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Analysis of barometric pressure, temperature and density effects on flow rate of gravimetric dust sampling pumps used in silica dust monitoring at a South African gold mine

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by

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DECLARATION

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DEDICATION

I dedicate this dissertation to the memory of my grandfather, Ntate Setsoto Hermans Tlisane.

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EXECUTIVE SUMMARY

The eagerness to overcome workforce health crises in the mining industry continues to be a challenge, undermining health system transformation globally and more specifically in South Africa. Despite policy implementation and interventions towards health system improvements in South Africa's mining sector, literature does not provide a detailed narrative on accurate analysis and calibration, when barometric pressure, temperature and air density variations occur, during crystalline silica dust-monitoring processes. Incorrect reporting of crystalline silica concentrations may therefore be a contributing factor in unceasing new cases of silicosis and other silica dust related health issues.

This study aimed to determine the impact of barometric pressure, air density and temperature on the concentration of respirable dust samples, using personal gravimetric dust sampling instrument. The study further sought to establish the impact these environmental variables may contribute and whether this can be quantified and applied on measurements taken to correct historical measurement results.

The following objectives were used to:

- Determine the impact of barometric pressure, air density and temperature on the flow rate of various gravimetric dust sampling pumps.
- Determine the impact of barometric pressure, air density and temperature on the concentration of respirable dust samples, using dust sampling instruments.
- Establish the impact of the environmental variables that may contribute to the differences in the results obtained.
- Establish whether the GilAir Plus and Tuff pumps do maintain a constant flow rate at various barometric pressure levels.
- Analyse gravimetric data to determine the percentage error, if correction factor needs to be applied.
- Analyse the particulate matter collected on the filter media to determine the type and particle sizes of the particulate.

When a personal airborne silica dust sampler is used underground, it is subjected to extreme ambient thermal conditions, such as barometric pressure, air density changes, and temperature variations due to changes in the geothermal gradient and the increase in virgin rock temperature. However, these changes are not accounted for, neither are they considered when sampling strategies are employed. The current industry sampling methodologies are applied in a manner that assumes that the airborne particulate sampling device, set at certain flow rate under certain conditions of barometric pressure, air temperature and density on surface, will maintain that flow rate when subjected to different ambient environmental conditions underground.

The study found that barometric pressure, air density and temperature changes do affect the GilAir Plus and Tuff gravimetric dust pump's flow rate and therefore underground conditions need to be considered when gravimetric sampling is conducted. The ability of an individual pump to adjust its flow rate as it encounters variations in barometric pressure, temperature and density is dependent on its age, amongst other factors. The GilAir-3 pumps were the only pumps that indicated an increase in flow rate as barometric pressure increased, unlike the GilAir Plus and Tuff pumps. The implications hereof are that the GilAir Plus and Tuff pumps over-compensate for the changes in environmental conditions.

The Tuff and GilAir plus, although at first glance seem to be exaggerating the exposure levels, should they be used as instruments of choice for monitoring dust exposures in industry, it could mean that the results obtained, may demand stricter dust control measures be implemented. Instruments of high accuracy in determining worker exposure to quartz are required. This remains that the primary reason for conducting measurements is not merely for compliance, but rather to improve dust control strategies.

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LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygiene
BP	Barometric pressure measured in kilopascal (kPa)
COPD	Chronic obstructive pulmonary disease
DMR	Department of Mineral Resources
HIV	Human Immunodeficiency Virus
IL-8	Interleukin-8
MTB	Mycobacterium Tuberculosis
NIOH	National Institute for Occupational Health
OEL	Occupational Exposure Limit
REL	Recommended exposure limit
SACM	South African Chamber of Mines
SEM	Scanning electron microscope
SiO_2	Silicon dioxide
TB	Tuberculosis
TNF	Tumour Necrosis Factor
TWA	Time weighted average
WHO	World Health Organisation
XRD	X-ray diffraction

DEFINITIONS AND ACRONYMS

Aerodynamic diameter: The diameter of a unit density sphere with the same velocity as the particle of interest.

Crystalline: Having a highly structured molecular arrangement. The atoms and molecules form a three-dimensional repeating pattern/ lattice.

Cumulative silica: an estimate of the average respirable crystalline silica concentration a person is exposed to on the job, over the course of a working year times the number of years worked. Measured in milligrams per cubic meter times years.

Datum: A fixed starting aspect of a scale, from which inferences are made- datum is an abstract coordinate system with a reference surface (such as sea level) that serves to provide known locations to begin surveys and create maps.

No-observed-adverse-effect- level (NOAEL): an exposure level at which there are no statistically and biologically significant increases in the frequency or severity of adverse effects between the exposed population and its appropriate control.

Quartz: The most common type of crystalline silica.

Silica: A compound formed from silicon and oxygen. It is a polymorph (it exists in more than one form or state- crystalline and non-crystalline) Crystalline silica takes the form of quartz (most common), cristobalite, tridymite and four rare forms.

Silicosis: One of the most destructive forms of pneumoconiosis (characterised by scarring of lung tissue) which is contracted by prolonged exposure to elevated levels of respirable silica dust or acute levels of respirable silica dust.

TWA: the equivalent average exposure over a specified period, which is usually a nominal eight-hour working period

CHAPTER ONE

1. INTRODUCTION

1.1. Introduction

Gold-mining in South Africa existed since 1886, leading to developing the city of Johannesburg and several towns around gold diggings, including Barberton and Pilgrim's Rest.[1,2] The Witwatersrand gold-producing area in South Africa is underlain by an underground geological formation, also known as the Witwatersrand basin. The Witwatersrand basin is the world's richest known gold deposit, contributing over 40% (>50,000 metric tonnes) of the world gold production.[3] This elliptical basin stretches over an arc of roughly 400 km traversing the Free State, North West and Gauteng provinces in South Africa.[4] Above 90% of gold-mining in the Witwatersrand basin is in a form of underground close cut design.[4] Gold production in South Africa reached its peak in the 1970s and continuously declined since then from being rated as number one in the top global gold-producing countries to position number seven in the year 2015.[5] The progressive decline is attributed to challenges related to: (a) high energy costs; (b) decreasing gold ore grade; (c) accessibility difficulties; (d) health and safety concerns; (d) labour unions' unrest and (e) economic uncertainties.[4] Even though the production decline is noteworthy, newly-mined SA gold only accounts for about 5% of the global supply, contributing over R1.6 billion in taxes and currently employs approximately 120000 individuals.[5]

Despite all these socio-economic benefits and large gold endowment, significant health challenges are associated with gold-mining. Main challenges that existed for almost a century, include over-exposure to crystalline silica dust, leading to silicosis.[6] Silicosis was ignored for a long time in the mining industry as gold firms could exercise power in avoiding litigation claims.[7] These claims were avoided by employers as there were no systems in place to hold them accountable for interpreting the legislation. A main aspect that was neglected in the designing phase of the Witwatersrand underground mines was to provide sufficient air, ensuring that airborne crystalline silica is sufficiently diluted.[8] Mining organisations paid little attention to diseases originating from mining activities. Instead, ailments were selectively termed "diseases associated with the industry". This led to several workers assuming the risk of being affected when working within the organisation and ignored its long-term effects to their health. Although regulatory and governing institutions, such as the South African Chamber of Mines (SACM) exist, most companies that constituted and continues to form part of SACM did not prioritise silicosis and other dreaded diseases affiliated with gold-mining, mainly due to poor systems and the lack of employee health registers.

This is further exacerbated by the industry preferring the migrant labour system, implying an under-estimation of exposure and the compensation system, undisclosed to the Black labour force.[8,9] Most of the miners only became more aware of silicosis with public consciousness through the recent South African Constitutional Court ruling in the case of Mankayi versus AngloGold Ashanti Ltd (Case CCT 40/10, 2011) ruling in favour of Mr Thembekile Mankayi. It allowed him to sue and claim from his former employer, AngloGold Ashanti Limited for sufferings resulting silicosis.[10] This further led to a class action against various mining houses, forcing the industry to attempt reducing crystalline silica exposures.[11,12] It should be considered that the challenges of silica exposures are not only unique or limited to gold-mining, but it is a common prevailing health challenge to other mining commodities (coal and aggregate) and building demolition sites. It is therefore important to understand the dynamics and scientific measurements above and below sea level that govern the exposure to crystalline silica dust and its characteristic emission into the environment.

The ultra-deep gold mines in South Africa could serve as an ideal experimental and test site for the measurements and calibration of parameters used in crystalline silica monitoring processes. This is best exemplified in the world's second deepest mine, known as Tau Tona (Figure 1), owned by AngloGold Ashanti Ltd. Tau Tona mine (~3570m below datum), is one amongst several mining sites, faced with challenges of sampling airborne crystalline silica dust. The prevailing ambient barometric pressure, temperatures and air density are significantly different from sea level conditions, where most instruments used in occupational hygiene monitoring are calibrated and set as a reference for sampling purposes.

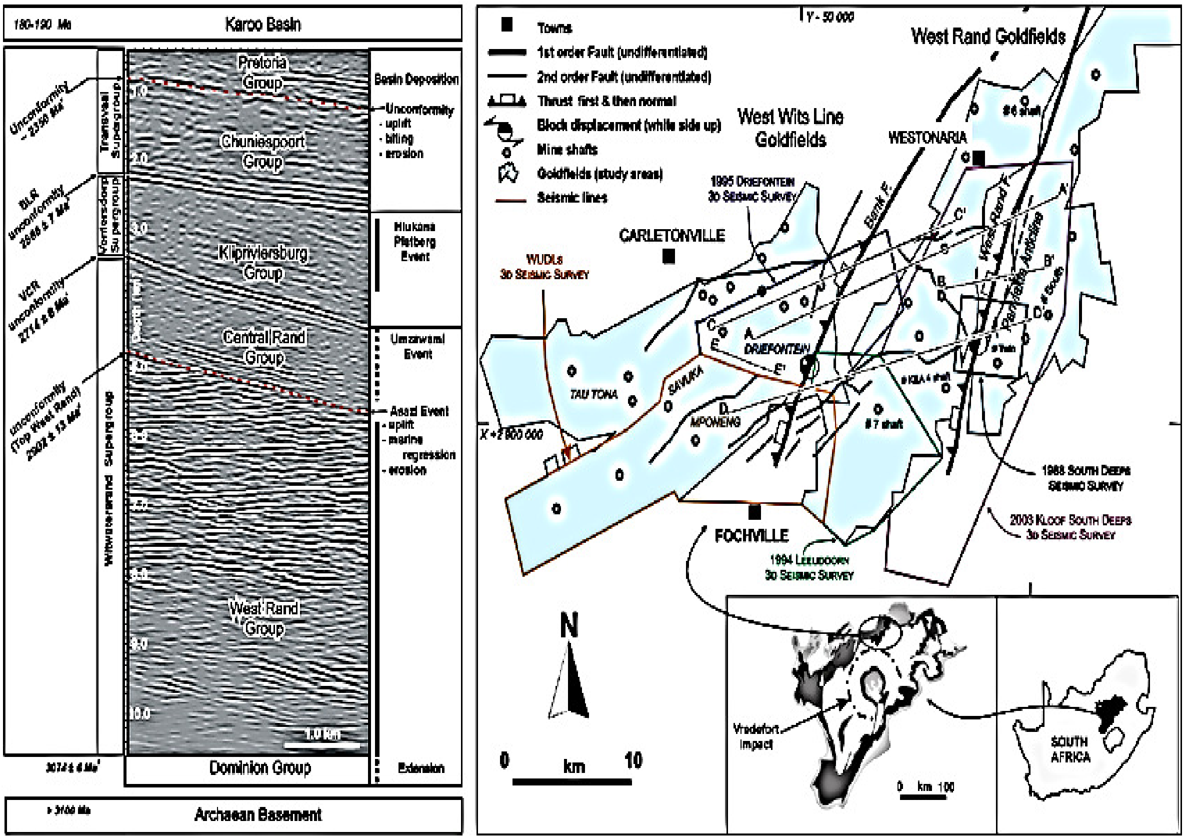

Figure 1: Location of Tau Tona gold mine relative to other West Wits line gold mines

Note that the world's deepest mine (Mponeng mine) is located adjacent to TauTona mine.

1.2. Silicosis, policy and current practice background

Silicosis is a fibrotic lung disease associated with crystalline silica exposure in the workplace.[7,8] The rate at which this disease progresses, depends on the concentration of crystalline silica deposition in the lungs and the quantity retained in the lungs. Silicosis in the gold-mining industry is due to chronic exposure to the contaminant, such as crystalline silica dust, over an extended period. Silicosis is an incurable disease, yet it is also completely preventable.[7]

The role of conducting air sampling in the mining industry, is to identify and quantify the levels of airborne contaminants to which the workers are exposed.[3] The results of these measurements assist in assessing the potential risk employees are exposed to, that may give rise to the onset of a disease. The results from air sampling measurements are compared to the Occupational Exposure Limits (OEL) and are used to determine the levels at which workers' protection is required.[13] The gold-mining industry conducts routine air sampling measurements to ascertain compliance to the set OEL.

