DPM.

2.7.2 Diesel particulate occupational exposure limits in South Africa

According to the Mine Ventilation Society of South Africa's (2014:305) study, South Africa (SA) did not have an occupational exposure limit for diesel particulate matter partly due to a lack of information on the health outcomes of exposed employees. As diesel particulate matter is not regarded as a regulated pollutant in SA, the Department of Minerals and Resources do not have information on the diesel particulate matter exposure on mine employees. However, according to the Hazardous Chemical Agents regulations of South Africa, an occupational exposure limit over an eight-hour time weighted average (TWA) of 0.16 mg/m^3 was set (South Africa 1993:245).

2.8 REDUCING DPM EMISSIONS

2.8.1 Occupational Health and Safety (OHS) Act No.85 of 1993

2.8.1.1 Long title of the OHS Act

The OHS Act sets out to ensure the health and safety of any person within the occupational environment, regardless of the severity of the hazard. In addition, it aims to remove or mitigate the hazard or risk as reasonably practicable. The long title of the OHS Act includes the provisions: “To provide for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery; the protection of persons other than persons at work against hazards to health and safety arising out of or in connection with the activities of persons at work; to establish an advisory council for occupational health and safety; and to provide for matters connected therewith” (South Africa 1993: 7).

2.8.2 General duties of the employer

According to section 8 of the OHS Act (South Africa 1993:10), every employer shall provide and maintain, as far as reasonably practicable, a working environment that is safe and without risk to the health of his employees. In this regard, the employer should make provisions to ensure that the necessary control measures are in place to reduce or eliminate exposure to diesel exhaust emissions.

2.8.3 DPM exposure control measures

A number of options and control strategies for the treatment and reduction of diesel particulate matter are available to industry, all of varying scopes, efficiencies and expense. These include fuels and fuel additives (low sulphur, ultra-low sulphur diesel and biodiesel), emissions-based maintenance programs, engine type/specification, exhaust after-treatment (diesel oxidation catalysts, diesel particulate filters, disposable-type filters, selective catalytic reduction), environmental cabins, administrative controls (limiting engine idle time, limiting the number of equipment allowed in a heading or drift, and remote control and automation) and personal protective equipment in the form of respirators. Combinations of emissions control measures can be applied in order to provide the most efficient use of the allocated resources (Esswein, Scott, Snawder and Breitenstein 2018:68, Franse 2022: 40 and Mohankumar and Senthilkuma. 2017:1231).

According to Esswein *et al* (2018:68) and Druley (2018: 1), controls to minimize DPM exposures involve the implementation of the hierarchy of controls which include elimination, substitution, engineering controls, administrative controls (including training and hazard communication), and as a last measure, use of personal protective equipment such as respirators. However, according to Druley (2018: 1), NIOSH states that elimination and substitution is often more difficult to enact after work has begun. Figure 7 below depicts the occupational hierarchy of controls for mitigating DPM exposure.

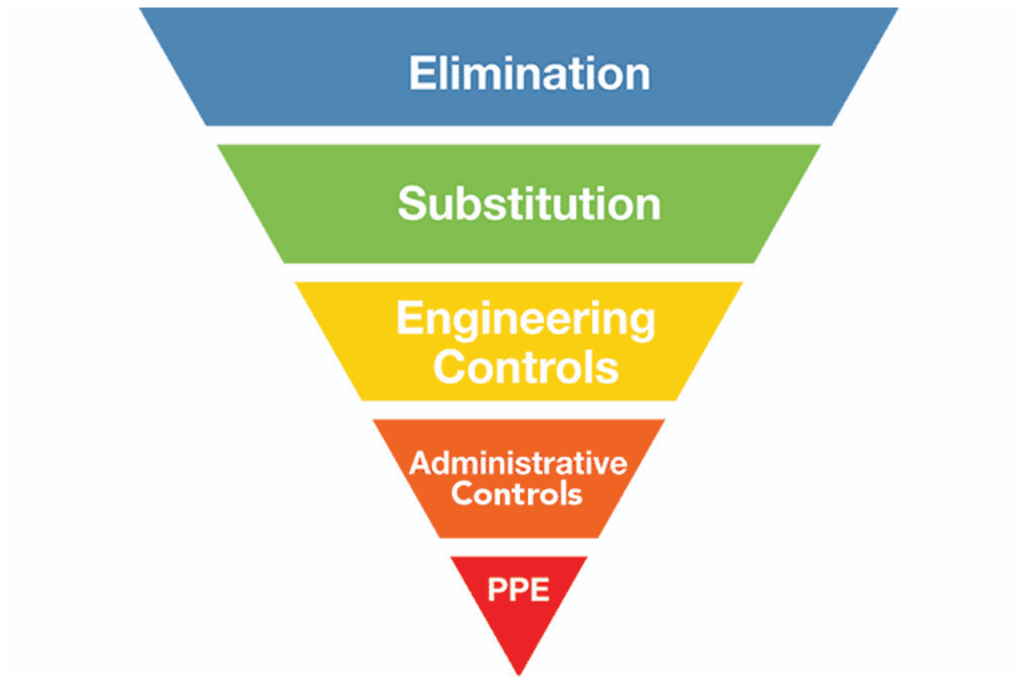

Figure 7: Hierarchy of controls (Druley 2018: 1).

2.8.3.1 Elimination

Elimination involves the process of physically removing the hazard from the occupational environment (Druley 2018: 1). Esswein *et al* (2018:68) stated that elimination can include locating diesel-driven machinery in an offsite location which may not completely eliminate exposure risk, but partial removal and eliminate some of the strongest point sources of DPM aerosol which typically are the array of diesel-powered machinery. However, Singh, Chauhan and Goel (2018: 509) stated that the elimination of diesel fuel as a fuel source is imperative. The elimination of diesel is possible through the use of alcohol with a bio-diesel blend.

2.8.3.2 Substitution

2.8.3.2.1 Electric powered vehicles

Substitution involves the process of replacing the hazard (Druley 2018: 1). Choi and Koo (2021: 1) indicated that the worldwide adoption of electric powered vehicles has increased over the past decade. One of the key reasons that government agencies promote electric-powered vehicles is due to their environmental benefits. Mohankumar and Senthilkumar (2017:1231) stated that biodiesel has low sulphur and aromatic content and contains nearly 10% oxygen which helps it to burn completely. However, from the point of view of electric forklift users, there is no direct consumption of fossil fuels, and no emission of harmful exhaust gas components takes place directly on the premises. It would be recognized that the utilization of electric forklift trucks is a more environmentally friendly solution.

2.8.3.2.2 Fuel substitution- Biodiesel

Biodiesel is a fuel produced from renewable sources such as vegetable oils, animal fats and recycled cooking oils which are long chain tri-glyceride esters with free fatty acids. Chemically it is defined as the mono alkyl (or mono ethyl) esters of long chain fatty acids derived from renewable sources. Biodiesel is typically produced through the reaction of a vegetable oil or animal fat with methanol or ethanol by using sodium hydroxide or potassium hydroxide as catalyst in the yield glycerine and biodiesel (Franse 2022: 40 and Mohankumar and Senthilkumar 2017:1231).

Biodiesel can be used in neat form or blended with petroleum diesel for use in diesel engines. Its physical and chemical properties as it related to operation of diesel engines are similar to petroleum-based diesel fuel. Bio-diesel also has some important advantages when compared to diesel fuel, namely it contains almost no sulphur; is biodegradable, non-toxic and a natural lubricant (Franse 2022: 40). Numerous studies showed that a blend of bio-diesel, cotton seed oil and methanol significantly reduced the DPM concentrations by 24%. Oxygen content in biodiesel promotes the oxidation of soot and helps the reduction of particle number concentration (Mohankumar and Senthilkumar 2017:1233).

As evidenced and indicated by the research of Dobrzynska *et al* (2019:9) in Europe, the best influence on the reduction of diesel particulate emission is the addition of nanoparticles of cerium dioxide and 10- 30% hydro treated vegetable oil (HVO) fuel. In addition, the results obtained confirm that the application of both HVO and nano-additives to diesel can achieve a significant reduction of carbon monoxide (52%) and hydrocarbon (47%) emissions compared to the B7 base fuel. Particulate emissions (up to 10% by mass of particulates and 7% by number of particulates) were found to be best reduced by adding nanoparticles of cerium dioxide to the B7 fuel (with 30% HVO), while the best results in reducing nitrogen oxide emissions were obtained by adding ferrocene nanoparticles to the B7 fuel with 30% HVO (Dobrzynska *et al*. 2019:9).

According to a study by Esswein *et al* (2018:68), the results of a recent simulated study in the mining industry found that the use of biodiesel 75 and gas/diesel fuel reduced DPM compared to diesel fuel alone, and concluded that use of alternative fuels have the potential to significantly reduce diesel emissions. Likhanov and Lopatin (2019: 2) stated that in 2001, the European Commission approved a strategy to gradually replace motor fuels with three main alternatives: natural gas, biofuels and hydrogen. In 2009, the European Union Renewable Energy Directive 2009/28/EC was issued, which aims to achieve a 10% share of biofuels used in the transport sector by 2020. In 2003, the European Commission adopted Directive 2003/30EC, which set the goal of increasing the share of biofuels in the total fuel balance for transport from 2% in 2005 to 5.75% in 2010. By 2030, it has planned to replace 25% of traditional fuels with biofuels.

2.8.3.2.3 Water emulsified fuel

According to Mohankumar and Senthilkumar (2017:1232), water emulsified fuel is another fuel modification principle used to control particulate matter and NOx emission simultaneously. This emulsion is created when primary fluid is dispersed throughout the secondary immiscible fluid, usually in spherical droplets form. This process can be done with or without the help of surfactant, usually accomplished with the help of a ternary diagram.

The main reason for the reduction of emissions is that during rapid evaporation, water droplets having a lesser boiling point than the surrounding fuel would explode rapidly. This process is called a micro-explosion event. This eventually increases pre-mixed combustion duration and the ignition delay period creates more time for fuel-air mixing, leading to a reduction in diesel particulate matter formation (Mohankumar and Senthilkumar 2017:1232). According to a study conducted by Lin, Lee, Lee, and Wu (2012:396), hydrated butanol–diesel blends were prepared by adding the specific ratios of water into the pure n-butanol, and then blending the hydrated butanol with a conventional diesel. The results of the study revealed that the amount of n-butanol blend added had a positive effect in reducing DPM levels.

2.8.3.2.4 Oxygenated fuel additives

According to Mohankumar and Senthilkumar (2017:1232), oxygenated fuel is a fuel that has a chemical compound containing oxygen. These oxygenated additives simply enhance combustion and the ignition quality of fuel by improving the cetane number, thereby reducing the ignition temperature of particulates. The various oxygenated additives used comprise methanol, ethanol, butanol, diethyl ether, diphenyl ether, diethylene glycol, dimethyl ether and nitromethane. Oxygen within the fuel structure generally decreases soot formation, but the effect depends on temperature as well and is also accounted for the reduction in the number of carbon-carbon bonds in the premixed flames.

2.8.3.3 Engineering controls: Pre-combustion

2.8.3.3.1 Injection timing

Diesel particulate matter emissions can be controlled to some extent by varying the injection timing parameter. When the injection timing is advanced, the DPM emissions will get reduced. This effect is mainly related to the ignition delay property. The reason behind this scenario is that while advancing injection timing, it will lead to increases in pre-mixed combustion duration which enhances fine mixing of fuel and air, thereby reducing DPM emissions. However, the NOx emission is increased by advancing the injection timing due to increased ignition delays. DPM emission increases when injection timing gets retarded and NOx emissions get reduced (Mohankumar and Senthilkumar 2017:1231).

2.8.3.3.2 Injection pressure

Mohankumar and Senthilkumar (2017:1231) stated that another pre-combustion technique adopted to reduce particulate matter is by varying injection pressure. The main reason behind this is when injection pressure gets increased, it leads to fine atomization. Fuel droplet size gets reduced, which leads to complete combustion. Another factor is that spray penetration length increases with high injection pressure, which leads to the proper utilization of air and improves fuel-air mixing rate.

Su *et al* (1995: 975) stated that higher injection pressure gives more energy to the fuel and produces a finer spray and faster spray tip penetration. Increased fuel injection pressure has been found to be effective in improving the fuel/air mixing and reducing DPM emissions. In addition, in the study by Su, Chang, Reitz and Farrell (1995: 978), the results indicated that when injection pressure increases from 90 MPa to 160 MPa, the particulate matter reduction of 78% was achieved due to proper mixing of the air-fuel mixture and fine atomization of the fuel.

2.8.3.3.3 Multiple injections

Another pre-combustion technology to control particulate matter is the use of multiple injection events within the same cycle. The key advantage of using this technology is that it will reduce both NOx and particulate matter simultaneously. Multiple injection technologies are made possible with the adoption of Common rail direct injection (CRDI) technology, which allows a shorter injection duration and variable injection timing. This precise control is made possible through the use of an electronic control solenoid valve which controls injection pressure and timing accurately (Mohankumar and Senthilkumar 2017:1231). In a study by Chen (2000: 2134), it was found that multiple injections, along with EGR, will reduce NOx and DPM effectively due to increased charge air entrained and increased lift-off length.

2.8.3.3.4 New diesel technologies

A study carried out in Ghana deduced that the use of low-sulphur diesels, as well as diesel oxidation catalysts are recommended. Although these do not produce a perfect safety margin, toxicity is reduced (Armah *et al.* 2021:2 and Mensah *et al.* 2020:4). New diesel technologies have dramatically reduced DPM levels by 99% in developed countries, but this is not the situation in Ghana, where traditional diesel exhausts are still used.

In a study by Taxell and Santonen (2017:244), it was found that the exhaust composition of new technology diesel engines, with multi-component emission reduction systems including the diesel particulate filter and oxidation catalyst differs from that of older diesel engines. The mass of DPM emissions was reduced by more than 90%. The proportion of EC in the particles were reduced and that of sulphates increased, reflecting the reduction of carbonaceous particles.

2.8.3.4 Engineering controls: Post-combustion

2.8.3.4.1 Diesel particulate filter

According to Apicella, Mancaruso, Russo, Trerossi, Oliano, Ciajolo and Vaglieco (2020:1), a diesel particulate filter (DPF) is an exhaust after treatment device that traps particulate matter such as soot and ash. A DPF typically uses a substrate made of a ceramic material that is formed into a honeycomb structure. There are wide varieties of DPF media available to collect the diesel particulates. The various DPF filters used are Alumina coated wire mesh, ceramic fibre and porous ceramic monoliths. Currently, the honeycomb ceramic monolith walls flow concepts have been widely used to collect diesel particulate matter. The honeycomb monolith traps the particulate matter as the gas flows through its porous walls (Prasad and Bella 2010: 75 and Mohankumar and Senthilkumar 2017:1231).

These filters are often named Ceramic wall flow filters. In these, alternate cells are plugged at one end and open at the opposite end. The exhaust gasses enter the cells that are open at the upstream end and flow through the porous walls to the adjacent cells. The adjacent cells are open at the opposite downstream end and the filtered gas exits from the opposite end to the atmosphere (Mohankumar and Senthilkumar 2017:1231). According to the results of a study by Apicella *et al* (2020:6), it was established that as the exhaust gas passes through the DPF system, the particle number is strongly reduced in the DPF at both engine loads at very low concentration.

2.8.3.5 Administrative controls

Administrative controls refer to changes in the way work tasks are performed to reduce or eliminate the hazard (OSHA 2021: 2). Esswein *et al* (2018:68) stated that administrative controls include evaluating DPM emission source strengths, prevailing wind patterns and employee worksite locations. In addition, another administrative control is limiting the time employees must spend in locations anticipated or determined to have exposure risks for DPM.

In addition, administrative controls effective for reducing DPM exposure include limiting the speed of diesel-powered vehicles and using one-way travel routes to minimize traffic congestion; prohibiting or restricting unnecessary idling or lugging of diesel engines; adopting a programme of regular engine maintenance; scheduling work to minimise the number of workers near the diesel-powered machinery while it is operating; restricting the amount of diesel-powered equipment and total engine horsepower operating in a given area; and ensuring that the number of vehicles operating in an area does not exceed the capacity of the ventilation system and designate areas that are off-limits for diesel engine operation and/or personnel travel (OSHA 2021: 2).

2.8.3.6 Personal Protective Equipment

According to the hierarchy of control, personal protective equipment is regarded as the last resort of control to hazards (Druley 2018: 1). As exposure to DPM is best controlled at its source or by other means described previously, respiratory protective equipment should only be used as a last resort (OSHA 2021: 2). According to Esswein *et al* (2018:68), as a last resort, the correct use of air-purifying, elastomeric half-masks and filtering face-piece (FFP) respirators having particulate efficiencies of FFP2 or greater and half-masks configured P-100 cartridges, and acid-gas cartridges can reduce exposures to particulate and gas/vapour phase of DPM emissions.

2.9 CONCLUSION

Ristovski *et al* (2012: 204) stated that the primary exposure mechanism to DPM is through inhalation. DPM is responsible for the development of upper and lower respiratory disease. In addition, the study conducted by Ristovski *et al* (2012: 201) showed that the DPM surface area and adsorbed organic compounds play a significant role in manifesting chemical and cellular processes that if sustained can lead to the development of adverse respiratory health effects. In addition, Anderson, Thundiyil and Stolbach (2012:173) stated that although DPM exposure is ubiquitous, there is no defined and studied safe level. Patient education and behavioral modification strategies may contribute to better overall health. Additionally, this data can enable policy-makers, after weighing the economic impact, to enforce or strengthen existing legislation that limits DPM exposure.

In addition, continuous and chronic exposure to diesel particulate matter contributes to the risk of developing respiratory inflammation and possibly respiratory diseases, as well as lung cancer (World Health Organization 2016:1). Currie *et al* (2014:16) stated that most of the pollution produced by diesel-powered vehicles occurred during idling and in the process of acceleration. Moreover, Wierzbicka *et al* (2014:213) stated that levels of occupational exposure to diesel engine exhaust emissions, namely diesel particulate matter, are usually higher than the general population. In addition, Li *et al* (2015: 1363) stated that occupational exposure to diesel particulate matter may be higher when workers are close to the emission sources.

It is clear from the research established in the literature review that DEEs have a profound impact on the health of persons exposed. Health effects range from irritation to the respiratory tract causing inflammation, breathing difficulties, aggravating asthma to the more severe carcinogenic properties that DEE contain. South Africa's current OEL for DPM is set at 16mg/m^3. International guidelines call for more stringent levels and measures for reducing DEE emissions. In addition, DPM is not regarded as a carcinogen notation in SA. This exposes a scarcity of concern and knowledge on DPM exposure. The next chapter will elaborate on the methodology of the research.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter outlines the methodology followed in its entirety for the research study. The study design, rationale behind the sampling tools used, research tools, sampling strategies, data collection procedures, data analysis and ethical considerations are included. Research methodology refers to the steps, strategies and procedures used for data gathering and analysis in research. The research was conducted at two paint manufacturing companies within eThekwini, KwaZulu-Natal, South Africa.

Data collection was conducted in two phases. The first phase was conducted with the utilisation of an adapted questionnaire. The second phase of data collection entailed conducting personal air samples on selected high-risk exposure employees. This was done to quantify the amounts of diesel particulate matter that employees were exposed to. This was done in order to address the aim and objectives of the study.

3.2 STUDY SETTING

The study site was located at two paint manufacturing companies, south of the city of Durban within the eThekwini Municipality, KwaZulu-Natal, South Africa. The municipality comprises an area of approximately 2297 km² and consists of a population of approximately 3.5 million inhabitants (Statistics South Africa 2011:1). The study was an above-ground diesel particulate matter (DPM) study and was conducted on the ground floor of both paint manufacturing companies. These specific paint manufacturing companies were selected to be part of the study due to the use of numerous diesel-powered forklift trucks used on site, which raised concerns of prolonged exposure to DPM of the forklift operators and other personnel working in close proximity. The diesel-powered forklift trucks were operated within the raw material stores, packaging and the distribution warehouse. Resitoglu *et al* (2014: 15) stated that diesel engines have high efficiency and reliability, together with their low-operating cost. In addition, Knothe *et al* (2005: 25) stated that diesel's durability and high torque capacity ensured its role in the most demanding applications within the industrial environment.

3.3 STUDY DESIGN

A cross-sectional descriptive study was conducted in an above-ground occupational setting at paint manufacturing companies, yielding quantitative results to illustrate the occupational conditions related to DPM exposure at one point in time. In addition, the stratified sampling method was utilized as employees were stratified into strata as per their job functions and further into strata of being exposed and the most exposed groups.

The study was conducted in two phases to address the objectives of the research. Phase One described the process of quantitative data collection from employees exposed to DPM. Data related to psycho-social information was captured through the use of a validated self-administered questionnaire which was adapted from a previous South African study on DPM. Phase Two described the steps of capturing quantitative data through personal air sampling of DPM exposure. The personal air sampling was conducted over an eight-hour working shift. However, the personal air sampling was conducted on employees representing the most exposed group or high-risk group of employees due to budget constraints.

3.3.1 Questionnaire design

This study used a questionnaire previously used in a South African study on DPM exposure in mines. Permission to utilize the questionnaire was requested from the author of the previous DPM exposure study and permission was successfully obtained by the researcher (Annexure J). The questionnaire was adapted to best suit the above-ground occupational environment and time of the current study. In addition, the questionnaire was adapted to meet Objective 1 of the study, to determine if there were any existing upper respiratory symptoms related to DPM experienced amongst the exposed group of employees.

The questionnaire had been validated as it originated from the American Thoracic Society Respiratory Health study. In addition, the questionnaire had been used in previous studies by the National Institute for Occupational Health and formed part of the European Community Respiratory Health Survey Two. The questionnaire was valid as it produced similar results within the previous studies relating to diesel particulate matter and the respiratory symptoms thereof. The questionnaire comprised three sections, namely Section A- Biographical information, Section B- Work history and Section C- Health issues. The three sections are explained further below.

3.3.1.1 Section A- Biological information

Section A of the questionnaire captured the employees’ biographical information such as name, age, gender, race, residential address, contact information and spoken home languages. It was optional for the employees to write their names, residential address and contact information. This presented the employees with the opportunity to remain anonymous.

3.3.1.2 Section B- Work history

Section B of the health questionnaire captured the employees' work history information. The information it captured related to which company the employee currently worked within; whether the employee was a contract or permanent employee; the shift the employee was working on that day; the number of hours a week the employee worked; the department in which they conducted their work; their occupation and length of time in years working in that job.

3.3.1.3 Section C- Health issues

Section C of the health questionnaire captured information such as the employees' upper respiratory symptoms, smoking status and related respiratory disorders. In addition, the health questionnaire set out to determine the upper respiratory symptoms amongst employees, which was Objective One of the study.

The questionnaire comprised sixteen questions in sections A and B and an additional thirty questions in Section C. The additional questions found in Section C were included to highlight confounding factors, hence obtaining more accurate results and conclusions. The questionnaires were compiled and administrated in English. The area managers assisted with translating information to isiZulu for employees who required it. Every questionnaire was numbered to correspond with each paint company. This was done to ensure that equal amounts of questionnaires were distributed to each paint company and were accounted for.

3.3.2 Personal air sampling

Following the administration of the health questionnaire, personal air sampling was conducted to determine the quantity of DPM the most exposed group of employees was subjected to. Personal air sampling was conducted over an eight-hour period. The sampling was carried out over two weeks at both paint manufacturing plants. The personal air samples were conducted to establish Objective Two of the research. Conducting the personal air sampling was an objective view to determine DPM exposure, whereby the health questionnaires pertain to the employees' perspectives, personal experiences and health-related issues. The personal air sampling was important to verify the validity of the questionnaires and establish the existence of a co-relationship between the data analysed.

3.4 DATA COLLECTION INSTRUMENT AND PROCEDURE

The pilot study included twenty employees. All study employees were provided with an information letter and an informed consent form in English (Annexure B). On completion of Annexure B, the employees completed the self-administered questionnaire. The employees were allowed to return the questionnaire after 1 day, allowing them time to complete it at home. Following the administration of the questionnaire, the personal air sampling was conducted. Personal air sampling pumps and sampling apparatus were attached to the most exposed group of employees. The personal air sampling was conducted on 20 of the most exposed employees. In addition, the personal air sampling was conducted over an 8hr period per participant to establish the employees' actual exposure in a working shift. The personal air sampling was conducted and analysed in accordance to the NIOSH 5040 method.

