



Performance comparison of the Nanozen Dustcount personal real-time monitor with a conventional respirable dust exposure sampling method

V Jansen

 **orcid.org/0000-0002-9852-7665**

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Supervisor: Mr CJ Van Der Merwe

Co-supervisor: Dr SJL Linde

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DECLARATION OF AUTHORS' CONTRIBUTIONS

This study was planned and performed by a research team. The contribution of each participating member is outlined in Table 1-1 below.

Table 1-1: Contributions of Authors

Name	Contribution
Ms V Wagner (Student)	<ul style="list-style-type: none"> • Study design and planning • Literature research • Conducting statistical analyses, data interpretation, writing of the article and formulating of recommendations • Writing of the dissertation
Mr CJ Van der Merwe (Supervisor)	<ul style="list-style-type: none"> • Assisting with the study planning and design • Approving the study protocol • Professional guidance and recommendations • Assisted with the interpretation of results • Review of the dissertation
Dr SJL Linde (Co-supervisor)	<ul style="list-style-type: none"> • Assisting with the study planning and design • Approving the study protocol • Professional guidance and recommendations • Assisted with the interpretation of results • Review of the dissertation

The following is a statement from the supervisors that confirms everyone's role in the study:

I declare that I have approved the article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of V Wagner's MHS in Occupational Hygiene Dissertation.



Mr CJ van der Merwe
Supervisor



Dr SJL Linde
Co-supervisor



Ms V Wagner
Student

PREFACE

This dissertation is presented for examination and consists of four chapters and two annexures:

- Chapter 1 provides a general introduction and problem statement related to respirable dust exposure sampling, along with a comparison of different sampling methods. It also includes the research aim, objectives and hypothesis.
- Chapter 2 comprises a literature review of studies pertinent to the topic as encapsulated by the title of this study.
- Chapter 3 represents the article titled, *Performance comparison of the Nanozen DustCount personal real-time monitor with a conventional respirable dust exposure sampling method*.
- Chapter 4, the concluding chapter, contains the main findings of the study, limitations, recommendations and suggestions for future research.
- Annexure A: Proof of ethics approval.
- Annexure B: Proof of language editing.

This dissertation follows the North-West University template for postgraduate studies, except for Chapter 3, which adheres to the Journal of Occupational and Environmental Hygiene (JOEH) guidelines. The prescribed guidelines were implemented where feasible, with adaptations made in cases where practical considerations necessitated minor deviations due to specific contextual needs.

The North-West University Harvard reference style was used, except in Chapter 3, where the Taylor & Francis Council of Science Editors (CSE) author–name style was applied. Citations are listed alphabetically by authors' surnames at the end of each chapter. United Kingdom English spelling is used throughout, except for direct quotes, titles of articles or journals, and names of organisations that use United States spelling.

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ABSTRACT

Title: Performance comparison of the Nanozen DustCount personal real-time monitor with a conventional respirable dust exposure sampling method

Introduction: The mining industry, a vital contributor to many economies, particularly in South Africa, poses significant health risks due to dust exposure. Dust from mining operations varies in composition and particle size, influencing its health impacts. Safeguarding workers' health has been a legislated priority since 1911, with legislation mandating exposure monitoring and the implementation of control measures.

Conventional gravimetric sampling is the most widely used and accepted standard for air monitoring, using a pump and filter system to collect samples in a worker's breathing zone over a shift. Although reliable, this method involves gravimetric analysis of the filter in a laboratory, which delays results and limits timely interventions.

Advancements in technology and the development of direct-reading instruments, such as the Nanozen DustCount® 9000-Z1 personal real-time monitor (Nanozen Industries Inc., Vancouver, Canada), provide faster, real-time dust exposure measurements. The accuracy of these devices must, however, be validated against conventional gravimetric methods, such as the Methods for the Determination of Hazardous Substances (MDHS14/4) method, to ensure their reliability.

A limited number of published studies have evaluated the performance of the DustCount, and even fewer assessed the performance of the DustCount through collecting samples side-by-side with conventional gravimetric sampling methods in a work environment.

Method: This study evaluated the performance of the DustCount device compared to a conventional gravimetric sampling method through quantitative analyses of secondary data. The data was collected by a company contracted to conduct exposure monitoring in various areas of an open-cast iron ore mine in the Northern Cape, South Africa. A dataset of 35 paired results from side-by-side monitoring was analysed. The real-time respirable dust concentration results obtained from the DustCount's optical particle counter were compared to those obtained using a cyclone following MDHS14/4, a conventional gravimetric sampling method. Additionally, the respirable dust concentration results from the DustCount's optical particle counter were compared to those collected by the DustCount's impactor and filter. Lastly, the respirable dust concentrations determined by the DustCount's impactors were compared to those obtained using the cyclone following the MDHS14/4 method.

Results: The geometric mean of the conventional gravimetric concentration (CGC) dataset was 0.416 mg/m³, with a coefficient of variance (CV) of 175%. In contrast, the DustCount real-time concentration (DRC) dataset had a lower geometric mean of 0.172 mg/m³ and a CV of 111%. Across all samples, the CGC method consistently reported higher respirable dust concentrations than the DRC method.

Bland-Altman (BA) analysis confirmed that the DustCount underestimated respirable dust concentrations, with a mean bias of -71.41%, standard deviation (SD) of 35.17%, and 95% limits of agreement ranging from -166.6% to 11.84%. This significant underestimation highlights a key limitation of the DustCount for precise exposure quantification.

Conclusion: The significant bias of -71.41% suggests that the DustCount instrument is inaccurate in measuring respirable dust concentrations, as it consistently underestimates values compared to the reference method. The large standard deviation of 35.17% and the wide limits of agreement (ranging from -166.6% to 11.84%) indicate a lack of precision, suggesting that the DustCount provides inconsistent measurements when compared to the reference method. Despite these limitations, the findings suggest that the DustCount has potential value as a real-time monitoring tool, as it does reflect temporal changes in respirable dust concentrations. With further refinement — particularly regarding the ease with which correction factors can be established — the instrument's real-time capabilities could facilitate immediate interventions and enhance workplace safety by providing near-instantaneous feedback.

Word count: 535

Key terms: Airborne, Direct-reading, Gravimetric, Mining, Risk Assessment, Size-selective

LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variation
BA	Bland-Altman
ARD	Arizona Road Dust
CGC	Referring to conventional gravimetric sampling method equipment and results
CI	Confidence Interval
CLT	Central Limit Theorem
COPD	Chronic Obstructive Pulmonary Disease
CV	Coefficient of Variance
CWP	Coal Worker's Pneumoconiosis
DO	Dorr Oliver
DoEL ¹	Department of Employment and Labour, South Africa
DMR	Department of Minerals and Resources, South Africa
DRC	Referring to DustCount real-time sampling equipment and results
GM	Geometric mean
GMCC	Gravimetric Mass Calibration Coefficient
GSD	Geometric standard deviation
HCA	Hazardous Chemical Agent
HSE	Health and Safety Executive
IARC	International Agency for Research on Cancer

¹ The Department of Labour was renamed to the Department of Employment and Labour. Both titles reflect the same overarching focus on employment-related matters and the regulation of labour policies.

ICMM	International Council on Mining and Metals
JOEH	Journal of Occupational and Environmental Hygiene
IS	Intrinsically safe
ISO	International Organization for Standardization
LOD	Limit of detection
LPM	Litre Per Minute
MHS Act	Mine Health and Safety Act
NIOSH	National Institute for Occupational Health and Safety
NWU	North-West University
OEL	Occupational Exposure Limit
OHS Act	Occupational Health and Safety Act
OSHA	The Occupational Safety and Health Administration
OPC	Optical Particle Counter
PEL	Permissible Exposure Limit
pDR	Personal DataRAM™
PM	Particulate matter
PM _{2.5}	Ultrafine particles of 2.5 micrometres or smaller
PM ₄	Ultrafine particles of 4 micrometres or smaller
PM ₁₀	Ultrafine particles of 10 micrometres or smaller
PNOS	Particles Not Otherwise Specified
PSD	Particle size distribution
RD	Respirable Dust
RCS	Respirable Crystalline Silica
RHCA	Regulations for Hazardous Chemical Agents 2021
ROUT	Robust outlier detection test
SD	Standard deviation

TWA	Time Weighted Average
USA	United States of America
WHO	World Health Organization

LIST OF UNITS AND SYMBOLS

g/cm^3	Grams per cubic centimetre
$\mu\text{g/m}^3$	Micrograms per cubic metre
mg/m^3	Milligrams per cubic metre
nm	Nanometres
μm	Micrometres
cm	Centimetres
g	Gramme
LPM	Litres Per Minute

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CHAPTER 1 INTRODUCTION

1.1 Background

Various industrial activities are known to generate fine dust that poses a health risk to workers. In the mining sector, these activities include cutting, grinding, drilling, blasting, excavation, loading, unloading, and ore transportation — all of which can result in substantial dust exposure (Duarte *et al.*, 2022:2; Onder & Yigit, 2009:393). These exposures occur via physiological routes, which are pathways through which hazardous agents enter the body, potentially leading to adverse health effects (Osman *et al.*, 2019:563; Reed *et al.*, 2020:2). Inhaling dust particles, particularly those containing harmful chemical substances, can damage the lungs and airways (Hashemi *et al.*, 2018:77).

Respirable dust (RD) refers to dust particles with an aerodynamic diameter of less than 10 µm and a median size of 4 µm (Brown *et al.*, 2013:1). These small particles can bypass the ciliated airways, reaching the alveolar region of the lungs, where they might accumulate and contribute to respiratory diseases (Barone *et al.*, 2021:134; Fan *et al.*, 2020:2). The composition of RD particles and their deposition location in the lungs influence the health risks associated with exposure. Exposure to RD particles containing respirable crystalline silica (RCS) or fine coal particles can lead to various illnesses such as silicosis, coal workers' pneumoconiosis (CWP), chronic obstructive pulmonary disease (COPD), and asthma, among others (Kakooei *et al.*, 2011:122).

Exposure to hazardous agents, including RCS in ore mining, can negatively affect worker health and lead to conditions like silicosis (Calvert *et al.*, 2003:122; Stewart, 2020:1153). The Safety in Mines Research Advisory Committee has identified dust as the leading occupational health hazard in the South African mining industry (Biffi *et al.*, 2000:1).

To address the health hazard posed by dust, specifically RD exposure, effective exposure monitoring systems are needed to assess workers' exposure for regulatory compliance, epidemiological studies, and mitigation efforts (Biffi *et al.*, 2000:1). Legislative requirements as set out in the *Mine Health and Safety Act* 29 of 1996 oblige employers to identify hazardous exposure areas and monitor workers' exposure to occupational hazards (Department of Mineral Resources, 2018:11). Results of exposure monitoring programmes are used to evaluate and select control measures intended to reduce the associated health risks (Bharath, 2019:301; NASEM, 2018:10).

The process of risk mitigation consists of three steps: exposure monitoring, result interpretation, and the implementation of controls to prevent overexposure (Aven, 2016:3). Exposure sampling programmes must be developed following national and internationally recognised standards (Stanton *et al.*, 2007:8).

Occupational exposure to dust, particularly RD, must be accurately measured to provide essential information to address the associated health and safety risks to workers through the timely and informed implementation and maintenance of control measures (Donoghue, 2004:284). Exposure sampling plays a vital role in the protection of worker health and safety, as it aids in risk assessment and mitigation. Interpretations and findings of exposure sampling are used to guide the design and effective testing of control measures (Lioy and Weisel, 2014:3; Martinelli *et al.*, 2020:1).