At the current OEL of 0.1 mg/m³ silica dust exposures (as regulated by the South African Department of Mineral Resources and Department of Labour and targets of the World Health Organisation (WHO)), cases of silicosis still persists, despite global decline of new cases of silicosis exposures.[12] This subsequently resulted in the South African mining industry having to revise the milestones to 0.05 mg/m³ for silica dust and thus, the implementation of more stringent methods for controlling dust exposure in the workplace, were required. This OEL was only promulgated in 2008, contrary to other countries like the USA, where an OEL of 0.05mg/m³ came into effect 35 years earlier. This implied that the effect of allowing workers to be exposed to concentrations of silica, twice of those of other countries, might have detrimental effects on the workforce. The results of reducing the OEL will only be seen in the future.

When a personal airborne silica dust sampler is used underground, it gets subjected to extreme ambient conditions, such as barometric pressure changes, temperature changes due to changes in the geothermal gradient and virgin rock temperature changes. These changes are not accounted for, neither are they considered when sampling strategies are used. The industry sampling technique assumes that the airborne particulate sampling device, set at certain flow rate, when used under various conditions of barometric pressure, air temperature and density, will maintain the flow rate even after they are subjected to different ambient environmental conditions. Manufacturers of air sampling instrumentation became aware of these changes to the ambient air conditions which may affect the accuracy of the resultant concentration of airborne pollutant. In response to this, in 2014 some of the sampling instruments were modified or developed to adjust for changes in barometric pressures.

1.3. Field sampling and gravimetric measurement of crystalline silica dust

Sampling devices generally used in the mine where data was obtained, are the GilAir-3™ sampling pumps manufactured by Sensidyne in Florida, USA, an ISO 9001:2008 Certified organisation. Modifications on these pumps were made by the same manufacturer and developed sampling pumps said to maintain a constant flow rate, even under conditions of varying barometric pressure, the GilAir Plus™. Another manufacturer, Casella, developed an air sampling pump understood to maintain a constant flow under changing barometric pressure conditions, named Tuff™ series pump (Casella, Bedford, UK).

These challenges of a lack of reliable reference calibration, inaccuracies of measuring and reporting crystalline silica dust exposures, led to the initiation of this study. The study aimed to evaluate the impact changes in barometric pressure, temperature and air density may have on the flow rate of pumps used for gravimetric sampling with the purpose to determine underground mine workers' exposure to crystalline silica dust. The long-term goal is to inform the design of appropriate sampling-level interventions for improving the measurement quality taken during gravimetric dust sampling of crystalline silica dust.

1.4. Hypothesis

The underlying hypothesis of this study is the assumption that barometric pressure, air density and temperature changes that occur during surface calibration of dust-monitoring instruments and underground onsite measurement of crystalline silica using these surface calibrated instruments affect the gravimetric dust pump's flow rate leading to inaccurate reporting and under or over-estimation, both cases manifest certain levels of crystalline silica dust exposures and may posture significant health threats to the mining community at large. To appropriate the variations, both null and alternative hypotheses were considered:

The null hypotheses:

- H_0: Barometric pressure, air density and temperature change does not affect the gravimetric dust pump's flow rate.

- H_0: There are no significant variations in flow rate that can be attributed to barometric pressure, air density and temperature changes.

The alternative hypotheses:

- H_1: Barometric pressure, air density and temperature changes affect the gravimetric dust pump's flow rate.
- H_1: There are significant variations in flow rate that can be attributed to barometric pressure, air density and temperature changes.

1.5. Research objectives

The specific objectives of the study were to:

- Determine the impact of barometric pressure, air density and temperature on the flow rate of various gravimetric dust sampling pumps.
- Determine the impact of barometric pressure, air density and temperature on the concentration of respirable dust samples, using a gravimetric dust sampling instrument.
- Establish the impact of the environmental variables that may contribute to the differences in the results obtained.
- Establish whether the GilAir Plus and Tuff pumps do maintain a constant flow rate at various barometric pressure levels.
- Analyse gravimetric data to determine the percentage error, if correction factor is applied.
- Analyse the particulate matter collected on the filter media to determine the type and particle sizes of the particulate.

1.6. Study structure

This study comprises seven chapters: The Introduction in Chapter 1 provides a background to the study that outlines the challenges, hypothesis and objectives of the study. Chapter 2 provides a Literature Review which covers the fundamentals of silicosis, source of crystalline silica dust and associated characteristics. Details of the sample collection, preparation and analytical methodology are outlined in Chapter 3. The results are then divided into two chapters; Chapter 4 describes the silica characterisation results of the TauTona Gold Mine samples. A full discussion of the linkage and interpretation of the various results is provided in Chapter 5. Some final conclusions and several recommendations for further research are provided in Chapter 6. Research ethics approval letters for this study are included in the Appendix section of this study.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

Literature on silica dust exposures and silicosis does not provide much evidence on: (a) calibration of flow rate of gravimetric dust sampling pumps affecting the accuracy of results, (b) design of mines leading to clean air dispersion, (c) chemistry of silica dust source leading to silicosis and other airborne diseases and (d) aligning current policies with global best practices on silicosis prevention. This study however, only focusses on the calibration of the flow rate of the dust sampling pumps and not on the latter mentioned factors. It appears that silica dust related health aetiology in ultra-deep underground gold-mining environment was overlooked in literature on health system reforms. More focus was places on additional aspects of health system appraisals, such as Mycobacterium Tuberculosis (MTB) and the Human Immunodeficiency Virus *(*HIV*).* This chapter provides a detailed explanation on silica dust exposures, post-exposure effects and current processes routinely applied in silica interrelated measurements.

2.2. Silicosis aetiology

Mining activities in South Africa existed since more than 100 years ago and are associated with certain occupational illnesses. This is mainly due to poor ventilation practices and ignorance concerning prevention of adverse health outcomes associated with mining activities and safety measures needed to be considered in mining. Silicosis is one of the three most common forms of pneumoconiosis associated with specifically, gold-mining.[14] Silicosis is defined as an interstitial fibrotic lung disease caused by the accumulation of inhaled particles of one of the forms of crystalline silica, particularly quartz, in the lung tissue.[15,16] Those most at risk occupational exposure operations to the release of free silica, alpha quartz in particular are mining operations, quarrying, stonecutting, polishing, sandblasting and brick lining.[17] These activities involve handling of materials or substances containing crystalline silica, which are mechanically broken up to form dust that comprises inhalable and respirable fractions.[15,17]

2.3. Determinants of fibrogenesis

Fibrogenesis is the pathological response of several human tissues after chronic or severe repetitive injury, indicating autoimmune reactions and mechanical injury. In certain instances, fibrosis may result in permanent scarring, organ failure and death of tissue. Fibrosis is thus a result of a normal wound healing process, becoming unregulated due to repetitive injury.[18] Silicosis fibrosis and inflammation are initiated when phagocytic cells of the alveoli encounter a silica particle and attempt to ingest it, but are unable to further degrade the particle.[15,16,18] This immediately stimulates an inflammatory response mechanism, releasing cytokines. No matter what the nature of the fibrosis may be, fibrotic disorders share numerous growth factors, proteolytic enzymes, growth stimulating factors and fibrogenic cytokines, providing rise to the over-secretion, deposition and contraction of extra-cellular matrix components, damaging the normal tissue structure.[14,18] In the gold-mining sector, occupational exposure to silica appears as employees repetitively inhale silica-containing dust particles. This results in chronic interstitial pulmonary diseases with progressive fibrosis.

Fine and ultrafine particles of 0.1-2.0 µm can penetrate the lungs and lodge in the alveolar region of the lungs. They may undergo a process of phagocytosis by the alveolar macrophages, whilst some particles further penetrate the respiratory epithelium. When the macrophages dies, they release proteolytic enzymes (neutrophils) known as interleukin 1β and lysosomal hydrolases, resulting ultimately in silicosis if dust contains crystalline silica.[3] Although intense studies were conducted on the epidemiology of silicosis, little is known regarding the exact pathway from exposure to antigen to developing the disease.[14,18] This is further complicated by diverse pathways associated with exposure to crystalline silica (quartz) and therefore various cellular mechanisms initiating inflammatory responses and fibrogenesis.[18] Figure 2 illustrates cellular activities, with the pathways responsible for developing silicosis.

Figure 2 illustrates a key event in the genesis of fibrosis. The key event in developing silicosis is the interaction between the inhaled crystalline silica dust particle and the alveolar macrophage. It is the alveolar macrophages responsible for the initiation of the release of inflammatory response genes (tumour necrosis factor, Interleukin-8, growth factor cytokines, anti-oxidant enzymes) as depicted.

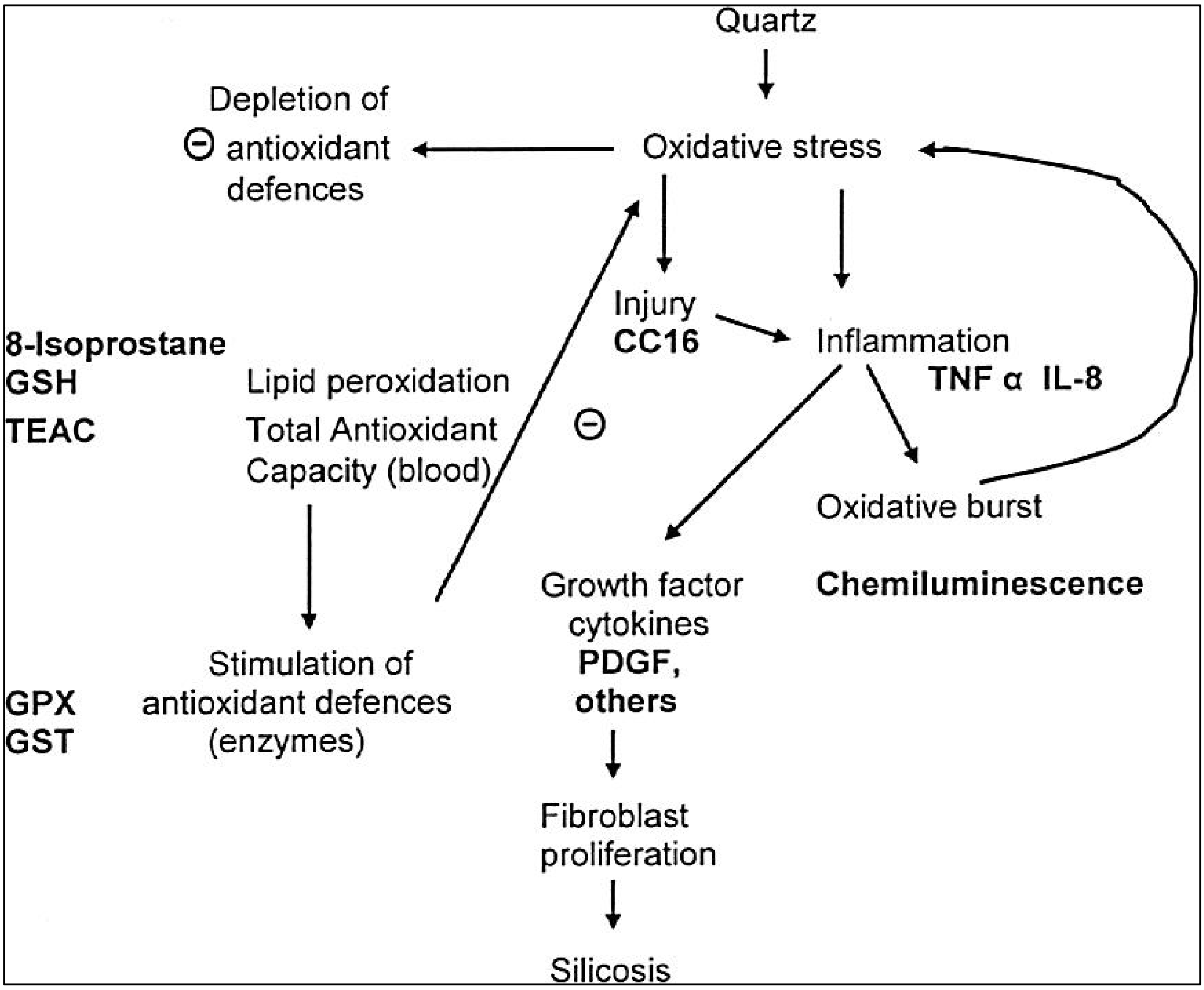

Figure 2: Proposed exposure pathways to silicosis[18]

2.4. Individual susceptibility to silicosis

Any environmental factor (antigen) responsible for causing an occupational related disease, indicates its inherent characteristics and the nature of the host organism. The characteristics of the host organism may include, but are not limited to, individual susceptibility, vulnerability and resistance to the antigen. In certain industries and experimental models, it is acclaimed that only a small percentage of the exposed workers contract the disease, after exposure to levels over a certain period. This difference in the disease outcome is not linked to a lack of individual resistance, but a strange phenomenon, resulting in the host becoming more vulnerable to a certain factor. This implies that, in the absence of such a factor, an individual may become less vulnerable.[19] Studies by Noweir *et al.*[20] attribute to this increased susceptibility to genetic make-up, blood group and paternal predisposition to crystalline silica dust.