3.4.1 Phase 1: Self- administered questionnaire

The questionnaire utilized (Annexure A) was adapted from a previous South African study on DPM exposure in mines by Pretorius and Grove (2017:301). The questionnaire had been validated as it originated from the American Thoracic Society Respiratory questionnaire and had been used in previous studies by the National Institute for Occupational Health and formed part of the European Community Respiratory Health Survey Two.

Stratified sampling was used to produce 120 self-administered questionnaires. The study was an above-ground DPM study and conducted on the ground floor of both paint manufacturing companies. Three sections of each paint company were identified where diesel-powered forklifts were used frequently. The three sections were raw material stores, production and packaging, and storage and distribution warehouse. Employees were identified and selected as per their job function and distance from the pollution source.

Employees who were deemed exposed and most exposed were selected as the primary employees for the research. An information and consent form (Annexure B) followed by the questionnaire were handed to the employees by the researcher with assistance of the respective area managers. The questionnaire was explained in English by the researcher. The area managers assisted with translating information to isiZulu for employees who required it. For the purpose of confidentiality, all self- administered questionnaires remained anonymous.

The employees were allowed to take the health questionnaire home with them to have them completed. The employees were allowed a maximum of one day to complete the questionnaire and return them to their work area managers the next day. The researcher collected and consolidated the health questionnaires for statistical interpretation. Data was initially captured on Microsoft Excel and the process of sorting, cleaning and editing the data was done. Common themes were then established into codes. The assistance of a professional statistician was employed for the interpretation of data.

3.4.1.1 Pilot study

The pilot study was conducted prior to the commencement of the main study to test the understanding and reliability of the questionnaires. In addition, the purpose of piloting the questionnaire was to remove any unclear/ambiguous items on the questionnaire to ensure trustworthiness of the tool. Participation in the pilot study was voluntary and employees were handed information and consent forms (Annexure B). In addition, the employees were handed an evaluation form (Annexure D). The evaluation form provided information on the understanding, quality and clarity of the questions within the questionnaires. There were twenty employees who consented to be part of the pilot study.

The employees identified for the pilot study performed similar job functions of operating diesel powered forklift trucks and performing duties within close proximity of the pollution source. The employees were handed the questionnaire on a Friday afternoon and were allowed to return them on Monday morning. This allowed the employees to review the questionnaire over the weekend. Reviewing and amendments were carried out respectively to the questionnaire after the pilot study. The employees and data obtained from the pilot study were not used in the final data analysis and sample size.

3.4.1.2 Study population

The total population at the paint manufacturing companies was approximately 362 staff. Figure 8 below depicts the population structure at the paint manufacturing plants.

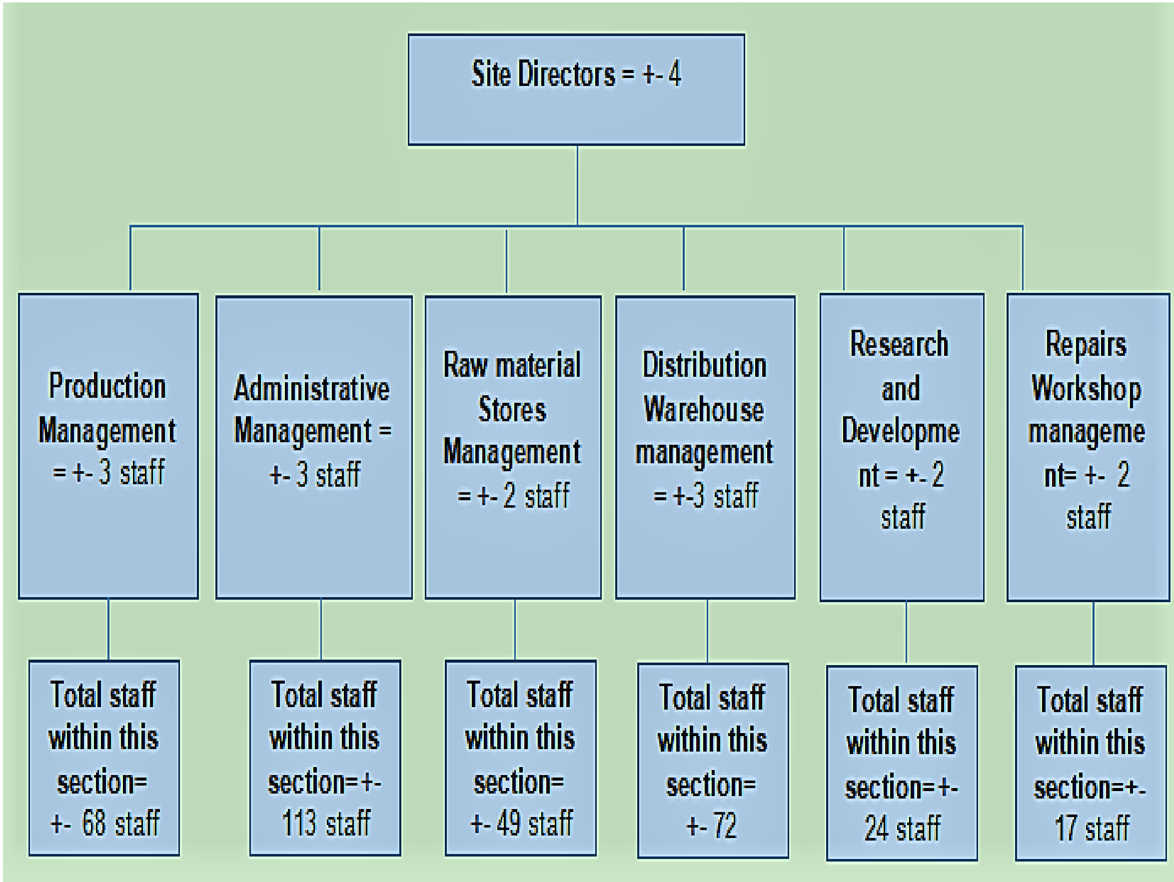

Figure 8: **Population structure at the paint manufacturing companies**

Employees who worked in close proximity to the source of pollution was selected to participate in the study. They formed the exposed group of employees. Diesel-powered forklift truck drivers were included in the study, and represented the most exposed group of employees. The questionnaire was administered to the exposed and most exposed group of employees. In addition, the employees comprised male and female employees who conducted duties in various parts of the plants. The age of employees ranged between 18 and approximately 60 years. The employees spent 8hrs in their designated work areas and generally started work at 08h00 and finished at 16h00.

3.4.1.3 Inclusion criteria

- Employees over the age of 18 years.
- All employees working within the raw material stores, production and packaging, storage and distribution warehouse, mechanical repairs block and employees driving diesel

powered forklift trucks within these areas (Annexure G- Floor plans indicating areas were employees for the study operated within).

- All employees who read the information letter and agreed by signing the consent form to participate in the study.

3.4.1.4 Exclusion criteria

- Employees under the age of 18 years.
- Employees over the age of 60 years.
- All visitors.
- All administrative employees situated in offices.
- The directors and management.
- Security at the main entrance gate.
- Employees of the pilot study.

3.4.1.5 Questionnaire sampling strategy

The self-administered questionnaire was provided to 120 consented employees using the stratified systematic sampling technique. Stratified systematic sampling technique was used for its simple and easy-to-use nature. Employees who were exposed to DPM within the paint manufacturing plants were identified. This involved a walk-through of the plant identifying the different work areas, types and number of diesel-powered forklifts used in a specific area and lastly, employees who were in closed proximity to DPM emissions. The information and consent letter were filled in by the selected employees before they filled in the questionnaire.

3.4.1.6 Sampling size

The minimum sampling size was 101 employees in which the margin of error was set at 5%. The total population of staff at both paint manufacturing plants were approximately 362. Through stratified sampling, a total of 136 employees were selected to participate in the study. A total of 120 employees consented to participate in the study. In order to ensure a higher accuracy representation, a larger sample population than the minimum sampling size was chosen. Table 1 below describes the population breakdown.

Table 1: **Study sample population breakdown**

Research Site	Total population	Sample selected	Actual response
Company A and B	362	136	120

3.4.2 Phase 2: DPM air sampling

3.4.2.1 Personal air sampling strategy

The personal air sampling was conducted within the same month over ten days. In addition, the personal air sampling was conducted on the most exposed group of employees over an eight-hour work shift. The personal air samples were connected to diesel-powered forklift truck drivers who performed their duties within the raw material storage warehouse, production, packaging, storage and distribution warehouse. Twenty personal air samples were taken over ten days. In addition, four blank samples were taken as directed within the NIOSH 5040 method manual. The control samples were taken under similar conditions, weather, manner and times as the twenty initial samples. The control samples were taken to ensure reliability of the results. Figure 9 below depicts the personal air sampling strategy.

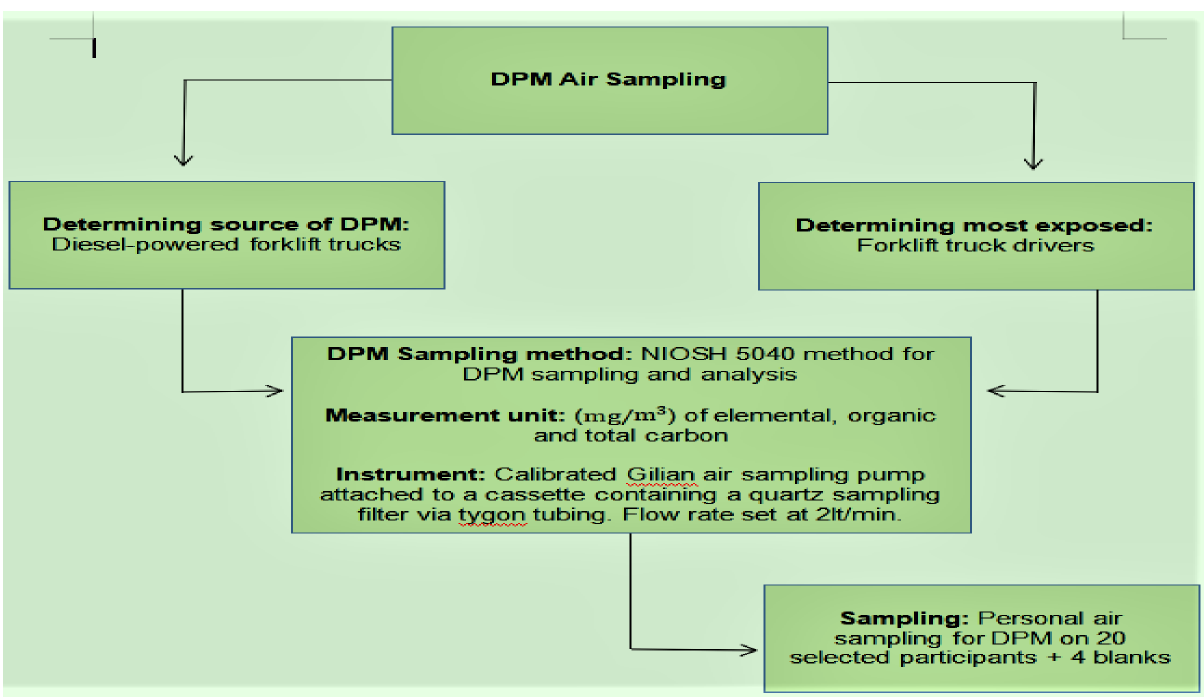

Figure 9: Personal air sampling strategy

3.4.2.2 NIOSH Method 5040- Personal air sampling for diesel particulate matter (as Elemental Carbon)

Birch (2010:1) stated that exposure to diesel exhaust particulates and other fine particle pollution is of concern due to studies indicating that a positive link exists between airborne levels and respiratory illness and mortality. A carbon analysis method based on a thermal- optical technique was evaluated and published as method 5040 in the NIOSH Manual of Analytical Methods (NMAM). The method was initially published in 1996 and was later updated. In addition, within sample analysis, total carbon (TC), organic carbon (OC) and elemental carbon (EC) are determined.

Elemental carbon is a selective marker of exposure in workplaces were diesel-powered equipment is operated. In addition, elemental carbon is accepted internationally as a surrogate measure of exposure to this industrial pollutant and the NIOSH method 5040 has been used in numerous industrial hygiene surveys. The thermal optical analyser design has improved, although the operation principal remains the same. The analyser is equipped with a pulse diode laser and photo-detector that permit continuous monitoring of the sample filter transmittance (Birch. 2010:1).

In addition, the NIOSH method 5040 was used in an underground mining study in South Africa to obtain elemental carbon, organic carbon and total carbon values. This method proved reliable when correctly set up and utilized for DPM sampling (Pretorius *et al* 2017: 301). Li *et al* (2015: 1363) stated that occupational exposure to diesel particulate matter may be high when workers are close to the source of emission. In addition, Hodas *et al* (2016: 837) stated that the indoor occupational environment is of particular importance when considering the respiratory health effects associated with diesel particulate matter exposures because employees who spend the majority of their time indoors are exposed to two to three orders of the magnitude larger than exposures to outdoor emissions. Therefore, the most exposed or high-risk group of employees within the study were identified as the forklift truck drivers and the diesel mechanics within the mechanical repairs workshop. Personal air samples were set up and taken from the most exposed employees.

According to the NIOSH Method 5040, the apparatus needed to conduct the personal air samples for DPM were 37mm quartz-fibre filters which were to be preheated (in low temperature asher 2 to 3 hours, or muffle furnace for 1 to 2 hours at ~ 800 °C), in a 3-piece cassette with filter support (stainless steel screen, cellulose pad, or a second quartz filter), calibrated personal air sampling pumps with flexible tubing, a thermal-optical analyser, metal punch for removal of 1.5 cm^2 rectangular portion of filter, a syringe, aluminium foil, a needle for lifting filter punch portions, forceps, volumetric flasks (class A) and an analytical balance.

3.4.2.2.1 Setting up the sampling train

3.4.2.2.2 Calibration- Each personal air sampling pump was calibrated with a representative sampler in line. Calibration of sampling pumps were done in order to determine accurate readings of the mass of DPM to volume of air ratios ($\mathrm{mg/m^3}$). The NIOSH method 5040 recommended the sampling pump flow rate to be set at 2 to 4 L/min. The volume minimum (VL/MIN) was 142L @ 40 mg/m^3. The Volume max (VL/MAX) was 19m^3 (for filter load of ~ 90 mg/cm^2).

3.4.2.2.3 Flexible tubing attachment- The sampler outlet was attached to the personal sampling pump with flexible tubing. The flexible tubing was connected to the filter cassette. Figure 10 below depicts a typical sampling train for conducting personal air samples for DPM.

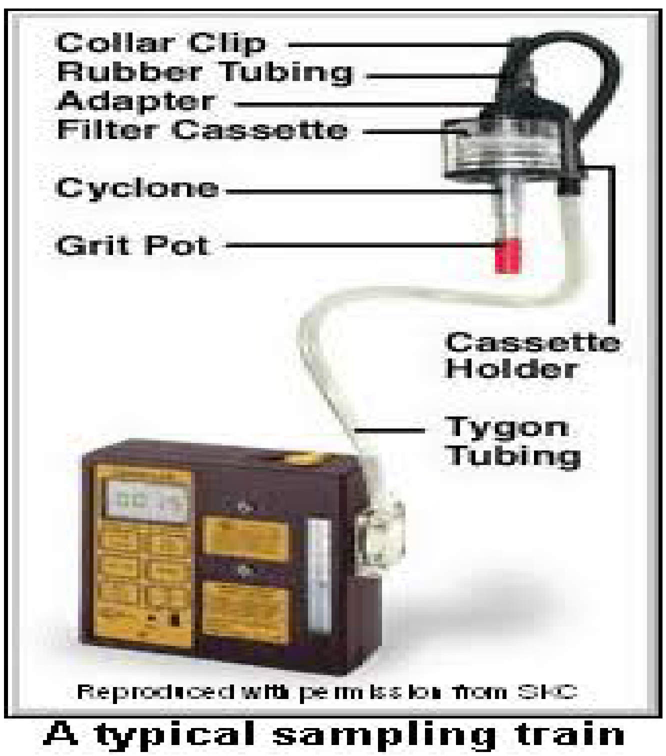

Figure 10: A typical sampling training for diesel particulate matter sampling. It consists of a personal air sampling pump, tygon/ flexible tubing, a cassette holder, a cyclone with grit

pot, a filter cassette with 37mm preheated quartz filter and a collar clip (Evaluation of airborne contaminants 2018:3).

3.4.2.2.4 Flow rate and attachment of sampling train to participant- The flow rate was set as recommended between 2-4 lt/min. The apparatus was connected to the employee's breathing zone and was removed after a working shift of eight hours. Figure 11 below depicts the correct positioning of the personal air sampling apparatus.

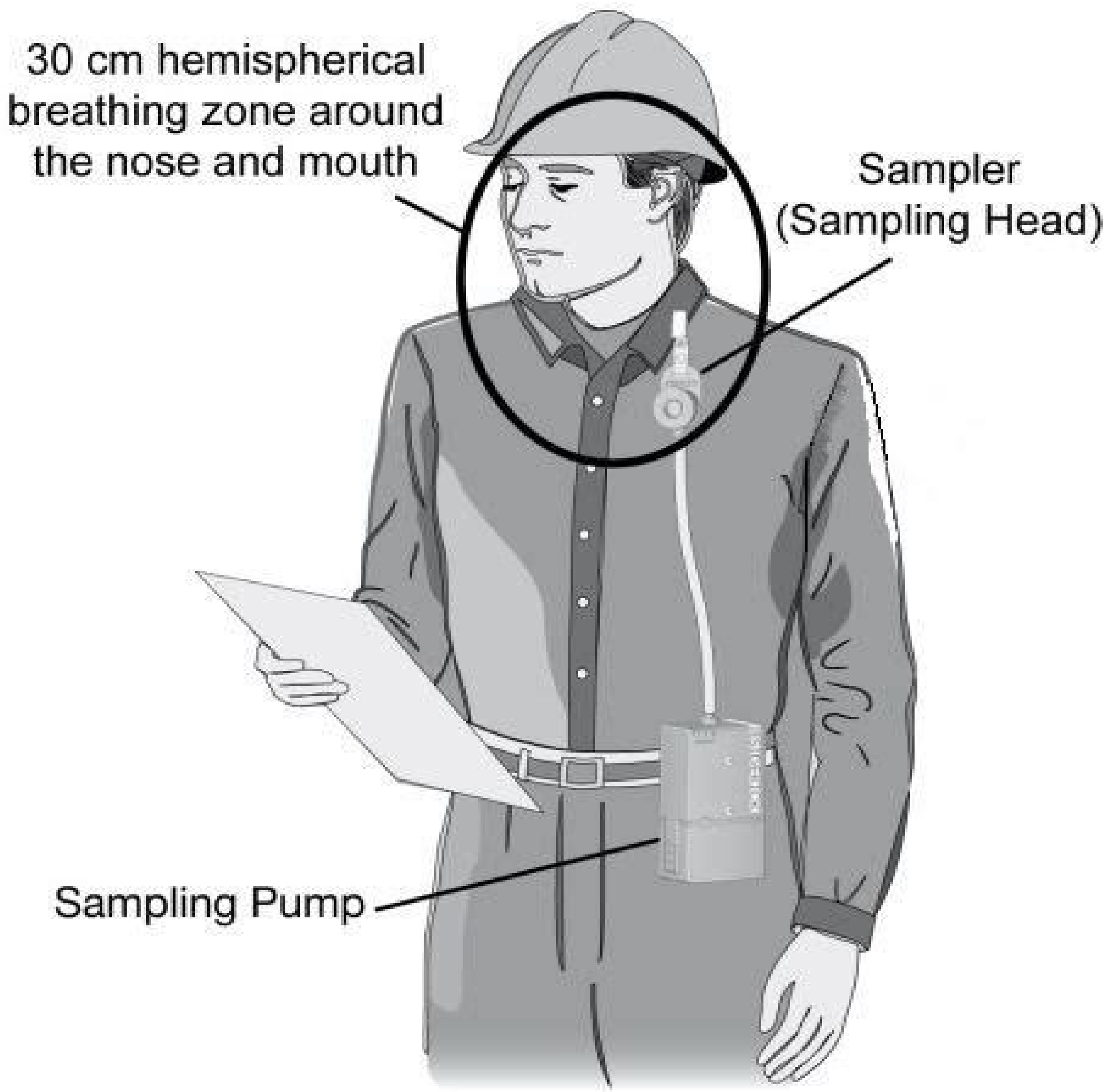

Figure 11: The correct positioning of the personal air sampling apparatus (Step-by-step Guide to Air Sampling 2017:4).

Figure 12 below depicts an actual participant of the study with the personal air sampling train attached to him. The sampling train consisted of a Gilian air sampling pump set inside an air sampling bag/pouch attached around the employee's waist, tygon tubing attached to a pre-loaded 37mm plastic cassette containing a preheated quartz filter media. The sampler was attached within 30cm hemispherical breathing zone around the nose and mouth with a collar clip.

Figure 12: Sampling train attached to an employee

3.4.2.3 Post-sampling: After the personal air sampling was conducted, the top piece of the cassette was replaced and the samples were labelled and packed securely for transportation to the laboratory for analysis. In addition, NIOSH Method 5040 indicated that diesel particulate samples from occupational settings generally do not require refrigerated shipment unless there is potential for exposure due to elevated temperatures. Filter samples are normally stable under laboratory conditions. Some OC loss may occur over time if samples contain OC from other sources, such as cigarette smoke. Absorption of OC vapour after sample collection did not occur, even with samples having high (e.g., 80%) EC content.

3.4.2.3.1 Preparation of samples for analysis

The analysis of the personal air sampling quantified the levels of EC, OR and TC. The personal air sampling was conducted to establish the second objective of the research, which was to quantify the levels of diesel exhaust emissions the high risk group of employees were exposed to. According to the NIOSH 5040 manual, analysis of samples is advised as follows.

3.4.2.3.2 Sample preparation: The researcher placed the sample filter on a freshly cleaned aluminium foil surface. Isopropyl alcohol or acetone can be used to clean the foil. He allowed residual solvent to vaporize from the surface prior to use and punched out a representative portion of the filter. The researcher took care not to disturb deposited material and avoid hand contact with sample. A needle inserted at an angle is useful for the removal of the filter portion from the punch body. Newer instruments have an externally mounted bracket to support the quartz sample holder while the previous sample is removed and a new one is loaded. Through a hole in the side of the standard punch, a needle was used to push the filter portion from the punch onto the sample holder. Alternative approaches also can be used, depending on the user’s preference, as long as contamination is avoided.

3.4.2.3.3 Calibration and quality control: The researcher analysed at least one replicate sample. For sets of up to 50 samples, replicate 10% of the samples. For sets over 50 samples, replicate 5% of the samples. If a filter deposit appears uneven (this should not be the case if the cassette is sealed properly), take a second portion for analysis to check evenness of deposition. Analyse three quality control blind spikes and three analyst spikes to ensure that instrument calibration is in control. Prepare spike as follows:

a) With a 10 microgram (mg) or other syringe, apply an aliquot of OC standard solution directly to filter portion taken from a pre-cleaned filter. For best results, the pre-cleaned filter punch should be cleaned again in the sample oven prior to application of the aliquot. With a small aliquot (e.g., 10mg), disperse standard solution over one end of filter portion to ensure standard is in laser beam. To prevent possible solution loss to surface, hold the portion off the surface. Larger volumes can easily penetrate to the underside of the filter portion.

b) Allow water to evaporate and analyse spikes with samples and blanks. A pronounced decrease in filter transmittance during the first temperature step of the analysis indicates water loss. Allow portions to dry longer if this occurs. Spiked punches also can be dried in the oven, if desired. For quick drying, the 'clean oven' comm and on the menu can be selected and cancelled after about 4 seconds. The time allowed may depend on instrument, but oven temperatures should be below 100 °C to avoid boiling the solution. This approach is convenient and prevents potential adsorption of organic vapours in laboratory air. The analyser was adjusted to the settings in accordance to manufacturer's recommendations. The sample portion was placed into a sample oven.

3.4.2.3.4 Instrument blanks determination- Determine instrument blank (results of analysis with freshly cleaned filter portion) for each sample set.