Over the years, various exposure sampling equipment and methods have been developed (Harper, 2020:2). Conventionally, a gravimetric sampling method is used to measure exposure levels. A primary limitation of this method is the extended turnaround time to obtain results (Pampena *et al.*, 2020:718). Gravimetric sampling requires the filter used during the sampling process to be gravimetrically analysed in a laboratory, resulting in only one data point per exposure sampling session (Kenny *et al.*, 2001:40). The process of obtaining RD exposure results can take several days to weeks before they become available, potentially delaying the implementation of necessary control measures (Harper, 2020:6; Hart *et al.*, 2018:744). However, timely access to accurate RD exposure data is crucial to prompt identification of areas where exposure exceeds control limits. This allows for the immediate application of control measures, helping to prevent detrimental effects on employees' health (Pampena *et al.*, 2020:718).

The mining industry employs more than 480 000 people, representing a significant portion of the South African workforce (Stats SA, 2023). The substantial workforce of the mining industry highlights the importance of accurate exposure sampling data to mitigate health and safety risks through effective control measures, as a large portion of this workforce is exposed to RD. Exposure to RCS is prevalent in the mining environment and an improved understanding of RD exposure will help to control RCS (Brouwer & Rees, 2020:2). In line with the South African Mine Health and Safety Council's 2014 Occupational Health and Safety Summit Milestones, efforts are focused towards protecting employees through significant occupational health improvements (Mine Health and Safety Council, 2014).

Key goals include that 95% of exposure measurement results shall be below the respective occupational exposure limits (OELs) for RCS, coal and platinum dust, along with a reduction in occupational lung diseases such as CWP (Mine Health and Safety Council, 2014).

Improved exposure monitoring methods are essential to meet these objectives and in-depth research of available technology is crucial in this regard (Kuula *et al.*, 2019:2; Lippmann, 2013:1). One milestone aims to eliminate silicosis, targeting 95% of exposure measurement results to fall below half of the current OEL for respirable fused silica particulates, which is 0.1 mg/m³ (Mine Health and Safety Council, 2014). Real-time monitoring equipment can provide timely exposure data, enhancing swift mitigative actions when over-exposure is detected. This would not only enhance occupational health but also support the attainment of the milestones set out by the South African Mine Health and Safety Council.

In addressing the limitation of conventional gravimetric sampling, several technological advances have been made to improve the turnaround time of reportable results, such as real-time dust monitors (Harper, 2020:2). The main advantage of real-time dust monitors is that they give an instantaneous measure of airborne dust concentration, reducing the time and effort associated with conventional gravimetric sampling methods (Thorpe & Walsh, 2007:679). Another advantage of real-time monitoring is its ability to quickly identify peak exposure trends, enabling prompt corrective actions to be taken (Lemke, 2021:11). The sampling cut-point sizes of the instruments listed below are manufactured in accordance with ISO 7708:1995², *Air quality — Particle size fraction definitions for health-related sampling* protocols, ensuring accurate measurement of respirable dust (RD) in occupational environments. This standard defines respirable dust fractions based on aerodynamic diameter, with a 50% cut-off at 4 µm, aligning with global occupational health guidelines. Examples of devices designed for real-time measurement of RD that can be worn by workers include:

- TSI SidePak™ AM520 Personal Aerosol Monitor (TSI Inc., Minnesota, USA).
- Thermo Scientific pDR Series (Thermo Fisher Scientific, Waltham, MA, USA).
- Casella Apex2 (Casella, Kempston, Bedford, UK).
- SKC AirChek (SKC Inc., Eighty-Four, PA, USA).
- Nanozen DustCount® 9000-Z1 personal real-time monitor (Nanozen Industries Inc., Vancouver, Canada).

The devices listed above are commercially available, and their performance has been evaluated in research studies comparing them to conventional gravimetric sampling methods. These studies have, however, highlighted significant limitations, including probable inaccuracies, sensitivity to environmental factors, calibration requirements, and high costs (Thorpe & Walsh, 2007:680;

² ISO 7708:1995 Air quality – Particle size fraction definitions for health-related sampling

Wang *et al.*, 2016:1110). Chapter 2 of this study provides more details and reflects the findings of previous studies on this topic.

To evaluate the suitability of real-time monitoring instruments to assess respirable dust exposure within an actual work environment, they should be compared to conventional gravimetric sampling methods (Gussman *et al.*, 2002:4). While this study will highlight various aspects of dust exposure and methods used for measuring it, the primary focus is to compare RD sampling results obtained from two different types of equipment and methods at an opencast iron ore mine.

Specifically, this study evaluates the performance of the DustCount against a conventional gravimetric RD sampling method, investigating the accuracy of the DustCount in providing reliable RD exposure assessment results. Although several real-time monitors are available, this study focuses on the DustCount due to its relevance to the objectives of assessing real-time exposure sampling capabilities. The DustCount can support the timely implementation of control measures by providing users with exposure monitoring data both during, and at the end of each shift.

1.2 Problem Statement

A limitation of conventional gravimetric sampling methods is the slow turnaround time from sampling to results, which delays the implementation of control measures (ICMM, 2022:1; Pampera *et al.*, 2020:718). To address this, various real-time monitoring devices have been developed, however, their accuracy still requires rigorous validation against established methods. Validating these devices is essential for their reliable incorporation into exposure sampling programmes (Kuula *et al.*, 2019:2). Despite its potential, the accuracy of the DustCount has not been widely examined in studies comparing its performance to conventional gravimetric sampling methods. The DustCount was selected as the real-time instrument for this study due to the limited number of published research studies available on this device and its potential for higher sensitivity compared to other real-time monitors. If proven accurate, the DustCount could be beneficial in various work environments, particularly in remote mining locations where real-time dust monitoring is crucial for occupational health and safety. This study aims to contribute to the existing body of knowledge by analysing data collected by a contracted company using the DustCount side-by-side conventional gravimetric sampling equipment following the MDHS14/4 method (HSE, 2019). This data will be further analysed to provide valuable insights into the DustCount's performance and its applicability for exposure monitoring. MDHS14/4 was selected because using MDHS 14/4 as a reference method ensures that DustCount readings are scientifically validated against a recognized standard. This comparison helps determine whether DustCount can be a reliable alternative to traditional gravimetric monitoring for workplace exposure assessments (Walsh *et al.*, 2008:4).

1.3 Research Objectives

The overall aim of this study was to evaluate the suitability of the DustCount for assessing respirable dust concentrations. The specific objectives were to compare respirable dust concentrations obtained using the DustCount's:

1. Optical particle counting technology with those obtained using the MDHS14/4 method and a cyclone.
2. Impactor-based particle size separation technique with those obtained using the MDHS14/4 method and a cyclone.
3. Optical particle counting technology with those obtained using the DustCount's impactor-based particle size separation and gravimetric analysis technique.

1.4 Hypothesis

A study conducted by Lemke (2021) compared personal RD sampling results obtained with the DustCount to those collected simultaneously, side-by-side, using conventional gravimetric sampling equipment. The results indicated poor agreement and correlation, with the DustCount underreporting the concentrations of exposure. This was possibly due to the gravimetric mass calibration coefficient (GMCC) applied to the DustCount results, and it was recommended that a more accurate GMCC be obtained (Lemke, 2021:27). The GMCC is a correction factor which is applied to the real-time measurements of the DustCount to improve the accuracy of the results. Studies have shown that results obtained by the DustCount are lower when compared to conventional gravimetric results, meaning that the device possibly under samples and underestimates exposure (Lemke, 2021:27; Cheng *et al.*, 2008:160; Van Ree, *et al.*, 2023).

Therefore, it is hypothesised that the results of this study will indicate a statistically significant difference and poor agreement between RD results obtained by the DustCount and RD results obtained using the MDHS14/4 conventional gravimetric method.

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CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The interrelation between occupational exposures and adverse health effects has been thoroughly studied since the late 1700s and great strides have been made since the fundamentals were established by the research of Dr Bernardino Ramazzini (Franco & Franco, 2001:1380). Excessive exposure to work-related hazards can harm health, making it essential to accurately assess exposure, ensure compliance with occupational exposure limits (OELs), and implement control measures to prevent adverse effects (Semple, 2005:423). Mining is an ancient occupation, where ores of different minerals are mined. The *Guidelines for the Gravimetric Sampling of Respirable Airborne Dust Concentrations in Coal Mines*, published by the South African Department of Mineral and Energy Affairs in 1988, describes acceptable samplers for gravimetric exposure monitoring. This document represents one of the earliest established guidance documents on conventional gravimetric exposure sampling equipment and methods for the mining sector in South Africa (cited by Belle, 2018:308).

As technology advances, opportunities arise to explore whether improved technology can enhance exposure sampling equipment and methods (Reed *et al.*, 2020:9). More than a decade ago, in 2012, the American National Research Council published a report titled *Exposure Science in the 21st Century: A Vision and a Strategy*. This report emphasised the need for advanced technology in exposure science to improve the accuracy of exposure sampling equipment and methods and to reduce turnaround times for results. Since then, the Center for Direct Reading and Sensor Technologies (NCDRST) was established within the National Institute for Occupational Safety and Health (NIOSH) to advance research on direct-reading methods. Significant progress has been made in developing real-time monitoring capabilities using the technologies which have been incorporated into the strategic goals of these institutions (Lippmann, 2013).

Recent initiatives by NIOSH include integrating wearable sensors and wireless exposure sampling devices, enabling faster actionable data from workplace exposure across various industries (Wolfe, *et al.*, 2024:1). According to the NIOSHTIC-2 bibliographic database, since the 2012 American National Research Council report, NIOSH has published over 50 articles related to real-time exposure monitoring, covering various aspects and adding a wealth of knowledge to the industry.

Several technological advances have resulted in the manufacturing of newly developed, commercially available monitoring equipment, enabling quicker turnaround times compared to conventional methods. The effectiveness of these monitoring devices is depending on their ability to provide accurate exposure assessment results (Hashimoto *et al.*, 2018:104).

It is, therefore, essential to investigate the accuracy of the newly developed monitoring equipment to determine whether it can serve as a viable alternative to established devices and methods before being integrated into existing exposure monitoring programmes (Kuula *et al.*, 2019:2).

2.2 South African OHS Legislation

South African occupational health and safety legislation requires employers to provide a safe working environment for employees. Currently, occupational health and safety in South African workplaces is regulated by two different acts, namely the *Mine Health and Safety Act* 29 of 1996 (MHS Act) and the *Occupational Health and Safety Act* 85 of 1993 (OHS Act). Both acts set legislated standards for health and safety in South African workplaces. However, there are some differences in the focus and standards since separate state departments govern the acts which are applicable in different work environments. The OHS Act applies to all industries, except maritime sectors or those specifically addressed by the MHS Act. The MHS Act applies to the mining industry as well as to facilities and structures associated with mining operations that are essential to the mining process, including sites such as processing plants where extracted minerals are handled (Swanepoel, 2016:2). Table 2-1 provides a summarised overview of the respective legislation.