Patterns of disease development were highly determined by an inherited factor of susceptibility or resistance. This extended to the length of exposure to the antigen being masked by familial resistance or susceptibility. A father's working history in an environment where silica was encountered, indicated that his sons were more likely to be more resistant to silicosis than those without such history, despite all other factors being the same amongst the various population groups. This suggests that a father's predisposition to crystalline silica may increase his son's tolerance to such exposure.

This study also indicated that the prevalence of silicosis was higher amongst workers with the blood group O or AB, than in those with the blood group B and least exposure was evident amongst workers of the blood group A.[19,20] More robust sampling, analysis and control methods need to be well implemented to address the effects of the antigen. The vulnerable population needs to be considered to reduce their susceptibility.

2.5. Symptoms of silicosis

Early manifestations of the disease are usually asymptomatic and most diagnoses are derived based on occupational history of exposure coupled with changes in the radiographic profile of the employee.[21] Some individuals might have cases of apnoea, associated with other diseases such as TB.[15] Patients with silicosis may have productive coughs, cases of weight loss, fatigue, respiratory failure and fever that might lead to death. Silicosis is mainly associated with higher prevalence of other pulmonary diseases, lung cancer and autoimmune diseases.[22] Conversely, HIV increases the risk to develop silicosis up to ten times.[23] Other diseases associated with silicosis are TB (extra-pulmonary and pulmonary), chronic obstructive pulmonary disease (COPD), lung cancer, scleroderma, rheumatoid arthritis and chronic renal failure.[22,24]

2.6. Lung function in silicosis

Silicosis are clinically presented in two forms: simple or complicated silicosis.[15,25,26] Simple (nodular) silicosis is characterised by multiple nodular opacities that are uniform in shape. Their particle size vary from one to 10 mm in diameter.[25] The distribution of the nodules consist throughout the lung but is more evident in the upper lobe and posterior portion of the lung.[15] Most patients with simple silicosis do not display any symptoms, excluding isolated cases of minor coughs and dyspnoea.[14,26,27] nodular opacities that are over 10 mm in diameter, characterise complicated (progressive massive fibrosis) silicosis. The disease may progress rapidly, often resulting in death within a few months or years.[15,27]

2.7. Geometry of gold mining and its association to silicosis

The configuration of mines mainly depends on, but is not limited to, the type of mineral deposits and location of the minerals. With the continuous decline of ore grades and advancement in the field of geological exploration, there are global trends that aimed to increase the influence of production. This resulted in compromising the design of the mine. This led to challenges, including insufficient ventilation flow, inadequate water supply and intolerance to extreme temperature and pressure conditions. In several cases, these factors resulted in the geometry of the mine being directly proportional to silica dust exposures.[8]

2.7.1. History of gold mining and epidemiology

Public concern over the impact of mining activities on both the environment and employees, demanded that the global mining industry consider a more sustainable framework.[28] For gold-mining, several issues are to be addressed to assess sustainability. Perceived as a finite and non-renewable resource, long-term gold production trends include, declining ore grades and increasing solid wastes (tailings, waste rock) and open cut mining. Conversely, core sustainability issues include water, energy and chemical consumption and pollutant emissions, also known as 'resource intensity'. It is important to recognise the links between gold production trends and resource intensity, as this is critical in understanding future sustainability challenges.

2.7.2. Anatomy of an underground gold mine

The Witwatersrand basin is 350 x 200 km and comprises 5 to 8 km thick succession of sediments that formed due to volcanic intrusions. This basin is believed to have been formed between 3074 and 2714 million years. Due to its grandeur and wealth in gold, it was named the largest gold province in the world.[1,2,4] This basin produced over 40 000 metric tonnes in gold production and 150 000 tonnes of uranium. In South Africa, mining for gold currently occurs at depths of 3.5 km below surface, with deposits being sedimentary in nature and the gold-rich conglomerate reefs occur in quartzite host rocks, but combined with the gold bearing reef, uranium is deposited.[3,4]

The main configuration of deep level mines is such that there is only one shaft barrel system, used for the transportation of men, material and ventilating the mines. Fresh air is introduced to the mine through a ten-metre diameter, 3000 m deep downcast shaft system and is returned to the surface primarily by means of main exhaust fans located on the top of an up-cast shaft barrel system.[15]

The fresh air is distributed to various ventilation districts through auxiliary fans and ventilation appliances ensuring that the distribution to respective areas within a mine is in accordance to the design parameters. The main driving factors considered when planning the required volume of air at a ventilation district are: the tonnage of ore to be mined and the sequence of mining and strategy that will be used to extract the ore.

Depending on these parameters, fresh air can be introduced to a ventilation district, or air can be re-used if there are means to cool the air. This poses certain challenges regarding the impurities that will be contained in the air. This includes (but are not limited to) gas accumulations, increase in the dust and radiation levels in the ventilation district where mining transpires. As return air is re-used to ventilate a working area. Constraints within the system are introduced, provided that the travel distance of the air increases. This implies that the air is prone to accumulating increased levels of dust and radiation prior to exiting the mine. In an era of low grades being mined, the following challenges are experienced:

- Mine slowdowns due to non-conformance to regulations pertaining to silica dust exposures.
- Radioactivity levels.
- Increasing concerns regarding improving sustainability.
- Improving crystalline silica dust-monitoring.

Control systems implementation is therefore an imperative goal for the mining industry.

2.8. Source and chemistry of silica

Silicon dioxide is an abundant mineral compound found in nature. It primarily takes the form of crystalline, indicating quartz in sand, soil, rock and dust in several industrial processes.[3,15] Silica is insoluble in water and acids and slightly solube in alkali.[14] Water solubility is lower for crystalline than amorphous silica and acids that are slightly soluble. An increase in temperature and pH and the presence of trace metals increases quartz' solubility. A compound silicon dioxide (SiO_2) is formed when oxygen and silicon molecules are combined.[18] Quartz is highly reactive and can therefore interact with minerals to form various compounds.[24,28] The toxicity of quartz in the lungs of living organisms therefore depends on the minerals with which they interact.

2.9. Morphology of the crystalline silica dust particle

Silica is broadly classified according to its surface structure, into either crystalline or amorphous forms. Since no reported cases reflect that the latter has been associated with diseases in humans, it will not be explored. The seven most generic forms of crystalline silica are:

- Quartz.
- Tridymite.
- Cristobalite.
- Moganite.
- Melanophlogite.
- Coesite.
- Stishovite.[24]

The structure of each of these silicas also include trace quantities of the following elements in their structures:

- Aluminium.
- Iron.
- Manganese.
- Magnesium.
- Calcium.

The arrangement of the elements around a tetrahedral shape, determines the form of crystalline silica polymorph. The polymorphs quartz, tridymite and cristobalite hold higher toxicity than coesite, stishovite and keatile.[19,24] The common polymorphs of crystalline silica may change shape and form depending on the variation of pressure and temperature to which the elements are exposed.

2.10. Toxic effects of crystalline silica

The severity of silicosis depends on the dose of silica in the surrounding environment, the duration of exposure, the polymorph of silica involved (amorphous or crystalline) and the percentage of free silica in the dust particle. Freshly ground crystalline silica is the most potent type causing diseases, as their morphology can "cut" through alveolar macrophages with ease, causing inflammatory response actions.[24,29] In the gold-mining industry and particularly the TauTona mine, the most customary rock type encountered, is quartzite, conglomerates and shales. The rock content comprises up to 67% quartz. Drilling and blasting operations causes human exposure. Fine particles of quartz become airborne.

2.10.1. Best practices for crystalline silica monitoring

The primary reason for conducting dust-monitoring is to quantify the exposure levels of pollutant (dose) the employee is exposed to. Controlling measurements may be mounted to prevent adverse health outcomes.[30,31] Exposure is calculated using the following formula: Accumulated silica dose = fraction of respirable dust x % free silica (mg/m^3) x number of years of exposure.[31] The dose is furthermore used to determine the levels of compliance to the OEL.[32]

2.10.2. Legislation on crystalline silica limits in various mining countries

Despite efforts of most mining countries to reduce their OEL to crystalline silica through the years, disabilities and death relating to silicosis still occur.[22] There have been efforts from government of respective countries to lower the OEL for respirable crystalline silica and several values have been suggested. National Institute of Occupational Safety and Health (NIOSH) and ACGIH suggest an OEL of 50 µg/m^3 whilst the WHO suggests a value of 40 µg/m^3 whilst other studies suggest an even lower value of 5-10 µg/m^3.[12,13,15,19]

2.10.3. Crystalline silica regulation in the USA

Historically, the USA used the American's NIOSH time weighted average (TWA) OEL as a legal limit. The OEL (TWA) at such time stipulated was 0.05 mg/m^3 crystalline silica.[32-33] It has been discovered that the limits described above did not prove to be protective against silicosis and therefore in 2013, the Occupational Safety and Health Administration proposed the adoption of the NIOSH REL of 0.03 mg/m^3 for crystalline silica for mining and maritime industry. The American Conference of Governmental Industrial Hygienists (ACGIH) opted to use the 0.025 mg/m^3 threshold limit value (TLV) as an equivalent eight-hour TWA for quartz. The governing authority in Alberta requires that an equivalent adjustment to the TWA be made for employees working in excess of eight hours. Trends in the incidents of disease have decreased in line with the reduction in regulatory levels of exposure.[22,33]

2.10.4. South African Legislation pertaining to silica

The DMR legislation pertaining to crystalline silica in South Africa states:

- The concentration of free silica in the respirable fraction of dust will not exceed 0.1 mg/m^3.[12]
- The concentration of respirable dust will not exceed 3 mg/m^3.[34]

Despite interventions by various mining countries to apply more stringent legislation in an effort to reduce legal limits to crystalline silica, the Occupational Exposure Limits according to Churchyard do not seem to be protective against silicosis.[16] There seems to be no limit that can be regarded as risk-free and safe and therefore the journey towards the realisation of zero harm regarding silicosis should be invested in eliminating worker exposure to airborne crystalline silica through mechanisation.

2.11. Instrumentation and techniques commonly used to measure dust exposures

In the early 1800s, little was known about instruments that can be used to measure exposure. Gravimetric dust sampling and monitoring, is a measure that ensures, through continuous monitoring, dust levels in the mine are monitored and incidents where levels exceed the OEL are investigated and addressed.[31,33,34] These interventions are embarked upon, in an effort to detect possible exposure to increased silica dust levels, dust control measures be recommended and enforced and in some cases, workers may also be referred to occupations where exposure levels are minimal or less hazardous to their health.[31] The results of the measurements obtained, using gravimetric sampling and analysis, are also used to compile a dose register, used to give an account of the employee's exposure levels, whilst in the employment of a particular company.

Occupational monitoring results are also used to classify the various employees in homogenous exposure groups, according to their pollutant concentration classifications. These classifications are used to compile reports to the DMR, giving account of employees' quarterly exposure levels The measurements are further compared to the industry milestones requirements, and are used to account for each individual mine's compliance to the set milestone targets. The employee's exit medical certificate also contains a portion, where an account of historical exposure data is required and this is obtained from gravimetric measurement results. There have been specific instruments applied in the environmental monitoring to quantify personal exposure levels, amongst them are the following:

2.11.1. Air sampling pumps

Air sampling of crystalline silica is defined as the acquiring of the pollutant (crystalline silica) from a known volume of air, quantifying the amount of contaminant acquired, expressing it as a concentration.[29] The instrument used to capture the pollutant is a pump, attached to a flexible tube and sampling device. These components are collectively termed 'a sampling train'.[31,32] Various air sampling pumps are found on the market and are used according to applications for which they are required. The most commonly encountered air sampling pumps, used in the mine where the study was conducted for personal exposure monitoring, are the GilAir-3 pumps (Figure 3). They have inefficiencies though, as the volume these pump types draw is largely influenced by changes in the ambient barometric pressure and air density conditions. The manner in which the sampling methodology is interpreted by individuals sampling in the industry, assumes that this pump type maintains a constant flow rate at various barometric pressures and density conditions underground.[31].