3.4.2.3.5 Measurement- Adjust analyser settings according to manufacturer's recommendations. Place sample portion into sample oven. Forms of carbon that are difficult to oxidize (e.g., graphite) may require a longer period and higher temperature during the oxidative mode to ensure that all EC is removed (the EC peak should never merge with the calibration peak). Adjust time and temperature accordingly. A maximum temperature above 940 °C should not be required. Determine EC and OC mass in mg. Analyser results are reported in units mg/cm^2 of C.

The reported values are normally based on a sample portion of about 1.5 cm^2, which is the area of the standard punch provided by the manufacturer. If the portion area used differs from the value entered in the ocecpar.txt file, multiply the result by 1.5 (or value in ocecpar.txt file) and divide the product by the actual area analysed to obtain the area-corrected result (i.e., reported result x 1.5/portion area = corrected result in mg/cm^2). This is most easily done in the data spreadsheet. Alternatively, the correct results will be obtained with the data calculation program if the portion area is entered in the parameter file (ocecpar.txt), but this approach is cumbersome when punches of different areas are used because correct results will not be obtained for all punch sizes.

3.4.2.3.6 Calculations: Multiply the reported (or area-corrected) EC result (mg/cm^2) by filter deposit area, cm^2, (typically 8.5cm^2 for a 37mm filter) to calculate total mass, mg, of EC on each filter sample (WEC). The researcher did the same for the blanks and calculate the mass found in the average field blank (W b). The mass of OC is calculated similarly, but the mean OC field blank may underestimate the amount of OC contributed by adsorbed vapour. A quartz filter placed beneath the sample filter can provide a better estimate of the adsorbed OC. Calculate the EC concentration (CEC) in the air volume sampled, V (L):

$$\text{CEC} = \frac{WEC - WB}{V} mg/m^3$$

3.5 DATA ANALYSIS

3.5.1 Questionnaire data analysis

The questionnaires were collected from the consented employees upon completion. The researcher captured the data onto Microsoft Excel and the process of sorting, cleaning and editing the data was done. Common themes were established into codes. Highlighting was used as a colour-coding indexing system to identify different themes that emerged. Themes were added up until data saturation was reached. The excel data collected was given to the data analyst to analyse and interpret. The data was analysed with IBM® SPSS® Statistics version 27.0. Significant correlations between variables were presented. Inferential techniques included the use of correlations and chi square test values, which are interpreted using the p-values, where statistical significance was expected at a $p < 0.05$ level. Bar charts, line graphs and pie charts were used to illustrate significant correlations of data.

3.5.2 Personal air sampling data analysis

Once all the personal air samples were taken, the cassettes were shipped to an accredited lab for analysis. The results of the analysis were captured onto Microsoft Excel and given to the data analyst to analyse and interpret. The data was analysed with IBM® SPSS® Statistics version 27.0. An independent samples t-test was conducted by the analyst to determine if there were any significant differences between the readings obtained at the two paint manufacturing companies in the research for each of the variables. Data from the questionnaires and personal air sampling were analysed together to identify any significant correlations.

3.6 VALIDITY AND RELIABILITY

3.6.1 Questionnaire

The pilot and actual study were conducted under a similar occupational environment, conditions, weather and time period. The pilot study was conducted prior to the commencement of the main study to test the understanding and reliability of the questionnaires. In addition, the purpose of piloting the questionnaire was to remove any unclear/ambiguous items on the questionnaire to ensure trustworthiness of the tool. The questionnaire (Annexure A) was previously used in a South African study on DPM exposure in mines and originated from the American Thoracic Society Respiratory Health study. Moreover, the questionnaire had been used in previous studies by the National Institute for Occupational Health and formed part of the European Community Respiratory Health Survey Two. The questionnaire was adapted to best suit the above-ground occupational environment and time of the current study. This validated the use of the questionnaire, making it a reliable data collection tool to address Objective One of the study.

3.6.2 Sampling method for DPM and personal air sampling equipment

According to numerous studies, the NIOSH 5040 method was the internationally recognized method for DPM sampling and analysis (McLaughlin *et al.* 2020:1, Birch 2010:1, Pretorius *et al.* 2017: 301 and Niekerk *et al*. 2002:3). The personal air sampling was conducted over ten days with the repeated use of the same personal air sampling pumps to monitor the levels of DPM. Two samples per day were conducted. All sampling processes and instructions were consistent throughout the ten days. Four control samples were taken on the eleventh day under the same conditions and times as the ten aforementioned personal air samples.

The control samples were taken in order to ensure reliability of the results and as per instruction of the NIOSH 5040 method (Annexure F). Reliability of the personal air sampling pumps was conducted via calibration of the equipment. In addition, pre- and post-calibration was conducted on all of the personal air sampling pumps to further validate data captured. This included calibrating the personal air sampling pumps to a prescribed flow rate of 2 lt/min. This ensured that the readings obtained were reliable for interpretation. In addition, sampling filter media had been preheated to the prescribed temperature prior to use.

3.7 DUT ETHICS APPROVAL TO CONDUCT THE STUDY

3.7.1 Ethical process

The research proposal was submitted to the Faulty Research Committee (FRC) and thereafter to the Durban University of Technology's Institutional Research Ethics Committee (IREC), where it was reviewed, approved and issued with an ethics clearance number (IREC Reference Number: 045/18) (Annexure E). The researcher requested gatekeeper's permission from both the paint manufacturing companies, which was granted by both the companies' management.

A confidentiality agreement was drawn up between the companies and the researcher to maintain the image of the company. Permission was sought from the author of the study which the questionnaire was adapted from. Permission was granted from the author. Once relevant permissions had been granted, the study commenced with the data collection processes.

3.7.2 Ethical principles

The study was carried out with anonymity and fairness throughout the data collection process. All questions in the questionnaire were designed in a manner that was not intrusive or offensive to the employee's. Employees we're not harmed in any way throughout the study. All employees working at the paint manufacturing companies may not experience direct benefit from the study but they may benefit indirectly in the future. This is in keeping with the principle of beneficence with regard to research. The personal air sampling did not cause any harm or interference to the employees in any way. Employees were requested to continue with their duties as usual.

3.7.3 Letter of information and consent

A letter of information and consent was provided to all employees, administered with a hand-delivered self-administered questionnaire (Annexure B). The letter of information indicated to employees that participation was voluntary. No coercion was used in the study. Respondents were informed that they may leave the study at any time if they wished to do so, without being subjected to any form of prejudice. They were also assured that all information and data collected in the study remained strictly confidential.

The employees' privacy and the emotional well-being were protected at all times during the course of the study. All completed questionnaires and information and consent forms were collected by the researcher in ballot boxes to ensure the confidentiality and anonymity of the respondents. All data collected, inclusive of electronic data, was securely stored in a locked cupboard that was only accessible by the researcher. Data will be stored for a period of five years, thereafter it will be disposed of by means of shredding. All electronic copies will be deleted.

3.7.3 Anonymity and confidentiality

Anonymity and confidentiality was achieved by not asking employees to provide, on the questionnaires, information such as their names, contact details, addresses and where they currently work. All completed questionnaires were collected separately from the signed consent forms, in sealed ballot boxes. The study sites name and address remained confidential throughout the study as per the confidentiality agreements between the companies and the researcher.

3.8 CONCLUSION

The cross-sectional descriptive study was conducted in an above-ground occupational setting at paint manufacturing companies located South of Durban, KZN, South Africa. The study yielded quantitative results to illustrate the occupational conditions related to DPM exposure at one point in time. The study was conducted in a two-phase approach whereby employees completed a questionnaire and personal air sampling for DPM was done. The personal air samples taken were done in accordance with the NIOSH 5040 method and compared to relevant recommended OELs.

All ethical procedures were followed and maintained throughout the study. Following the methodology behind this study, the results gave great insight into the data collected. From these results, appropriate controls may be implemented in the future as per the occupational hierarchy of controls to reduce and eliminate DPM exposure. The aim of the next chapter is to present the findings that were obtained from both the questionnaire and the personal air sampling.

CHAPTER 4

RESULTS

4.1 INTRODUCTION

This chapter presents the findings of the research as obtained from the research collection tools used in the study. This includes of completion of the questionnaire and air sampling for diesel particulate matter (DPM) exposure. The findings will be discussed in two phases. Phase 1 reported on Objective 1 of determining the employees' response to the questions in the questionnaire. The results of the data obtained in the questionnaire are discussed below. Phase 2 followed Objective 2 which was to quantify the level of exposure the highest risk group of employees were subjected to over an eight-hour work shift. In addition, the results of data obtained from the personal air sampling for DPM are discussed. The personal air samples were conducted and sent to an accredited laboratory for analysis. The personal air samples were analysed in accordance with the NIOSH 5040 method.

The questionnaire was the primary research tool used to collect data from the selected group of employees and were distributed to 60 employees in Company A and 60 employees in Company B. The data collected from the responses were entered into Microsoft Excel and analysed with IBM® SPSS® Statistics version 27.0. The results in this chapter were presented in the form of cross-tabulations, tables, figures, calculations and narratives for the quantitative data collected. Significant correlations between variables are also discussed. Inferential techniques include the use of correlations and chi square test values, which are interpreted using the p-values, where statistical significance was expected at a $p<0.05$ level.

4.2 PHASE 1: QUESTIONNAIRE ANALYSIS

4.2.1 Study population

Seventy-six suitable employees were identified at company A, but only 60 consented to complete the questionnaire. The participation rate for Company A was 86%. At Company B, 64 suitable employees were identified, but only 60 consented to complete the questionnaire, resulting in a participation rate of 94%. Between the two paint manufacturing companies, 120 out of 136 employees identified consented to complete the questionnaires (n=120). Company A had a bigger staff compliment, but Company B yielded a greater participation rate. This information is represented in Table 2 below. All employees who met the inclusion criteria for the study were approached and an 87% return rate was achieved. Table 2 below depicts sample size from Companies A and B.

Table 2: **Company A and B study sample size**

Research site	Total population	Sample selected	Actual response
Company A	185	72	60
Company B	177	64	60

4.2.2 The research instrument

The study was conducted in two phases to address the objectives of the research. Phase One collected quantitative data from employees exposed to DPM through the use of a self-administered health questionnaire. Phase Two captured quantitative data through personal air sampling of employees exposed to DPM. The results of the personal air sampling are discussed later in this section.

The research questionnaire comprised 46 items, with a level of measurement at a nominal or an ordinal level. The questionnaire was divided into 3 sections which aimed to determine Objective 1 of the study, namely to determine if any existing upper respiratory symptoms related to DPM were experienced amongst the exposed group of employees. These 3 sections are illustrated in Table 3 below:

Table 3: **The 3 sections of the questionnaire (Annexure A)**

Section	Question type	Number of items
A	Biographical information	7
B	Work History	8
C	Health Issues	31

4.2.3 Demographics

This section summarises the biographical characteristics of the respondents. Questions in section A were based around the employee's age, gender, race and primary home language. These questions were presented to employees in order to investigate possible correlations or co-founders to diesel exhaust exposure (DEE) and related health effects. The demographics are aligned to the population distribution of the eThekwini region, KwaZulu-Natal (South Africa Gateway 2021:2).

4.2.3.1 Section A- Biographical information

4.2.3.1.1 Age and gender of employees

The overall gender distribution by age is depicted in table 4 below.

Table 4: **The overall gender distribution by age**

Categories		**Gender**		**Total**
Age (years)		Male	Female	
18 - 25	Count	5	10	15
	Age (years) percentage	33.3%	66.7%	100.0%
	Gender percentage	5.3%	38.5%	12.5%
	Total percent	4.2%	8.3%	12.5%
26 - 33	Count	24	4	28
	Age (years) percentage	85.7%	14.3%	100.0%
	Gender percentage	25.5%	15.4%	23.3%
	Total percent	20.0%	3.3%	23.3%
34+	Count	65	12	77
	Age (years) percentage	84.4%	15.6%	100.0%

	Gender percentage	69.1%	46.2%	64.2%
	Total percent	54.2%	10.0%	64.2%
Total	Count	94	26	120
	Age (years) percentage	78.3%	21.7%	100.0%
	Gender percentage	100.0%	100.0%	100.0%
	Total percent	78.3%	21.7%	100.0%

Overall, the ratio of males to females is approximately 4:1 (78.3%: 21.7%) ($p < 0.001$). Within the age category of 26 to 33 years, 85.7% were male. Within the category of males only, 25.5% were between the ages of 26 to 33 years. This category of males between the ages of 26 to 33 years formed 20.0% of the total sample. The age distributions are not similar as there are more respondents older than 33 years ($p < 0.001$). This is in keeping with Statistics South Africa (2017:1), as it was found that 70% of eThekwini's population were between the ages of 18- 64 years.

4.2.3.1.2 Racial composition

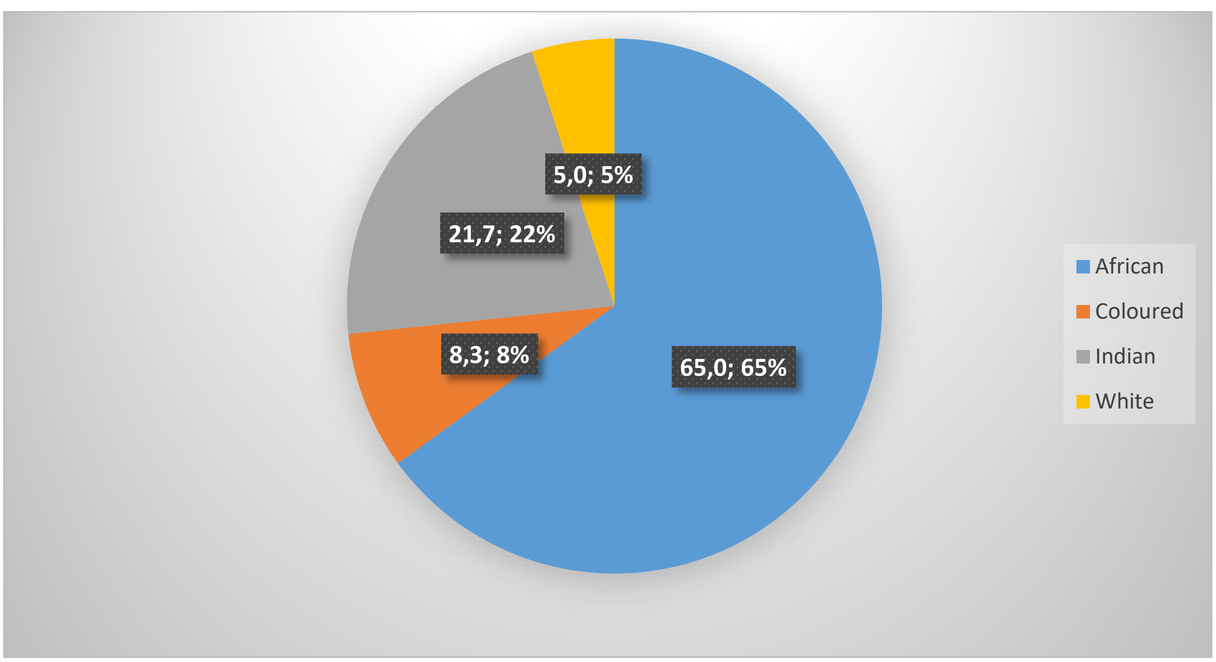

Figure 13: Racial composition of the sample group (%)

Approximately two-thirds of the respondents were African (65.0%), with a fifth being Indian (21.7%). There were smaller groupings of the remaining race groups ($p < 0.001$). All respondents resided within eThekwini and surrounding areas. This is in keeping with current information, whereby over 51% of eThekwini's residents are African, approximately 25.1% of the population were Indian, while 15.3% are White and 8.6% are designated as Coloured (Statistics South Africa 2017:1). The largest ethnic group are the Zulus (World Population Review 2022:1).

4.2.3.1.3 Home language

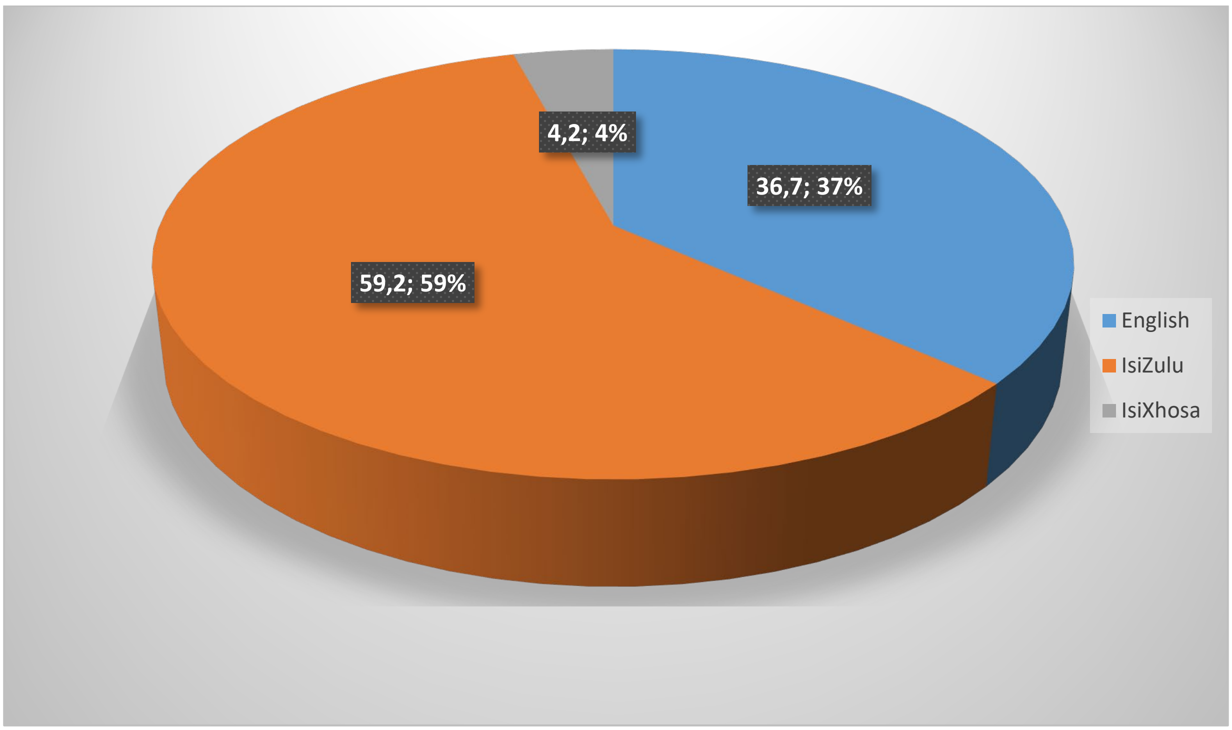

Figure 14: The home language of employees (%)

The majority of the respondents spoke IsiZulu (59.2%), with 36.7% speaking English ($p < 0.001$). IsiZulu is the largest spoken language in KwaZulu-Natal, where 78% of people speak it as a primary home language, with English contributing to 13% and the 9% remaining being designated IsiXhosa and other languages spoken in South Africa (South Africa Gateway 2021:2).

4.2.4 Section analysis

The section that follows analyses the scoring patterns of the respondents per variable per section. These variables include type of employment, work area, occupation, length of employment, respiratory symptoms experienced while performing duties, smoking status and related respiratory disorders of employees. The results are first presented using summarised percentages for the variables that constitute each section. Results were then further analysed according to the importance of the statements.

4.2.4.1 Section B: Work history

This section summarises the employees' responses related to their work history.

4.2.4.1.1 Scoring patterns

The tables below summarise the scoring patterns. The sample comprised equal numbers of respondents from both paint manufacturing companies. Table 5 below indicates the work status of the respondents.

Table 5: **Work status of respondents from Company A and Company B**

Research site	Permanent	Contract
Company A	119 (99.2%)	1 (0.8%)
Company B	120 (100%)	0

All but one respondent was permanently employed ($p < 0.001$). This is due to the one respondent forming part of the contractors hired by the companies. In addition, none of the respondents indicated that they worked shifts. All respondents indicated that they worked a standard work-hour week (40 hours).

4.2.4.1.2 Work area of employees

Figure 15 below indicates the department/ work area that respondents currently worked in.

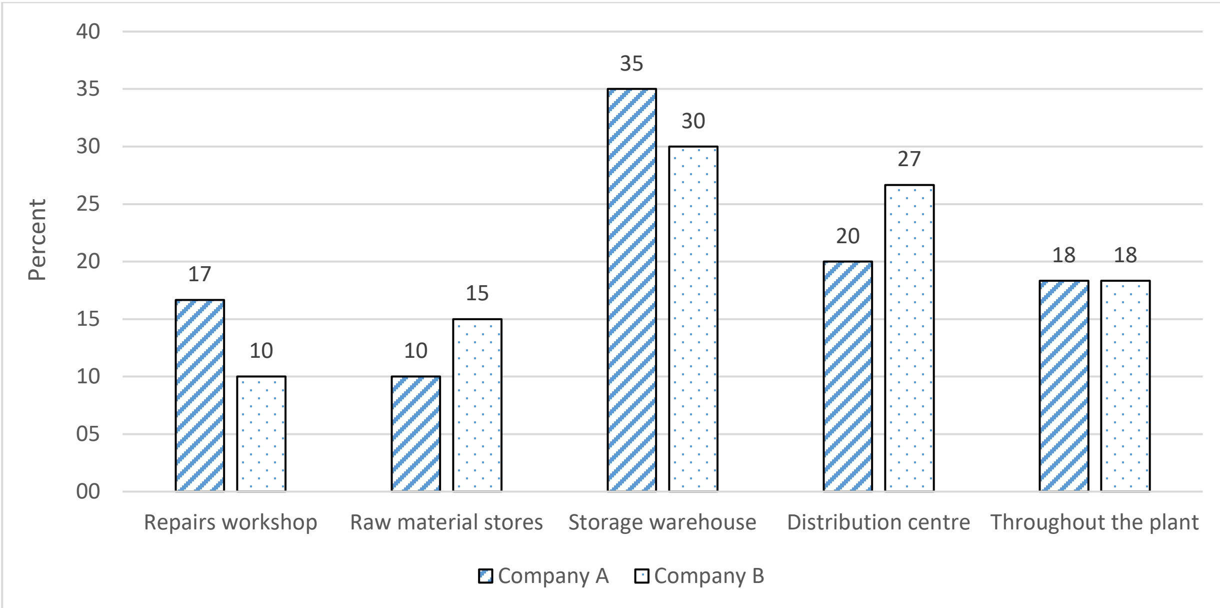

Figure 15: Employees' work areas

Approximately a third of the respondents worked in the storage warehouse (32.5%), with 23.3% being in the distribution centre. Smaller numbers of respondents worked in the raw material stores, repairs workshop and throughout the plant (p = 0.030).

4.2.4.1.3 Occupation of employees

Figure 16 below indicates the current job function/ occupation of the respondents.

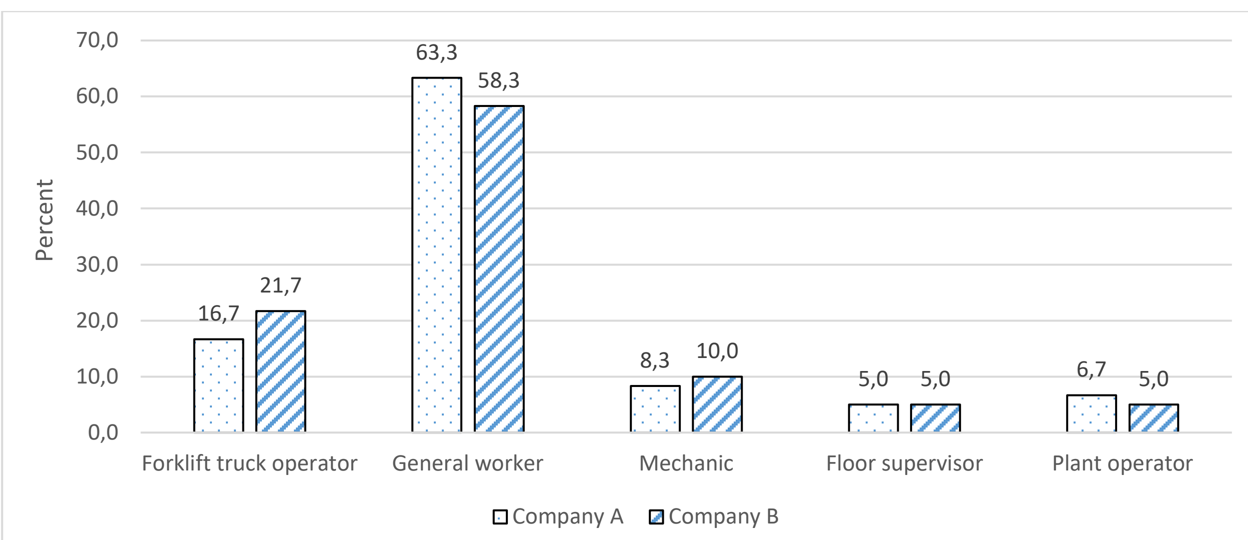

Figure 16: Employees' occupations

Overall, most of the respondents were general workers (60.8%), with slightly less than a fifth (19.2%) being forklift operators. There were similar and smaller numbers of respondents in the remaining occupations (20%) ($p < 0.001$).