Table 2-1 Summary of South African OHS Legislation (Stanton *et al.*, 2007)

South African Legislation	Scope	Government Enforcement Department	OEL for RD	Reference
OHS Act	Provides health and safety regulations for workplaces, including factories and offices	DoEL	Under the HCA Regulations below	Occupational Health and Safety Act 85 of 1993
Regulations for HCA under the OHS Act	Governs chemical and particulate hazards in general workplaces	DoEL	RD falls within the category of PNOS, with an OEL of 5 mg/m ³ , but it may vary based on the specific composition/type of dust	Occupational Health and Safety Act: Regulations for Hazardous Chemical Agents, 2021

(table continues on next page)

South African Legislation	Scope	Government Enforcement Department	OEL for RD	Reference
MHS Act	Establishes health and safety standards for the mining industry	DMPR	OEL for general respirable dust is 3 mg/m ³ and stricter for mineral-specific hazards like Silica	Mine Health and Safety Act 29 of 1996

Clarification of abbreviations as used in **Table 2-1** above:

DMPR - Department of Mineral and Petroleum Resources
HCA - Hazardous Chemical Agents
OEL - Occupational Exposure Limit
PNOS - Particles Not Otherwise Specified
RHCA - Regulations for Hazardous Chemical Agents, 2021

DoEL - Department of Employment and Labour
MHS Act - Mine Health and Safety Act
OHS Act - Occupational Health and Safety Act
RD - Respirable Dust

2.2.1 South African Mine Health and Safety Legislation

The *Mines' Phthisis³ Allowances Act* 34 of 1911 was a significant milestone in South Africa's mining legislative history. It marks one of the earliest efforts to address the high incidence of lung disease among mine workers (Donsky, 1993:153). This was followed by the *Mines and Works Act* 12 of 1911, one of the first formal health and safety requirements in the country. The *Mines and Works Act* was amended in 1926 and further in 1956 before being repealed by the *Minerals Act* 50 of 1991. In 1994, the Leon Commission was established by the South African government to conduct a comprehensive investigation into the health and safety aspects of mines. The findings from this investigation led to the promulgation of the *Mine Health and Safety Act* 29 of 1996 (Plimmer, 1997:41). The objective of the MHS Act is to protect the health and safety of mining employees and other persons at mines (Department of Mineral Resources and Energy, 1996:2).

Chapter 1, Section 1 (b) of the MHS Act sets the framework for health and safety regulations in South African mines (*Mine Health and Safety Act* 29 of 1996). Section 1 (b) outlines the responsibilities of mine owners and employers to provide safe working conditions and conduct regular risk assessments. Chapter 2, Section 11 (a–b) of the MHS Act requires the employer to identify hazards and assess the risks to the health and safety of employees. The employer should eliminate, control, or minimise the risk as far as reasonably practicable. Furthermore, the MHS Act requires the employer to institute a programme to monitor the hazards to which employees are exposed. Air monitoring is necessary to detect RD concentrations that exceed the regulated occupational exposure limit (OEL) values and to evaluate the suitability of existing controls.

³ Phthisis is a medical term that was historically used to describe debilitating lung disease such as Pulmonary Tuberculosis and Silicosis (Frith, 2014:29).

Chapter 9(2) states that workers' occupational exposure to health hazards be maintained below the limits set out in Schedule 22.9(2)(a) and highlights the importance of occupational hygiene monitoring in Schedule 22.9(2)(a) of the MHS Act. The MHS Act defines an OEL as "*The time-weighted average (TWA) concentration for an 8-hour workday and a 40-hour workweek to which nearly all workers may be repeatedly exposed without adverse health effects*". TWA exposure sampling refers to the calculation which combines the mass concentration results and the exposure sampling duration to determine the average airborne concentration during a typical 8-hour workday.

The table of OELs for airborne pollutants under Schedule 22.9(2)(a) of the MHS Act, as amended by Government Notice 989 of October 5, 2006, specifies an OEL of 3 mg/m³ for respirable particles not otherwise specified (PNOS) (Mine Health and Safety Act 29 of 1996). Section 2.3.1 provides further information as to dust and the constituents of RD. Within the mining industry specifically, respirable crystalline silica (RCS) content is a major concern (Kesilwe, 2012:4).

The OEL for RCS under the MHS Act is 0.1 mg/m³, identical to that of the USA Occupational Safety and Health Administration's Permissible Exposure Limit (OSHA PEL) for RCS which is 0.1 mg/m³ as well. In comparison, the American Conference of Government Industrial Hygienists' Threshold Limit Value (ACGIH-TLV) is lower, at 0.025 mg/m³ (ACGIH, 2021). These low exposure limits emphasise the importance of early detection of overexposures, as the strict limits relative to other chemicals highlight the serious health risks posed by RCS (Breedt, 2012:1).

2.2.2 South African Health and Safety Legislation (non-mining industry)

The OHS Act aims to ensure the safety and well-being of individuals working in general industry. It also aims to safeguard members of the public from risks associated with the activities of workers (Moyo *et al.*, 2015:498). The primary goal of the OHS Act is to proactively prevent and mitigate work-related injuries and health issues. The OHS Act regulates health and safety across various diverse industries in South Africa, encompassing all non-mining sectors (Absolute Health Services, 2024). The regulations of the OHS Act set OELs to limit worker exposure to workplace hazards, including chemical exposure.

The differences between the MHS Act and the OHS Act influence the validation and implementation of new exposure sampling technologies. The adoption of new exposure monitoring technology is affected by varying validation requirements based on environmental conditions—whether mining-specific or general workplace settings.

The MHS Act is subject to approval processes by the DMPR, whereas the OHS Act is under the governance of the DoEL. Additionally, the MHS Act and OHS Act differ in their regulatory approaches, with one being more risk-based and the other more compliance-based.

The two acts also outline different consequences for non-compliance, which may impact how quickly new technology is adopted and enforced. If a technology is intended for both mining and non-mining industries, it will likely require dual compliance, ensuring it meets both the MHS Act and OHS Act standards for broader applicability.

2.2.3 Regulations for Hazardous Chemical Agents

The Ministry of Employment and Labour of South Africa, under the Occupational Health and Safety Act, 1993 and following consultation with the Advisory Council for Occupational Health and Safety, published the *Regulations for Hazardous Chemical Agents* on March 29, 2021, repealing the *Hazardous Chemical Substances Regulations*, 1995, (Occupational Health and Safety Act: Regulations: Hazardous Chemical Agents 2021). These regulations do not specifically mention the mining industry, and as stated in definition 3(a–b) of the OHS Act and Regulation 103 of the MHS Act, they do not apply to the mining sector. However, they emphasise the importance of statutory obligations that employers must comply with to protect the workforce (Misra et al., 2023:4).

Based on the provisions of the Regulations for HCA:

- Subregulation 5 states that an employer must ensure that a risk assessment is conducted to identify HCA present in the workplace. This assessment should evaluate the potential health risks associated with exposure to these agents.
- Subregulation 6 requires air monitoring to quantify exposure to HCA in the workplace, comparing exposure levels to OELs specified in the regulation's annexes.
- Subregulation 10 mandates that employers must prevent, or where not reasonably practicable, adequately control the exposure to HCA.

2.3 Dust and Its Physiological Effects

Dust is composed of solid particles, either organic or inorganic, generated by activities such as handling, grinding, and rapid impacts of materials like rock or ore (Kesilwe, 2012:7). Other sources include soil, pollen, skin cells, microscopic organisms, hair, and textile fibres. Due to their small size and low weight, dust particles can easily become airborne, creating widespread exposure in various environments (Wippich *et al.*, 2020:431). More than just a nuisance, dust inhalation can pose serious health risks (American Thoracic Society, 2002:787). The health effects of dust inhalation depend on particle size, deposition region in the lung, and chemical composition.

Dust exposure deteriorates environmental air quality and poses health risks across diverse settings (Ritz, *et al.*, 2019:883).

All airborne dust poses potentially adverse health risks, with the severity of the risk depending on the size and chemical composition of the particles due to the variety of particle sizes and materials it can contain (Riediker *et al.*, 2019:1; Stacey *et al.*, 2014:513). Smaller particles, such as PM_{2.5}, can penetrate deep into the lungs, leading to long-term respiratory and systematic health effects⁴ (Vanka, *et al.*, 2022:2). Occupational exposure to dust is linked to diseases such as chronic obstructive pulmonary disease (COPD) and pneumoconiosis (Fan *et al.*, 2020:2). COPD and pneumoconiosis are progressive, incurable diseases that severely impair lung function and quality of life (Ayaaba *et al.*, 2017:1).

Certain types of dust can cause allergic reactions, respiratory illness or exacerbate existing conditions like asthma, particularly when harmful particles are present in the dust (Ayaaba *et al.*, 2017:3). Workers in the coal mining industry are particularly at risk of inhaling dust particles such as RCS and coal dust, which can lead to severe health conditions, including black lung disease (pneumoconiosis), silicosis and lung cancer (Cassidy *et al.*, 2007:37; Kauppinen *et al.*, 2020:526). Exposure to dust containing RCS has also been associated with other irreversible and adverse health effects such as systematic autoimmune disorders and renal diseases (Merget *et al.*, 2002:626; Pollard, 2016:1; Vanka *et al.*, 2022:1). To mitigate these health risks, employers implement dust control systems, monitor worker exposure concentrations and provide personal protective equipment to limit harmful exposure (Pampena *et al.*, 2020:718). These strategies commence with exposure sampling and analysis to identify hazardous constituents, such as RCS. Size-selective exposure sampling provides essential data for implementing effective control measures, since considering particle size can assist with the selection of suitable control measures (Stacey *et al.*, 2014:513).

2.3.1 Respirable Dust

Inhalation of dust particles, especially those containing hazardous chemical constituents, can harm the lungs and airways (Habybabady *et al.*, 2018:76). RD refers specifically to the fraction of inhaled dust with an aerodynamic diameter under 10 µm and a median diameter of 4 µm (Stacey *et al.*, 2014:513). These fine particles can bypass the ciliated airways and reach the alveolar or

⁴ PM is particulate matter consisting of a mixture of different sized particles from different sources. PM_{2.5} is fine and ultrafine particles of 2.5 µm or smaller (Vanka *et al.*, 2022:2)

gas exchange region of the lungs, where they may accumulate and cause respiratory conditions such as COPD and pneumoconiosis (Barone *et al.*, 2021:134; Fan *et al.*, 2020:2).

The health effects of RD exposure can be disabling, with severe socio-economic implications, particularly for workers and their families who may face financial hardship due to occupational illness-related job losses (Ayaaba *et al.*, 2013:3; Fan *et al.*, 2020:2). In mining operations, RD exposure is prevalent and a significant concern in the South African mining industry where high levels of RD exposure have been linked to a high incidence of occupational diseases (Stanton *et al.*, 2006:60; Naidoo, 2013:1). To address these risks, it is essential for mining operations to implement effective exposure monitoring and dust control measures to protect the health of workers and reduce the burden of disease.

2.4 Monitoring of Exposure to Dust

Personal exposure sampling for dust began in the mid-20th century, mainly due to the need to protect workers in industrial settings. Exposure sampling measures the mass concentration of hazardous airborne contaminants in the workplace (Gorner *et al.*, 2001:43). Assessment of dust levels caused by mining operations is required to provide essential information when selecting and implementing control measures to reduce and manage the health risks associated with exposure to RD (Cauda & Patts, 2018).

Exposure sampling can be conducted using various methodologies, determined by the relevant standards for the airborne pollutant in question (Belle, 2018:305). The acceptance of gravimetric-based, size-selective sampling for determining workplace RD exposure concentrations initiated the development of personal dust sampling devices to monitor the air employees breathe. The personal gravimetric sampling train, hereafter referred to as conventional gravimetric sampling equipment, has gained acceptance since 1960 (Belle, 2018:307). Conventional gravimetric sampling has been considered a reliable tool for the measurement of personal exposure to airborne dust and is often referred to as the “golden standard” (Koehler & Peters, 2015:3/22).