Figure 3: Dust sampling pumps

2.11.2. Sampling device (filter and cyclone)

2.11.2.1. Cyclone

When dust particles enter the respiratory system, they will lodge at various regions, depending primarily on the particle sizes. Inhalable particles are those that will enter the respiratory system, lodging in the upper zonal region; these are particles of 70 µm and greater. Particles of aerodynamic diameter of 10 µm - 69 µm lodge in thoracic region. Respirable particles that can penetrate deep into the alveolar regions of the lungs have an aerodynamic diameter of four µm and less, causing silicosis.[31-32] A graph depicted in Figure 4 represents the various sizes of particles. The most significant feature of this curve is the point at which 50% of either particle type will enter the respective regions within the respiratory system. This point is often referred to as a 50% cut-off point. Thoracic particles and Inhalable particles have a 50% cut off point at ten µm and 70µm respectively. For respirable particles, this point coincides with respirable fractions of 4 µm aerodynamic size.[30-34]

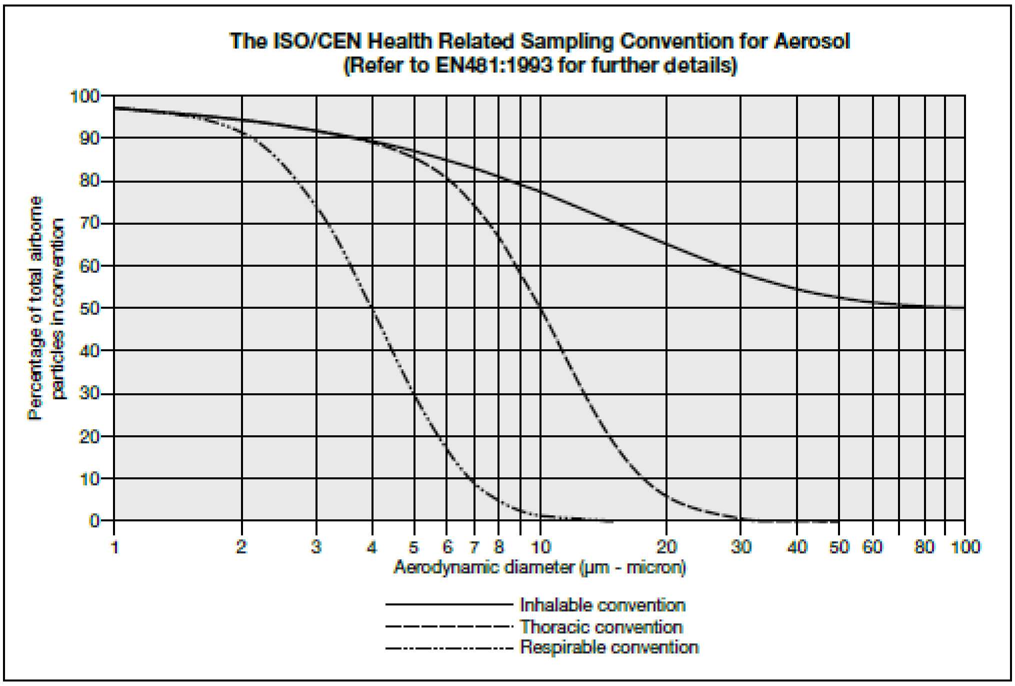

Figure 4: Graph representing the 50% cut off point for different particle sizes

A cyclone is an instrument attached to the filter media and is a size selective separator of particles below a certain aerodynamic size.[31]

Figure 5 depicts the Higgins-Dewell cyclone sampling head, fitted to a two-stage filter cassette containing silver filters, separating the respirable dust particles from the inhalable and thoracic particles. There is a vortex created when the pump sucks air, causing heavier particles to be deposited on the grit pot of the cyclone, whilst smaller particles are deposited on the filter paper inside the cassette.[33-36] When the flow rate is set above the recommended rate, the effect is that a smaller cut-off point is realised implying that, less than the diameter of recommended particles, settle in the filter. This implies an exaggerated concentration of pollutant, similarly, if the flow rate is reduced to less than the initial set rate, less particles of the desired fraction of pollutant is collected.

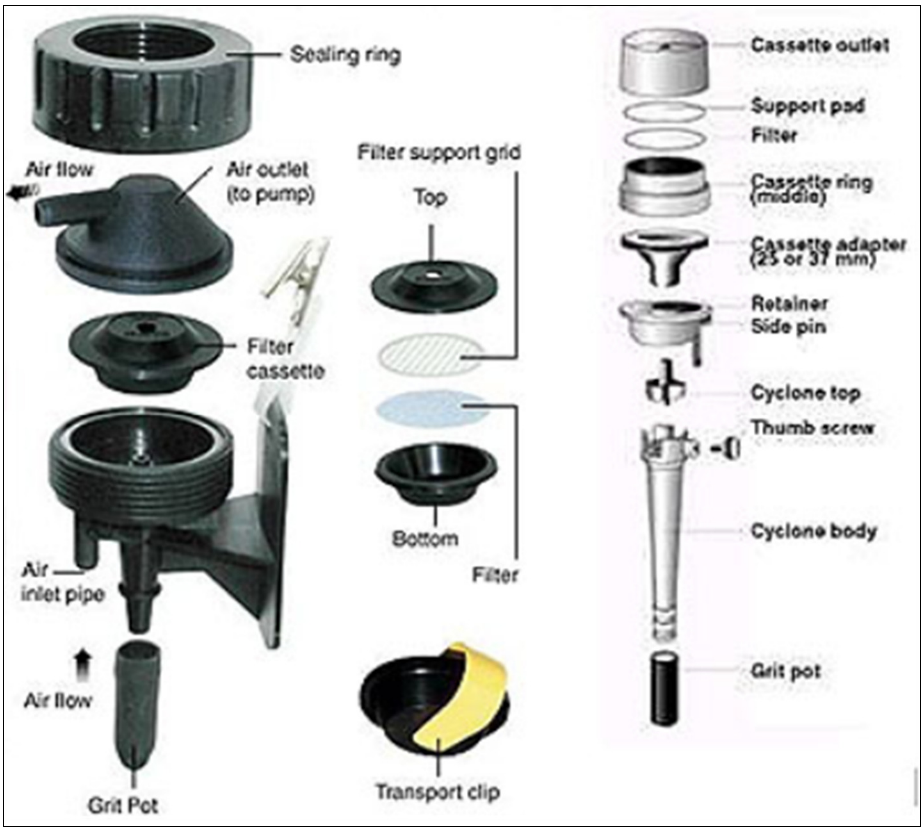

Figure 5: Higgins Dewell Cyclone

2.11.2.2. Silver membrane filters

The commonly used membrane filters in most of the deep level mining houses in South Africa, are the mixed cellulose ester (MCE) filters. They are used as filters of choice as they are highly porous, measuring pollutants up to high flow rates; they are also inexpensive compared to other filter types. Their main disadvantage is that they are highly hygroscopic. They were not used in the study due to their hygroscopic nature.

Silver membrane filters, comprising 99% inorganic silver, are not commonly used in industry as filter media, mainly because they are so expensive.[31,37-38] There are however, advantages to using them over the traditional polyvinyl chloride (PVC) filters and MCE filters. These advantages are:

- Uniform porosity and thickness on the filter membrane.
- They are chemically inert.

- Resistant to increased temperatures and can thus be subjected to aggressive conditions underground.
- It contains no fibres that can contaminate the sample.
- The particles are easily observable and is therefore an ideal filter type that can be used for X-ray diffraction (XRD) and other analyses of silica.[33,37,38].

2.11.2.3. Barometers and thermometers

As air descends through the mine, it is exposed to an increase in temperature due to the effect of geothermal gradient.[39] In the mining industry, a dual thermometer instrument, known as a whirling hygrometer is used to measure temperatures underground. The instrument is whirled at 200 rotations per minute, producing an equivalent velocity of 3.0 m/s as per manufacturer's specifications.[40,41]

2.11.3. X-Ray diffraction technique

X-Ray diffraction can distinguish the three crystalline forms of silica as their strongest reflections are all different.[42] Crystalline silica determination with XRD used the NIOSH manual of analytical methods (NISOH 7500). [43,44] This method is used to distinguish the three silica polymorphs, indicating quartz, cristobalite and tridymite. Exposure associated with each polymorph could result in various diseases. A method involving analysis by infra-red (IR) is NIOSH 7602 and 7603, can distinguish the various crystalline silica polymorphs, provided that the amorphous silica and silicates in a sample are not presented in large quantities.

Another method involving analysis by visible absorption spectrometry is possible and could have been used to determine crystalline silica. This method is classified as NIOSH 7601. Its limitation indicates that the various polymorphs cannot be distinguished. XRD is used to study the crystal shape of the respirable. This methodology is applied to crystalline silica as each polymorph is arranged in a unique arrangement of atoms which give off non-distinctive X-ray diffractive patterns.[45]

The filters used for collecting dust particles were silver filters and not the traditional PVC and MCE filters. These were chosen due to their less hygroscopic nature and low scattered X-ray background, rendering XRD a choice analysis method. This analysis method is furthermore preferred due to its ability to quantify the exact constituents of crystalline dust. The quantification of the amount of crystalline silica obtained using silver filters, is derived by comparing the intensities of the light scattered on the filters prior and post to depositing dust onto them. The ratio obtained indicates the measure of the absorption of X-rays by the sample.[46]

2.11.4. Scanning electron microscopy

There are various measurements that can be done on the silica molecule identification, including using a conventional optical microscope or a scanning electron microscope, depending on the particle size of interest. The advantage of using the optical microscope is that the true colour and true reflection of the particular mineral is attained.

Due to particle size limitation, this study did not engage in further discussions on the aspects of the optical microscope as its lens size cannot determine specimen of a resolution of detection levels 10 µm. Other methods of higher resolution of detection levels were thus used in this study. The Scanning Electron Microscope (SEM) were used to establish the surface topology and elemental composition of specimen surfaces.

The microscope uses electron beams to form an image on the surface, or to analyse the elemental composition of a sample.[36] The SEM was used in this study, to assess the physical characteristics of silica. The energy dispersive spectrophotometry was used in conjunction with SEM to assess the texture of the silica particles. To complement the XRD phases identification, SEM was used to quantify the silica contained and to assess its physical characteristics (textures, morphologies).

SEM can further be enhanced by adding energy dispersive spectrophotometry (EDS) for back scattered electron imaging. This forms the basis of this study as the crystalline structure of the particle is an important determinant in developing silicosis.

2.12. Critical review of key parameters in silica dust exposures and post exposure effects

The review of the literature revealed that the latency of the onset of silica exposure, disease symptoms and manifestation, occurs postliminary to the exposure, posing challenges in dealing with the control measurements to reduce exposure levels. Critical reviews of literature demonstrate that the effects of control measures selected to reduce silica exposure, can only be monitored in a prolonged period after exposure to the substance. Measures were recently incorporated, serving as early warning systems to predict possibilities of silicosis due to exposure, including the MOSH leading practice invention called the 'aerosol monitor'. Gravimetric dust sampling and monitoring is such a measure, ensuring through continuous monitoring, that dust levels in the mines are monitored. Incidents where levels exceed the OEL are investigated and addressed. These interventions are embarked upon to: detect possible exposure to increased silica dust levels; dust control measures be recommended and enforced and in some cases; workers may also be transferred to occupations where exposure levels are minimal or less hazardous.

The results of the measurements obtained, using gravimetric sampling and analysis, are also used to compile a dose register, reflecting the employees' exposure levels, whilst employed at the company. The results from occupational monitoring are also used to compile quarterly exposure reports to the DMR, to classify the various employees in homogenous exposure groups, according to their pollutant concentration. The measurements are compared to the milestones requirements and provide a report on each individual mine's compliance to the set milestone targets. The employees' exit medical certificates also comprise a section where historical exposure data is required. This information is obtained from the gravimetric measurement results. Due to the nature and implications of the results derived from gravimetric sampling of silica dust data within the mining industry, it becomes imperative that the way sampling is conducted and data collected, should be of immense accuracy and precision, to provide an indication of a worker's true exposure.

CHAPTER THREE

3. METHODOLOGY

3.1. Research design and study area

The research design was a case study design in which qualitative and quantitative methods were used in data collection, presentation and analysis. The focus of the case study was on TauTona Gold mine (Coordinates 26°24′58″S 027°25′39″E, one of the deepest mines globally (>3 km), owned by Anglo Gold Ashanti, located in the West Witwatersrand basin (Carletonville Goldfield), South Africa.

The study was conducted at underground station areas forming the main geographical units (ventilation districts), located 60.96 m vertical distance apart. The pumps used were static pumps, placed within strategic areas in the main intake airways. This criterion was applied to all the pumps used for sampling, indicating all measurements were taken in through ventilation at 9 to15m from the station. The station areas are the main levels of entry into each underground workplace. It indicated a constant barometric pressure and air density; they are likely to hold meaning and significance to the locations where the study were conducted, concerning potential interventions focussed on environmental factors that might influence the gravimetric flow rate.

The main activities at the stations where samples were acquired during the study, were human and material transportation to and from the mine.

3.2. Quantitative study and analytical procedures

3.2.1. Static samples

The static air samples were collected using GilAir-3 standard sampling pumps: (Sensidyne, Florida, USA); GilAir Plus constant flow pumps (Sensidyne, Florida, USA), and Tuff constant flow pumps (Casella, Bedford, UK). These suction pumps were connected to Higgins-Dewell cyclone sampling heads by connecting tubes directly attached to the pumps and the prepared cyclones. These were fitted to two-stage filter cassettes, containing silver filters, to form a sampling train, according to the NIOSH method 7500. [29,35,36] Each sampling train was calibrated on surface to a recommended flow rate of 2.2 L/min using an electronic airflow calibrator; the

Defender Calibrator.[48,49] The calibration was performed prior and post-exposure to the underground environment.

The flow meter used in this study was the type that electronically detects and times a passing piston. Consequently it measures and displays the flow on an LCD screen. Although it is a more expensive instrument in comparison to other flow meter types available in industry, its advantages include the following: High accuracy, low back pressure, large range of detection 50-5000 ml/min.[29] The device was used in the study, when considering the advantages over the other calibration devices available. The pumps were calibrated to 2.2 L/min, prior to sampling and if a pump, at the end of sampling, deviated by more than 5% from the initial calibration flow, the sample was discarded. The main pump types used for the study were the GilAir-3 sampling pumps, indicating standard equipment used for routine hygiene monitoring at the mine where the study was performed.