4.2.4.1.4 Length of Employment

Figure 17 below indicates the length of employment.

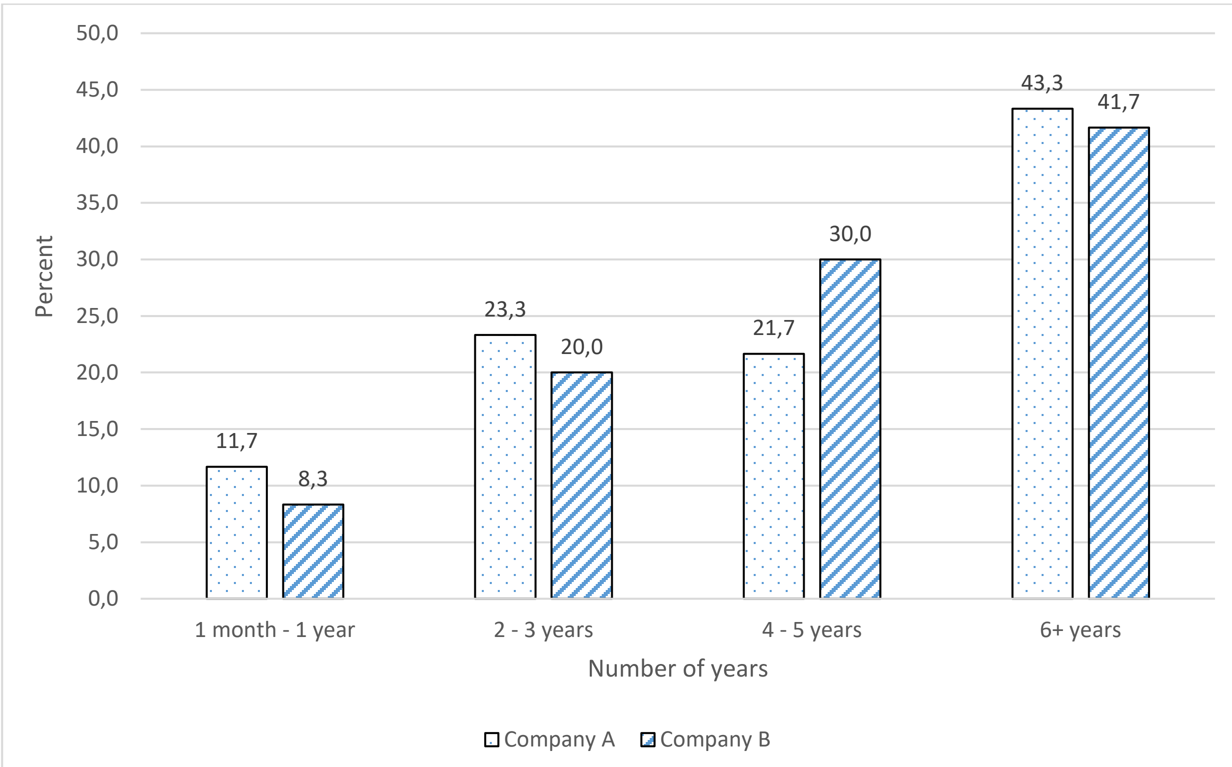

Figure 17: Length of Employment

It was observed that more respondents had longer periods of service ($p < 0.001$). More than two-thirds (company A= 65% and company B= 71.7%) had more than 4 years of experience. This indicates a stable workforce and lower turnover within the companies.

4.2.5 Health issues- Section C

Section C summarises information captured from respondents such as the respiratory symptoms experienced while performing duties, smoking status and related respiratory disorders. It was important for the researcher to understand the existence of respiratory symptoms to determine if a correlation existed between the employees and source of pollution.

4.2.5.1 Scoring patterns

The tables below summarise the scoring patterns for health-related responses of employees. The sample comprised equal numbers of respondents from both of the paint manufacturing companies. The tables below indicate the health issues of the respondents.

4.2.5.1.1 Shortness of breath

None of the respondents indicated any shortness of breath issues while performing their duties at work. A small number (n = 2, 1.7%) indicated that they sometimes experienced shortness of breath whilst doing tasks outside of work ($p < 0.001$). None of the respondents indicated any wheezing in the chest while performing duties at work. As highlighted in Chapter 2, exposure to diesel exhaust emissions have an adverse effect on the respiratory health of the exposed. Symptoms of diesel exhaust emission exposure include shortness of breath, coughing, tightness of chest, wheezing, dyspnea and chest pain (Geravandi *et al.* 2015: 1, Gorguner and Akgun 2010: 31 and Podlewski *et al.* 2017:136). However, factors such as existing respiratory disorders, duration of exposure and concentration of emission are to be considered.

4.2.5.1.2 Coughing at work

Table 6 below indicated the employees' response to coughing at work.

Table 6: Employees' response to coughing at work

Coughing at work	Frequency	Percent
Yes, sometimes	14	11.7%
No	106	88.3%
Total	120	100%

Some respondents (n= 14, 11.7%) indicated that they coughed at their workstations ($p < 0.001$). Approximately two-thirds of the respondents indicated that the coughing stopped after moving away from their work zones ($p < 0.001$). In addition, this study was conducted prior to Covid-19.

4.2.5.1.3 Coughing phlegm

Table 7 below summarise the responses regarding coughing phlegm.

Table 7: **Employees' response regarding coughing phlegm**

Coughing phlegm	Response	Frequency	Percent
Do you cough up phlegm whilst working in your work area?	Yes, sometimes	6	42.9%
Do you cough up phlegm after your work shift?	Yes, sometimes	10	71.4%
When you wake up in the morning, do you cough up phlegm?	No	120	100%

For each statement, there was a significantly smaller number of respondents who did exhibit symptoms ($p < 0.001$).

4.2.5.1.4 Exposure to diesel exhaust emissions

Table 8 below determines whether respondents were exposed to diesel exhaust emissions.

Table 8: Respondents' view on diesel exhaust emission exposure

Diesel exhaust emissions exposure	Frequency	Percent
Strongly Agree	30	25.0%
Agree	60	50.0%
Disagree	28	23.3%
Strongly Disagree	2	1.7%
Total	120	100%

Three-quarters of the sample (75.0%) indicated that they had been exposed to diesel exhaust emissions ($p < 0.001$).

4.2.5.1.5 Duration of exposure to diesel exhaust emissions

Table 9 below indicates the descriptive statistics for the number of hours that respondents are exposed to diesel exhaust emissions per day.

Table 9: Number of hours that respondents are exposed to diesel exhaust emissions per day

N	Minimum	Maximum	Mean	Std. Deviation
120	0.0	8.0	1.7	2.2

The mean and standard deviation is 1.7 ± 2.2 hours per day. All the respondents (n = 120) believed that exposure to diesel-powered forklifts impacted their general health.

4.2.5.1.6 Smoking status

Table 10 below depicts the smoking status of employees.

Table 10: Smoking status of employees

Smoker	Frequency	Percent
Yes	23	19.2%
No	97	80.8%
Total	120	100%

With regard to smoking, approximately a fifth of the respondents indicated that they smoked (19.2%) ($p < 0.001$).

4.2.5.1.7 Duration of time smoking

Table 11 below indicates the length of time that respondents had been smoking.

Table 11: Length of time that respondents had been smoking

Duration	Frequency	Percent
1 month - 1 year	12	52.2%
2 - 3 years	2	8.7%
4 - 5 years	4	17.4%
6+ years	5	21.7%
Total	23	100%

More than half of the respondents indicated that they had been smoking for less than a year ($p < 0.001$). Smoking causes cancer, heart disease, stroke, lung diseases, diabetes and chronic obstructive pulmonary disease (COPD), which includes emphysema and chronic bronchitis (CDC 2020:1). According to Wu, Jin and Carlsten (2018: 834), epidemiological studies have provided strong evidence for associations of diesel exhaust emission inhalation with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence that exposure to diesel exhaust emissions could aggravate existing respiratory disorders caused by smoking.

4.2.5.1.8 Quantity of cigarettes smoked per day

Table 12 below indicates the number of cigarette packs smoked per day by employees who smoked.

Table 12: Number of cigarette packs smoked per day by employees who smoked

Quantity smoked per day	Frequency	Percent
Less than 1 pack	9	42.9%
1 pack	10	47.6%
More than 1 pack	2	9.5%
Total	21	100%

Approximately 90% of the respondents indicated that they smoked at most 1 pack per day ($p < 0.001$).

4.2.5.1.9 Smoking and respiratory health

Figure 18 below indicates responses to whether the upper respiratory health worsened after respondents started smoking.

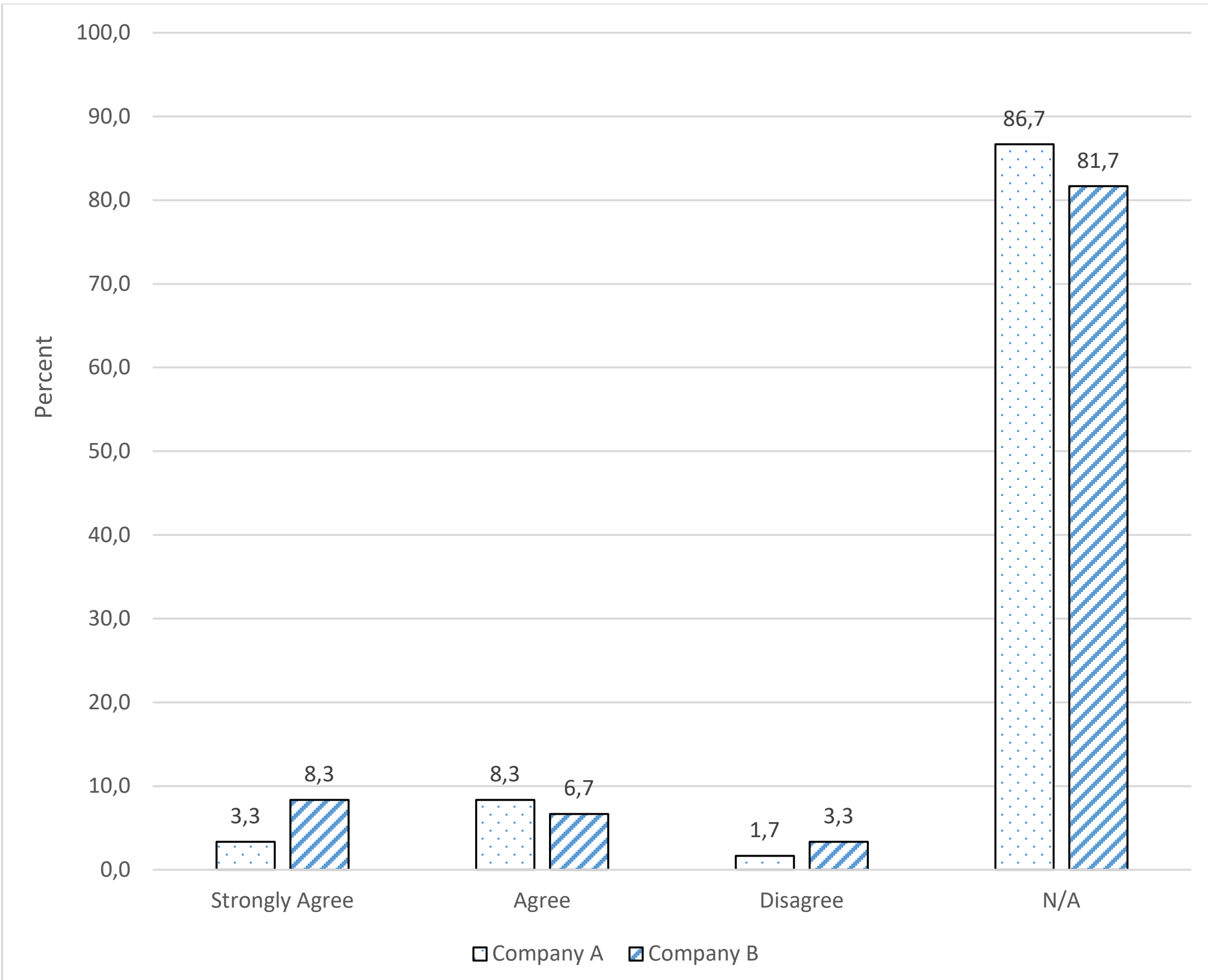

Figure 18: Participant responses to smoking worsening upper respiratory health

Approximately 84% of the respondents indicated that their upper respiratory health had worsened after they started smoking cigarettes ($p < 0.001$). It has been established that smoking causes damage to the respiratory system and over a period of time may cause cancer, heart disease, stroke, lung diseases, diabetes and chronic obstructive pulmonary disease (COPD), which includes emphysema and chronic bronchitis (CDC 2020:1).

4.2.5.1.10 Smoking-related questions

Table 13 below depicts employees' responses relating to smoking.

Table 13: Employees responses related to smoking

Smoking-related questions	Response	Frequency	Percent
Do you experience shortness of breath after smoking a cigarette?	No	18	78.3%
Do you experience chest tightness after smoking a cigarette?	No	18	78.3%
Do you cough up phlegm after smoking a cigarette?	Yes	1	4.3%

Approximately 73% of employees responded that they did not experience any shortness of breath after smoking a cigarette. In addition, approximately 73% of employees responded that they did not experience any tightness in their chests after smoking a cigarette. All the respondents indicated that there were no non-respiratory symptoms that they experience whilst working in their current work areas.

4.2.6 Cross-Tabulations

A Chi square test of independence was performed to determine whether there was a statistically significant relationship between the variables. The null hypothesis states that there is no association between the two. The alternate hypothesis indicates that there is an association. The null hypothesis was accepted and the alternate was rejected.

4.2.6.1 Statistically significant values

There were only two significant values for all of the biographical interactions with all of the section B and C statements. The tables below summarise the results of the chi square tests.

4.2.6.1.1 For how long have you been working in this department/ occupation?" and "Age (years)

Table 14: Chi square test of employees' length of time in department/occupation and age

			Age (years)			Total
			18 - 25	26 - 33	34+	
For how long have you been working in this department/ occupation?	1 month - 1 year	Count	6	6	0	12
		Percent (%) within For how long have you been working in this department/ occupation?	50,0%	50,0 %	0,0%	100,0%
		% within Age (years)	40,0%	21,4 %	0,0%	10,0%
		% of Total	5,0%	5,0%	0,0%	10,0%
	2 - 3 years	Count	7	15	4	26
		% within For how long have you been working in this department/ occupation?	26,9%	57,7 %	15,4 %	100,0%
		% within Age (years)	46,7%	53,6 %	5,2%	21,7%
		% of Total	5,8%	12,5 %	3,3%	21,7%
	4 - 5 years	Count	1	7	23	31
		% within For how long have you been working in this department/ occupation?	3,2%	22,6 %	74,2 %	100,0%
		% within Age (years)	6,7%	25,0 %	29,9 %	25,8%
		% of Total	0,8%	5,8%	19,2 %	25,8%
	6+ years	Count	1	0	50	51
		% within For how long have you been working in this department/ occupation?	2,0%	0,0%	98,0 %	100,0%
		% within Age (years)	6,7%	0,0%	64,9 %	42,5%
		% of Total	0,8%	0,0%	41,7 %	42,5%
Total		Count	15	28	77	120
		% within For how long have you been working in this department/ occupation?	12,5%	23,3 %	64,2 %	100,0%

	% within Age (years)	100,0 %	100, 0%	100,0 %	100,0%
	% of Total	12,5%	23,3 %	64,2 %	100,0%

Significant values were found for the statements: "For how long have you been working in this department/ occupation?" and "Age (years)" (*p* < 0.001).

4.2.6.1.2 Which paint industry do you currently work in?" and "Home Language"

Table 15: Chi square test of company employees worked in and home language

			Home Language			Total
			English	IsiZulu	IsiXhosa	
Which paint industry do you currently work in?	Company A	Count	15	42	3	60
		Percent (%) within Which paint industry do you currently work in?	25,0%	70,0%	5,0%	100,0%
		% within Home Language	34,1%	59,2%	60,0%	50,0%
		% of Total	12,5%	35,0%	2,5%	50,0%
	Company B	Count	29	29	2	60
		% within Which paint industry do you currently work in?	48,3%	48,3%	3,3%	100,0%
		% within Home Language	65,9%	40,8%	40,0%	50,0%
		% of Total	24,2%	24,2%	1,7%	50,0%
Total		Count	44	71	5	120
		% within Which paint industry do you currently work in?	36,7%	59,2%	4,2%	100,0%
		% within Home Language	100,0%	100,0%	100,0 %	100,0%
		% of Total	36,7%	59,2%	4,2%	100,0%

Significant values were found for the statements: of “Which paint industry do you currently work in?” and “Home Language” (p = 0.025).

Further cross-tabulations were done for having experienced “Breathing Problems” and all of the remaining statements. Again, significant results were only obtained for 4 statements relating to coughing and phlegm. This is shown in the tables below.

4.2.6.1.3 Do you find yourself coughing whilst working in your current work area? and Breathing-related problems

Table 16: Chi square test of employees coughing whilst working in their current work area and breathing-related problems

		Breathing related problems		Total
		No	Yes	
Do you find yourself coughing whilst working in your current work area?	Yes, sometimes	0	14	14
	No	104	2	106
Total		104	16	120

Significant values were found for the statements: “Do you find yourself coughing whilst working in your current work area”? and Breathing-related problems (p = 0.000).

4.2.6.1.4 Do you find that you stop coughing once you are away from the area in which you work? and Breathing-related problems

Table 17: Chi square test of employees coughing once away from work and breathing related problems

		Breathing related problems		Total
		No	Yes	
You find that you stop coughing once you are away from the area in which you work?	Agree	0	5	5
	Disagree	0	8	8
	Strongly Disagree	0	1	1
	N/A	104	2	106
Total		104	16	120

Significant values were found for the statements: Do you find that you stop coughing once you are away from the area in which you work? and Breathing-related problems (p = 0.000).

4.2.6.1.5 Do you cough up phlegm whilst working in your work area? and Breathing related problems

Table 18: Chi square test of employees coughing up phlegm at work and breathing-related problems

		Breathing related problems		Total
		No	Yes	
Do you cough up phlegm whilst working in your work area?	Yes, sometimes	0	6	6
	No	104	10	114
Total		104	16	120

Significant values were found for the statements: "Do you cough up phlegm whilst working in your work area"? and Breathing-related problems ($p < 0.001$).

4.2.6.1.6 Do you cough up phlegm after your work shift? and Breathing-related problems

Table 19: Chi square test of employees coughing up phlegm after work and breathing related problems

		Breathing related problems		Total
		No	Yes	
Do you cough up phlegm after your work shift?	Yes, sometimes	6	4	10
	No	98	12	110
Total		104	16	120

Significant values were found for the statements: "Do you cough up phlegm after your work shift"? and Breathing-related problems ($p < 0.028$).

4.2.6.2 Logistic Regression

Logistic regression is the statistical technique used to identify the relationship between predictors (independent variables) and a predicted variable (the dependent variable) where the dependent variable is binary. The only significant logistic relation was between "Breathing Problems" (dependent variable) and "Do you cough up phlegm after your work shift?" (independent variable).

Table 20: Variables of breathing problems and coughing phlegm after a work shift

Table 20 below depicts the variables of breathing problems and coughing phlegm after a work shift.

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
								Lower	Upper
Step 1[a]	Do you cough up phlegm after your work shift?(1)	-1.695	0.714	5.628	1	**0.018**	0.184	0.045	0.745
	Constant	-0.405	0.645	0.395	1	0.530	0.667		

a. Variable(s) entered on step 1: Do you cough up phlegm after your work shift?

Table 21: **The odds ratio for age, gender and race**

Variables in the Equation

		B	S.E.	Wald	df	Sig.	Exp(B)	95% C.I.for EXP(B)	
								Lower	Upper
Step 1[a]	Do you cough up phlegm after your work shift?(1)	-2.314	0.809	8.178	1	**0.004**	0.099	0.020	0.483
	Age (years) (18 – 25 reference)			1.790	2	0.409			
	Age (years)(1) (26 – 33)	-0.116	1.214	0.009	1	0.924	0.891	0.082	9.620
	Age (years)(2) (> 33)	0.912	1.045	0.761	1	0.383	2.489	0.321	19.291
	Gender (1) (Female) (male reference)	0.466	0.763	0.372	1	0.542	1.593	0.357	7.110
	Race (African reference)			4.819	3	0.186			
	Race(1) (Coloured)	1.587	0.841	3.561	1	0.059	4.887	0.940	25.393
	Race(2) (Indian)	-0.630	0.896	0.494	1	0.482	0.533	0.092	3.085
	Race(3) (White)	0.644	1.188	0.294	1	0.588	1.904	0.186	19.540
	Constant	-0.724	1.204	0.362	1	0.547	0.485		

a. Variable(s) entered on step 1: Age (years), Gender, Race.

The odds of coughing phlegm halved after adjustment (0.184 to 0.099). It can be interpreted as follows:

A respondent who coughs phlegm experiences a reduction of 90% in the odds of having breathing problems that someone who does not cough phlegm. This can be alternatively stated as a respondent who does not cough phlegm is 10.12 times more likely to have breathing problems than one who does cough phlegm. It is also observed that even though age, gender and race are not significant, some of the odds [Exp (B)] are still high.

Females are 1.593 times more likely to suffer from breathing problems than their male counter parts. Coloured respondents are 4.887 times more likely than African respondents of having breathing problems. Phase 2, personal air sampling results are presented below. The personal air sampling was conducted to achieve Objective 2 of the research study, which was to quantify the level of exposure the most high-risk group of employees were subjected to over an eight-hour work shift.

4.3 PHASE 2: PERSONAL AIR SAMPLING ANALYSIS

4.3.1 Personal air sampling results

Personal air sampling was conducted within the same month over ten days at the paint manufacturing companies. Personal air sampling was conducted on the most exposed group of employees who consented to the study over an eight-hour work shift. In addition, the personal air sample apparatus was attached to diesel-powered forklift truck drivers of companies A and B, who performed their duties within the raw material storage warehouse, production, packaging, storage and distribution warehouse.

Ten personal air samples were taken from each company over ten days. In addition, four blank samples were taken as required by the NIOSH 5040 methodology. The control samples were taken under similar conditions such as weather and temperature, the same manner and times as the initial twenty samples. The control samples were taken to ensure reliability of the results. The results of the personal air sampling are shown in the tables below.

Table 22: Company A personal air sampling results

Sample number	Employee name	Organic carbon(mg/ m^3)	Elemental carbon (mg/ m^3)	Total carbon (mg/ m^3)	OEL for DPM (mg/m^3)
A1	X1	0,081	0,004	0,085	0.16
A2	X2	0,056	0,006	0,062	0.16
A3	X3	0,039	0,005	0,044	0.16
A4	X4	0,055	0,007	0,062	0.16
A5	X5	0,038	0,007	0,045	0.16
A6	X6	0,054	0,011	0,064	0.16
A7	X7	0,023	0,01	0,033	0.16
A8	X8	0,026	0,008	0,034	0.16
A9	X9	0,044	0,008	0,052	0.16
A10	X10	0,069	0,011	0,079	0.16
A11	Blank sample (Control 1)	0,014	<0.001	0,014	0.16
A12	Blank sample (Control 2)	0,02	<0.001	0,02	0.16

A total of twelve personal air samples inclusive of two blank samples were taken from employees of company A. The results of elemental carbon, as a marker for DPM, indicate that employees were subjected to low levels of DPM. These levels were below the recommended OEL of 0.16 mg/m^3 for all samples taken.