During exposure sampling, sample collection media is placed within the work environment for a specified duration of time (Hashimoto *et al.*, 2018:104). A volume of air is drawn through a sampling head containing a filter by using a pump. The dust is captured by the filter. The collected dust is then weighed and analysed to assess exposure during the sample period (Hwang *et al.*, 2017:379). The mass of dust collected on the filter, along with the sampling duration and flow rate, is used to calculate the mass concentration (mg/m^3). This value is typically compared to the OEL to determine the presence of overexposures. Airborne exposure sampling can be done either by way of personal or static exposure sampling (HSE, 2019:6).

Static exposure sampling is when the position of the sampling head is fixed next to the workstation or contaminant source and provides a measurement of the general airborne particles present in the workplace. A limiting factor in static exposure sampling is that the concentration of airborne pollutants measured with a personal sampling head within the breathing zone⁵ of a worker is generally higher than those measured at a fixed location because localised or transient exposure events may occur as workers move through areas with varying contaminant concentrations. Consequently, static sampling can lead to underestimation of personal exposure. During personal exposure sampling, an air sample is collected within the worker's breathing zone by attaching the sampling head to the collar. This method ensures that the air captured, represents the air inhaled by the worker and is therefore the preferred approach to determine individual exposure (Cherrie, 2004:374; HSE, 2019:6). In contrast, static exposure sampling is more suited for evaluating the effectiveness of control measures than personal exposure (Cherrie, 2004:374). To compare worker exposure to the OELs as set out in Table 2-1, personal exposure sampling near the breathing zone is required. Personal exposure sampling results are compared with OELs, as they are accepted to be representative of human exposure and risk (Cherrie, 2003:183).

2.4.1 Conventional Exposure Sampling of Respirable Dust

When determining the respirable fraction of the airborne particles in personal exposure assessments, a size-selective device such as a cyclone is typically used as part of the sampling head. These cyclones follow ISO 7708:1995, *Air quality — Particle size fraction definitions for health-related sampling*, protocols on the respirable curve with a 50% sampling efficiency for particles with an aerodynamic diameter of 4 µm. Particle size-selective exposure sampling aims to capture particles with the potential to penetrate the lower respiratory tract. These respirable particles are small enough to pass beyond the bronchioles during inhalation, and can pose significant health risks (Brown *et al.*, 2013:1). Therefore, to assess exposure to RD accurately, sampling equipment capable of capturing the respirable fraction is essential (Mine Health and Safety Act 29 of 1996).

Collecting a sample of the respirable fraction of dust is generally conducted by attaching a cyclone to a filter cassette. The cyclone serves to separate larger particles that are not of concern from the respirable particles. As the sampling pump draws air through the cyclone and filter, the cyclone creates a centrifugal force. This cyclonic action causes larger particles to descend into a

⁵ Breathing zone in terms of personal exposure sampling is defined as a 30 cm radius extending in front of the human face (ISO 16258-1:2015 Workplace air — Analysis of respirable crystalline silica by X-ray diffraction Part 1: Direct-on-filter method).

grit pot while the filter inside the cassette traps smaller, respirable-sized particles (Kenny *et al.*, 2001:38). Figure 2-1 illustrates an example of a conventional gravimetric sampling train.

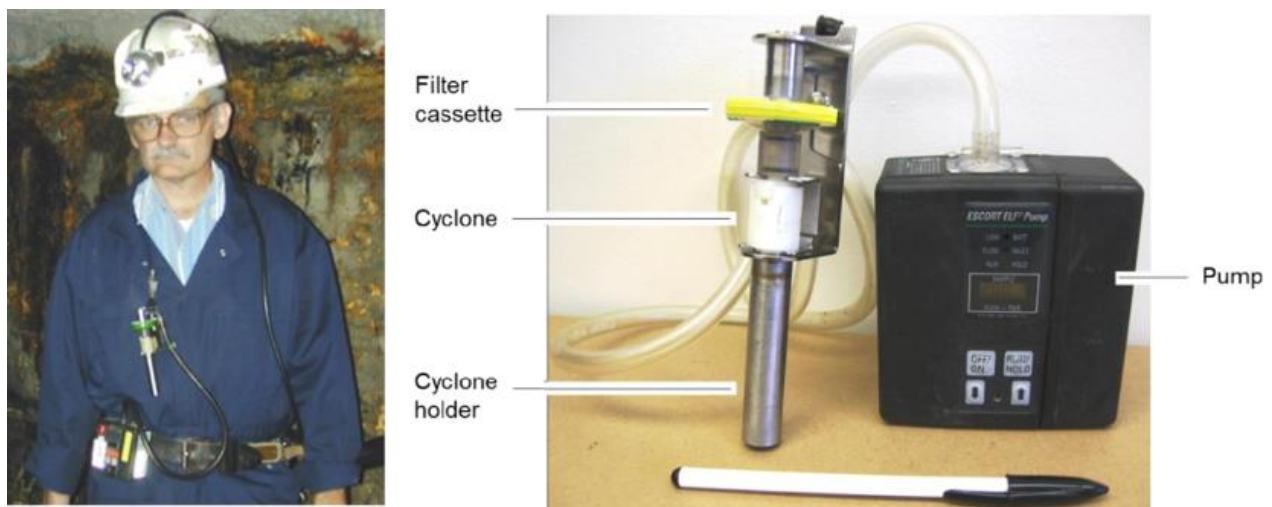


Figure 2-1 Conventional gravimetric exposure sampling train (NIOSH, 2021:23)

The two main cyclone design styles are Higgins and Dewell (HD) or Dorr-Oliver (DO), are manufactured from different materials, including stainless steel, conductive nylon, or aluminium. Selecting the appropriate cyclone for the particles being sampled is essential for accurate results (Colinet, 2010:4). A cyclone must meet the requirements of ISO 7708:1995 to ensure the validity of the results. If a cyclone does not meet the required standard, the results obtained may either underestimate or overestimate RD exposure (Belle, 2018:306). Each cyclone is designed to operate at a specific flow rate to collect particles according to a specific size range.

Following sampling, the dust collected can be quantitatively and qualitatively analysed by an analytical laboratory. Methods generally used are MDHS14/4⁶ conventional gravimetric analysis (Lee *et al.*, 2017:698). Examples of commercially available cyclones for size-selective sampling include the Mesa Labs Dorr-Oliver (DO) Cyclone (Mesa Laboratories Inc., Lakewood, CO, USA), Casella Higgins-Dewell (HD) Cyclone (Casella Ltd., Kempston, Bedford, UK), SKC Aluminium Cyclone (SKC Inc., Eighty Four, PA, USA) and SKC Dorr-Oliver (DO) Cyclone (SKC Inc., Eighty Four, PA, USA).

One pertinent challenge of controlling dust exposure in mining is the inability to obtain exposure results quickly. A known limitation of the conventional gravimetric method is the lag of several

⁶ MDHS14/4: General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols

days before results from the laboratory analyses are available, delaying necessary actions to address overexposures (Harper, 2020:6). Additionally, conventional gravimetric exposure sampling only provides a single data point per sampling session and filter (Kenny *et al.*, 2001:40), making it difficult to assess exposure conditions promptly (Kim *et al.*, 2004:708).

Conventional gravimetric exposure sampling was primarily developed for regulatory compliance monitoring rather than transient worker exposure assessments. As a result, it is impractical for determining short-term, high-concentration RD exposures, especially in industries where silica content is of concern. Gravimetric analysis has detection limits, and a sample collected over a short period (in terms of minutes) may not accumulate sufficient particle mass on the sample filter to analyse (Rasmussen *et al.*, 2019:2). Non-routine investigations often require exposure samples collected over short periods. For this purpose, equipment capable of accurately capturing high-concentration exposures with temporal variations is essential to enable prompt hazard identification and mitigation.

This challenge becomes even more pronounced in mining environments, where conditions are constantly changing. Local geology can vary significantly across different areas of a mine affecting the constituents of respirable dust (Volkwein *et al.*, 2004:2). For instance, as mining advances and the rock face being mined changes, the concentration of RCS may also change. According to Patts *et al.* (2020), estimating daily personal exposure to RD containing RCS is particularly difficult due to variability in tasks, dust composition, and environmental conditions across different working areas. These dynamic changes underscore the limitations of conventional gravimetric methods and highlight the need for advanced, real-time monitoring technologies capable of addressing these challenges.

Ongoing initiatives to improve the accuracy of exposure assessments encouraged the development of new sampling equipment and strategies, such as real-time dust monitors (Wang, *et al.*, 2016:1110). Personal, wearable, real-time dust monitors may be the solution to the constraints of conventional gravimetric exposure sampling methods and equipment (Volkwein *et al.*, 2004:6).

2.4.2 Real-Time Exposure Sampling of Respirable Dust

Real-time sampling refers to the use of instruments that measure, process and display measurement information as the RD is sampled, providing results continuously or at the end of the shift. These sampling instruments typically provide configurable functions such as data logging and alarm settings. With a real-time dust monitor, data is logged at pre-set intervals during exposure sampling, resulting in several data points recorded throughout the sampling session.

Real-time sampling instruments can serve as screening tools or examine the variability of peak exposures during a shift as they provide logged data at various intervals throughout the workday. One key advantage of instantaneous measurements of airborne dust concentrations is a reduction in the time and effort associated with conventional gravimetric methods (Thorpe, 2006:98).

Additionally, real-time monitoring allows for the identification of peak exposure trends, enhancing prompt implementation of corrective actions (Lemke, 2021:10). Time-stamped and logged data, when combined with visual observations, can help indicate when peak exposures occur (Siegel *et al.*, 2019:3).

The suitability of real-time sampling instruments to assess RD exposure within real work environments is evaluated by comparing them to conventional exposure sampling equipment (Gussman *et al.*, 2002:4). While several real-time monitors are available, this study focuses on the Nanozen DustCount® 9000-Z1 (DustCount) personal real-time monitor (Nanozen Industries Inc., Vancouver, Canada), which may offer greater sensitivity than other available monitors, as it features a detection range of 1 µg/m³ to 21.5 mg/m³ (Rasmussen *et al.*, 2019:13).

2.4.3 The Nanozen DustCount

The DustCount is a wearable, real-time (direct reading) particle exposure monitor designed to determine the concentration of hazardous aerosols in the workplace, including silica, wildfire smoke, airborne active pharmaceuticals, and mining particulates associated with the mining of coal, iron, copper, diamonds, and lead. The DustCount can also be used for area exposure sampling. Weighing approximately 500 g, the device is available in intrinsically safe (IS) and non-IS versions. It combines the advantages of real-time dust monitoring with a built-in filter cassette, enabling subsequent sample composition analysis (Nanozen Industries Inc., 2020). An example of the DustCount can be seen in Figure 2-2.

The DustCount offers USB and Bluetooth connectivity, making it easy to download data. It supports interchangeable impactors for PM_{2.5}, PM₄, and PM₁₀ and is designed to operate with a size-separating impactor at a flow rate of 1 Litre per minute (LPM). In addition, the static air tube inlet can be attached to the collar of an employee, similar to conventional personal exposure sampling methods (Nanozen, 2021). As such, the positioning of the DustCount inlet aligns with typical occupational hygiene practices and is consistent with the equipment commonly used for conventional gravimetric exposure sampling (Mischler *et al.*, 2019:3).