The sampling medium used to collect the respirable dust was silver membrane filters; 25 mm diameter and a pore size of 0.45 µm. These were selected in the study due to their inherent nature of being non-hygroscopic, implying that they are less prone to be affected by moisture changes in the atmosphere at which they are exposed.

The mass of respirable dust on the filters were weighed on a Sartorious microbalance with an accuracy of one µg. Weighing of filters was conducted a day after samples were exposed to the underground environment. Gravimetric determination of the mass was calculated by comparing mass differences between the filter prior exposure to pollutant and following exposure to pollutant.

3.2.1.1. Measurement of environmental factors that influence flow rate on a pump

Barometric pressure readings were obtained using a digital barometer (Greisinger electronic barometer, GPB3300, Germany), calibrated at an approved calibration facility. The readings were captured on surface at the mine each day, prior to the pumps going underground. Upon arriving at each level underground, a five-minute settling time was observed for all pumps before flow rate measurements were captured-pre-and post-exposure at the underground environment and back at the laboratory on surface. Temperature readings, including wet-bulb and dry-bulb temperature measurements, were captured, using a whirling hygrometer, whirled at an average speed of three revolutions per second in air velocities below 3 $m.s^{-1}$, for about 30 seconds, whereafter the temperatures were captured as quickly as possible, starting with the wet-bulb temperature. [50] Air density was calculated using a mathematical algorithm, using data incorporating barometric pressures and temperatures.[6,7] The readings were captured at the strategic areas identified, where barometric pressure (BP) readings were also captured.

3.2.1.2. Sample size (n)

To attain the required sample size, previous tests by Freestone *et al.*, using power analysis, calculated the sample size of four sampling events required, per area of interest, to attain a 95% confidence interval. The pump failure rate on the mines was determined to be 5%. This was incorporated in the sample size calculation to compensate for pump failures. A recalculate total of five pumps per sampling event, was required for this study. Three gravimetric sampling pump types used in the study were i) GilAir-3 pump ii) GilAir Plus and the iii) Tuff pump. A total of 15 samples were drawn on each station area, using the GilAir-3 pump. These three sampling strategies were used with the GilAir-3 sampling pump:

- Five purely observational samples, where no adjustments for flow rates were established (controls).
- Five pumps where underground adjustments were established at hourly intervals (experimental).
- Five pumps with a single flow rate adjustment was created on arrival underground at the station where sampling were conducted (experimental).

Five samples with the Tuff and GilAir plus were also captured. No adjustments were made to the underground flow rates of the Tuff and GilAir plus sampling pumps. A total of 25 sample pumps per station area were obtained. Reporting focussed on the observational samples only, as comparative assessments could be drawn from these.

3.2.1.3. Exclusion criteria for samples sent for analysis by XRD

Pumps with flow rates prior and post sampling deviating from 2.2 L/min by more than 5% were excluded from the XRD analysis. This indicates that the pump might have not been operated for the entire sampling duration. Filters that did not indicate changes in mass prior and post sampling when weighed gravimetrically, were not sent for further analysis and were thus discarded. Analysis was conducted only on functional pumps, during sampling.

3.2.2. Crystalline silica analysis by X-ray diffraction

All filters attached to operational pumps and those indicating mass differences during monitoring were sent for XRD analysis at the CSIR laboratory. The NIOSH 7500 method was used for the XRD analysis technique to analyse the amount of silica contained on each filter. The method comprised the calibration with standard filters prepared by wet deposition from NIST standard reference material. The certified standard NIST SRM1878a was used to obtain the calibration curve for the α-quartz dosage. A Philips PW 3710 diffractometer was used (CuKα anticathode, 40 kV operating tension, 40 mA operating current) to quantify α-quartz. The scan range was fixed as: $2\theta = 26.3°\text{-}27.3°$ (corresponding to the high intensity 101 reflection of α-quartz).[42,51]

3.2.3. Physical and chemical characterization of samples

The chemical and physical characterisation of quartz contained in the sample was conducted using the SEM, combined with energy dispersive X-ray analysis (FEI model XL30) equipped with a thin-window system for X-ray microanalysis.[52] Six samples for SEM and EDS analysis were selected based on the quartz content in the sample, as per XRD analysis. Two filters were selected with a high silica dust content and two with an average percentage dust. Two additional filters contained low and below detection levels of silica. The dry silver filter papers were randomly cut into 1 cm^2 sizes, appropriate to fit into the specimen chamber of the SEM. A thin layer of carbon was deposited on the surfaces of the samples, generating an electrically conducive carbon coating; this coating was deposited on the sample by high vacuum evaporation using an Emitech K950 DC.

The samples were mounted on electron microprobe stubs and SEM analysis was performed on each sample, in conjunction with a computer controlled field emission SEM equipped with EDS detection system to determine whether the particles detected were crystalline silica particles. This was completed at the University of Pretoria's Laboratory for Microscopy and Microanalysis. Analysis of surface areas of specific particles on the filters was conducted using EDS analysis at beam energy of 10.00 keV and 20.00 keV. Morphological images were captured of particles with unusual shapes, including visible particle distribution on the samples.

3.3. Data presentation methods and results analysis

3.3.1. Data presentation

Descriptive data were presented using a combination of narrative statements and tables incorporated within texts. Tables describe prevailing environmental conditions underground with flow rates and 50% cut-off points for each pump type used. Bar charts were used to compare crystalline silica concentrations per level, differentiating the concentrations attained with the various pump types. Scatter plots are used for characterisation of the quartz content analysed with SEM and EDS with plots of geographical locations, indicating where each sample was collected.

3.3.2. Data analysis

Data was analysed using Microsoft excel data package, and STATISTIX version 8.

3.3.3. Descriptive statistics

The data was reported as average ± standard deviations. The inter-variable relationships amongst measured and calculated parameters were evaluated through correlation analysis. The Pearson correlation coefficient (r) measures the strength of linear relationships between two quantitative variables, assisting to reveal differences amongst variables relevant to changes in pressure, temperature, flow rate and concentration. Descriptive statistics were used to interpret outcomes and changes observed.

3.3.4. Ethical considerations and limitations of the study

This research received authorisation for the study to be conducted from AngloGold Ashanti's TauTona gold mine. The Academic Advisory Committee (AAC) of the University of Pretoria also approved the study. The research received prior ethical approval from the Research Ethics Committee (REC) of the Faculty of Health Sciences, University of Pretoria. The study was limited to measuring silica dust parameters and did not cover aspects such as radiation, human subjects and clinical trials. Due to access limitation of other mines, excluding TauTona, there was wide spread sampling executed on various mining station levels with data cross verification on a similar aspect, assisting to identify consistencies and completeness of the compiled dataset.

3.3.5. Hypothesis testing

A one-way non-parametric test (ANOVA) and a Kruskal-Wallis H- test model was used to measure differences between means of more than one group

3.3.6. Data management and proportionate distribution of samples

An audit trail was compiled, containing a list of all the research material recorded. The data was secured on a custom excel database spreadsheet that is password protected. Hard files with backup information and study material were kept in a locked and secure safe. TauTona environmental management personnel were recruited to assist in setting up of instrumentation and data collection. The personnel were trained on interpreting the data collection instruments, sample and underground logistics. In addition, a statistician was also engaged to assist with statistical analysis

CHAPTER FOUR

4. RESULTS

4.1. Summative profile of studied samples

Of the total pumps (n=300) that were initially used for the project, 92.3% were functional; the ratio of samples obtained from GilAir-3, GilAir Plus and Tuff pumps were (7:2:1) respectively. Table 1 summarises the prevailing environmental conditions that dust pump types were subjected to. The average underground BP of 111.1 kPa (100.2-120.0 kPa) for the duration of the study, indicated a marked increase from the surface BP of 83.8 kPa (83.5-84.0 kPa). The natural wet-bulb temperatures on surface ranged between 10.0°C to 17.0°C, whilst underground temperatures were between 24.0°C to 27.2°C. The air density on surface was within normal daily variation throughout the duration of sampling, ranging between 0.978 kg/m^3 to 1.025 kg/m^3, whilst the underground air density was between 1.152 kg/m^3 to 1.371 kg/m^3.

Table 1: Environmental conditions at the different stations underground

Level	Barometric pressure (kPa)		Natural wet bulb temperature (°C)		Air density (kg/m^3)		
	Surface	Underground	Surface	Underground	Surface	Underground	Delta
66	83.7	100.2	10.1	24.0	1.025	1.152	0.128
75	83.7	103.0	14.2	24.0	1.005	1.169	0.164
83	83.7	105.7	13.0	24.8	1.005	1.203	0.198
87	83.7	106.6	17.0	27.2	0.987	1.205	0.218
94	84.0	109.9	17.0	25.4	0.978	1.253	0.275
97	83.7	110.6	15.1	26.2	0.998	1.267	0.271
100	83.5	112.5	16.3	24.5	0.978	1.280	0.302
106	83.9	113.9	15.0	25.1	1.000	1.300	0.300
109	84.0	115.54	16.0	26.0	0.987	1.320	0.330
112	84.0	116.5	15.0	26.8	1.001	1.326	0.325
116	83.9	118.3	14.5	26.4	1.004	1.353	0.349
120	83.9	120.0	10.0	26.3	1.023	1.371	0.348

Table 2 depicts surface and underground sampling flow rates. The average surface flow rate for both GilAir-3 and GilAir Plus pumps was 2.204 L/min, whilst that of the Tuff pumps was 2.208 L/min. Significant differences in flow rates was observed amongst the pumps on surface upon initial calibration (p=0.019). When the same pumps were placed underground, flow rates for GilAir-3, GilAir Plus and Tuff pumps were 2.273 L/min, 2.134 L/min and 2.110 L/min respectively. These measurements were comparatively lower for underground concerning the GilAir Plus and Tuff pumps, whilst the GilAir-3 pump types indicated higher flow rates underground compared with the initial 2.2 L/min surface calibration. Further comparison between pump types indicated a significantly higher flow rate for the GilAir-3 pump when underground pre-flow rate is compared with GilAir Plus and Tuff pumps respectively (p<0.001).

Table 2: Pre-flow rates of pumps on surface and underground

Pump	N	Surface	Underground	Difference		p-value
		Average ± Stdev Surface	Average ± Stdev Underground	Average ± Std Error	95% C.I.	
GilAir-3	181	2.204±0.003	2.273±0.064*	0.068±0.005*	(0.059; 0.078)	<0.001
GilAir Plus	57	2.204±0.002	2.134±0.093	-0.071±0.012	(-0.095;-0.045)	<0.001
Tuff	39	2.208±0.011+	2.110±0.194	-0.097±0.031	(-0.161;-0.035)	<0.001
p-value		0.019	<0.001	<0.001		

Difference: Shapiro-Wilk Normality Test p < 0.05

Underground vs Surface: Wilcoxon Signed Rant Test

Pump comparison: Kruskal-Wallis One-Way Nonparametric AOV

*GilAir-3 vs GilAirPlus and Tuff; +Tuff vs GilAir-3 and GilAir Plus

Further analyses of the GilAir-3 pumps determined whether any significant changes in flow rates between surface and various underground levels existed. Table 3 signifies substantial differences between surface and underground pre-flow rates excluding level 66 (p=0.251) and 109 level (p=0.820). The non-significant difference may be due to a Type 2 error. There is a general trend of increase in the flow rates for the GilAir-3 pumps when underground, compared to calibrated surface flow rates, compared to calibrated surface flow rates, except for pumps at 66 level.

Table 3: Pre-flow rates of the GilAir-3 pump on surface and at different levels

Level	n	Surface	Underground	Difference		
		Average ± stdev	Average ± stdev	Average ± Std Error	95% C.I.	p-value
66	14	2.204±0.003	2.185±0.058	-0.018±0.015	(-0.051;0.015)	0.251
75	15	2.203±0.003	2.312±0.026	0.109±0.006	(0.095;0.123)	<0.001
83	15	2.205±0.003	2.252±0.031	0.047±0.008	(0.030;0.064)	0.001
87	15	2.203±0.002	2.289±0.035	0.086±0.008	(0.066;0.105)	<0.001
94	13	2.204±0.002	2.320±0.057	0.116±0.016	(0.081;0.150)	0.001
97	29	2.204±0.003	2.283±0.084	0.079±0.016	(0.047;0.111)	<0.001
100	10	2.210±0.007	2.278±0.038	0.068±0.013	(0.040;0.097)	0.008
106	14	2.203±0.002	2.254±0.032	0.051±0.009	(0.032;0.070)	0.001
109	15	2.203±0.004	2.209±0.050	0.004±0.013	(-0.023;0.032)	0.820
112	15	2.204±0.002	2.313±0.055	0.109±0.014	(0.080;0.140)	<0.001
116	14	2.205±0.003	2.282±0.049	0.077±0.013	(0.050;0.105)	0.002
120	12	2.205±0.003	2.294±0.046	0.089±0.013	(0.050;0.118)	0.003

Underground vs Surface: Wilcoxon Signed Rank Test

Environmental factors were studied. Table 4 depicted their influence compared to changes in flow rates on GilAir-3 pumps, depicted in Table 4. Amongst the environmental factors investigated, the dry and wet-bulb temperatures influenced the observed changes in flow rate; although significant, the correlation coefficient was not strong enough. The implication was an association between the observed increase in flow rate of GilAir-3 pumps with dry and wet-bulb temperatures.