Table 23: Company B personal air sampling result

Sample number	Employee name	Organic carbon(mg/ m^3)	Elemental carbon (mg/ m^3)	Total carbon (mg/ m^3)	OEL for DPM (mg/m^3)
B1	Y1	0,043	0,007	0,05	0.16
B2	Y2	0,05	0,006	0,056	0.16
B3	Y3	0,045	0,006	0,051	0.16
B4	Y4	0,036	0,003	0,039	0.16
B5	Y5	0,049	0,007	0,056	0.16
B6	Y6	0,026	0,004	0,03	0.16
B7	Y7	0,029	0,004	0,033	0.16
B8	Y8	0,075	0,006	0,081	0.16
B9	Y9	0,032	0,004	0,036	0.16
B10	Y10	0,015	0,002	0,017	0.16
B11	Blank sample (Control 1)	0,012	<0.001	0,012	0.16
B12	Blank sample (Control 2)	0,011	<0.001	0,011	0.16

There were twelve personal air samples, inclusive of two blank samples taken from employees of Company B. The results of elemental carbon as a marker for DPM indicate that employees were subjected to low levels of DPM. These levels were below the recommended OEL for all samples taken. In total, twenty-four personal air samples were taken from companies A and B. The recommended OEL for DPM was 0.16 mg/m^3 (South Africa 1993:245). All personal air samples taken were below the recommended OEL. This could be due to various observed factors such as adequate ventilation, good maintenance of diesel powered forklift trucks and duration of exposure to pollutants.

4.3.2 T-test

An independent samples t-test indicated that there were no significant differences between the readings obtained at the two paint manufacturing factories in the research, for each of the variables. The results of the t-test are shown in the table below.

Table 24: T- test indicating significant differences between variables

	P-value
Flow rate pre (lt/minute)	0.609
Flow rate post (lt/minute)	0.782
OEL for DPM (mg/ m^3)	1.000
Organic Carbon (mg/ m^3)	0.329
Elemental Carbon (mg/ m^3)	0.085
Total Carbon (mg/ m^3)	0.257

The results are analysed as a collective hereafter. The results are presented for elemental and total carbon as mg/m^3. The South African standard for the upper limit of elemental carbon and that for total carbon is 0.16 mg/m^3 (South Africa 1993:245).

The results indicate that there is a significant difference for the recorded data when compared to the standard.

Table 25: One-sample statistics for recorded data when compared to the standard

One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
ELEMENTAL CARBON (mg/ m3)	24	.00525	.003300	.000674
TOTAL CARBON (mg/ m3)	24	.04442	.021571	.004403

The results were significantly lower than the national standard of standard of 16 mg/m^3.

Table 26: One-sample test for recorded data of elemental and total carbon

One-Sample Test

	Test Value = 16						
	t	df	Significance		Mean Difference	95% Confidence Interval of the Difference	
			One-Sided p	Two-Sided p		Lower	Upper
ELEMENTAL CARBON (mg/ m3)	-23743.412	23	<.001	<.001	-15.994750	-15.99614	-15.99336
TOTAL CARBON (mg/ m3)	-3623.707	23	<.001	<.001	-15.955583	-15.96469	-15.94647

It is noted that the mean value for each type is much smaller than the standard of 16 mg/m^3 ($p < 0.001$).

4.4 CONCLUSION

The research investigated the upper respiratory symptoms and related exposure to diesel exhaust emissions amongst employees at selected paint manufacturing companies within eThekwini, KwaZulu-Natal, South Africa. Data was collected in two phases. Phase One was achieved through the use of a questionnaire as the primary research tool, which addressed Objective One of the study, namely to determine if there were any existing upper respiratory symptoms related to DPM exposure experienced amongst the exposed group of employees.

Results from the questionnaire on the age of employees, work area, occupation, length of employment, respiratory symptoms experienced while performing duties, smoking status and related respiratory disorders of employees show no significant data, indicating that there were existing upper respiratory symptoms due to DPM exposure amongst respondents. Phase Two was conducted to address Objective Two of the research, namely to quantify the levels of DPM that employees were exposed to. Phase Two was achieved by conducting personal air samples on the most exposed group of employees. Twenty-four personal air samples were conducted on employees from Company A and Company B.

The results of elemental carbon as a marker for DPM indicate that employees were subjected to low levels of DPM. These levels were below the recommended OEL for all samples taken. In total, twenty-four personal air samples were collected from both companies. The recommended OEL for DPM was 0.16 mg/m^3 (South Africa. 1993:245). All personal air samples taken were below the recommended OEL. This could be due to various factors such as adequate ventilation, good maintenance of diesel-powered forklift trucks and duration of exposure to pollutants. The results of chapter 4 are further discussed in chapter 5. Thereafter, recommendations to mitigate and eliminate DPM exposure from the occupational environment are discussed in the ensuing chapters.

CHAPTER 5

DISCUSSION

5.1 INTRODUCTION

The research set out to investigate the upper respiratory symptoms and related exposure to diesel exhaust emissions amongst employees at selected paint manufacturing companies within eThekwini, KwaZulu- Natal, South Africa. Data was collected in two phases. Phase One was achieved through the use of a questionnaire as the primary research tool, which addressed Objective One of the study, to determine if there were any existing upper respiratory symptoms related to diesel particulate matter (DPM) exposure experienced amongst the exposed group of employees. Phase Two was conducted to address Objective Two of the research, which was to quantify the levels of DPM that employees were exposed to. Phase Two was achieved by conducting personal air samples on the most exposed group of employees. There were 24 personal air samples conducted on employees from Company A and Company B.

The results from the questionnaires in Phase 1 were analysed in relation to the results from Phase 2 on personal air sampling. In addition, a review of the current health and safety measures for DPM exposure and control within the paint companies were reviewed. A limited number of personal air samples were taken and analysed due to budget constraints. However, this did not significantly limit the study as the most exposed group of employees were identified and personal air sampling was conducted on them and analysed. The cross-sectional field study results are discussed below.

5.2 DEMOGRAPHICS

The participation rate for Company A was 86%. At Company B, 64 suitable employees were identified, but only 60 consented to complete the questionnaire, resulting in a participation rate of 94%. Between the two paint manufacturing companies, 120 out of 136 employees consented to complete the questionnaires (n=120). Company A had a bigger staff complement. However, Company B yielded a greater participation rate. The response rate for this study was more than initially required. All but one respondent was permanently employed by the companies, which could be due to the companies employing contractors who conducted work for short periods of time.

English was the preferred language of communication at both companies. However, the results suggest that the home languages of the majority of the respondents was IsiZulu followed by smaller groups speaking English and other national languages. This is in keeping with research as IsiZulu is the most spoken language in KwaZulu-Natal, South Africa, where 78% of people speak it as a primary home language, with English contributing to 13% and the 9% remaining is designated to IsiXhosa and other languages spoken in South Africa (South Africa Gateway 2021:2).

Of the 120 respondents in the study, approximately two-thirds were African (65.0%), with a fifth being Indian (21.7%). There were smaller groupings of the remaining 13.3%, which consisted of Whites and Coloureds. All respondents resided within eThekwini and surrounding areas. These results are in keeping with current information whereby over 51% of eThekwini's residents are African, nearly one-quarter of the population is Indian or Asian, while 15.3% are White and 8.6% are Coloured. The largest ethnic group is the Zulus (World Population Review 2022:1).

The predominant age group was found to be above 34 years old. Moreover, the ratio of males to females is approximately 4:1 (78.3%: 21.7%). It was found in various studies that males dominated the workforce where heavy-duty diesel-powered machinery was used and repaired, which included mining and mechanical repair workshops (Pronk *et al.* 2009: 445 and Mohankumar and Senthilkumar 2017:1228). Within the age category of 26 to 33 years, 85.7% were male. Within the category of males only, 25.5% were between the ages of 26 to 33 years.

This category of males between the ages of 26 to 33 years formed 20.0% of the total sample. According to Statistics South Africa (2017:1), 70% of eThekwini's population was between the ages of 18- 64 years and over 60% of the workforce comprised males. However, a recent study's findings have suggested that exposure to diesel exhaust emissions are more harmful for females than males, prompting more changes in women's blood components related to inflammation, infection and cardiovascular disease (Tursman 2022:1).

Approximately a third of the respondents (32.5%) worked in the storage warehouse, with 23.3% being in the distribution centre. Smaller numbers of respondents worked in the raw material stores, repairs workshop and throughout the plant. Most of the respondents were general workers (60.8%), with slightly less than a fifth (19.2%) being forklift operators. The remaining respondents were employed as mechanics, plant operators and supervisors. More than two-thirds had more than 4 years of experience. This indicates a stable workforce and low turnover within the companies.

5.3 HEALTH ISSUES

None of the respondents indicated any shortness of breath issues. A small number (n = 2, 1.7%) indicated that they sometimes experienced shortness of breath whilst doing work outside. Factors such as the type of task performed outside, duration of task, presence of pollutants that can invoke a respiratory response and pre-existing respiratory disorders should be considered when evaluating respondents who claimed to have experienced shortness of breath whilst working outside. Studies have shown that exposure to diesel exhaust emissions has a profound impact on human respiratory health (Ristovski *et al*. 2012: 201, Armah *et al.* 2021:2, Hu *et al.* 2012: 146, Mohankumar and Senthilkumar 2017:1228 and Wierzbicka *et al.* 2014:213). Another study found that the occupational exposure to diesel exhaust emissions is very common in heavy-duty vehicles such as forklift trucks found within factories (Podlewski *et al*. 2017:135).

According to Ping and Guang (2017: 836), animal and epidemiological studies have shown that both short-term and long-term exposure to DPM could pose a risk to health. From the animal studies, it is suspected that long-term DPM exposure can increase the risk of lung tumours. However, it was noted that the occupational environmental DPM concentrations are usually lower than the animal experimental DPM concentration. Moreover, Ping and Guang (2017: 836) indicated that long-term exposure to DPM resulted in a higher risk of lung cancer. The epidemiological studies included miners, construction, truckers and railroad workers. The relative risk of lung cancer ranged from 1.13 to 5.10 under different DPM exposure conditions.

Exposure to gases found in diesel exhaust emissions such as carbon monoxide, carbon dioxide, oxides of nitrogen and sulphur dioxide, even at low doses, can have a detrimental effect on the breathing function of persons exposed (Geravandi *et al.* 2015: 1, Gorguner and Akgun 2010: 31 and Podlewski *et al.* 2017:136). According to research, the World Health Organization's (WHO) guidelines for carbon monoxide exposure are expressed at four averaging times as follows: 100 mg/m^3 for 15 minutes (min), 60 mg/m^3 for 30 min, 30 mg/m^3 for 1 hour (hr) and 10 mg/m^3 for 8 hrs (WHO 2018: 70).

In addition, according to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:233), the OEL for CO over an 8 hr TWA is set at 50ppm. According to Ram (2019: 231), CO_2 is neither a direct nor indirect health hazard in normal concentrations of 500-1200 ppm. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa 1993:233), the OEL for CO_2 over an 8hr TWA is set at 10000ppm. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa. 1993:249), the OEL-STEL/C is set at 0.5ppm. According to the OHS Act, Regulations for Hazardous Chemical Agents (South Africa. 1993:245), the OEL- over an 8hr TWA for NO and NO_2 are set 50 ppm and 0,4 ppm.

None of the respondents indicated any wheezing in the chest. This could be due to the respondents not being subject to levels of diesel exhaust emission gases that invoked a profound respiratory response. Some respondents (n= 14, 11.7%) indicated that they coughed at their work-stations and approximately two-thirds of the respondents indicated that the coughing stopped after moving away from their work zones. Research studies have indicated that diesel exhaust exposure could lead to several problems like acute eye affections, bronchial irritation, nausea, light headiness, phlegm and cough (Mohankumar and Senthilkumar 2017:1228, Wu, Jin and Carlsten 2018: 834, Ali *et al.* 2018:3 and Taxell and Stantonen 2017:246).

Grahame *et al* (2014:627) found that oxidative stress levels in workers at a bus depot were elevated after a workday, compared to before work, and were more highly elevated at the end of a second consecutive workday than after the first workday. Relative to the general U.S. population, workers in the trucking industry most consistently exposed to higher levels of diesel exhaust had significantly elevated rates of both lung cancer and ischemic heart disease.

5.4 EXPOSURE TO DIESEL EXHAUST EMISSIONS

According to research by Wu, Jin and Carlsten (2018: 834), epidemiological studies have provided strong evidence for associations of diesel exhaust emission exposure with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence of the adverse effects related to short-term exposure, whereas fewer studies have addressed the longer-term health effects. Short-term exposure to diesel exhaust emissions has been associated with significant increases in coughing, phlegm production and coughing, tightness in the chest and chest pain resulting in hospitalizations, emergency department visits or home medical visits (Taxell and Stantonen 2017:246).

Three-quarter of the sample (75.0%) indicated that they had been exposed to diesel exhaust emissions and all of the respondents (n = 120) believed that exposure to diesel-powered forklifts emissions impacted their general health. Diesel engines are considered to be one of the largest contributors to pollution caused by exhaust emissions, which are responsible for several health problems (Mohankumar and Senthilkumar 2017:1228, Wierzbicka *et al.* 2014:213) and Armah *et al.* 2021:2). Li *et al* (2015: 1363) indicated that occupational exposure to diesel exhaust emissions may be higher when workers are close to the emissions source.

Additionally, Hodas *et al* (2016: 837) stated that the indoor occupational environment is of particular importance when considering the health effects associated with diesel particulate matter exposure because employees who spend the majority of their time indoors are exposed to two to three orders of the magnitude larger than exposures to outdoor emissions. According to CAREX Canada (2017:1), occupations that may be exposed to diesel exhaust from the use of on-road engines include forklift operators and bus and trucking company workers.

Epidemiological studies have been conducted to establish the short-term health effects associated with diesel exhaust exposure. Animal studies where rats were the chosen species for research showed that when exposed to five different levels of DPM (0, 0.03, 0.1, 0.3, 1 mg/m^3) for 6 h/day for one week, showed mild effects on the lungs for the exposure group were observed. However, all the adverse effects disappeared after a period of recovery. The study indicated that short-term DPM exposure can cause adverse effects on both heart and lungs, but the adverse effects are reversible after a period of recovery. Overall, short-term DPM exposure could result in a series of adverse effects on the brain, lungs and cardiovascular system. From the study, it is concluded that the brain and cardiovascular system are more sensitive to DPM exposure than the lungs. However, the adverse effects will disappear after a period of recovery in clean air (Ping and Guang 2017:4).

Human research studies indicated that short-term or acute exposure to DPM results in some non-cancer health effects, such as acute irritation, asthma, cough and light headedness, especially for asthma patients and sensitive groups, who are more easily affected by the DPM (Ping and Guang 2017:4). Other human studies have shown that health non-smoking volunteers exposed to DPM exhaust for a short-period, suggested that short-term exposure could cause bronchial inflammation, eye irritation, nasal irritation and headaches.

Retrospective studies within South African mines have shown that employees are exposed to significantly high levels of diesel exhaust emissions emitted from the underground mining diesel powered machinery, which has had a profoundly negative impact on the respiratory health of employees (Pretorius *et al.* 2017: 301). Currie *et al* (2014:16) stated that most of the pollution produced by diesel-powered vehicles occurred during idling and in the process of acceleration.

Furthermore, Chen *et al* (2017:2) stated that pollution emitted from diesel-operated vehicles is one of the leading preventable threats to global health.

5.5 SMOKING

The results indicate that approximately a fifth of the respondents replied that they smoked, and more than half of the respondents indicated that they had been smoking for less than a year. This smoking habit predisposes these workers to more severe health effects when combined with diesel particulate matter and renders them to be a higher risk. Approximately 90% of the respondents indicated that they smoked at most one pack per day. In addition, approximately 84% of the respondents indicated that their upper respiratory health had worsened after they started smoking cigarettes. Approximately 73% of employees responded that they did not experience any shortness of breath after smoking a cigarette. In addition, approximately 73% of employees responded that they did not experience any tightness in their chests after smoking a cigarette.

All the respondents indicated that there were no non-respiratory symptoms experienced whilst working in their current work areas. According to research, smoking had been shown to causes cancer, heart disease, stroke, lung diseases, diabetes and chronic obstructive pulmonary disease (COPD), which includes emphysema and chronic bronchitis (CDC. 2020:1). According to Wu, Jin and Carlsten (2018: 834), epidemiological studies have provided strong evidence for associations of diesel exhaust emission inhalation with inflammatory lung and cardiovascular diseases. In general, there is sufficient evidence that exposure to diesel exhaust emissions could aggravate existing respiratory disorders caused by smoking.

5.6 PERSONAL AIR SAMPLING RESULTS

Personal air sampling was conducted within the same month over ten days at the paint manufacturing companies. The personal air sampling was conducted on the most exposed group of employees who consented to the study, over an eight-hour work shift. In addition, the personal air sample apparatus was attached to diesel-powered forklift truck drivers of Company A and Company B, who performed their duties within the raw material storage warehouse, production, packaging, storage and distribution warehouse.

Ten personal air samples were taken from each company over ten days. In addition, four blank samples were taken as required by the NIOSH 5040 methodology. The control samples were taken under similar conditions such as weather and temperature, the same manner and times as the initial twenty samples. The control samples were taken to ensure reliability of the results. The results of elemental carbon as a marker for DPM indicate that employees were subjected to low levels of DPM. These levels were below the recommended OEL for all samples taken. In total, twenty-four personal air samples were taken from Company A and Company B.

The recommended OEL for DPM was 0.16 mg/m^3 (South Africa. 1993:245). All personal air samples taken were below the recommended OEL. This could be due to various observed factors such as adequate ventilation, good maintenance of diesel-powered forklift trucks and duration of exposure to pollutants. A study by Pronk *et al* (2009: 454) revealed that EC levels in forklift drivers at a dockyard were found between the range of 4 and 36mg/m^3, except for one study which reported levels of 122mg/m^3. Significantly lower EC exposure levels in dockyard forklift drivers were reported when exhaust filters were used compared to levels when no exhaust filters were used.

Alves *et al* (2015: 11530) found that modern diesel engines have extremely low diesel particulate emissions, almost at the level of the measurement error of the existing gravimetric method. Moreover, Alves *et al* (2015: 11537) stated that based on a study on several diesel powered vehicles in Europe, it was found that inappropriate maintenance, repair or use and accelerated catalyst ageing may be pointed out as possible factors justifying the higher emissions emitted from diesel engines. Additionally, Lee *et al* (2015: 17) stated that the composition and generation of diesel exhaust varies depending on the age of the diesel engine, type of engine, fuel characteristics, driving cycle, and whether the exhaust is filtered. Furthermore, Alves *et al* (2015: 11527) stated that amongst other factors, the composition of diesel exhaust emissions depends on driving conditions, vehicle age and category, fuel, lubricant and after-treatment technology.

Pronk *et al* (2009: 445) further stated that one study found that EC exposure was generally higher for mechanics in stand-alone workshops. This was due to a number of factors such as ventilation, size of the workshop and the number of workers within that workspace. Moreover, Mohner and Wendt (2016: 186) found that diesel exhaust exposure was also influenced by various factors such as weather conditions, type of vehicle and ventilation. Pronk *et al* (2009: 445) further stated that colder weather, compared to warmer weather, resulted in greater personal exposure levels for mechanics.

A study by Taxell and Santonen (2017:244) found that the exhaust composition of new technology diesel engines, with multi-component emission reduction systems including the diesel particulate filter and oxidation catalyst, differs from that of older diesel engines. The mass of DPM emissions was reduced by more than 90%. The proportion of EC in the particles was reduced and that of sulphates increased, reflecting the reduction of carbonaceous particles.

5.7 CONFOUNDING FACTORS

The smoking history of employees was considered as a confounding factor in this study. In addition, other contaminants such as dust should also be considered in the study because such contaminants might exacerbate the health effects of DPM. Additional confounding factors would include employees who had pre-existing respiratory conditions. However, no employees in this study indicated having any pre-existing respiratory conditions. Another confounding factor was the forklift truck age and maintenance history. Research has shown that diesel engine emissions can be significantly affected as the engine deteriorates due to normal wear or a lack of proper service. Normal engine wear can result in decreased injection pressures and delayed fuel injection timing. A number of different engine malfunctions can cause retarded or delayed injection timing, which increases DPM emissions (Dieselnet 2018: 1).

5.8 LIMITATIONS OF THE STUDY

Although this study design was similar to that of studies conducted internationally, it did have certain limitations. The study was carried out at one point in time and gives no indication of the sequence of events, whether exposure occurred before, after or during the onset of the outcome of the study.

A major limitation of the study was analysing exposed employees' medical files to validate answers received within the health questionnaire. Due to the companies' Health and Safety policy, the researcher was unable to obtain this type of data. This is stipulated in the OHS Act, whereby an employer must keep records of the results of all assessments and medical surveillance reports of employees, provided that these personal medical records be made available for viewing only to an occupational health practitioner (South Africa 1993: 221). This data would have been beneficial to corroborate the findings of this study and possibly further validate what other studies have mentioned.

In addition, the study investigated the current respiratory health of employees. It is not the intention to infer causality. Another major limitation of the study was the number of personal air samples taken and analysed. Due to budget constraints, a limited number of personal air samples were taken. A broader sample population and a longer period of sampling would have been beneficial to verify the findings of this study and further validate the results of other studies within the occupational environment.

5.9 CONCLUSION

The results of the study strongly indicate that employees are subjected to very low levels of DPM. The recommended OEL for DPM was 0.16 mg/m^3 (South Africa 1993:245). All personal air samples taken were below the recommended OEL. This could be due to various observed factors such as adequate ventilation, good maintenance of diesel-powered forklift trucks and duration of exposure to pollutants. Although the levels of DPM that employees were subjected to were low, the following chapter aims to address Objective Three of the research, namely to make recommendations to mitigate DPM exposure in the workplace.

CHAPTER 6

RECOMMENDATIONS AND CONCLUSION

6.1 INTRODUCTION

In the previous chapter, the results of the findings were analysed and discussed. This chapter summarizes the main findings and concludes with the way forward to improve on safeguards against occupational exposure to diesel exhaust emissions. In addition, this study provides recommendations for diesel-powered forklift truck driver exposure. The improvements below may be applied to all above and below ground occupational environments where diesel-powered machinery are operated. According to Chen *et al* (2017:2), pollution emitted from diesel operated vehicles are one of the leading preventable threats to global health.

Despite extensive research on DPM and the related health effects, DPM is not regarded as a notation carcinogen in SA (South Africa 1993:236). Therefore, this study aspired to provide further information and evidence in aiding to close the knowledge gap and emphasize the importance of reducing diesel exhaust emissions exposure. Although the study was conclusive on the etiology of diesel exhaust emissions and DPM, there were no significant correlations between the source of DPM levels and the most exposed employees. Nevertheless, recommendations are made to improve the working environment according to the hierarchy of controls, alternate fuel sources and the identification of opportunities for future research. Finally, a summary is presented in conclusion of the study.

6.2 OCCUPATIONAL HEALTH AND SAFETY (OHS) ACT NO.85 OF 1993

6.2.1 Long title of the OHS Act

The OHS Act sets out to ensure the health and safety of any person within the occupational environment regardless of the severity of the hazard. In addition, it aims to remove or mitigate the hazard or risk as reasonably practicable. The Long title of the OHS Act includes the provisions: “To provide for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery; the protection of persons other than persons at work against hazards to health and safety arising out of or in connection with the activities of persons at work; to establish an advisory council for occupational health and safety; and to provide for matters connected therewith” (South Africa 1993: 7).

6.2.2 General duties of the Employer

According to section 8 of the OHS Act (South Africa 1993:10), every employer shall provide and maintain, as far as reasonably practicable, a working environment that is safe and without risk to the health of his employees. In this regard, the employer should make provisions to ensure that the necessary control measures are in place to reduce or eliminate exposure to diesel exhaust emissions.