The DustCount uses laser-based optical particle detection with time-of-flight features to determine the size and concentration of aerosol particles. The impactors separate particles based on their

aerodynamic size before the particles enter the monitoring system. Larger particles are separated by inertia and do not pass around the impactor, while smaller respirable particles (PM₄ or PM_{2.5}) pass around and are measured by die optical sensors inside the device's sampling chamber (Marple, 2004).

The device also allows for post-sampling chemical analysis, as air passes through the sampling chamber and deposits particles on a filter (Dalton, 2022:243). It detects and counts particles, displaying their mass concentration in $\mu\text{g}/\text{m}^3$ and provides real-time information on mass concentration distributions over the PM_{2.5}, PM₄, and PM₁₀ fractions of the particle size range (Rasmussen *et al.*, 2019:13). The DustCount can possibly address a known limitation of other real-time exposure sampling systems such as the TSI DustTrak, Thermo Fisher or Sensidyne monitors, in that the DustCount is lightweight. The DustCount is well-suited for environments that require continuous exposure monitoring on the move. In contrast, the other real-time exposure sampling equipment is typically bulkier and better suited for stationary or industrial environments the sensitivity range.



Figure 2-2 Nanozen DustCount® 9000-Z1 (Nanozen Industries Inc., 2020)

The following is an overview of the principle of operation of optical particle counters (OPCs), the technology used in the DustCount. Figure 2-3 also gives an illustration of the operation of an OPC.

A laser-based detection system with a sampling chamber is built into the device; a pump draws sampled air containing particles through this chamber, and as particles penetrate the laser beam the optical sensor captures some of the scattered light emitted by the laser-illuminated particles passing through the chamber. The signal received from the photodetector translates each dispersed light pulse to its appropriate size category. The intensity of the scattered light assists in the size determination of the particles based on the pulse height and then stores this information in the data logger. The number of particles passing through the device's sampling chamber is then counted and grouped into size ranges as each dispersed pulse correlates to a particle count (Chen *et al.*, 2024:3; Santi *et al.*, 2010:970). An OPC enables the determination of particle counts based on particle sizes. Typically, particles with diameters greater than 0.05 μm can be quantified, while particles as small as 2 nm can be detected (Chen *et al.*, 2024:3). The DustCount's alarm settings and data logging capabilities can play a critical role in monitoring peak exposures. The threshold alerts can help immediately trigger corrective actions to protect workers when dust concentrations exceed user-defined limits. These real-time alerts and continuous data logging features provide information that can be essential for identifying trends, evaluating risks, and implementing improvements in workplace environments, to mitigate exposure.

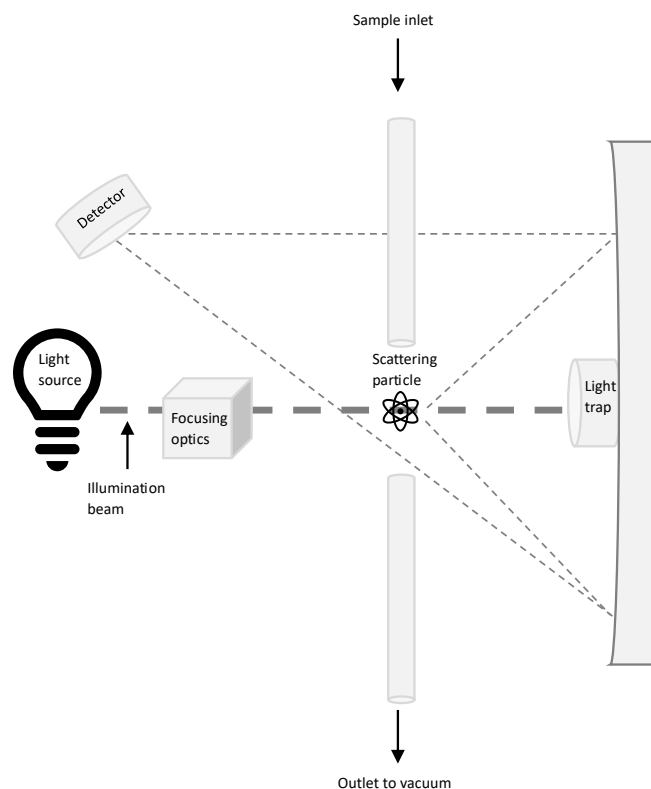


Figure 2-3: An overview of the operation of OPC (Adapted from Welker, 2012:183)

In the DustCount, these 20 size ranges are called particle size bins (0.5 µm to 10 µm). The unit provides for single particle size selection and mass conversion using these 20-particle size bins and has a detection range of 1 µg/m³ to 21.50 mg/m³ (Rasmussen *et al.*, 2019:13). Mass concentration is estimated using pre-calibrated algorithms which recognise the pulse as a particle when the pulse height exceeds a specific threshold voltage, resulting in the measured number of particles and their sizes (Sachweh *et al.*, 1998). This is done by assuming the density and shape of particles typical to the type of dust sampled.

The DustCount calculates the volume of each particle based on size and then multiplies this with the assumed density to determine the mass of each particle. The total mass of all particles in the sampled air is added up and divided by the volume of air sampled over time to determine the mass concentration (Bezantakos *et al.*, 2020:362). For accurate mass concentration results, the DustCount needs to be calibrated to the specific type of dust being sampled to ensure that the particle size to mass conversion is accurate as it is based on typical characteristics of specific dust types. For this, a reference sample from an accepted method, such as the conventional gravimetric sampling method, is required.

Generally, the DustCount is calibrated with ultrafine⁷ Arizona road dust (ARD), meaning variation in ore dust compared to the dust the device was calibrated with, can lead to inaccurate results (Huang *et al.*, 2022:2).

Real-time monitoring devices use light scattering or OPC principles to measure the concentration of airborne particles by detecting the amount of light scattered by the particles. Different types of dust particles have varying densities and specific gravity, which can impact the accuracy of exposure measurement devices. Particles with higher densities will have greater masses for a given volume. The light scattering responses of real-time exposure measurement devices can be influenced by the size, shape and optical properties of the particles sampled, as they are typically calibrated for a specific particle size range (Vosburgh, *et al.*, 2022:5). Dust types outside this calibration range may lead to inaccurate readings, either overestimating or underestimating exposure concentrations. Table 2-2 lists some types of dust commonly found in the South African Mining Industry.

⁷ Ultrafine refers to very small PM, typically less than 100 nm in size (Traboulsi *et al.*, 2017:1).

For instance, a denser dust particle, such as gold ore dust with a density of 2.7–3.0 g/m³, will weigh more than less dense dust, such as ultrafine ARD, which has a density of 2.65 g/m³, when measured at the same volume. Since the DustCount measures concentration based on the number of particles per unit volume of air, rather than their mass, the density differences between the dust types may affect measurement accuracy (Wang, *et al.*, 2016:1110).

Table 2-2: Specific gravity and density of common ore dust

The chemical component of ore	Specific gravity and density range (g/cm³)
Coal Dust (Roux, 2021:233)	1.1–1.8
Silica Dust (Quartz) (Chubb & Cauda, 2017:17)	2.65
Gold Ore Dust (Surimbayev, <i>et al.</i> 2024)	2.7–3.0
Chromite Ore Dust (Millspaugh <i>et al.</i> 2018)	4.1–4.7
Iron Ore Dust (He <i>et al.</i> 2019)	2.4–3.0
Copper Ore Dust (Franks <i>et al.</i> 2013:12)	2.5–3.5
Arizona Road Dust (ISO, 2016)	2.65

2.5 Performance Evaluation of Sampling Methods and Equipment

Real-time devices for exposure sampling have been studied and tested for several years (Vosburgh, *et al.*, 2022:2). Previous studies about the testing of real-time exposure sampling devices had observations and recommendations as summarised in Table 2-3. This section is limited to studies investigating the use of real-time devices for sampling inhalable and respirable fractions of airborne dust and how the results of the real-time devices compare to conventional gravimetric methods.

Table 2-3: Summary of previous studies that compared real-time and conventional methods for measuring RD and PM across different devices

Scope of study	Real-time exposure sampling equipment evaluated in the study	Conventional Gravimetric/Reference exposure sampling equipment included in the study	Conclusions/Main findings
Comparison of Portable, Real-Time Dust Monitors Sampling Actively, with Size-Selective Adaptors, and Passively. Thorpe & Walsh, (2007).			
To assess the performance of three real-time, portable dust monitors to measure industrial dust concentrations under controlled conditions within a dust chamber	<ul style="list-style-type: none"> Split 2 (SKC Ltd), Microdust Pro (Casella Ltd), and DataRAMm (Thermo Electron Ltd) 	<ul style="list-style-type: none"> Casella Higgins–Dewell cyclone for RD fraction IOM sampler for inhalable dust fraction 	<ul style="list-style-type: none"> The Microdust Pro with the Higgins–Dewell cyclone adaptor was the most accurate across all dust types for measuring respirable dust concentrations, showing close agreement with the reference respirable concentrations The Split 2 with the GS-3 cyclone and DataRAM with the GK 2.05 cyclone adaptors showed differences from the reference concentrations, indicating slightly lower accuracy for these setups in measuring respirable dust The dust monitor responses were sensitive to changes in particle size
Comparison of the TSI Model 8520 and Grimm Series 1.108 Portable Aerosol Instruments Used to Monitor Particulate Matter in an Iron Foundry. Cheng (2008)			
To assess the performance of two real-time dust monitors in an iron foundry	<ul style="list-style-type: none"> TSI Model 8520 DustTrak Grimm Series 1.108 Aerosol Spectrometer 	<ul style="list-style-type: none"> The SA Model 241 Dichotomous Sampler was used as a reference 	<ul style="list-style-type: none"> The DustTrak results were higher than that of the Aerosol Spectrometer The DustTrak overestimated the PM levels, and the Aerosol Spectrometer underestimated the dust concentrations
Emissions and Exposures Associated with the Use of an Inconel Powder during Directed Energy Deposition Additive Manufacturing. Van Ree, <i>et al.</i>, (2023)			
Used a real-time monitor to investigate personal exposure and measure real-time particle number concentration of additive manufacturing operators	<ul style="list-style-type: none"> Nanozen DustCount® 9000-Z1 real-time monitoring device 	<ul style="list-style-type: none"> P-Trak® Ultrafine Particle Counter (TSI Inc., Minnesota, USA) Grimm Aerosol Technik Dust Monitor Sampler (Grimm Aerosol Technik GmbH, Ainring, Germany) 	<ul style="list-style-type: none"> The personal exposure particle number concentration peaks measured by the Nanozen DustCount® 9000-Z1 were, on average, lower than the results provided by the P-Trak and Grimm Dust Monitor which were used for area monitoring, but the concentration peaks were similar
Using the DustCount 9000 real-time dust monitor to assess personal respirable dust exposures at a mine in Namibia. Lemke (2021)			
Assess personal exposure using a real-time monitor side-by-side with conventional gravimetric exposure sampling equipment	<ul style="list-style-type: none"> Nanozen DustCount® 9000-Z1 real-time monitoring device 	<ul style="list-style-type: none"> Gillian GillAir personal sampling pumps with GX1 cyclone (Envirocon Model) 	<ul style="list-style-type: none"> Nanozen DustCount® 9000-Z1 real-time monitoring device underestimated exposure concentrations when compared to the conventional gravimetric results

(Table continues on next page)