Table 4: Pearson correlations of selected underground environmental factors with GilAir-3 flow rates (n = 168)

Variable	PrFR-UG		Crystalline silica concentration	
	r	α	r	α
UG-BP	0.092	0.237	0.1095	0.2482
UG-DB	**0.338**	**<0.001**	0.3134	0.007
UG-WB	**0.189**	**0.014**	0.110	0.2466
UG_Density	0.061	0.433	0.0825	0.3849

LEGEND:

r = Pearson Coefficient

α = p-value

UG_DB = Underground Dry-bulb Temperature

UG_WB = Underground Wet-bulb

UG_Density = Underground density

PrFR_U = Pre-flow rate underground

The flow rates of GilAir Plus pumps were further analysed for flow rate changes at the various underground levels. These were compared to the initial pump calibrations on surface. Table 5 indicates no significant changes present between surface and underground flow rates. A general trend where flow rates underground decreased below the initial 2.2 L/min calibration levels was also evident. Lower sample numbers were mainly a cause of the pumps being inoperative for the whole sampling duration.

Table 5: Pre-flow rates of the GillAir Plus pump on surface and at different levels

Level	n	Surface Average ± stdev	Underground Average ± stdev	Difference Average ± Std Error	95% C.I.	p-value
66	5	2.201±0.002	2.20±0.050	-0.002±0.023	(-0.065;0.061)	0.787
75	3	2.202±0.001	2.183±0.022	-0.019±0.012	(-0.070;0.033)	0.181
83	5	2.203±0.002	2.131±0.050	-0.072±0.022	(-0.134;-0.010)	0.059
87	6	2.204±0.003	2.160±0.073	-0.044±0.031	(-0.123;0.035)	0.529
94	5	2.206±0.002	2.157±0.101	-0.049±0.046	(-0.176;0.078)	0.419
97	11	2.205±0.002	2.151±0.100	-0.054±0.030	(-0.122;0.013)	0.142
100	2	2.202±0.003	2.183±0.014	-------	(--------;-------)	-------
106	4	2.204±0.003	2.087±0.085	-0.117±0.044	(-0.256;0.023)	0.100
109	2	2.205±0.004	2.064±0.001	-------	(--------;-------)	-------
112	5	2.202±0.002	2.105±0.120	-0.097±0.053	(-0.245;0.051)	0.100
116	5	2.204±0.003	2.061±0.116	-0.143±0.051	(-0.285;0.010)	0.106
120	4	2.206±0.004	2.082±0.142	-0.125±0.070	(-0.347;0.098)	0.100

Underground vs Surface: Wilcoxon Signed Rank Test

Comparative assessments were conducted using Pearson's correlation to determine which environmental factors listed in Table 6 influenced the flow rates of GilAir Plus pumps. Table 6 identifies that underground BP and density significantly influenced the flow rates of the pumps. There was a negative correlation between the flow rates of underground BP and density, with correlation factors of 0.443 and 0.451 respectively. This implied that the decrease in flow rates observed are marginally associated with an increase in underground BP and an increase in air density.

Table 6: Pearson correlations of selected underground environmental factors with GilAir Plus flow rates (n = 48)

Variable	PrFR-UG	
	r	α
UG-BP	**-0.443**	**0.002**
UG-DB	0.194	0.187
UG-WB	-0.124	0.402
UG_Density	**-0.451**	**0.001**

LEGEND:

r = Pearson Coefficient α = p-value

UG_DB = Underground Dry-bulb Temperature UG_WB = Underground Wet-bulb

UG_Density = Underground density PrFR_UG = Pre-flow rate underground

Tuff pumps' availability for the study were limited, comparing with the GilAir-3 and GilAir Plus pump types, due to pumps received from the Original Equipment Manufacturer (OEM). Pump failure rates were also higher amongst these pump types, compared to the additional pump types used in the study. Excluding pumps at 75 level, a general decline was indicated in the underground flow rates using Tuff pumps from the initial surface calibrated values. Table 7 indicates though, that the observed differences are statistically insignificant.

Table 7*:* Pre-flow rates of the Tuff pump on surface at different levels

Level	n	Surface	Underground	Difference		Level
				Average ± Std	95% C.I.	p-value
		Average ± stdev	Average ± stdev	Error		
66	4	2.205±0.003	1.949±0.509	-0.257±0.253	(-1.062;0.549)	0.361
75	4	2.205±0.001	2.413±0.108	0.062±0.054	(-0.233;0.110)	0.584
83	4	2.207±0.001	2.130±0.116	-0.077±0.058	(-0.261;0.107)	0.201
87	3	2.205±0.002	-------	-------	(--------;-------)	-------
94	2	2.202±0.002	-------	-------	(--------;-------)	-------
97	6	2.206±0.003	2.093±0.0136	-0.113±0.056	(-0.257;0.030)	0.094
100	2	2.251±0.001	-------	-------	(--------;-------)	-------
106	3	2.202±0.002	-------	-------	(--------;-------)	-------
109	4	2.210±0.001	2.048±0.134	-0.162±0.064	(-0.367;0.043)	0.100
112	4	2.205±0.002	2.174±0.192	-0.031±0.097	(-0.339;0.277)	0.855
116	----	-------	-------	-------	(--------;-------)	-------
120	3	2.204±0.002	-------	-------	(--------;-------)	-------

Underground vs Surface: Wilcoxon Signed Rank Test

Table 8 depicts Pearson's correlations of the underground environmental factors with Tuff pump flow rates. None of the environmental factors indicated, seemed to be strongly associated with the observed decrease in flow rate noted on the Tuff pumps, as they descend underground.

Table 8*:* Pearson correlations of selected underground environmental factors with Tuff pump flow rates (n = 35)

Variable	PrFR-UG	
	r	α
UG-BP	0.022	0.902
UG-DB	0.035	0.840
UG-WB	0.035	0.841
UG_Density	0.017	0.923

LEGEND:

r = Pearson Coefficient α = p-value

UG_DB = Underground Dry-bulb Temperature UG_WB = Underground Wet-bulb

UG_Density = Underground density PrFR_UG = Pre-flow rate underground

Table 9 indicates the average respirable dust concentration, using various dust sampling pumps on each level. There are no consistencies noted concerning dust concentrations measured using various pumps, however all pump types indicated that the lowest dust concentrations were measured at 120 level. The GilAir-3 pump recorded highest dust concentrations at 106 level, whilst the GilAir Plus and Tuff pumps indicated elevated dust concentrations at 87 levels. The general dust concentration at 87 levels were high and visible even on the day when sampling was conducted.

The characteristics of the particulate matter collected is summarised, using the 50% cut-off point; analysis are indicated by SEM and distributing a particle size (Table 12). The table also reflects GilAir-3 type samples as there was insufficient number of GilAir Plus and Tuff pump type available for the study, however, the main focus of the study was on GilAir-3 pumps and not on other pump types

The selectivity of the size of filtered particles depends on the type of the cyclone and the operating flow of the sampling pump. The flow rate needs to be kept stable throughout the duration of sampling to prevent introducing errors in determining the exposure levels. The cyclone heads therefore conform to the criteria set by the ACGIH/CEM/ISO size selection curve with a 50% cut point at 4.0µm. This implies that at this stage, the specified size of fraction of dust particle collected with a 50% efficiency. The average cut-off point on surface was 4.36 µm for a pre-flow rate of 2.2 L/min. When pumps were consigned underground, the cut-off aspect ranged from 4.12-4.40 µm when the average pre-flow rates were used. Using the model depicted in Figure 6, it can be clearly seen that most of the particles were observed on the left-hand side of the 4 µm particle size. There are implications for the change observed in the cut-off points between surface and underground. The observations indicate that the respirable curve tends to shift to the left, signifying that smaller particles will settle on the filter when exposed to the environmental factors and flow rates underground.

Table 9*:* Respirable dust concentration sampled with different personal sampling pumps at different levels

Level	n	GilAir-3		n	GilAir Plus		n	Tuff	
		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.
66	5	0.136±0.020	(0.111;0.161)	5	0.141±0.009	(0.129;0.154)	4	0.142±0.022	(0.107;0.177)
75	5	0.137±0.018	(0.137;0.160)	3	0.127±0.013	(--------;-------)	4	0.240±0.053	(0.156;0.324)
83	5	0.116±0.011	(0.103;0.130)	5	0.117±0.038	(0.069;0.164)	4	0.381±0.130	(-0.406;1.169)
87	5	0.300±0.088	(0.192;0.409)	6	0.463±0.078	(0.382;0.545)	3	0.418±0.082	(0.214;0.622)
94	3	0.280±0.082	(0.077;0.484)	5	0.252±0.041	(0.201;0.304)	2	0.274±0.006	(--------;-------)
97	10	0.156±0.040	(0.127;0.184)	11	0.141±0.060	(0.101;0.181)	6	0.161±0.031	(0.129;0.193)
100	1	Incomplete data		2	Incomplete data		2	Incomplete data	
106	6	0.483±0.172	(0.303;0.663)	4	0.394±0.053	(0.311;0.479)	3	0.352±0.007	(--------;-------)
109	6	0.170±0.070	(0.097;0.243)	2	0.186±0.000	(--------;-------)	3	0.139±0.031	(--------;-------)
112	5	0.214±0.020	(0.189;0.239)	5	0.175±0.021	(0.150;0.201)	4	0.194±0.055	(0.107;0.280)
116	4	0.179± 0.013	(0.158;0.200)	5	0.219±0.055	(0.152;0.287)		No data	
120	4	0.094±0.041	(0.029;0.159)	3	0.036±0.030	(--------;-------)	3	0.084±0.020	(--------;-------)

No statistical analysis completed due to small sample numbers and sampling from the same air sample (paired data)

Table 10: Percentage crystalline silica on filters sampled with different personal sampling pumps at different levels

Level	n	GilAir-3		n	GilAir Plus		n	Tuff	
		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.
66	4	12.999±2.372	(9.213;16.762)	3	12.977±2.098	(--------;-------)	2	18.905±4.009	(--------;-------)
75	5	25.794±6.492	(25.794;33.856)	3	19.587±2.974	(--------;-------)	4	35.270±6.00*	(25.721;44.819)
83	4	18.760±5.228	(10.441;27.079)	2	18.985±3.189	(--------;-------)	4	15.168±11.190	(-2.638;32.973)
87	5	28.094±6.700	(19.775;36.413)	6	39.500±2.863	(36.495;42.505)	3	27.84±7.625	(--------;-------)
94	3	32.313±9.277	(9.268;55.359)	5	31.972±4.995	(25.769;38.175)	2	31.615±4.985	(--------;-------)
97	8	26.494±6.775	(20.830;32.157)	9	31.048±12.397	(21.519;40.577)	5	24.174±5.080	(17.866;30.482)
100	1	Incomplete data		2	Incomplete data		2	Incomplete data	
106	6	33.667±7.160	(26.153;41.181)	4	38.050±5.893	(28.673;47.427)	3	36.660±1.218	(--------;-------)
109	6	29.488±6.090	(23.096;35.880)	2	23.615±0.021	(--------;-------)	3	33.297±7.936	(--------;-------)
112	5	30.188±2.454	(27.141;33.235)	5	33.892±3.685	(29.316;38.468)	4	36.332±11.714	(17.693;54.972)
116	4	25.152± 5.405	(16.552;33.753)	5	21.784±4.391	(16.331;27.237)		No data	
120	4	25.250±11.292	(7.282;43.218)	3	46.650±13.036	(--------;-------)	3	28.577±4.187	(--------;-------)

No statistical analysis completed due to small sample numbers and sampling from the same air sample (paired data)

Table 11: Crystalline silica concentration sampled with different personal sampling pumps at different levels

Level	n	GilAir-3		n	GilAir Plus		n	Tuff	
		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.		Average ± stdev	95% C.I.
66	4	0.019±0.002	(0.015;0.022)	3	0.018±0.001	(0.016;0.021)	2	0.026±0.003	(_____;_____)
75	5	0.035±0.011	(0.022;0.049)	3	0.025±0.003	(0.018; 0.031)	4	0.082±0.002	(0.080;0.085)
83	4	0.022±0.006	(0.015;0.030)	2	0.030±0.005	(_____;_____)	4	0.023±0.003	(0.018;0.028)
87	5	0.086±0.039	(0.037;0.134)	6	0.181±0.020**	(0.161;0.202)	3	0.113±0.018	(0.067;0.158)
94	3	0.086±0.008	(0.066;0.106)	5	0.080±0.014	(0.063;0.097)	2	0.087±0.015	(_____;_____)
97	8	0.045±0.018	(0.029;0.060)	9	0.042±0.012	(0.033;0.052)	5	0.037±0.008	(0.028;0.047)
100	1	Incomplete data		2	Incomplete data		2	Incomplete data	
106	6	0.156±0.036	(0.118;0.193)	4	0.152±0.038	(0.092;0.211)	3	0.129±0.003	(0.121;0.137)
109	6	0.049±0.016	(0.032;0.066)	2	0.044±0.00004	(_____;_____)	4	0.034±0.024	(0.004;0.073)
112	5	0.064±0.008	(0.054;0.075)	5	0.059±0.006	(0.052;0.066)	4	0.066±0.003	(0.060;0.071)
116	4	0.045±0.007	(0.033;0.056)	5	0.047±0.008	(0.034;0.057)		No data	
120	4	0.020±0.005	(0.012;0.029)	2	0.021±0.004	(_____;_____)	3	0.024±0.003	(0.016;0.031)

No statistical analysis completed due to small sample numbers and sampling from the same air sample (paired data)

Table 12: 50% calculated cut off for the Higgins-Dewell cyclone using the average surface and underground pre-flow rates for the GilAir-3 pump

Level	Surface Cyclone 50% cut off (µm)	Underground-Cyclone cut off (µm)
66	4.36	4.40
75	4.36	4.14
83	4.36	4.26
87	4.36	4.18
94	4.36	4.12
97	4.36	4.20
100	4.35	4.21
106	4.36	4.26
109	4.36	4.35
112	4.36	4.14
116	4.36	4.20
120	4.36	4.17

Note: BGI HD design: 50% cut off = (4.6) *((Flow rate/2.1)$^{-1.1}$

Of the filters that collected particulate matter, six filters were selected based on respirable dust content. Their morphological characteristics are depicted in Table 13, 14 and Figure 8 below.