6.3 DIESEL PARTICULATE MATTER EXPOSURE CONTROL MEASURES

A number of options and control strategies for the treatment and reduction of diesel particulate matter are available to industry, all of varying scopes, efficiencies and expense. These include fuels and fuel additives (low sulphur, ultra-low sulphur diesel and biodiesel); emissions-based maintenance programs; engine type/specification; exhaust after-treatment (diesel oxidation catalysts, diesel particulate filters, disposable-type filters, selective catalytic reduction); environmental cabins; administrative controls (limiting engine idle time, limiting the number of equipment allowed in a heading or drift, and remote control and automation); and personal protective equipment in the form of respirators. Combinations of emissions control measures can be applied in order to provide the most efficient use of the allocated resources (Esswein *et al.* 2018:68, Franse 2022: 40 and Mohankumar and Senthilkumar 2017:1231).

According to Esswein *et al* (2018:68) and Druley (2018: 1), controls to minimize DPM exposures involve implementation of the hierarchy of controls which include elimination, substitution, engineering controls, administrative controls (including training and hazard communication), and as a last measure, use of personal protective equipment such as respirators. However, according to Druley (2018: 1), NIOSH states that elimination and substitution are often more difficult to enact after work has begun. Figure 19 below depicts the occupational hierarchy of controls for mitigating DPM exposure.

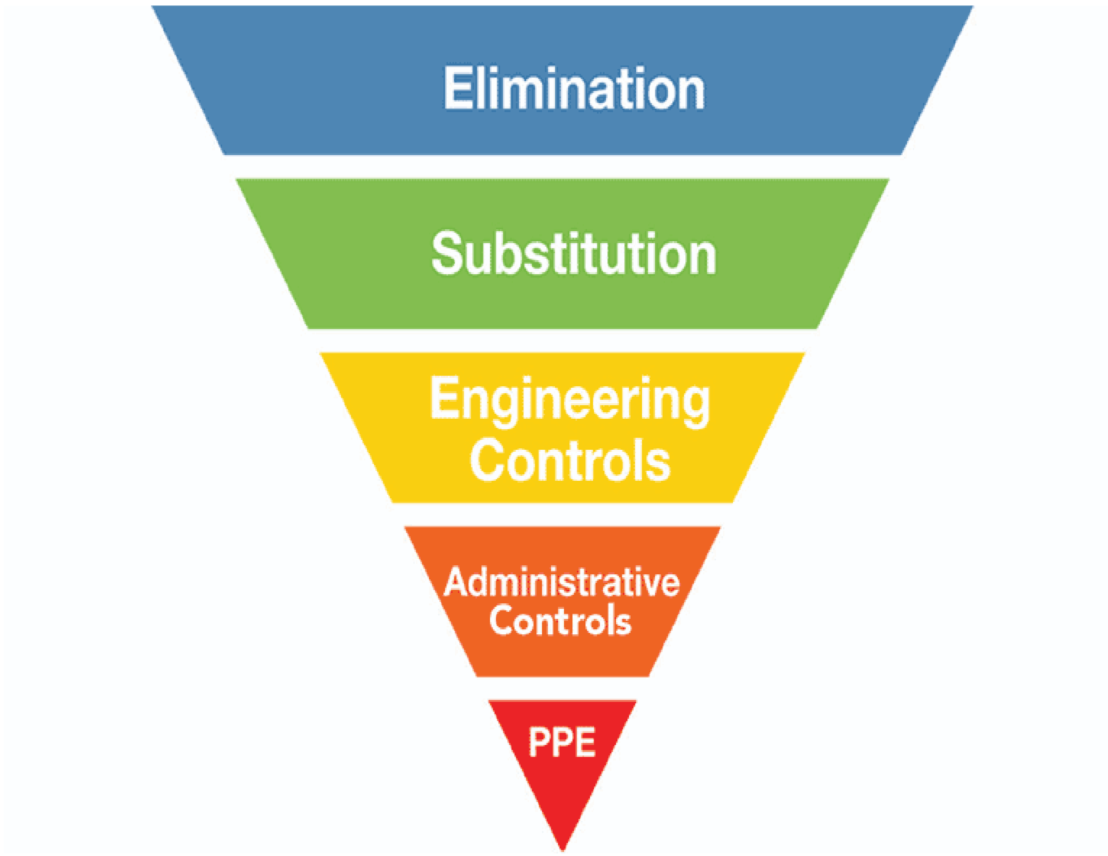

Figure 19- Hierarchy of Controls (Druley 2018: 1).

6.3.1 Elimination

Elimination involves the process of physically removing the hazard from the occupational environment (Druley 2018: 1). Esswein *et al* (2018:68) stated that elimination can include locating diesel-driven machinery in an offsite location, which may not completely eliminate exposure risk but may result in partial removal and eliminate some of the strongest point sources of DPM aerosols which typically are the array of diesel-powered machinery. However, Singh *et al* (2018: 509) stated that the elimination of diesel fuel as a fuel source is imperative. The elimination of diesel is possible through the use of alcohol with a biodiesel blend.

6.3.2 Substitution

6.3.2.1 Electric-powered vehicles

Substitution involves the process of replacing the hazard (Druley 2018: 1). Choi and Koo (2021: 1) indicated that the worldwide adoption of electric-powered vehicles has increased over the past decade. One of the key reasons that government agencies promote electric-powered vehicles is due to their environmental benefits. Mohankumar and Senthilkumar (2017:1231) stated that biodiesel has low sulphur and aromatic content and contains nearly 10% oxygen which helps it to burn completely. However, from the point of view of electric forklift users, there is no direct consumption of fossil fuels and no emission of harmful exhaust gas components takes place directly on the premises. It would be recognized that the utilization of electric forklift trucks is a more environmentally friendly solution.

6.3.2.2 Fuel substitution- Biodiesel

Biodiesel is a fuel produced from renewable sources such as vegetable oils, animal fats and recycled cooking oils, which are long chain tri-glyceride esters with free fatty acids. Chemically it is defined as the mono alkyl (or mono ethyl) esters of long chain fatty acids derived from renewable sources. Biodiesel is typically produced through the reaction of a vegetable oil or animal fat with methanol or ethanol by using sodium hydroxide or potassium hydroxide as catalyst in the yield glycerine and biodiesel (Franse 2022: 40 and Mohankumar and Senthilkumar 2017:1231).

Biodiesel can be used in neat form or blended with petroleum diesel for use in diesel engines. Its physical and chemical properties as it relates to operation of diesel engines are similar to petroleum-based diesel fuel. Biodiesel also has some important advantages when compared to diesel fuel; contains almost no sulphur; is biodegradable, non-toxic and a natural lubricant (Franse 2022: 40). Numerous studies showed that a blend of bio diesel, cotton-seed oil and methanol significantly reduced the DPM concentrations by 24%. Oxygen content in biodiesel promotes the oxidation of soot and helps the reduction of particle number concentration (Mohankumar and Senthilkumar 2017:1233).

As evidenced by the research of Dobrzynska *et al* (2019:9) in Europe, the best influence on the reduction of diesel particulate emission is the addition of nanoparticles of cerium dioxide and 10- 30% hydro treated vegetable oil (HVO) fuel. In addition, the results obtained confirm that the application of both HVO and nano-additives to diesel can achieve a significant reduction of carbon monoxide (52%) and hydrocarbon (47%) emissions compared to the B7 base fuel. Particulate emissions (up to 10% by mass of particulates and 7% by number of particulates) were found to be best reduced by adding nanoparticles of cerium dioxide to the B7 fuel (with 30% HVO), while the best results in reducing nitrogen oxide emissions were obtained by adding ferrocene nanoparticles to the B7 fuel with 30% HVO (Dobrzynska *et al.* 2019:9).

According to a study by Esswein *et al* (2018:68), the results of a recent simulated study in the mining industry found that the use of biodiesel 75 and gas/diesel fuel reduced DPM compared to diesel fuel alone, and concluded that use of alternative fuels have the potential to significantly reduce diesel emissions. Likhanov and Lopatin (2019: 2) stated that in 2001, the European Commission approved a strategy to gradually replace motor fuels with three main alternatives: natural gas, biofuels and hydrogen. In 2009, the European Union Renewable Energy Directive 2009/28/EC was issued, which aims to achieve a 10% share of biofuels used in the transport sector by 2020. In 2003, the European Commission adopted Directive 2003/30EC, which set the goal of increasing the share of biofuels in the total fuel balance for transport from 2% in 2005 to 5.75% in 2010. By 2030, it has planned to replace 25% of traditional fuels with biofuels.

6.3.2.3 Water emulsified fuel

According to Mohankumar and Senthilkumar (2017:1232), water emulsified fuel is another fuel modification principle used to control particulate matter and NOx emission simultaneously. This emulsion is created when primary fluid is dispersed throughout the secondary immiscible fluid, usually in spherical droplets form. This process can be done with or without the help of surfactants, usually accomplished with the help of a ternary diagram.

The main reason for the reduction of emissions is that during rapid evaporation, water droplets having a lesser boiling point than the surrounding fuel would explode rapidly. This process is called a micro-explosion event. This eventually increases premixed combustion duration and more ignition delay period creates more time for fuel-air mixing, leading to a reduction in diesel particulate matter formation (Mohankumar and Senthilkumar 2017:1232). According to a study conducted by Lin *et al* (2012:396), hydrated butanol–diesel blends were prepared by adding the specific ratios of water into the pure n-butanol, and then blending the hydrated butanol with a conventional diesel. The results of the study revealed that the amount of n-butanol blend added had a positive effect in reducing DPM levels.

6.3.2.4 Oxygenated fuel additives

According to Mohankumar and Senthilkumar (2017:1232), oxygenated fuel is a fuel that has a chemical compound containing oxygen. These oxygenated additives simply enhance combustion and the ignition quality of fuel by improving the cetane number, thereby reducing the ignition temperature of particulates. The various oxygenated additives used comprise methanol, ethanol, butanol, diethyl ether, diphenyl ether, diethylene glycol, dimethyl ether and nitromethane. Oxygen within the fuel structure generally decreases soot formation, but the effect depends on temperature as well, and is also accounted for by the reduction in the number of carbon-carbon bonds in the premixed flames.

6.3.3 Engineering controls: Pre-combustion

6.3.3.1 Injection timing

Diesel particulate matter emission can be controlled up to some extent by varying the injection timing parameter. When the injection timing is advanced, the DPM emissions will be reduced. This effect is mainly related to the ignition delay property. The reason behind this scenario is that advancing injection timing will lead to an increase in the premixed combustion duration which enhances fine mixing of fuel and air, thereby reducing DPM emissions. However, the NOx emission is increased by advancing the injection timing due to increased ignition delay. DPM emission increases when injection timing gets retarded and NOx emission is reduced (Mohankumar and Senthilkumar 2017:1231).

6.3.3.2 Injection pressure

Mohankumar and Senthilkumar (2017:1231) stated that another pre-combustion technique adopted to reduce particulate matter is varying injection pressure. The main reason behind this is that when injection pressure gets increased, it leads to fine atomization and fuel droplet size gets reduced, which leads to complete combustion. Another factor is that spray penetration length increases with high injection pressure, which leads to proper utilization of air and improves fuel-air mixing rates.

Su *et al* (1995: 975) stated that higher injection pressure gives more energy to the fuel and produces a finer spray and faster spray tip penetration. Increased fuel injection pressure has been found to be effective in improving the fuel/air mixing and reducing DPM emissions. In addition, in the study by Su *et al* (1995: 978), the results indicated that when injection pressure increases from 90 MPa to 160 MPa, the particulate matter reduction of 78% was achieved due to proper mixing of the air-fuel mixture and fine atomization of the fuel.

6.3.3.3 Multiple injections

Another pre-combustion technology to control particulate matter is the use of multiple injection events within the same cycle. The key advantage of using this technology is that it will reduce both NOx and particulate matter simultaneously. Multiple injection technologies are made possible with the adoption of Common rail direct injection (CRDI) technology, which allows shorter injection duration and variable injection timing. This precise control is made possible through the use of the electronic control solenoid valve which controls injection pressure and timing accurately (Mohankumar and Senthilkumar 2017:1231). In a study by Chen (2000: 2134), it was found that multiple injections along with EGR will reduce NOx and DPM effectively due to increased charge air entrained and increased lift-off length.

6.3.3.4 New diesel technologies

A study carried out in Ghana deduced that the use of low-sulphur diesels, as well as diesel oxidation catalysts, is recommended. Although these do not produce a perfect safety margin, toxicity is reduced (Armah *et al.* 2021:2 and Mensah *et al.* 2020:4). New diesel technologies have dramatically reduced DPM levels by 99% in developed countries, but this is not the situation in Ghana, where traditional diesel exhausts are still used.

A study by Taxell and Santonen (2017:244) found that the exhaust composition of new technology diesel engines, with multi-component emission reduction systems including the diesel particulate filter and oxidation catalyst, differs from that of older diesel engines. The mass of DPM emissions was reduced by more than 90%. The proportion of EC in the particles was reduced and that of sulphates increased, reflecting the reduction of carbonaceous particles.

6.3.4 Engineering controls: Post-combustion

6.3.4.1 Diesel particulate filter

According to Apicella *et al* (2020:1), a diesel particulate filter (DPF) is an exhaust after treatment device that traps particulate matter such as soot and ash. A DPF typically uses a substrate made of a ceramic material that is formed into a honeycomb structure. There are wide varieties of DPF media available to collect the diesel particulates. The various DPF filters used are Alumina coated wire mesh, ceramic fibre, and porous ceramic monoliths. Currently, the honeycomb ceramic monolith walls flow concepts have been widely used to collect diesel particulate matter. These honeycomb monoliths trap the particulate matter as the gas flows through its porous walls (Prasad and Bella 2010: 75 and Mohankumar and Senthilkumar 2017:1231).

These filters are often called ‘Ceramic wall flow filters’. In these, alternate cells are plugged at one end and open at the opposite end. The exhaust gases enter the cells that are open at the upstream end and flow through the porous walls to the adjacent cells. The adjacent cells are open at the opposite downstream end and the filtered gas exits from the opposite end to the atmosphere (Mohankumar and Senthilkumar 2017:1231). According to the results of a study by Apicella *et al* (2020:6), the exhaust gas passes through the DPF system, the particles number is strongly reduced in the DPF at both engine loads at very low concentration.

6.3.4.2 Administrative controls

Administrative controls refer to changes in the way work tasks are performed to reduce or eliminate the hazard (OSHA 2021: 2). Esswein *et al* (2018:68) stated that administrative controls include evaluating DPM emission source strengths, prevailing wind patterns and employee worksite locations. In addition, another administrative control is limiting the time employees must spend in locations anticipated or determined to have exposure risks for DPM.

In addition, administrative controls effective for reducing DPM exposure include limiting the speed of diesel-powered vehicles and using one-way travel routes to minimize traffic congestion; prohibiting or restricting unnecessary idling or lugging of diesel engines; adopting a programme of regular engine maintenance; scheduling work to minimise the number of workers near the diesel-powered machinery while it is operating; restricting the amount of diesel-powered equipment and total engine horsepower operating in a given area; ensuring that the number of vehicles operating in an area does not exceed the capacity of the ventilation system; and designate areas that are off- limits for diesel engine operation and/or personnel travel (OSHA 2021:2).

6.3.4.3 Personal Protective Equipment

According to the hierarchy of control, personal protective equipment is regarded as the last resort of control for hazards (Druley 2018: 1). As exposure to DPM is best controlled at its source or by other means described previously, respiratory protective equipment should only be used as a last resort (OSHA 2021: 2). According to Esswein *et al* (2018:68), as a last resort, the correct use of air-purifying, elastomeric half-masks and filtering-face piece respirators having particulate efficiencies of FFP2 or greater and half-masks configured P-100 cartridges and acid-gas cartridges can reduce exposure to the particulate and gas/vapour phase of DPM emissions.

6.3.4.4 Educational improvements

Mohankumar and Senthilkumar (2017:1233) further stated that the economic costs of use of internal transport are a typical component of the company’s accounting, whereas the environmental and occupational health consequences associated with it are often overlooked. According to Anderson, Thundiyil and Stolbach (2012:173), although DPM exposure is ubiquitous, there is no defined and studied safe level. Patient education and behavioral modification strategies may contribute to better overall health. Additionally, this data can enable policy-makers, after weighing the economic impact, to enforce or strengthen existing legislation that limits DPM exposure.

Figure 20 below depicts a summary of DPM emission control techniques for pre- and post-combustion.

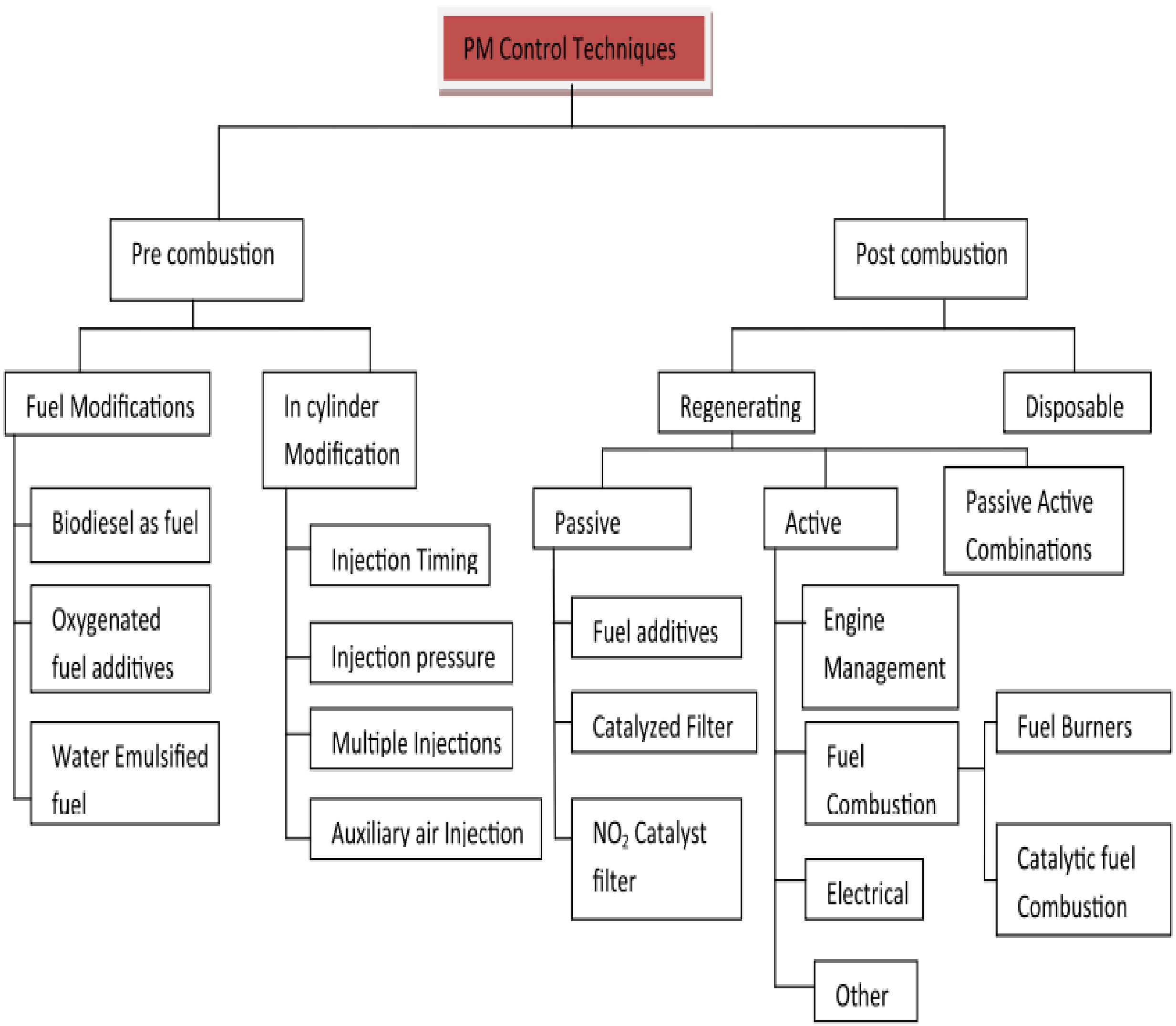

Figure 20: Layout of DPM control technologies (Mohankumar and Senthilkumar. 2017:1231).

6.4 FUTURE RESEARCH

Abundant studies exist both nationally and internationally on DPM exposure in the underground occupational environments. However, limited above-ground studies have been conducted in South Africa in respect of DPM exposure and the health effects thereof. This study can be expanded by conducting research at various industries such as dockyards, container storage yards, foundries, soft drink companies and retailers. A larger sample population and more personal air sampling shall yield more in-depth results.

An advantage of validity exists for future researchers to obtain access to employees' medical history files. This data shall be beneficial to corroborate the findings of the study and possibly further validate what other studies have mentioned. Furthermore, South Africa has very limited research on ultra-fine DE particles or nano particles. According to Grahame *et al* (2014:627), exhaust fumes from diesel engines are especially rich in ultra-fine particles and therefore may contribute greatly to the health effects.

Ultra-fine particles (particles with a diameter of less than $PM_{0.1}$) are of specific concern because their small size engenders them with a large reactive surface area and allows them to penetrate deep into the respiratory tract. Furthermore, Ali *et al* (2018:3) stated that ultra-fine particles have the ability to penetrate deep into the lungs, thereby posing a high health risk, and they are more toxic as compared to other particles. In addition to an association to lung cancer, diesel particulates have also been found to increase the risk of developing bladder cancer (Mohankumar and Senthilkumar 2017:1228).

6.5 CONCLUSION

In summary, research studies have outlined the negative health effects associated with exposure to diesel emissions. The literature reviewed highlighted that adequate control measures in place would result in low levels of exposure to DPM. This was supported in the current study. The main objectives of this study have been achieved and it can be concluded through the personal air sampling that employees were subjected to very low levels of DPM.

The recommended OEL for DPM in South Africa was 0.16 mg/m^3 (South Africa 1993:245). The key for these companies are to continue to uphold good maintenance on diesel-powered forklift trucks and health and safety measures to further reduce exposure levels and ultimately eliminate diesel exhaust emission exposure. In addition, more studies are needed on the above-ground occupational environment to further strengthen existing research with the aim of having

OELs for DPM reduced even further and acknowledge the carcinogen nature of DPM in South Africa, as well as regarding it as a carcinogen under the notation section of the hazardous chemical substances regulations, Table 1, for prohibited hazardous chemical agents.

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ANNEXURE A: Questionnaire

An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions among employees at selected paint manufacturing industries within eThekwini. KwaZulu- Natal. South Africa.

Date: ____

Please tick the appropriate boxes and answer the following questions below. The questions below will mostly be about yourself, your work history and upper respiratory health symptoms/disorders you may experience or have.

Section A: Biographical Information

1. Name and Surname (optional):____
2. Age: [18-25 years] [26-33 years] [34 and older]
3. Gender: [Male] [Female]
4. Race: [African] [Coloured] [Indian] [White] [Other]
5. Residential Area (optional):____
6. Contact number (optional): ____
7. Home Language: [Afrikaans] [English] [IsiZulu] [IsiXhosa]

Section B: Work History

8. Which paint industry do you currently work in? : Company A | Company B

9. Are you currently a permanent or contract worker? : Permanent | Contract

10. Do you work shifts? : Yes | No

11. Which shift are you working today? : Morning: 07.30am-16.00pm | Afternoon: 16.00pm-01.00am | Night: 01.00am-07.30am

12. Please indicate the number of hours you work in a week:

8hrs | 16hrs | 24hrs | 32hrs | 40hrs | 48hrs | 56hrs

13. Which department/ work area are you currently working in?

Repairs workshop | Raw material stores | Storage warehouse | Distribution centre | Throughout the plant

14. What is your current job function/ occupation?

Forklift truck operator | General worker | Mechanic | Floor supervisor | Plant operator

15. For how long have you been working in this department/ occupation?

1 month-1 year	2-3 years	4-5 years	More than 6 years

Section C: Health Issues

16. **Upper respiratory health symptoms**

16.1 During your work shift, do you experience shortness of breath?

Yes	No	Unsure

16.2 If you experience shortness of breath, during which part of the day does it occur?

Morning	Afternoon	Evening	Night	All the time	N/A

16.3 If you experienced shortness of breath, does your breathing return to normal once you leave the area in which you are working.