Scope of study	Real-time exposure sampling equipment evaluated in the study	Conventional Gravimetric/Reference exposure sampling equipment included in the study	Conclusions/Main findings
Performance Evaluation of Real-time DustTrak Monitors for Outdoor Particulate Mass Measurements in a Desert Environment. Javed & Guo, (2021)			
Compare the performance of real-time monitors to conventional gravimetric sampling equipment	<ul style="list-style-type: none"> • TSI DustTrak DRX® aerosol monitor 	<ul style="list-style-type: none"> • Low-volume Harvard Impactor samplers with polyurethane foam impaction substrates 	<ul style="list-style-type: none"> • The results of the DustTrak significantly deviated from the reference method • The DustTrak overestimated the fine PM and underestimated the coarse PM
Comparison of real-time instruments and gravimetric method when measuring particulate matter in a residential building. Wang, <i>et al.</i>, (2016)			
Assess real-time instruments against conventional gravimetric equipment to measure PM _{2.5} levels	<ul style="list-style-type: none"> • Aerotrak Optical Particle Counter (OPC) (model 8220. TSI, Inc., Shoreview, MN) • DustTrak DRX mass monitor (model 8534, TSI, Inc., Shoreview, MN) 	<ul style="list-style-type: none"> • Personal Modular Impactor (PMI); (PMI_{2.5}; SKC, Inc., Eighty Four, PA) and AirChek XR5000 Pump (SKC, Inc.) • DataRAM pDR-1500 (Thermo Scientific, Franklin, MA) nephelometric monitor with a cyclone 	<ul style="list-style-type: none"> • The real-time monitors had systematic and proportional biases that were significant when compared to the results of the reference sampling equipment • The study suggested the use of correction factors to improve accuracy

Table 2-4 provides a critical evaluation of the DustCount in terms of available published literature relevant to this study:

Table 2-4 Critical evaluation of the DustCount

<p>Key components of published research studies</p>	<p>Using the DustCount 9000 real-time dust monitor to assess personal respirable dust exposures at a mine in Namibia.</p> <p>Lemke (2021)</p>	<p>Emissions and Exposures Associated with the Use of an Inconel Powder during Directed Energy Deposition Additive Manufacturing.</p> <p>Van Ree, et al., (2023)</p>
<p>Objectives and Scope:</p>	<p>The study aimed to compare respirable dust (RD) levels measured by the DustCount alongside conventional gravimetric sampling equipment in an open-cast mining environment. It sought to assess whether DustCount could serve as an early warning tool for excessive dust exposure and enable the implementation of control measures. The study's scope is broad, focusing on real-world mining applications and not a controlled experimental setting.</p>	<p>The study aimed to investigate emissions and worker exposure during Directed Energy Deposition (DED) additive manufacturing using Inconel powder. Its specific objectives included characterising Inconel powder particles, assessing particle number concentrations and emission rates in the work area, and establishing personal respiratory exposure to harmful metals for AM operators in a South African research facility. The study was conducted in a controlled laboratory-like setting, limiting its applicability to real-world industrial environments.</p>
<p>Methodology:</p>	<p>DustCount devices were calibrated using a generalized gravimetric correction coefficient (GMCC). However, the study noted that the blending of dust samples may not have been the optimal approach, as it does not account for variations in dust characteristics and mineralogy. The study recognized the need for more representative dust samples to calculate accurate GMCC values.</p>	<p>To quantify the personal exposure, the two AM operators wore two samplers for each AM process. Namely an Institute of Occupational Medicine (IOM) multi-dust sampler for collecting gravimetric data and metal concentration analysis and a Nanozen DustCount® model 9000-Z1 for real-time particle number concentration monitoring (PM10 range: 0.3–20.8µm). Sampling followed established Health and Safety Executive (HSE) methods.</p>
<p>Results:</p>	<p>The DustCount device consistently reported significantly lower dust concentrations in real-time measurements compared to gravimetric methods (on average, half the gravimetric results). This discrepancy raises concerns about the reliability of DustCount for accurately reflecting worker exposure levels. Although no overexposures were detected based on established occupational exposure limits (OELs), the study emphasized that DustCount's inaccuracy could undermine its effectiveness as a monitoring tool, especially given the severe health risks associated with respirable dust exposure.</p>	<p>Personal exposure monitoring with DustCount reported particle concentrations (~102 p/cm³) lower on average than area monitoring tools (e.g., Grimm and P-Trak). This difference highlights a potential discrepancy in DustCount's real-time measurements, which may underestimate exposure levels.</p>
<p>Exposure Assessment:</p>	<p>Worker exposure metrics were based on typical work durations. While the study discussed the health implications of DustCount's underreporting, it did not delve into particle size distribution or variability in emissions under different environmental conditions (e.g., humidity, and temperature).</p>	<p>Worker exposure was evaluated based on typical work durations, focusing on harmful metal content in the respirable dust. While the study addressed the health implications of exposure, it did not assess particle size distribution or variability in emission factors under environmental conditions such as humidity or temperature.</p>

Key components of published research studies	Using the DustCount 9000 real-time dust monitor to assess personal respirable dust exposures at a mine in Namibia. Lemke (2021)	Emissions and Exposures Associated with the Use of an Inconel Powder during Directed Energy Deposition Additive Manufacturing. Van Ree, <i>et al.</i>, (2023)
Critical Reflection:	<p>The study highlighted limitations such as the influence of weather conditions on results, limited data set size, and inadequacies in GMCC evaluation. Recommendations included using fallout dust samples to determine site-specific GMCC values, building a dust mineral library, and using aluminium cyclones with conductive cassettes. While the study's findings were context-specific, the recommendations could be applied to other industrial settings, enhancing DustCount's reliability.</p>	<p>A key limitation was the study's time constraints, which restricted the scope to exposure monitoring. Additionally, the controlled laboratory setting does not fully replicate industrial conditions, which limits generalizability to broader manufacturing environments. The study was not aimed at a comprehensive evaluation of the DustCount device's performance. Nevertheless, it contributes valuable exposure data specific to the specialized additive manufacturing industry.</p>

Literature indicates that the accuracy of real-time exposure monitoring devices decreases when the size, shape or composition of the dust being measured, differs from that used to calibrate the device. Most of the real-time monitors exhibited significant proportional and systematic biases when the results were compared to the reference conventional gravimetric sampling methods. The DustCount underestimated personal exposure concentrations relative to conventional gravimetric sampling methods but showed similar concentration peaks for area monitoring.

For the remainder of this study, the following terms will be used: 'CGC' will be used to refer to the conventional gravimetric sampling method equipment and results, and 'DRC' will be used to refer to the DustCount real-time sampling equipment and results.

2.6 Statistical Analysis Techniques for Comparatively Evaluating Exposure Sampling Methods

The statistical analysis technique used to compare two or more exposure sampling methods depends on the nature of the data and what the statistical evaluation is intended to investigate (Kim, et al., 2017:174). It is imperative to apply the correct statistical tests to ensure that results and conclusions are valid and reliable (Ali & Bhaskar, 2016; 668).

In this study, the primary objective was to investigate the concordance between the two exposure sampling methods, as the aim was to determine to what extent the two methods agree when used to measure the same variable (Ranganathan, *et al.*, 2017:190).

Correlation and agreement cannot be used interchangeably. Correlation analyses assess whether a relationship exists between two measurements of the same variable, while agreement measures evaluate the concordance between the results from two methods (Ranganathan, *et al.*, 2017:187). Since both methods aim to quantify the same variable, a high correlation is expected. However, a high or strong level of correlation does not imply that the values from the different methods agree (Giavarina, 2015:141). Correlation analysis is often misinterpreted as evidence of interchangeability between methods, even when there is poor agreement (Mansournia et al., 2021:1).

Although correlation analysis can effectively measure the strength and direction of the relationship, it does not assess differences and is therefore insufficient for comparing the performance of the two methods. Instead, it only indicates how closely two variables are related to each other (Doğan, 2018:139). Correlation and regression can assess relationships between variables but do not account for the differences, making them unsuitable statistical methods for evaluating the comparability of results (Giavarina, 2015:142).

Descriptive statistical methods that are appropriate to use and that were applied are listed below in Table 2-5 (Mishra, *et al.*, 2019:298).

Table 2-5 Statistical analysis methods identified for quantitative analysis

Statistical Method	Description of analysis and parameter(s) tested
Clustered column chart (Evergreen, 2019:3-1)	The columns are visual representations of the different data values. They help to indicate how different groups of data relate to one another and identify trends across categories.
Bland-Altman (BA) plots (Mansournia <i>et al.</i> , 2021; Kaur & Stoltzfus, 2017)	BA plots are an effective method for comparing the agreement between two measurement methods. They assess the overall level of agreement between the results of two exposure sampling methods and highlight any differences between them. The level of agreement will be assessed by using BA plots.
Outlier testing (Motulsky & Brown, 2006:2)	An outlier is a data point that is far from the other results in a dataset. Just because a value might seem like an outlier does not mean it should be excluded, as this can impact the accuracy of the dataset. For this reason, outlier testing can be performed, a statistical approach that will provide the researcher with results to make an informed decision as to whether a data point should be regarded as an outlier and excluded or not.
Robust outlier detection test (ROUT) outlier testing (Solzin <i>et al.</i> , 2020:1461).	The ROUT outlier test can identify multiple possible outliers in a dataset.
Grubbs outlier testing (Adikaram, <i>et al.</i> , 2015).	Grubbs or maximum normed residual test is a statistical test that can be used to identify outliers in a univariate dataset.
Tukey schematic box-plots (Dawson, 2017:3)	Tukey Schematic Box-plots can be used as an informal investigation to identify outliers in the dataset. It is to be approached with caution, particularly when the dataset is not normally distributed, as it can incorrectly flag an observation as an outlier.
Descriptive statistics (Nick, 2008)	Descriptive statistics is a succinct statistical approach used to present a dataset visually and summarise its characteristics. It provides a clear display of results, including measures such as minimum, maximum, mean, median, standard deviation, and interquartile range, calculated for all variables. This method is used to estimate and describe the central tendency, variability, and overall distribution of a dataset.
Distribution (Altman, 1995)	Distribution refers to the pattern or arrangement of data points in a dataset. It describes how values are spread across the range of possible outcomes. Data can follow a normal distribution, where values are symmetrically distributed around the mean, or a non-normal distribution, which includes skewed, or other irregular patterns.
Comparison of means (MacFarland & Yates, 2016)	The Mann-Whitney U test is a non-parametric test used to determine whether there are statistically significant differences between the distributions of two independent groups. It assesses whether one group tends to have higher or lower values than the other, without assuming a normal distribution.

2.7 Conclusion

Workers exposed to dust containing hazardous particles, such as RCS, are at risk of developing debilitating and irreversible diseases. Legislation requires employers to assess this risk through exposure monitoring and use the data to implement appropriate control measures. Conventional gravimetric exposure sampling is the standard method for determining worker exposure to hazardous particles in work areas, but real-time technology may offer more detailed and timely information. To effectively use real-time devices, such as the DustCount, it is essential to validate their accuracy. This is evaluated by comparing the results obtained from the real-time device with those from conventional gravimetric exposure sampling methods and equipment.

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CHAPTER 3 ARTICLE

Guidelines for authors

The author followed the instructions and guidelines of the Journal of Occupational and Environmental Hygiene (JOEH) in Chapter 3, with the exception of the placement of figures and tables. While JOEH guidelines require figures to be placed after the references section, for the purpose of improving readability and interpretation, figures and tables in Chapter 3 have been included within the text. After examination of the dissertation, these placements will be adjusted to align with the criteria of the journal before submission for review to the journal.