The aerodynamic sizes of the particles observed using the SEM were found to be between 4.1 µm to 7.8 µm. Particle sizes of significance in the initiation and onset of disease are those which are respirable in nature and are said to be of an aerodynamic diameter that is less than 10 µm. Table 14 excluded these particle sizes.

Table 13: Characteristics of particulate matter on filters

Filter number	Number of particles counted	Average aerodynamic particle size (µm)	Standard Dev	Min	Max	Respirable (mg/m³)
108	79	4.6	5.7	1.0	47.2	0.150
16	132	4.1	3.2	1.2	15.9	0.293
116	190	4.1	2.8	1.1	18.9	0.139
261	131	4.7	3.2	1.2	15.3	0.380
222	44	7.8	10.1	1.4	45.5	0.255
219	92	6.9	9.5	0.9	52.3	0.196

(Aerodynamic diameter = Actual diameter x 1.183 (SIMRAC COL 515 report)

Table 14: Sizes larger than and equal to 10µm excluded

Filter number	Number of particles counted	Average aerodynamic particle size (µm)	Standard Dev	Min	Max	Respirable (mg/m³)
16	123	3.5	2.1	1.2	8.7	0.293
108	76	3.7	2.3	1.0	10.0	0.150
116	181	3.6	1.8	1.1	9.2	0.139
219	74	3.4	1.8	0.9	9.3	0.196
222	36	3.8	1.8	1.4	8.1	0.255
261	120	3.9	2.0	1.2	9.5	0.380

Aerodynamic diameter = Actual diameter x 1.183 (SIMRAC COL 515 report)

The distribution of the aerodynamics particles (Sizes larger than and equal to 10 µm excluded) measured using SEM are shown in Figure 6 below. The distribution follows a sigmoid shaped curve, with 30-94 percentile values being below 4 µm aerodynamic sizes.

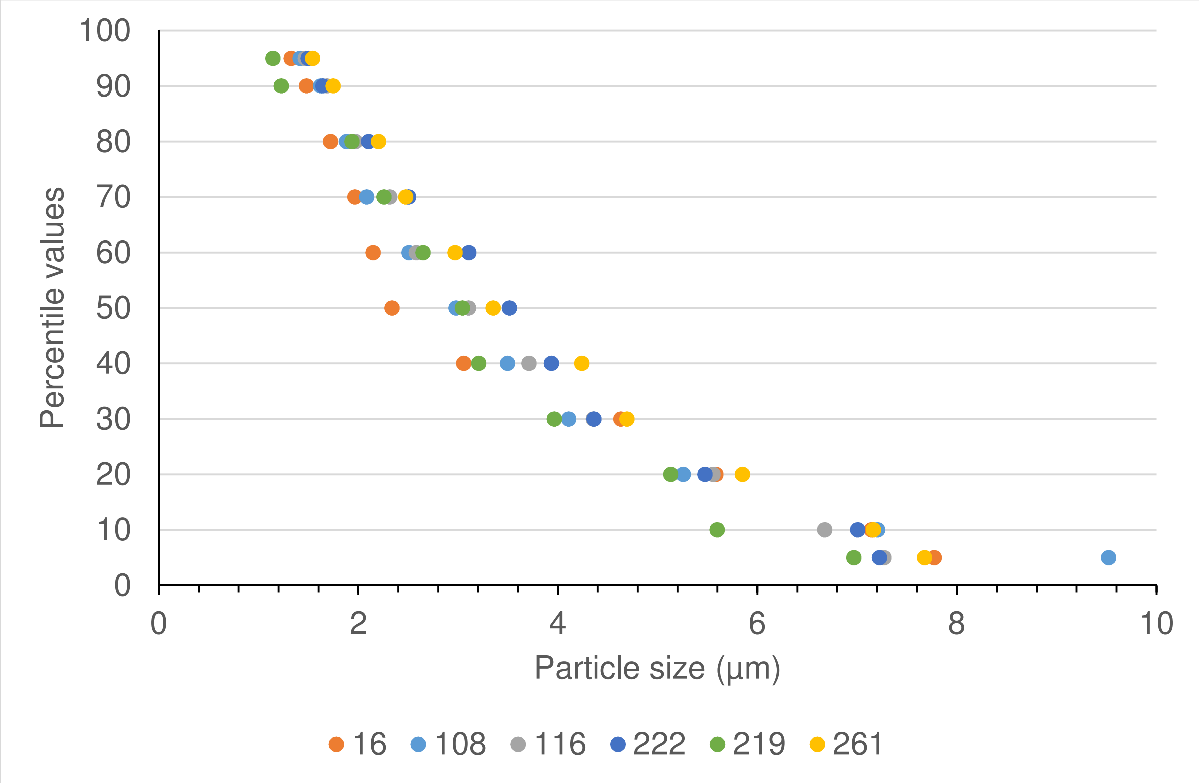

Figure 6: Percentile distribution of aerodynamic particle sizes counted on selected filters

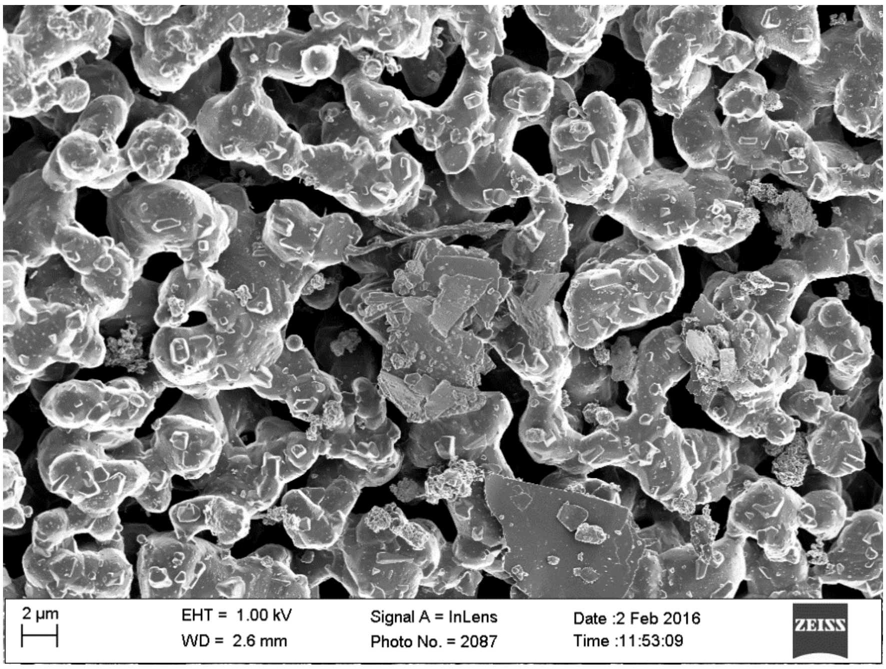

Figure 7: SEM image of a filter containing 42.26% crystalline silica

CHAPTER FIVE

5. DISCUSSIONS

5.1. Descriptive statistics of the thermal environmental conditions

The prevailing thermal and BP conditions depicted in Table 1 are typical of normal surface summer conditions in the Johannesburg/Carletonville area.[50] The underground thermal environmental conditions are stable throughout the year, except for levels closest to surface (levels above 87 Level), which are considered to be in the purported first critical zone concerning environmental control strategy. These levels may indicate a slight temperature increase or decrease depending on the season of the year. At these levels, the effects of auto-compression are less than indicated at depths below 2000 m and no refrigeration is applied to the air ventilating within the mine.[49]

Heat added to the ventilating air in the mine increases with the depths below surface. Table 1 depicts the results obtained in this phenomenon well, where the shallower levels in general, displayed lower station temperatures than the deeper levels. Air density underground also increased with increments in depths below surface, whilst air density on surface remained constant at an average of 1.0 kg/m^3. The underground BP elevated with increasing depths below surface, whilst the surface BP remained stable at an average of 84.0 kPa, typical of barometric pressures in the Carletonville area.

Personal dust sampling instruments used in the industry, proved to successfully quantify individual exposure to pollutants. When the same instruments were used for deep level mining, challenges are encountered due to prevailing environmental conditions, unique to deep level mining.[51] It was further noted that with the exposure of dust sampling pumps to the underground environmental conditions, their behaviour concerning flow rate differed depending on the type of pumps used (Table 2).

Typically, in the ultra-deep mining industry, GilAir-3 pump types are used widely and the flow rates of these pumps increased with increasing temperature, BP and density conditions. The change in flow rates observed using these pumps (Table 3) are also noted to be significant, excluding those flow rates measured at level 66 and level 109. Not all pumps types displayed this phenomenon. Further investigations, with a larger sampling size and other pump types are suggested, determining whether similar observations will be attained.

Air sampling flow metres and equipment operated at conditions entirely different (effectively ±1,500 m) to the reference sea level conditions where pumps are typically calibrated. The appropriate volumetric flow metre must be selected with care to provide sufficient settling time, ensuring accurate measurement of volumetric flow. Research also indicated that flow metres may contribute to Type 1 errors (error in measurement) to the apparent change in the pump flow rate.

In a fixed mass of air molecules (such as contained in a balloon), the volume occupied by these molecules depends on the ambient temperature and pressure. If the ambient pressure is reduced and or the temperature is increased; the volume occupied by the provided mass of air will increase. The humidity content of the air also influences the air density (kg/m^3). The addition of water vapour to air (humidity) reduces the density of the air.

If it is necessary to compare flow rates taken under various temperature or pressure conditions, a correction factor relative to a set standard temperature and pressure should be applied. The limitation of the study indicates that due to sample size, a factor could not be identified that could be applied ensuring the necessary correction. Another challenge to adjusting flow rate is :the use of a cyclone and the effect it may have on the 50% cut off point.

5.2 Barometric pressure effect on GilAir-3 pumps

Pearson's correlations as indicated in Table 4, between underground BPs and GilAir-3 flow pre-flow rates, implied a correlation coefficient of 0.092 (p=0.237). Although a positive correlation between BP and flow rate increase existed, the difference observed is statistically insignificant. Therefore the null hypothesis is not rejected. No association between BP increase and increase in the pump post-flow rate exists. This suggests that longer settling time might have been required for pumps, enabling the necessary flow adjustments to the ambient conditions, prior to measuring the flow rate. The expectations were that the changes attributable to BP on the pumps would be evident at levels below 66 level, given that the barometric pressure at 66 level is below sea level conditions, but changes due to BP were still noted on the said level as well, although the change was not statistically significant.

The above therefore suggest that the effect of BP alone, might not be the sole determinant of the changes observed in the behaviour of the pumps. Literature suggests that the pumps' age can significantly influence the observed behaviour of pumps under various conditions of environmental variations.[49] As the pumps age, some control systems can no longer compensate for changes in pump characteristics. All the GilAir-3 pumps used in the study vary in the number of years they were used in the mine; this might have influenced the results obtained.

5.2.1 Density effect on pre-flow rate of GilAir-3 pumps

A one-way analysis of variance was computed for density, yielding a 95% confidence value of 1.0014 $kg.m^{-3}$ (0.9780-1.024 $kg.m^{-3}$). A one-way Kruskal-Wallis test was performed to determine whether any significant differences occurred between the mean densities of various working places, yielding a test statistic of 107.09 ($p=0.00$). This implies differences in mean densities between levels exist. Pairwise comparisons were then used to determine where such differences occurred, using the Bonferroni correction. This resulted in distinguishing five groups wherein the mean densities were insignificantly different ($p=0.05$) from each other, indicating: 66 levels and the following levels: 100,106, 109, 112 levels. It is therefore concluded that density influenced the flow rates of the pumps, although the impact thereof on 66, 100, 106, 109 and 112 levels were statistically insignificant.

Underground densities were compared to flow rates using Pearson correlations. The results seen in Table 4, indicated positive correlations between densities and pre-flow rates underground ($r=0.061$) as well as the changes in flow rates between surface and underground ($r=0.999$). The differences noted though, were statistically insignificant ($\alpha=0.433$) for underground density but was statistically significant ($\alpha<0.001$) when underground and surface densities were compared. The implications of these results indicated change in density between surface and underground influences increased flow rates of the GilAir-3 pumps.