Yes	No	Unsure	N/A

16.4 Do you experience shortness of breath whilst performing any activities outside of work?

Yes, all the time	Yes, sometimes	No	N/A

16.5 During your work shift, do you experience wheezing in your chest?

Yes | No | Unsure

16.6 If you experience wheezing in your chest, during which part of the day does it occur?

Morning | Afternoon | Evening | Night | All the time | N/A

16.7 If you experienced wheezing in your chest, does it return to normal once you leave the area in which you are working?

Yes | No | Unsure | N/A

16.8 Do you experience wheezing in your chest whist performing any activities outside of work?

Yes | No | Unsure | N/A

16.9 Do you find yourself coughing whilst working in your current work area?

Yes, all the time | Yes, sometimes | No

16.10 You find that you stop coughing once you are away from the area in which you work?

Strongly agree | you c | Agree | whil | Disagree | ur w | Strongly disagree | N/A

Yes, all the time	Yes, sometimes	No

16.12 Do you cough up phlegm after your work shift?

Yes, all the time	Yes, sometimes	No

16.13 When you wake up in the morning, do you cough up phlegm?

Yes, all the time	Yes, sometimes	No

16.14 In your current occupation, do you feel you are exposed to diesel exhaust emissions?

Strongly agree	Agree	Disagree	Strongly disagree

16.15 How many hours in a work shift would you say you are you exposed to diesel exhaust emissions?

1hr	2hrs	3hrs	4hrs	5hrs	6hrs	7hrs	8hrs

16.16 Do you feel that exposure to diesel powered forklifts impacts on your general health?

Strongly agree	Agree	Disagree	Strongly disagree

16.17 Are you a smoker?

Yes	No

16.18 For how long have you been smoking?

1 month-1 year	2-3 years	4-5 years	More than 6 years	N/A

16.19 How many packs of cigarettes do you smoke a day?

Less than one	One pack	More than one	N/A

16.20 Your upper respiratory health worsened after you started smoking?

Strongly agree	Agree	Disagree	Strongly disagree	N/A

16.21 Do you experience shortness of breath after smoking a cigarette?

Yes	No	N/A

16.22 Do you experience chest tightness after smoking a cigarette?

Yes	No	N/A

16.23 Do you cough up phlegm after smoking a cigarette?

Yes	No	N/A

16.24 Do you experience any of the following non-respiratory symptoms whilst working in your current work areas?

Headaches | Nausea | Vomiting | Light headedness | Other | No

16.25 If you chose other to the above question, please specify:

____

16.26 Please indicate if you are allergic to any of the following allergens:

Dust | Pollen | Smoke | Formaldehyde and Volatile organic compounds (VOC's) | No allergies

16.27 Do you currently suffer from any of the following respiratory disorders?

Asthma | Emphysema | TB | Pneumonia

Pleural effusion | Vascular disease | Chronic Bronchitis | Other | None

16.28 If you chose other to the above question, please specify the respiratory disorder:

____

16.29 If yes to question 16.27 and 16.28, please specify how long you have had this respiratory disorder.

1 month-1 year | 2-3 years | 4-5 years | 6 years and more | N/A

16.30 Are you currently receiving treatment for the above respiratory disorder?

Yes	No	N/A

Thank you for answering all of the above questions.

ANNEXURE B- Letter of Information and Consent

LETTER OF INFORMATION

Title of the Research Study: An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions among employees at selected paint manufacturing industries within eThekwini, KwaZulu-Natal, South Africa.

Principal Investigator/s/researcher: Michael Brendan Kinsey (Bachelor of Technology: Environmental Health (DUT)).

Co-Investigator/s/supervisor/s: Supervisor: Dr. Ivan Niranjan (D. Tech: Quality (DUT)). Co-Supervisor: Mrs. Ana Paula Lopes Doherty Bigara (Master of Technology: Environmental Health (NMMU)).

Brief Introduction and Purpose of the Study: The study as a whole is focused upon investigating the upper respiratory health and related exposure to diesel exhaust emissions among employees at selected paint manufacturing industries within eThekwini, South Africa. The aim of the study is to investigate the upper respiratory symptoms and exposure to diesel exhaust emissions among employees. The objectives of the study are to determine the upper respiratory symptoms among employees and to quantify the levels of diesel exhaust emissions employees are exposed to.

Outline of the Procedures: You will be identified as per your job function. The background and importance of the study will be made known to you. Participation in the study will be voluntary. It is highly advisable that you show genuine consideration and honesty towards the research. A questionnaire will be used as a data collection tool. The questionnaire sets out to investigate the upper respiratory health symptoms of employees participating within the study. The questionnaire will be administered by the researcher. You will be given a questionnaire which can be completed at home. You may be required to spend at least 10 minutes completing the questionnaire. In addition, ten personal air sampling apparatus will be set up on you should you represent the high risk group, namely a diesel powered forklift operator. The personal air sampling apparatus will need to remain on you throughout the eight hours of a working shift, including during the lunch/ tea breaks. The personal air samples will be removed at the end of the work shift and be sent to the relevant accredited laboratory for analysis and interpretation of sampling media.

Risks or Discomforts to You: The study will not contain any physical attributes that may bring discomfort to you, however if you request to omit information to conserve anonymity, the researcher shall do so accordingly.

Benefits: The information obtained from this study will be utilized towards understanding the respiratory health of employees exposed to diesel exhaust emissions and essentially to broaden the knowledge on reducing and eliminating the harmful effects experienced due to exposure to diesel exhaust emissions. Identifying signs and symptoms of exposure to diesel exhaust emissions and determining control measures to reducing and eliminate diesel exhaust emissions will greatly benefit the health of those exposed. The availability of all information and conclusions/ recommendations from this research will be made available to the companies involved upon request. Benefits to the researcher will include publication.

Reason/s why You May Be Withdrawn from the Study: You may choose to withdraw from the study with no adverse consequences. The researcher may also choose to withdraw you from the study on the account that you may feel uncomfortable or be non-compliant.

Remuneration: Participating in this study will not result in any monetary benefits.

Costs of the Study: You will not be expected to cover any costs towards the study.

Confidentiality: The study may be made available to the relevant paint companies facility management teams upon request, however if you request to be made anonymous the researcher will do so accordingly to the best of his ability.

Research-related Injury: Any injury that occurs during or after the research may not have any direct relation to compensation.

Persons to Contact in the Event of Any Problems or Queries: Please contact the researcher Mr. Michael Brendan Kinsey (0749199279), my supervisor Mr. Ivan Niranjan (031 261 3644) or the Institutional Research Ethics Administrator on 031 373 2375. Complaints can be reported to the DVC: Research, Innovation and Engagement Prof S Moyo on 031 373 2577 or moyos@dut.ac.za.

Gratitude: Thank you for taking the time to participate in this research study. Your contribution is highly appreciated. The information obtained from the questionaire will be handled with the utmost confidenciality. In addition, your contribution will positively impact on the health and wellbeing of employees in various occupational environments who are exposed to diesel exhaust emissions.

CONSENT

Statement of Agreement to Participate in the Research Study:

- I hereby confirm that I have been informed by the researcher, Michael Brendan Kinsey about the nature, conduct, benefits and risks of this study. Research Clearance Number: IREC 045/18.
- I have also received, read and understood the above written information (Participant Letter of Information) regarding the study.
- I am aware that the results of the study, including personal details regarding my sex, age, date of birth, initials and diagnosis will be anonymously processed into a study report.
- In view of the requirements of research, I agree that the data collected during this study can be processed in a computerized system by the researcher.
- I may, at any stage, without prejudice, withdraw my consent and participation in the study.
- I have had sufficient opportunity to ask questions and (of my own free will) declare myself prepared to participate in the study.
- I understand that significant new findings developed during the course of this research which may relate to my participation will be made available to me.

____________________ __________ ____________________

Full Name of Participant **Date** **Signature/Right Thumbprint**

I Michael Brendan Kinsey herewith confirm that the above participant has been fully informed about the nature, conduct and risks of the above study.

Michael Brendan Kinsey __________ ____________________

Full Name of Researcher **Date** **Signature**

____________________ __________ ____________________

Full Name of Witness (if applicable) **Date** **Signature**

____________________ __________ ____________________

Full Name of Legal Guardian (if applicable) Date **Signature**

Annexure C: Gatekeepers Permission Request Letter for Conducting Research

Mr Michael Kinsey
Durban University of Technology
Department of Community Health Studies
Durban
4000

30/09/2019

Request for Permission to Conduct Research

Dear Sir/Madam

My name is Michael Brendan Kinsey, a Master of Health Sciences: Environmental Health student at the Durban University of Technology. The research I wish to conduct for my Masters of Health Science Dissertation involves: An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions among employees at selected paint manufacturing industries within eThekwini, KwaZulu-Natal, South Africa.

I hereby seek your consent to conduct the research within your company. Data for the research will be captured via two means; a questionnaire which will need to be answered by participants identified to take part in the study and via personal air sampling. The identity of the company and employees who participate will remain strictly confidential. In addition, the results of the questionnaire and personal air sampling will not be published in any journal article.

I have provided you with a copy of my proposal which includes copies of the data collection tools and consent and/ or assent forms to be used in the research process, as well as a copy of the approval letter which I received from the Institutional Research Ethics Committee (IREC).

If you require any further information, please do not hesitate to contact me Michael, Brenden Kinsey, on my cell: 0749199279 or on email: mbkinsey1@live.com . Thank you for your time and consideration in this matter.

Yours Sincerely,
Mr MB. Kinsey
Researcher
Master of Health Sciences
Student
074 919 9279
Mbkinsey1@live.com --

I. Niranjan (Dr)
Supervisor
031 373 2034
ivann@dut.ac.za --

Mrs. A. Bigara
Co-Supervisor
031 907 7649
ana@mut.ac.za --

Gatekeeper's permission

Date: ________________________

Signature: ________________________

Annexure D- Pilot Study Questionnaire Evaluation form

Questionnaire Evaluation Form

Please mark one box only

1. What is your opinion of the topic presented in this questionnaire?

Extremely interesting	
Interesting	
Average	
Boring	
Very boring	

2. Do you think the topic raised in the questionnaire was adequately covered?

Yes	
No	

3. What is your opinion about the Letter of Information?

Very clear	
Clear	
Adequate	
Unclear	
Needs revising	

4. How would you describe the instructions accompanying each of the questions?

Very clear	
Clear	
Adequate	
Unclear	
Needs revising	

5. Do you think the questionnaire is too long?

Yes	
No	

6. What is your opinion of the wording of the questionnaire?

The meaning of all questions is absolutely clear	
The meaning of most questions is clear	
The questions will not be understood by laypersons	
The questionnaire needs to be revised because it is unclear	

7. If you had any difficulty answering any question/s, please write the number/s of the question/s in the space below with a suggestion on how the question/s can be improved?

ANNEXURE E- IREC Approval

DUT
DURBAN
UNIVERSITY OF
TECHNOLOGY

Institutional Research Ethics Committee
Research and Postgraduate Support Directorate
2nd Floor, Berwyn Court
Gate 1, Steve Biko Campus
Durban University of Technology

P O Box 1334, Durban, South Africa, 4001

Tel: 031 373 2375
Email: lavishad@dut.ac.za .
http://www.dut.ac.za/research/institutional_research_ethics

www.dut.ac.za

9 March 2020

Mr M B Kinsey
PO Box 42973
Umzinto
4200

Dear Mr Kinsey

An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions among employees at selected paint manufacturing industries within eThekwini, KwaZulu-Natal, South Africa.

The Institutional Research Ethics Committee acknowledges receipt of your final data collection tool for review.

We are pleased to inform you that the data collection tool has been approved. Kindly ensure that participants used for the pilot study are not part of the main study.

In addition, the IREC acknowledges receipt of your gatekeeper permission letters.

Please note that FULL APPROVAL is granted to your research proposal. You may proceed with data collection.

Any adverse events [serious or minor] which occur in connection with this study and/or which may alter its ethical consideration must be reported to the IREC according to the IREC Standard Operating Procedures (SOP's).

Please note that any deviations from the approved proposal require the approval of the IREC as outlined in the IREC SOP's.

Yours Sincerely,

Professor J K Adam
Chairperson: IREC

ANNEXURE F- NIOSH Method 5040

DIESEL PARTICULATE MATTER (as Elemental Carbon) 5040

C	AW: 12.01	CAS: none	RTECS: none

METHOD: 5040: Issue 3 **EVALUATION: FULL** **Issue 1: 15 May 1996** **Issue 3: 15 March 2003**

OSHA : no PEL
NIOSH: no REL
ACGIH: 20 :g/m³ as elemental carbon (proposed [1])

PROPERTIES: nonvolatile solid

SYNONYMS (related terms): diesel particulate matter, diesel exhaust, diesel soot, diesel emissions

SAMPLING

SAMPLER:	FILTER: quartz-fiber, 37-mm; sizeselective sampler may be required [2].
FLOW RATE:	2 to 4 L/min (typical)
VOL-MIN:	142 L @ 40 :g/m³
-MAX:	19 m³ (for filter load of ~ 90 :g/cm²)
SHIPMENT:	Routine
SAMPLE STABILITY:	Stable
BLANKS:	2 to 10 field blanks per set

ACCURACY

RANGE STUDIED:	23 to 240 :g/m³ (See also ref. [2].)
BIAS:	None (See also ref. [2].)
OVERALL PRECISION ($Ö_{rT}$):	0.085 at 23 :g/m³ (See also ref. [2].)
ACCURACY:	± 16.7% at 23 :g/m³ (See also ref. [2].)

MEASUREMENT

TECHNIQUE:	Thermal-optical analysis; flame ionization detector (FID)
ANALYTE:	Elemental carbon (EC). Total carbon is determined, but an EC exposure marker was proposed. See [2] for details.
FILTER PUNCH SIZE:	1.5 cm² (or other [2])
CALIBRATION:	Methane injection
RANGE:	1 to 105 :g per filter portion (See also [2].)
ESTIMATED LOD:	0.3 :g per filter portion
PRECISION ($þ_r$):	0.19 @ 1 :g C, 0.01 @ 10 to 72 :g C

APPLICABILITY: The working range is approximately 6 to 630 :g/m³, with an LOD of ~ 2 :g/m³ for a 960-L air sample collected on a 37-mm filter with a 1.5 cm² punch from the sample filter. If a lower LOD is desired, a larger sample volume and/or 25-mm filter may be used (e.g., a 1920-L sample on 25-mm filter gives an LOD of 0.4 :g/m³). The split between organic carbon (OC) and EC may be inaccurate if the sample transmittance is too low. The EC loading at which this occurs depends on laser intensity. In general, the OC-EC split may be inaccurate when EC loadings are above 20 :g/cm². High loadings can give low (and variable) EC results because the transmittance remains low and relatively constant until some of the EC is oxidized. The split should be reassigned (prior to EC peak) in such cases [3]. An upper EC limit of 800 :g/m³ (90 :g/cm²) can be determined.

INTERFERENCES: Total carbon (as OC and EC) is determined by the method, but EC was recommended as a measure of workplace exposure because OC interferences may be present [2, 3]. Cigarette smoke and carbonates ordinarily do not interfere in the EC determination. Less than 1% of the carbon in cigarette smoke is elemental. If heavy loadings of carbonate are anticipated, a size-selective sampler (impactor and/or cyclone) should be used [2]. For measurement of diesel-source EC in coal mines, a cyclone and impactor with a submicrometer cutpoint are required to minimize collection of coal dust. A cyclone and/or impactor may be necessary in other workplaces if EC-containing dusts are present.

OTHER METHODS: Other methods for determination of EC and OC have been employed, but these are not equivalent to the method described herein. Information on other methods is summarized elsewhere [2].

REAGENTS:

1. Aqueous solutions of reagent grade (99+%) sucrose, 0.1 to 3 mg C per mL solution. Ensure filter spike loading range brackets that of samples.
2. Ultra pure $H_2 0$, Type I, or equivalent.
3. UHP helium (99.999%), scrubber also required for removal of oxygen.
4. Hydrogen, purified (99.995%), cylinder or hydrogen generator source.
5. Ultra Zero air (low hydrocarbon).
6. 10% oxygen in helium balance, both gases UHP, certified mix.
7. 5% methane in helium balance, both gases UHP, certified mix.

EQUIPMENT:

1. Sampler: Quartz-fiber filter, precleaned (in low temperature asher 2 to 3 h, or muffle furnace for 1 to 2 h at ~ 800 °C), 37-mm, in a 3-piece cassette with filter support (stainless steel screen, cellulose pad, or a second quartz filter). Alternative samplers may be required in dusty environments. See ref. [2] for details.

   NOTE 1: High purity, high efficiency, binderfree quartz-fiber filters must be used (e.g., Pall Gelman Sciences Pallflex Tissuequartz 2500QAT-UP.

   Precleaned filters are available from several laboratories. Filters also can be purchased and cleaned in-house. Filters should be cleaned in a muffle furnace operated at 800-900°C for 12 hours. Check (analyze) filters to ensure removal of OC contaminants. A shorter cleaning period may be effective. OC results immediately after cleaning should be below 0.1 µg/cm². OC vapors readily adsorb onto clean filters. Even when stored in closed containers, OC loadings may range from 0.5 µg/cm² after several weeks.

   NOTE 2: Cellulose supports give higher OC blanks than screens and quartz filters. Bottom quartz filters can be used to correct for adsorbed vapor; see ref. [2].

2. Personal sampling pump with flexible tubing.
3. Thermal-optical analyzer; see ref. [2].
4. Metal punch for removal of 1.5 cm² rectangular portion of filter.

   NOTE: A smaller portion (e.g., taken with cork borer) may be used, but the area must be large enough to accommodate the entire laser beam (i.e., beam should pass through the sample, not around it). The area of the portion must be accurately known, and the sample must be carefully positioned (the filter transmittance will decrease dramatically when the sample is properly aligned). A filter portion \$0.5 cm^2 with diameter or width # 1 cm is recommended.

5. Syringe, 10-:L.
6. Aluminum foil.
7. Needle (for lifting filter punch portion).
8. Forceps 9. Volumetric flasks, Class A.
10. Analytical balance.

SPECIAL PRECAUTIONS: Hydrogen is a flammable gas. Users must be familiar with the proper use of flammable and nonflammable gases, cylinders, and regulators. According to the instrument manufacturer, the instrument is a Class I Laser Product. This designation means there is no laser radiation exposure during normal operation. Weakly scattered laser light is visible during operation, but does not pose a hazard to the user. The internal laser source is a Class IIIb product, which poses a possible hazard to the eye if viewed directly or from a mirror-like surface (i.e., specular reflections). Class IIIb lasers normally do not produce a hazardous diffuse reflection. Repairs to the optical system, and other repairs requiring removal of the instrument housing, should be performed only by a qualified service technician.

SAMPLING:

1. Calibrate each personal sampling pump with a representative sampler in line.

   NOTE: Both open- and closed-faced cassettes have been used. Both configurations generally give even deposits. At higher flow rates (e.g., 4 L/min), small spots occasionally have been observed in the center of the filters when closed-faced cassettes are used. This material likely consisted of impacted diesel agglomerates and/or non-diesel particulate matter. EC results for multiple portions of the filters were in good agreement, so the spots had little analytical impact. Other samplers also can be used (see ref. [2]) provided an even deposit of diesel particulate results. An even deposit is necessary because the sample portion analyzed must be representative of the entire deposit. If the deposit is not homogeneous, the entire sample must be analyzed. An impactor/cyclone may be needed in some cases. [2]

2. Attach sampler outlet to personal sampling pump with flexible tubing.
3. Sample at an accurately known flow rate. Typical rates are 2-4 L/min (note: Lower flows (e.g., 1 L/min) have been used in mines to prevent overloading).
4. After sampling, replace top piece of cassette, if removed, and pack securely for shipment to laboratory.

   NOTE: Diesel particulate samples from occupational settings generally do not require refrigerated shipment unless there is potential for exposure to elevated temperatures (that is, well above collection temperature). Filter samples normally are stable under laboratory conditions. Some OC loss may occur over time if samples contain OC from other sources (for example, cigarette smoke). Sorption of OC vapor after sample collection has not occurred, even with samples having high (e.g., 80%) EC content.

SAMPLE PREPARATION:

5. Place sample filter on a freshly cleaned aluminum foil surface. Isopropyl alcohol or acetone can be used to clean the foil. Allow residual solvent to vaporize from the surface prior to use. Punch out a representative portion of the filter. Take care not to disturb deposited material and avoid hand contact with sample. A needle inserted at an angle is useful for removal of the filter portion from the punch body. Newer instruments have an externally mounted bracket to support the quartz sample holder while the previous sample is removed and a new one is loaded. Through a hole in the side of the standard punch, a needle can be used to push the filter portion from the punch onto the sample holder. Alternative approaches also can be used, depending on the user's preference, as long as contamination is avoided.

CALIBRATION AND QUALITY CONTROL:

6. Analyze at least one replicate sample. For sets of up to 50 samples, replicate 10% of the samples. For sets over 50 samples, replicate 5% of the samples. If a filter deposit appears uneven (this should not be the case if the cassette is sealed properly), take a second portion (step 5) for analysis to check evenness of deposition.
   NOTE: Precision of replicate analyses of a filter is usually better than 5% (1 to 3% is typical).
7. Analyze three quality control blind spikes and three analyst spikes to ensure that instrument calibration is in control. Prepare spike as follows:
   a. With 10-:L (or other) syringe, apply an aliquot of OC standard solution directly to filter portion taken (step 5) from a precleaned filter. For best results, the precleaned filter punch should be cleaned again in the sample oven prior to application of the aliquot.
      NOTE: With small aliquots (e.g., # 10 :L), disperse standard solution over one end of filter portion to ensure standard is in laser beam. To prevent possible solution loss to surface, hold the portion off the surface. Larger volumes can easily penetrate to the underside of the filter portion.
   b. Allow water to evaporate and analyze spikes with samples and blanks (steps 9 and 10).
      NOTE: A pronounced decrease in filter transmittance during the *first* temperature step of the analysis indicates water loss. Allow portions to dry longer if this occurs. Spiked punches also can be dried in the oven, if desired. For quick drying, the 'clean oven' command on the menu can be selected and canceled after about 4 seconds. The time allowed may depend on instrument, but oven temperatures should be below 100 °C to avoid boiling the solution. This approach is convenient and prevents potential adsorption of organic vapors in laboratory air.
8. Determine instrument blank (results of analysis with freshly cleaned filter portion) for each sample set.

MEASUREMENT:

9. Adjust analyzer settings according to manufacturer's recommendations (see instrument operation manual and background information in ref. [2]). Place sample portion into sample oven.
   NOTE: Forms of carbon that are difficult to oxidize (e.g., graphite) may require a longer period and higher temperature during the oxidative mode to ensure that all EC is removed (the EC peak should never merge with the calibration peak). Adjust time and temperature accordingly. A maximum temperature above 940 °C should not be required.
10. Determine EC (and OC) mass, :g. Analyzer results are reported in units :g/cm^2 of C. The reported values are normally based on a sample portion of about 1.5 cm^2, which is the area of the standard punch provided by the manufacturer. If the portion area used differs from the value entered in the ocecpar.txt file, multiply the result by 1.5 (or value in ocecpar.txt file) and divide the product by the actual area analyzed to obtain the area-corrected result (i.e., reported result x 1.5/portion area = corrected result in :g/cm^2). This is most easily done in the data spreadsheet. Alternatively, the correct results will be obtained with the data calculation program if the portion area is entered in the parameter file (ocecpar.txt), but this approach is cumbersome when punches of different areas are used because correct results will not be obtained for all punch sizes.