The Journal of Occupational and Environmental Hygiene (JOEH) provides specific guidelines for authors, detailing requirements for formatting and ethical considerations prior to submission for approval.

Formatting: Submission documents are to be structured with an abstract, introduction, methodology, results, and discussion sections. The specified font is 12-point Times New Roman, with double spacing. References follows the Council of Science Editors (CSE) style, typically aligned with scientific standards for occupational hygiene publications.

Ethical standards: Authors must ensure the research adheres to ethical guidelines and is approved by an ethical review board.

(Title page)

Performance comparison of the Nanozen DustCount personal real-time monitor with a conventional respirable dust exposure sampling method.

Keywords:

Airborne, Direct-reading, Gravimetric, Mining, Risk Assessment, Size-selective

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V Wagner; CJ Van Der Merwe; SJL Linde

Occupational Hygiene and Health Research Initiative (OHHRI), North-West University,
Potchefstroom Campus, South Africa

Corresponding Authors: Mr CJ Van Der Merwe

Occupational Hygiene and Health Research Initiative (OHHRI)

North-West University, Potchefstroom Campus

Private Bag X6001

Potchefstroom

2520

South Africa

Tel: 018 299 2079

Email: corne.vandermerwe@nwu.ac.za

3.1 Abstract

The mining industry, crucial to economies like South Africa's, poses significant health risks due to exposure to dust which can vary in composition and particle size. Since 1911, safeguarding workers' health has been a priority, with legislation enforcing exposure monitoring and control measures. Advancements in technology and the development of direct reading instruments, such as the Nanozen DustCount® 9000-Z1 (DustCount), provide faster, real-time dust exposure results.

This study evaluated the DustCount's performance against conventional gravimetric sampling using quantitative analyses of secondary data. A dataset of 35 paired results collected through side-by-side monitoring, performed by a consultancy company, was analysed. The study compared the DustCount's real-time respirable dust concentration measurements with gravimetric exposure data obtained following Methods for the Determination of Hazardous Substances (MDHS14/4). Additionally, the DustCount's filters were gravimetrically analysed to contrast its impactor-based gravimetrically analysed results, with its optical particle counter technology results.

The geometric mean of the conventional gravimetric sampling (CGC) dataset was 0.416 mg/m³, with a coefficient of variance (CV) of 175%. In contrast, the DustCount (DRC) real-time dataset had a lower geometric mean of 0.172 mg/m³ and a lower CV of 111%. Across all samples, the CGC method consistently reported higher respirable dust concentrations than the DRC method.

Bland-Altman (BA) analysis confirmed that the DustCount underestimated respirable dust concentrations, with a mean bias of -71.41% (SD 35.17%) and a 95% limit of agreement ranging from -166.6% to 11.84%. This significant underestimation highlights a key limitation of the DustCount to precisely quantify exposure.

Qualitative considerations showed that while conventional gravimetric sampling is more affordable and robust, it takes longer to produce results and is less user-friendly. The DustCount, although more expensive, provides faster results and are easier to use. An improvement in the ease of calibration of the device and easier access to correction factors could enhance the accuracy of its real-time measurements. The DustCount can facilitate exposure investigations by logging peaks and linking exposure excursions to specific activities, as shown in Figure 3-7, for example, increased dust exposure peaks were logged at around 09:00 by a DustCount unit sampling unit worn by an employee working in the primary crusher area.

Despite the above limitations, the findings suggest that the DustCount has potential value as a real-time monitoring tool, particularly when used to complement conventional methods. Its real-time capabilities could facilitate immediate interventions and enhance workplace safety by providing near-instantaneous feedback, though it cannot be relied upon as a standalone tool for compliance purposes. While measuring RD concentrations, the DustCount identified activities with peak exposure periods which, if representative of the entire shift duration, would result in an 8-hour time-weighted average (TWA) exposure exceeding the occupational exposure limit, indicating its potential value in investigative processes.

3.2 Introduction

Mining industries are often the cornerstone of economies, this is particularly true with regards to South Africa (Moraka and Jansen van Rensburg 2015,669). The mining industry, however, goes hand-in-hand with a significant risk of adverse health effects resulting from dust exposure (Stewart 2020,1153). Mining operations generate dust particles of varying sizes and chemical composition, which significantly influence the health risks associated with exposure (Kakooei et al. 2011,122). In South Africa efforts to safeguard worker health began as early as 1911, with the

introduction of legislation mandating exposure monitoring and mitigation control (Donsky 1993,190; NASEM 2018,10).

To ensure the accuracy of the information obtained, exposure monitoring should be conducted with equipment and methods adhering to legislated requirements (Semple 2005, 421).

Conventional gravimetric sampling has long been the accepted method for monitoring workers' exposure to inhalable and respirable dust (Belle 2018, 305). Exposure monitoring involves sampling equipment, typically a pump connected to a sampling head fitted with a filter, positioned in the breathing zone of a worker. The equipment is worn throughout the shift, after which the filter is gravimetrically analysed to determine the level of exposure. The results are then compared to legislated exposure limits to assess compliance and the potential for adverse health effects (Martinelli et al. 2020,4).

The primary limitation of this method is the slow turnaround time from sampling to obtaining results, which can take several days, limiting the timely intervention of control measures (Harper 2020,6). Recent advances in real-time monitoring technologies, such as the DustCount personal real-time monitor (Nanozen Industries Inc., Vancouver, Canada), offer the potential for faster exposure monitoring results (Wang et al. 2016,1110). The DustCount uses optical particle counting (OPC) technology and has a built-in filter cassette, enabling subsequent sample composition analysis (Nanozen Industries Inc. 2020). The DustCount has configurable functions such as data logging and alarm settings. Data is logged at pre-set intervals during exposure sampling, resulting in several data points being recorded throughout the sampling session. It is, however, necessary to evaluate the accuracy of these devices by assessing them against the

approved standard conventional gravimetric methods and equipment, such as MDHS14/4⁸ conventional gravimetric analysis (Kuula et al. 2019).

Calibration of real-time dust monitors is essential to ensure accurate and reliable measurement of airborne particulate matter (PM) (Santi et al. 2010:969). This process involves comparing the real-time monitor's measurements to those of a reference-grade instrument or the gravimetric method, the standard for accuracy in exposure assessment (ICMM 2022,4). When discrepancies are identified, correction factors are applied through software adjustments either to correct the monitor's readings or to adjust the collected real-time data. Factors such as wear, contamination, or environmental conditions can cause sensor deviations over time, making periodic re-calibration necessary to maintain consistent accuracy (Thorpe 2007,107).

This study evaluates the performance of the DustCount (Nanozen Industries Inc. Vancouver, Canada) against the MDHS14/4 conventional gravimetric sampling method to determine the accuracy and reliability of the DustCount. Secondary data was used in this study as the actual exposure monitoring was conducted by a contracted company at an opencast iron ore mine in 2020, and the research team analysed this data. The objectives of this study are the comparison of the two different types of monitoring equipment through evaluating (1) real-time DustCount respirable dust (RD) exposure concentration results compared to conventional MDHS14/4 gravimetric method results, (2) gravimetric analysis results of the DustCount filters against the MDHS14/4 conventional gravimetric equipment, and (3) real-time DustCount respirable dust (RD) exposure concentration results compared to gravimetric analysis results of DustCount filters.

⁸ MDHS14/4: General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols

3.3 Method

This section provides details on how the contracted company collected the data and how the researcher used this data to assess the accuracy of the DustCount against the conventional sampling gravimetric method. The research protocols of several previous studies in the literature were reviewed and adapted to be used in this study.

For this study, the method was applied to secondary data previously collected by a consulting company at an open cast iron ore mine in South Africa for compliance purposes. Figure 3-1 below is a visual overview of the methodology applied to the secondary data in this study.

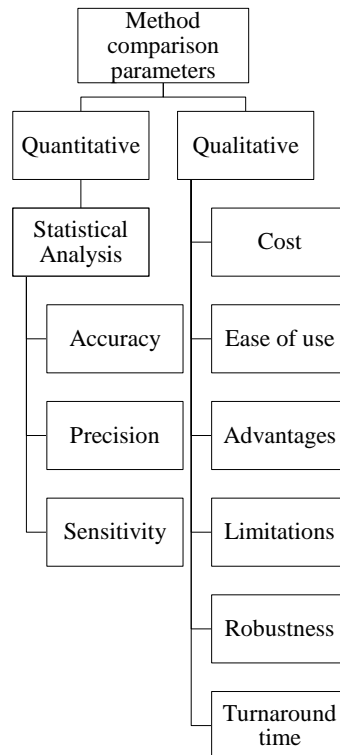


Figure 3-1 Comparison parameters that were considered when comparing the results of the DustCount real-time exposure monitoring equipment to the conventional gravimetric method

3.3.1 Data Gathering

This study used secondary data which was collected in 2020 by an Occupational Hygiene consultancy company contracted by an open cast iron ore mine in South Africa. The purpose of

exposure sampling conducted by this company was to determine whether exposure concentrations were compliant with the legislated exposure concentration limits as set out in the Mine Health and Safety Act 29 of 1996 (MHS Act). This section describes the steps followed by the contracted company to collect the data, and section 3.3.2 (page 55) elaborates on the steps taken in this study to process the data. Exposure sampling was conducted during October and November 2020 at an open-cast iron ore mine in the Northern Cape, South Africa. This period coincided with the summer season, characterized by high ambient temperatures and occasional rainfall. The mining processes and the movement of heavy vehicles transporting ore, generated significant amounts of fine dust, resulting in high levels of airborne dust in the area.

Based on historical RD exposure levels, specific areas of the opencast iron ore mine were selected to collect respirable dust (RD) exposure samples from (see Phase 1 in Figure 3-2). The different measurement locations at the mine included the primary crusher, tertiary crusher and the dense metal separating plant. The sampling programme included workers from various mining activities and occupations in these areas. Participation in the sampling programme was part of workers' and employers' conformance with their legislated duties. In terms of Chapter 2, Section 22 of the MHS Act (1996), it is the duty of employees to "(e) cooperate with any person to permit compliance with the duties and (f) comply with the health and safety measures implemented by the employer". In addition, the sampling procedure was explained to the workers in the presence of their supervisors, and the workers signed informed consent on the field sheets according to the mine's internal procedures.

Personal air sampling equipment was used for data collection. Specifically, the DustCount® 9000-Z1 (hereafter referred to as the DustCount) and Escort ELF personal flow pumps with cyclones. Details as to the sampling media and equipment used are listed in Sections 3.4.1.1 and

3.4.1.2. The sampling media (cyclone sampling head with cassette and filter or DustCount® 9000-Z1 tube inlets) were positioned in the workers' breathing zones following MDHS14/4 requirements, with side-by-side placement to ensure that the measurement results were comparable (Mischler et al. 2019; Volkwein 2006). The placement of the sampling media was statistically randomised using Microsoft Excel, alternating between the left and right positions. All sample results included in the analysis were worn for at least 60% of the shift duration. Most samples were worn for 70% to 80% or more of the shift. However, due to the limited dataset, sampling results covering at least 60% of the shift duration were included in the analysis.