5.2.2 Temperature effects on pre-flow rate of GilAir-3 Pumps

A comparison between dry-bulb temperature and pre-flow rates of the pumps (Table 4) indicates a positive correlation, with a Pearson correlation factor of 0.338 (p=0.0001). Comparisons between the mean dry-bulb temperatures and change in flow rate from surface to underground, indicate (r) of 0.3471 (p=0.0001). Similarly, correlations of wet-bulb temperatures against flow rate were performed, yielding the following results: Wet-bulb versus pre-flow rate (r) 0.189 (p=0.014) and wet-bulb versus change in flow rate: Pearson correlation factor of 0.2647 (p=0.0043).

The results indicate an impact of both dry and wet-bulb temperatures on the flow rate of pumps. The strength of association is higher for dry-bulb temperature than wet-bulb temperatures.

5.2.3 Environmental influences on the flow rates of GilAir-3 air sampling pumps

The results further indicate that BP, temperature and density differences between the surface conditions and underground environment influence flow rates of the GilAir-3 pumps differently. There is a stronger degree of association between changes in the pump flow rate and the dry bulb temperature, although each of the environmental parameters mentioned above emulate changes to the flow rates of the pumps.

5.2.4 The environmental effects on the pre-flow rates of GilAir-3 pumps on crystalline silica dust concentration

Pearson's correlations between silica concentration indicate:

- BP yielded a positive correlation factor of 0.1095 (p=0.2482).
- Density indicated a positive correlation factor of 0.0825 (p=0.3849).
- Wet-bulb temperature indicated a positive correlation factor of 0.1100 (p=0.2466).
- Dry-bulb temperature indicated a positive correlation factor of 0.3134 (p=0.007).

The above results indicate dry-bulb temperature as the most significant environmental factor contributing towards the silica concentrations. The other environmental factors did not prove to have statistically significant impact on the silica concentration. It is concluded that BP, density and wet-bulb temperature do not influence crystalline silica dust concentration.

5.3 Barometric pressure effect on GilAir Plus pumps

Table 5 indicates that the GilAir Plus pumps signified a decrease in average flow rates from surface to underground. Table 6 indicates Pearson's correlation between flow rates and BP using the GilAir Plus pumps with a negative correlation (r) -0.443 (α=0.002). BP changes between surface and underground significantly affected the flow rates of the GilAir Plus pumps.

5.3.1 Temperature influence on the pre-flow rates of GilAir Plus pumps

Table 6 indicates an observed negative correlation (r=.0.124) between the flow rates of the pumps and wet-bulb temperatures, although the difference observed is statistically insignificant (α=0.402). The dry-bulb temperatures and flow rates indicated a positive correlation (r=0.194), although the difference observed was also statistically insignificant (α=0.187). It is concluded that the flow rate did not significantly influence the flow rates of the GilAir Plus.

5.3.2 Density influence on the pre-flow rate GilAir Plus pumps

Pearson's correlations between the GilAir Plus pumps flow rate and density were negative (r=-0.451). Table 6 displays a statistically significant difference (α=0.001). An increase in density is therefore observed that negatively affected the flow rates of the GilAir Plus pumps. The null hypothesis is thus rejected, in favour of the alternative hypothesis.

5.4 Barometric pressure effects on Tuff pumps

Table 8 indicates that the Pearson correlation between the flow rates of Tuff pumps and BP indicates a positive linear correlation (r=0.022), although the observed relationship holds no statistical significance (α=0.902). The implication therefore, is that excluding a slight increase of the flow rates in the Tuff pumps in relation to the increase in BP moving from the surface to the deepest part of the mine, the observed difference in flow rates using the Tuff pumps is statistically insignificant. This trend is observed for all the Tuff pumps used, implying that the behaviour of the flow rates of the pumps compared to the increase in BP is linear. The changes observed however, are not statistically significant. The null hypothesis can thus not be rejected.

5.4.1 Density effects on pre-flow rate of Tuff pumps

Table 8 depicts a positive linear correlation between underground density and the flow rate ($r=0.017$), though the relationship is statistically insignificant ($\alpha=0.923$). A change between surface and underground density and flow rates indicates a stronger positive correlation of $r=0.996$. The relationship is statistical significant ($\alpha<0.001$). This implies that a change in density between surface and underground influenced the flow rate of the Tuff pumps.

5.4.2 Temperature responses on the pre-flow rate of Tuff pumps

Table 8 signifies the Pearson correlations as both wet and dry-bulb temperatures, indicating a positive correlation with flow rate; the observed differences were statistically insignificant ($\alpha>0.05$).

5.4.3. The various pump types flow rate differences

The various pump types each exhibit contrasting behaviours. The GilAir-3 pump type is the only pump type that indicated an increase in flow rate with increases in BP, temperature and density. The alternative pump types flow rates decreased below 2.20 L/min calibration levels. This indicates that the pumps compensating for the environmental conditions underground appear to be over-compensating for these changes. This will have implications in the particle sizes collected onto the filtration medium.

5.5 Characteristics of samples

The selectivity of the size of particles filtered depends on the cyclone type and the flow rate at which the sampling pump operates. The flow rate needs to be controlled to be stable throughout the duration of sampling, preventing errors of over- or under-sampling when determining the exposure levels. The cyclone heads conformed to the ACGIH/CEM/ISO criteria size selection curve, with a 50% cut point at 4.0 µm. This implied that at this point, the specified size of fraction of dust particle to be collected with a 50% efficiency. The average cut-off point on the surface was 4.36 µm. When pumps were dispatched underground, the cut-off point averaged 4.22 µm (4.12-4.40 µm). Figure 6 uses a model indicating implications for the change observed in the cut points for underground conditions for the current study. The observations indicate that respirable curve tends to shift to the left in relation to the initial calibration point (4.36µm), suggesting that smaller particles will settle on the filter when exposed to the environmental factors and flow rates underground. The mining industry practice currently, does not account for this factor, denoting that the respirable dose that employees are exposed to, are underestimated. This is evident in the number of samples that were collected on the filter, shown in Fig 6, where most particles of less than 4.0µm were collected.

When experimental filters (Fig 7) were compared to control filters using the SEM, irregularly shaped black particles appeared. An analysis of these particles using EDS, indicated that the particles contained substantial volumes of carbon with certain traces of silicon. Rods used during carbon coating implied to contain, amongst other minerals, traces of silicon, iron, aluminium, magnesium and tin, explaining the observed trace volume of silicon.

The results obtained therefore suggest that the carbon coating process introduced additional carbon artefacts interfering with the elemental composition of the analysed particles. This implied that the method applied for characterisation will have to be modified to attain an improved representation of the particulate composition of the substance collected on the filter.

Other elements indicating mainly oxides, were also deposited on the filter. These oxides are constituents of the earth's crust and may also contribute to developing chronic lung diseases. [3,6]

CHAPTER SIX

6. CONCLUSIONS

6.1. Conclusions and recommendations

It is concluded that BP, air density and temperature changes affect the gravimetric dust pump's flow rate; the null hypothesis is rejected, in favour of the alternative hypothesis. Underground conditions need to be considered when gravimetric sampling is conducted. Should the mine decide to continue using the standard gravimetric pumps, a correction factor is needed to account for the impact that BP, temperature and density has on the pump's flow rate. The study and the sundry samples used in this study, was insufficient. It could not determine a correction factor that can be used by each of the GilAir-3 pumps ensuring more accurate dose calculations.

The Tuff and GilAir plus, seemed to be exaggerating the exposure levels. Should the employer use the two mentioned pump types, improved dust control mechanisms can be mounted to protect the workers. It therefore remains that if the primary reason for conducting measurements is not merely compliance, but improving dust control strategies limiting the possibility of employees contracting silicosis, more robust or stringent methods of detecting silica dust exposure should be used.

Analysis of particulate matters using the SEM could provide clues on the distribution and size of the particles collected. The process used in the preparation of samples also interfered with the outcome of the minerals analysed. The carbon coating process needs to be reviewed. The volume of carbon applied onto the sample during preparation could be limited as this introduced bias in the outcome of the particles analysed.

It is well established that respiratory diseases associated with exposure to silica-containing dust are preventable, dramatically reducing silicosis in several developed and developing countries. In 1930, the International Labour Organisation (ILO) and the WHO indicated 2030 as the target in global elimination of silicosis.

Several campaigns were launched in South Africa to reduce dust exposure; the most observed campaigns materialised during 1960 to 1970, using a cartoon character titled “Stoffel Waterman”. The findings of the Leon Commission in 1995 though, concluded that there was insufficient change in dust exposure in SA gold mines during the last 50 years.

Although the sampling trends indicate several achievements reducing silica dust levels in the mining industry, the disease incident rate are still not significantly decreasing. Although quartz is known to be the main contributing factor in developing silicosis, other elements, naturally found in the earth’s crust (although found in traces), also emulate developing the disease outcome. These elements are primarily oxides, indicating magnesium. This finding was not part of the study objectives, but needs to be reported as it should be addressed in future studies. The recommendation is that the impact of these oxides be investigated further; efforts are made to reduce the burden of silicosis in the mining industry.

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Appendices

Appendix A: Ethical Approval letters and revisions

UNIVERSITEIT VAN PRETORIA
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Faculty of Health Sciences Research Ethics Committee

31/08/2017

Ms Neo Dikgale
Department of School of Health Systems and Public Health (SHSPH)
University of Pretoria

Dear Ms Neo Dikgale

RE.: 404/2014 ~ Letter dated 11 July 2017

Protocol Number	**404/2014**
Protocol Title	Analysis of barometric pressure, temperature and density effects on flow rate of gravimetric dust sampling pumps used in silica dust monitoring at a South African gold mine.
Principal Investigator	Ms Neo Dikgale **Tel:** 725731473 **Email:** NDikgale@AngloGoldAshanti.com **Dept:** School of Health Systems and Public Health (SHSPH)

We hereby acknowledge receipt of the following document:

- Extension for study until end of December 2018.

This will be processed in due course and filed.

With regards

Dr R Sommers; MBChB; MMed (Int); MPharMed; PhD
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

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The Research Ethics Committee, Faculty Health Sciences, University of Pretoria complies with ICH-GCP guidelines and has US Federal wide Assurance.
- FWA 00002567, Approved dd 22 May 2002 and Expires 20 Oct 2016.
- IRB 0000 2235 IORG0001762 Approved dd 22/04/2014 and Expires 22/04/2017.

UNIVERSITEIT VAN PRETORIA
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Faculty of Health Sciences Research Ethics Committee

30/10/2014

Approval Certificate
New Application

Ethics Reference No: 404/2014

Title: Analysis of barometric pressure, temperature and density effects on flow rate of gravimetric dust sampling pumps used in silica dust monitoring at a South African gold mine.

Dear Ms Neo Dikgale

The **New Application** as supported by documents specified in your cover letter for your research received on the 26/09/2014, was approved by the Faculty of Health Sciences Research Ethics Committee on the 29/10/2014.

Please note the following about your ethics approval:
- Ethics Approval is valid for 3 years.
- Please remember to use your protocol number (**404/2014**) on any documents or correspondence with the Research Ethics Committee regarding your research.
- Please note that the Research Ethics Committee may ask further questions, seek additional information, require further modification, or monitor the conduct of your research.

Ethics approval is subject to the following:
- The ethics approval is conditional on the receipt of 6 monthly written Progress Reports, and
- The ethics approval is conditional on the research being conducted as stipulated by the details of all documents submitted to the Committee. In the event that a further need arises to change who the investigators are, the methods or any other aspect, such changes must be submitted as an Amendment for approval by the Committee.

We wish you the best with your research.

Yours sincerely

*** Kindly collect your original signed approval certificate from our offices, Faculty of Health Sciences, Research Ethics Committee, H W Snyman South Building, Room 2.33 / 2.34.*

Dr R Sommers; MBChB; MMed (Int); MPharMed.
Deputy Chairperson of the Faculty of Health Sciences Research Ethics Committee, University of Pretoria

The Faculty of Health Sciences Research Ethics Committee complies with the SA National Act 61 of 2003 as it pertains to health research and the United States Code of Federal Regulations Title 45 and 46. This committee abides by the ethical norms and principles for research, established by the Declaration of Helsinki, the South African Medical Research Council Guidelines as well as the Guidelines for Ethical Research: Principles Structures and Processes 2004 (Department of Health).

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Faculty of Health Sciences
School of Health Systems and Public Health

22 July 2014

Ms N Dikgale
22108506
MSc (Community Health)

Dear Ms Dikgale

Approval Academic Advisory Committee

This serves to confirm that your protocol was served at the Academic Advisory Committee on 22 July 2014.

Your title: ***Analysis of barometric pressure, temperature and air density on flow rate of gravimetric dust sampling pumps and silica dust monitoring at a South African gold mine,*** was approved.

Please ensure that this title is reflected on your dissertation.

You can now submit to ethics.

Sincerely

Prof K Voyi
Chairperson
SHSPH Academic Advisory Committee

cc Dr N Claassen

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