CALCULATIONS:

11. Multiply the reported (or area-corrected) EC result (:g/cm^2) by filter *deposit area*, cm^2, (typically 8.5 cm^2 for a 37-mm filter) to calculate total mass, :g, of EC on each filter sample (W_{EC}). Do the same for the blanks and calculate the mass found in the average field blank (W_b). The mass of OC is calculated similarly, but the mean OC field blank may underestimate the amount of OC contributed by adsorbed vapor. A quartz filter placed beneath the sample filter can provide a better estimate of the adsorbed OC. [2]
12. Calculate the EC concentration (C_{EC}) in the air volume sampled, V (L):

$$C_{EC} = \frac{W_{EC} - W_b}{V}, mg / m^3$$

EVALUATION OF METHOD:

Details on the evaluation of this method are provided in a chapter of this NMAM Supplement. [2] The chapter includes a summary of interlaboratory comparison work conducted since the initial publication of the method. Background information and guidance on method use, including sampling requirements, also are provided. In general industry, 37-mm cassettes are normally suitable for air sampling, but there are exceptions. A cyclone in series with an impactor having a submicrometer cutpoint must be used in coal mines, and the Mine Safety and Health Administration (MSHA) has recommended use of a cyclone-impactor sampler in metal and nonmetal mines. [5] The impactor is commercially available [6]. A size-selective sampler (either impactor and/or cyclone) also may be required in other dusty environments [2], particularly if the dust is carbonaceous. If a sample contains carbonate, the carbonate carbon (CC) will be quantified as OC. A carbonate-subtracted result can be obtained through acidification of the sample portion or through separate integration of the carbonate peak [2] (*note: Trona and other compounds containing sodium can etch the quartz oven wall at elevated temperatures. Avoid spillage of these materials in the sample oven.*) These procedures are described in a Chapter of this Supplement. [2] The thermal-optical method is applicable to nonvolatile carbon species (i.e., particulate OC, CC and EC). The method is not appropriate for volatile or semivolatiles, which require sorbents for efficient collection.

REFERENCES:

[1] ACGIH [2001]. Cincinnati, OH: American Conference of Environmental Industrial Hygienists. Diesel Exhaust (Particulate and Particulate Adsorbed Components), Draft TLV-TWA Document, 2001.
NOTE: Recently, diesel exhaust has been taken off the ACGIH Notice of Intended Changes list. See reference [2].

[2] NIOSH [2003]. Manual of Analytical Methods (NMAM). O'Connor PF, Schlecht, PC, Monitoring of Diesel Particulate Exhaust in the W orkplace, *Chapter Q*, Third Supplement to NMAM, 4th Edition, NIOSH, Cincinnati, OH. DHHS (NIOSH) Publication No. 2003-154.

[3] Birch, ME, Cary, RA [1996]. Elemental Carbon-based Method for Monitoring Occupational Exposures to Particulate Diesel Exhaust Aerosol Sci Technol *25*:221-241.

[4] Birch, ME [1998]. Analysis of carbonaceous aerosols: interlaboratory comparison, Analyst, 123:851-857.

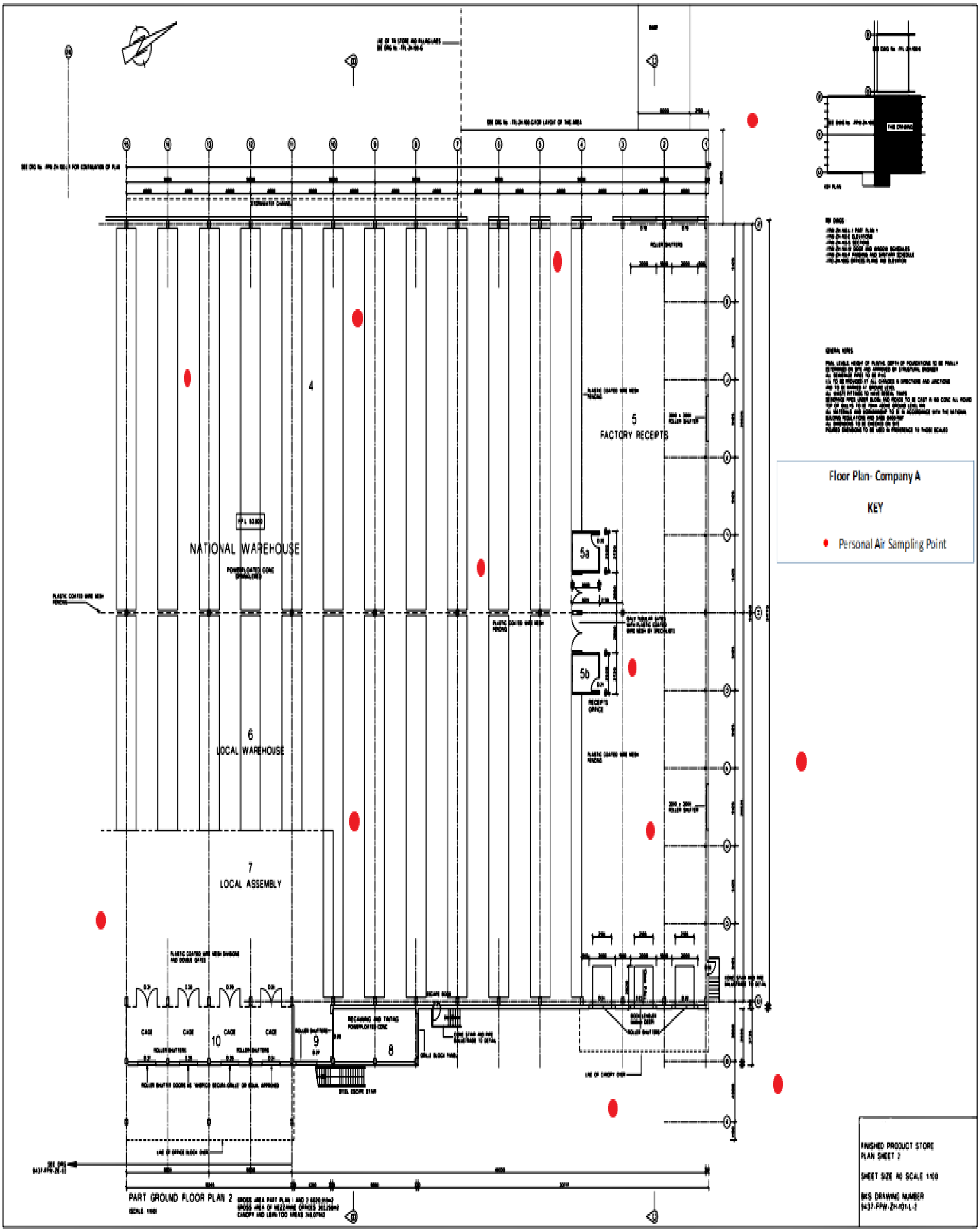
[5] Mine Safety and Health Administration (MSHA) [2001]. Department of Labor, 30 CFR Part 57, Diesel Particulate Matter Exposure of Underground Metal and Nonmetal Miners; Final Rule, Federal Register *Vol. 66*, No. 13, January 19.

[6] SKC, Eight Sixty-Three Valley View Road, Eighty-Four, PA 15330.

METHOD WRITTEN BY:

M. Eileen Birch, Ph.D., NIOSH/DART

Annexure G- Floor Plans Indicating Personal Air Sampling Points




Floor Plan- Company B
KEY
Personal Air Sampling Point
SOLVENT PLANT FLOORPLAN
ICI DULUX

Annexure H- Personal Air Sampling Pump Calibration Certificate

Technology Solutions
Measurement Science Laboratory

ANAB
ANSI National Accreditation Board
ACCREDITED
CALIBRATION LABORATORY
L2347.01

Certificate of Calibration

ANSI National Accreditation Board (ANAB) is a member of the International Laboratory Accreditation Cooperation (ILAC) Mutual Recognition Agreement (MRA). This arrangement allows for the mutual recognition of technical test and calibration data by the member accreditation bodies worldwide. For more information on the arrangement please consult www.ilac.org. The accuracies of all measurements were traceable to the SI (International System of Units) through NIST, NMISA, PTB or International Measuring Standards, unless otherwise noted. The uncertainties of measurement were estimated for a coverage factor of k=2 which approximates to a 95% confidence level.

American Standard Calibration Laboratory
Measurement Science Laboratory

GOLDILUX

Certificate No	L83491	As Found/As Left	Rev 0
Manufacturer	Casella		
Description	Air Sampling Pump Calibrator		
Model No	FlowDetective		
Serial No	1791196		
Plant No	AE173		
Calibrated for	Apex Environmental		
Address	Unit 4, 40 Beechgate Crescent, Southgate Business Park, Umbogintwini, 4126		
Temperature	(24.4 ± 2) °C		
Relative humidity	(48 ± 5) %rh		
Date of calibration	16 February 2022		
Expiry date	16 February 2023	Issue Date	16 February 2022

Calibrated by *Pieter W Botha* Digitally signed by Pieter Willem Botha Date: 2022.02.16 14:15:17 +02'00'

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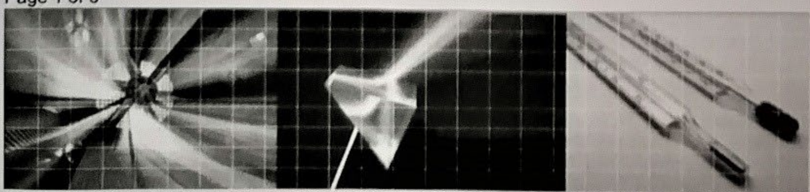
Technical Signatory *Pieter W Botha* Digitally signed by Pieter Willem Botha Date: 2022.02.16 14:15:24 +02'00'

Page 1 of 3



Hards Laboratories cc
T/A Technology Solutions
C3 Prospect Close
43 Regency Drive
R21 Corporate Park, Irene
Tel: +27 (0) 12 345 5358
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Technology Solutions
Measurement Science Laboratory

Certificate of Calibration

Certificate No L83491 As Found/As Left Rev 0

Standards and Equipment used

Description	Asset No	Cal due
Primary Flow Calibrator; Bubble Generator; Std Flow Cell; Std Sensor Block	TS282	22 June 2022
Thermo-Hygrometer	TS294	06 May 2022
Bios DryCal	TS278	Source Only
Air Sampling Pump	3675483	16 February 2023

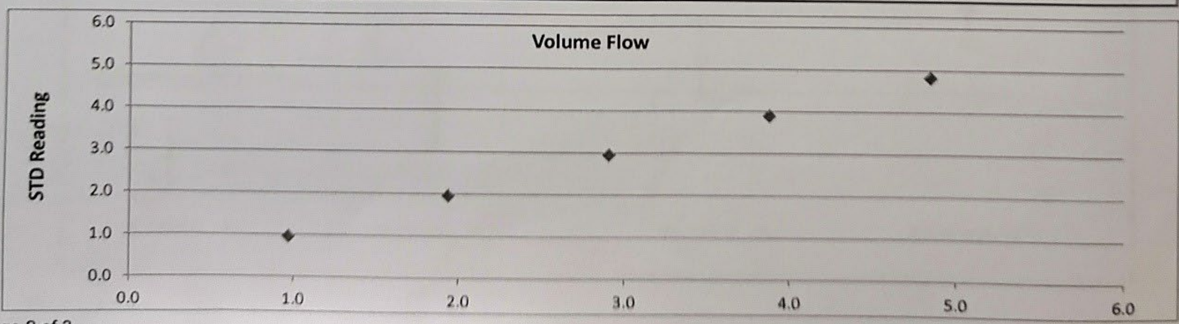
Procedure TS PL 024

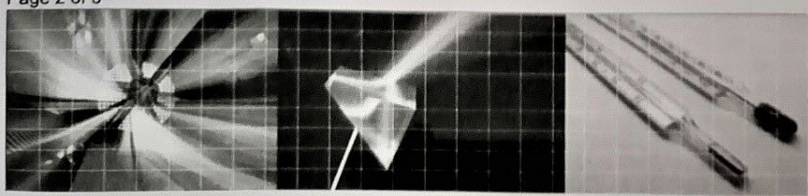
Results

Measurement Units LPM Range 5 LPM

Nominal Flow	STD Reading	STD Temperature (°C)	STD Pressure (psi)	UUT Reading	UUT Temperature (°C)	UUT Pressure (psi)	UUT Correction factor	Specification	Measurement Uncertainty (±)
1.00	0.970			0.966			1.00	0.05	0.01
2.00	1.940			1.958			0.99	0.10	0.01
3.00	2.910			2.954			0.99	0.15	0.02
4.00	3.880			3.897			1.00	0.20	0.03
5.00	4.850			4.824			1.01	0.25	0.04

Status	Instrument Received in Good Physical and Functional Condition.
Comments	The correction must be multiplied with the UUT reading to obtain the corrected value. The readings presented above are averaged data. LPM conditions are stated for prevailing gas temperature and pressure. (Volume Flow)





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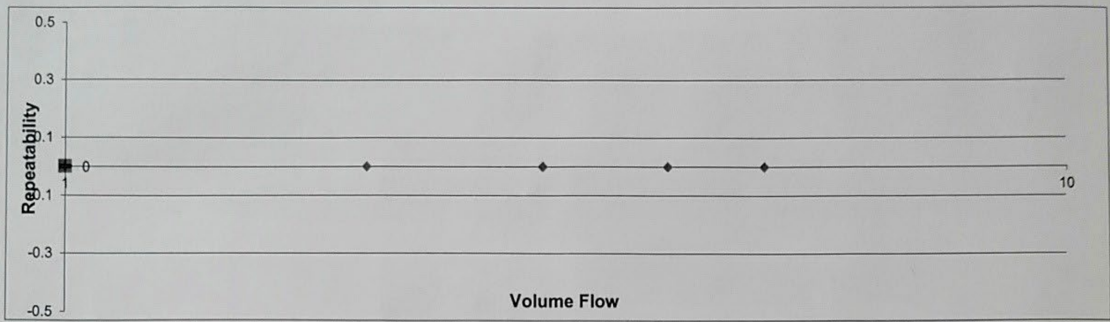
Repeatability Repeatability is defined as the closeness of the agreement between the results of successive measurements of the same measurand carried out under the same measurement conditions.



Compliance with Specifications - ILAC-G8

When a specification describes an interval with an upper and lower limit, a statement of compliance or non-compliance with specification is made where the ratio of the expanded uncertainty interval to the specified interval is reasonably small and fit for purpose.

Compliance: If the specification limit is not breached by the measurement result plus the expanded uncertainty with a 95% coverage probability, then compliance with the specification can be stated (See Case 1 of Fig.1). This can be reported as "Compliance" or "Compliance – The measurement result is within (or below) the specification limit when the measurement uncertainty is taken into account". In calibration this is often reported as "Pass";

Non-compliance: If the specification limit is exceeded by the measurement result minus the expanded uncertainty with a 95% coverage probability, then noncompliance with the specification can be stated. (See Case 4 of Fig.1) This can be reported as "Non-compliance" or "Non-compliance – The measurement result is outside (or above) the specification limit when the measurement uncertainty is taken into account". In calibration this is often reported as "Fail";

If the measurement result plus/minus the expanded uncertainty with a 95 % coverage probability overlaps the limit (See Case 2 and 3 of Fig.1), it is not possible to state either compliance or non-compliance. Where applicable in this report this condition is referred to as "Undetermined" and the user of the device must determine fitness for use in their measurement processes.

In cases where measurement uncertainty is not taken into account when making compliance statements, the shared risk approach is implemented and noted according on the calibration certificate.

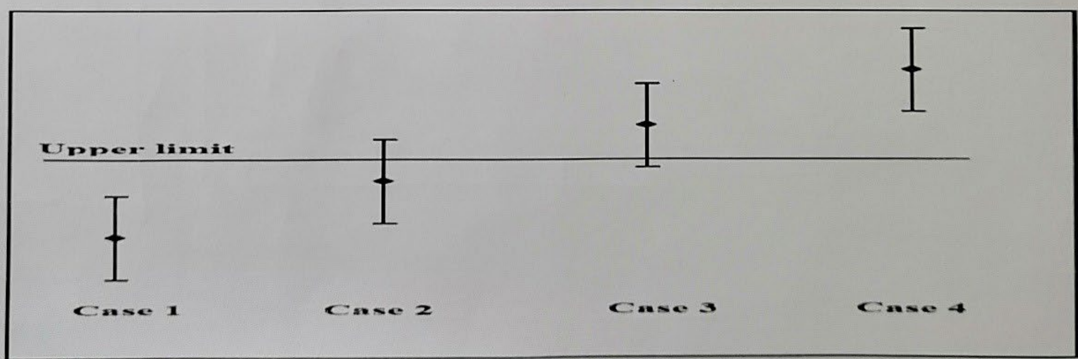
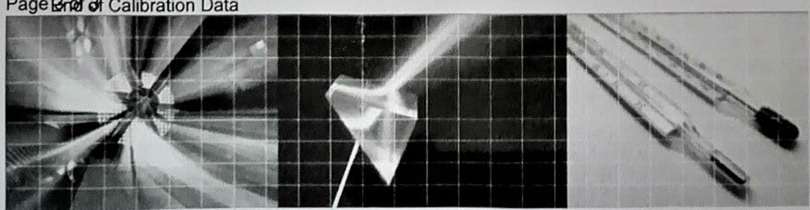


Fig. 1

End of Calibration Data



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Annexure I- Editors Letter

EDITING LETTER

696 Clare Road

Clare Estate

Durban

4091

25 November 2022

To: Whom it may concern

Editing of Master's thesis: Michael Kinsey

An investigation of upper respiratory symptoms and related exposure to diesel exhaust emissions amongst employees at selected paint manufacturing industries within eThekwini, KwaZulu-Natal, South Africa

This letter serves as confirmation that the aforementioned thesis has been language edited. Requisite academic writing conventions have been adhered to.

Any queries may be directed to the author of this letter.

Regards

MP MATHEWS

Lecturer and Language Editor

Mercimathews4@gmail.com

083 676 4778

Annexure J – Permission letter to adopt questionnaire

From: Michael Kinsey [mailto:mbkinsey1@live.com]
Sent: 22 June 2017 12:55 PM
To: Gill Nelson
Cc: ivann@dut.ac.za; Bigara, Ana
Subject: DPM Study

Hi Gill

I trust you are well. As per discussion telephonically, I am Michael Brendan Kinsey. I'm currently registered has a MHSc- Environmental Health student at the Durban University of Technology in KZN, student number: 21015825.

I'm currently undertaking my research on Diesel Exhaust and the respiratory effects thereof at selected paint manufacturing industries within EThekwini.

I currently seek permission to use a questionnaire used by your research team during your study on DPM exposure at mines within South Africa. I would really appreciate permission and full acknowledgment of the source will be made known.

Should you have any questions, please contact me on 074 919 9279 or via email.

Kind regards
Michael Brendan Kinsey
BTech: Environmental Health (DUT)
Cell: 074 919 9279
Email: mbkinsey1@live.com

MICHAEL KINSEY

From:	Michael Kinsey <mbkinsey1@live.com>
Sent:	22 November 2018 09:16 AM
To:	MICHAEL KINSEY
Subject:	Fwd: DPM Study
Attachments:	SKMBT_C28015021212540.pdf

-------- Original message --------
From: Cecilia Pretorius <CPretorius@csir.co.za>
Date: 2017/06/27 13:58 (GMT+02:00)
To: Gill Nelson <Gill.Nelson@wits.ac.za>
Cc: ivann@dut.ac.za, mbkinsey1@live.com, Ana@mut.ac.za
Subject: RE: DPM Study

Afternoon Michael,

I was the Principal Investigator for the DPM project in which we made use of a standard epidemiological questionnaire. The questionnaire was adapted to the South African mining industry and with a specific focus to DPM.

I hereby grant you permission to make use of the questionnaire. I've attached the paper that was presented at the International Mine Ventilation Congress 2014 for your reference.

Please let me know if you require any further information.

Kind regards,
Cecilia Pretorius

>>> On 2017/06/22 at 01:22 PM, in message <38C7A8888816E44EB215F6DEDE78926DCE524DF2@ELEUTHIA.ds.WITS.AC.ZA>, Gill Nelson <Gill.Nelson@wits.ac.za> wrote:
Dear Cecilia

Michael called me earlier. Are you able to assist him?

Regards
Gill

Annexure K- DUT Turn-it-in report

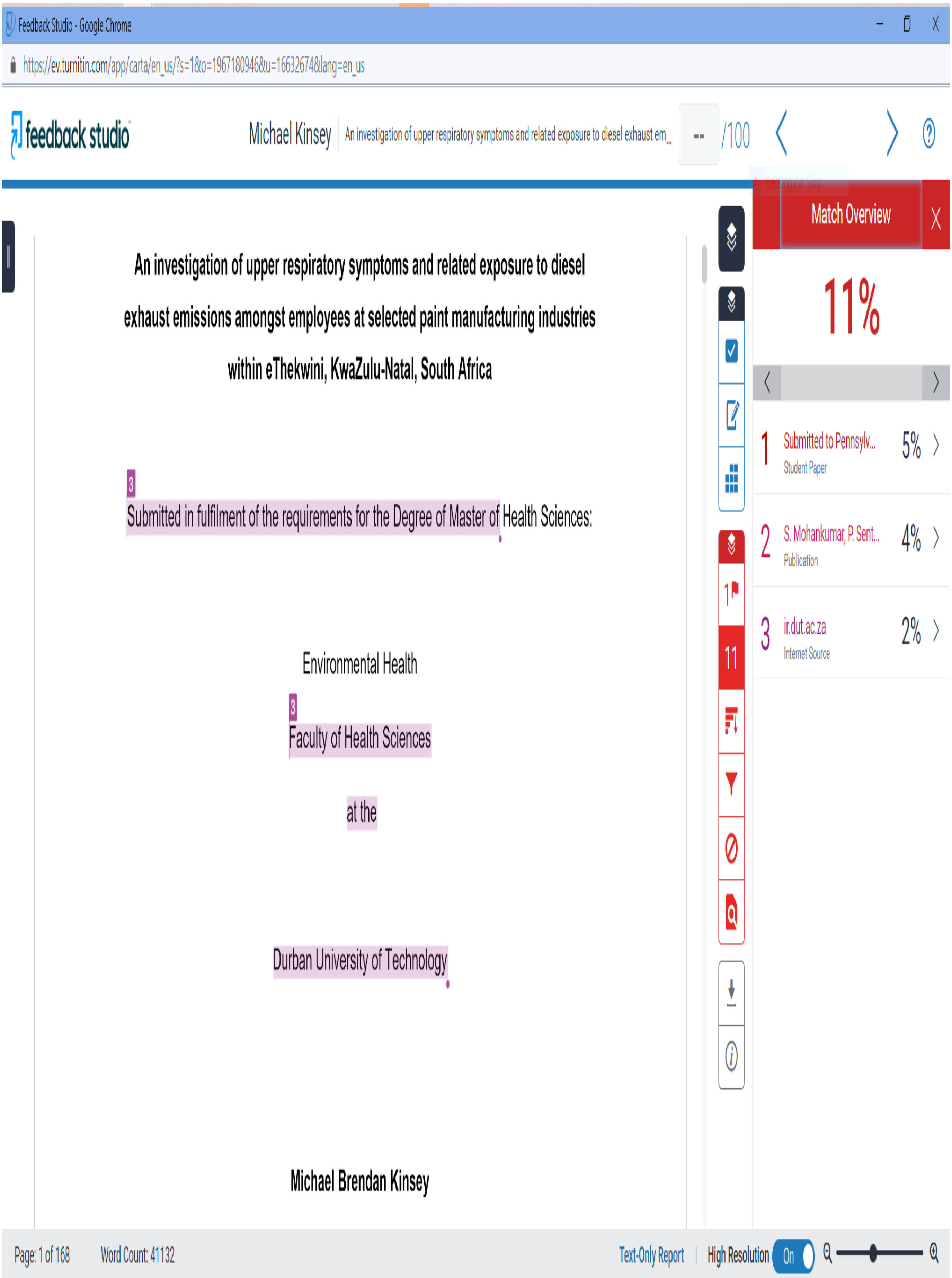
turnitin

Digital Receipt

This receipt acknowledges that Turnitin received your paper. Below you will find the receipt information regarding your submission.

The first page of your submissions is displayed below.

Submission author:	Michael Kinsey
Assignment title:	Research Methods
Submission title:	An investigation of upper respiratory symptoms and related ...
File name:	Thesis-_Michael_Kinsey_21015825.docx
File size:	4.39M
Page count:	168
Word count:	41,132
Character count:	230,581
Submission date:	30-Nov-2022 02:22PM (UTC+0200)
Submission ID:	1967180946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Michael Kinsey
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2 S. Mohankumar, P. Sent... 4%
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An investigation of upper respiratory symptoms and related exposure to diesel
exhaust emissions amongst employees at selected paint manufacturing industries
within eThekwini, KwaZulu-Natal, South Africa
Submitted in fulfilment of the requirements for the Degree of Master of Health Sciences:
Environmental Health
Faculty of Health Sciences
at the
Durban University of Technology
Michael Brendan Kinsey
Page: 1 of 168
Word Count: 41132
Text-Only Report
High Resolution
On