3.3.1.1 Exposure Sampling Equipment – The DustCount

The personal real-time sampling was done by using the DustCount alongside the conventional gravimetric sampling equipment as described above. The DustCount was operated at the optimum flow rate of 1 LPM⁹ with a 25 mm PVC filter. To determine RD, PM₄ concentrations (mg/m³) of particulate matter with an aerodynamic diameter <4 µm were determined by fitting the PM₄ impactor which follows the particle size fraction definitions for health-related sampling according to ISO 7708:1995 Air quality - Particle size fraction definitions for health-related sampling. The DustCount was calibrated using ultrafine Arizona Road Dust (ARD). Calculating mass concentration accounts for the difference in flow rates and filter sizes. The flow rates (2.2 LPM for 37 mm and 1.0 LPM for 25 mm filter) are scaled proportionally to the filter area, maintaining consistency in air flow velocity and mass collection. Since the difference in calculated values is less than 0.44%, this demonstrates that the effect of the difference in filter size and flow rate on the comparison of results is negligible and does not compromise the validity of the data.

⁹ LPM- Litre per minute

3.3.1.2 Exposure Sampling Equipment – Conventional Gravimetric (CGC)

Conventional gravimetric sampling was performed by using a Zefon EoS¹⁰ four-piece cassette equipped with a 2.2 L BGI Model Aluminium cyclone (BGI, Inc., Waltham, United States) and fitted with (0.5 µm pore size and 37 mm diameter) PVC filters. The Escort ELF pump (Zefon International, Ocala, United States) was operated at a flow rate of 2.2 LPM. The sampling train included the size-separating device used to ensure that only particles of the respirable fraction are collected and deposited on the filter inside the cassette.

The researcher performed a comprehensive quantitative and qualitative analysis of the secondary data provided by the mine and contracting company to evaluate the performance of the DustCount against the conventional gravimetric sampling method. The steps followed are outlined in section 3.3.2.

The dataset received contained 35 paired exposure sampling RD results, which were collected side-by-side (see Figure 3-3). The data was filtered and categorised according to the following parameters:

- Paired samples were grouped per work area.
- Sample ID in terms of test numbers were assigned to pairs (T1 to T35).
- Shift duration.
- Total exposure sampling time of each sample.
- Sampling pump and DustCount flow rate.
- Gravimetric (filter mass) results.

¹⁰ EoS- End of Shift, a cassette that was designed for on-site direct-on-filter Fourier-transform infrared spectroscopy (FTIR) analysis to determine RCS content

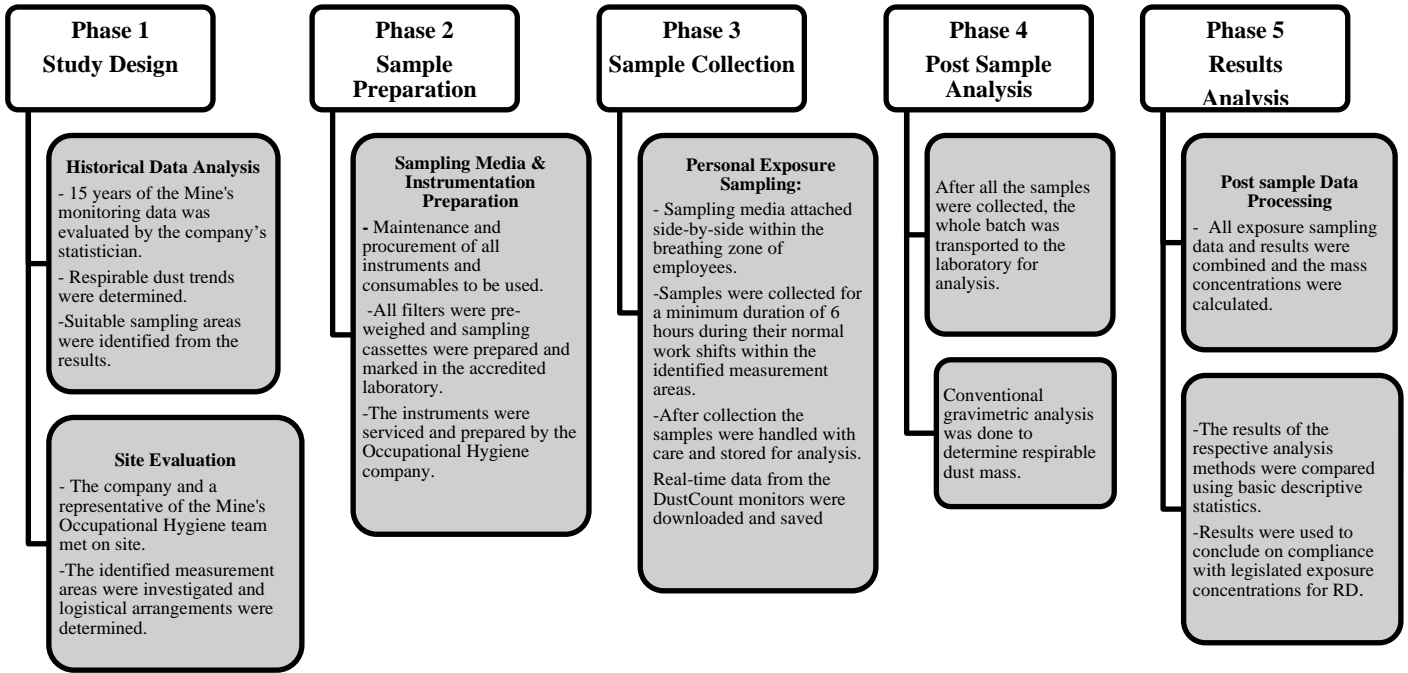


Figure 3-2 Summarised overview of the data collection process followed by the contracted company



Figure 3-3 Workers carrying out routing tasks whilst wearing sampling media (left); Side-by-side placement of sampling media (right)¹¹

¹¹ Photos were provided to the researcher by the contracted company that performed the exposure monitoring

3.3.2 Data processing

The objectives of this study were achieved through analysis of the data obtained from the contracted company. North-West University Statistical Consultation Services was consulted while planning the statistical data processing methodology for this study. All information governance was conducted according to the NWU Personal Information Privacy Policy, following data and information security rules. The study was approved and monitored by the North-West University Health Research Ethics Committee (HREC) (ethics number for the study NWU-00209-22-S1). To ensure an accurate comparison between the two methods, both quantitative and qualitative approaches, as identified in the literature, were applied.

3.3.2.1 Quantitative analysis

Quantitative analysis refers to empirical data structured as numbers (Punch 2008,61). Statistical methods were used to determine the accuracy of the RD exposure monitoring results of the DustCount by comparing them against results obtained by the conventional gravimetric equipment. GraphPad Prism 10 (GraphPad Prism, version 10, GraphPad Software Inc., USA) was used to perform statistical analyses and to create graphs.

The following suitable statistical methods which were used for the quantitative analysis were identified for this study and are outlined in Table 3-1.

Table 3-1 Statistical analysis methods identified for quantitative analysis

Statistical Method	Description of analysis and parameter(s) tested
Clustered column chart (Evergreen 2019,3-1)	The columns in the graph visually represent different data values, allowing for comparison between groups which helped to identify trends across categories.
Bland-Altman (BA) plots (Mansournia et al. 2021) (Kaur & Stoltzfus 2017)	The Bland-Altman (BA) method is effective for comparing the agreement between two measurement methods. BA plots were specifically used to evaluate the overall level of agreement and highlight differences between the two exposure sampling methods. The level of concordance between the results of these methods was assessed using Bland-Altman plots.

(Table continues on next page)

Statistical Method	Description of analysis and parameter(s) tested
Outlier testing (Motulsky and Brown 2006,2).	An outlier is a data point that significantly deviates from the other values in the dataset. While outliers may appear to be unusual, they should not be automatically excluded, as this could distort the overall accuracy of the data. Instead, outlier testing should be performed to help researchers make informed decisions about whether a data point should be considered an outlier and removed.
ROUT Outlier testing (Solzin et al. 2020,1461)	The ROUT (Robust Regression and Outlier) test was used to detect multiple potential outliers in the dataset.
Grubbs Outlier testing (Adikaram et al. 2015)	The Grubbs test, or maximum normed residual test, is another statistical approach applied to identify outliers in the dataset.
Tukey Schematic Box plots (Dawson 2011, 3)	Tukey's Schematic Box Plots can serve as an informal tool for identifying outliers. However, caution is needed when using this method, especially with non-normally distributed data, as it may incorrectly flag a data point as an outlier.
Descriptive statistics (Nick 2008)	Descriptive statistics offer a clear, concise way to summarise a dataset, providing essential measures such as minimum, maximum, mean, median, standard deviation, and interquartile range for all variables. This method helped estimate the central tendency, variability, and overall distribution of the data.
Distribution (Altman 1995)	Distribution refers to the way data points are spread across a range of possible values. Data can follow a normal distribution, where values are symmetrically centred around the mean, or exhibit a non-normal distribution, which may include skewed or other irregular patterns, as was used in this study's dataset. Anderson-Darling and Kolmogorov-Smirnov tests were used to investigate the normality of the distribution of the data.
Comparison of means (MacFarland and Yates 2016)	The Mann-Whitney U test is a non-parametric statistical test used to assess whether there were significant differences between the distributions of two independent groups. It examined whether one group tends to have higher or lower values than the other, without assuming a normal data distribution.
Coefficient of variation (CV) (Zady 2023)	The coefficient of variation (CV) is a key metric used to assess the variation of a dataset around the mean and is expressed as a percentage. The CV is preferred when the standard deviation of a dataset increases proportionally with the concentration and provides an indication of the performance of a method, especially when comparing datasets or evaluating the precision of a method. A CV of 5% or less is preferred, whereas any CV >10% can indicate a high level of variability.

Before statistical analysis was performed on the dataset, the quality of the dataset was investigated. High-quality occupational hygiene data greatly depends on the accuracy of exposure sampling results (De Vocht & Kromhout 2013). Accurate data allows for reliable risk

assessments and the implementation of effective control measures. Occupational hygiene exposure assessment data quality can be affected by several factors, such as the sampling strategy, equipment used, and analysis methods.

As this study compares real-time dust monitors with conventional gravimetric sampling equipment, only datasets collected side-by-side were included (Javed and Guo 2021; Kim et al. 2004). The quality of the dataset used in this study was maintained as the factors referred to in Table 3-2 were considered consistently:

Table 3-2 Data Quality Factors considered when processing the dataset

Data Quality Factor	Description
Blank field samples	Blank field samples were collected in each working area during sampling to ensure that sample handling did not result in contamination during the collection period.
Spoilt samples	If any samples were identified as spoilt based on laboratory analysis, they were excluded from the dataset. This ensured that only valid, uncontaminated results were included in the analysis.
Duration of sample collection	According to the NIOSH Occupational Exposure Sampling Strategy Manual (OESSM), a minimum sampling duration of 70% of the work shift is recommended (Leidel et al. 1977). Samples collected in this study were representative of a typical shift duration (Mbobu 2020).
Flow rate consistency	Results were considered invalid and were discarded if the deviation between the pre-sampling and post-sampling flow rates exceeded 5%. This ensured that any significant change in flow rate did not affect the accuracy of the sample collection.
Filter overload	If a filter became overloaded during sampling, the results were flagged as outliers. Filter overload is indicated by the presence of loose material in the filter cassette, visible darkening of the filter, or a noticeable reduction in the sampling pump flow rate (HSE ¹² 2019; OSHA ¹³ 2014).

After ensuring the quality of the dataset, the data was categorised and used to calculate the sample volume, RD mass concentration and 8-hour TWA mass concentration. This RD concentration result was used in the statistical analysis to evaluate the performance of the DustCount against the conventional gravimetric exposure sampling equipment. Schedule

¹² HSE – Health and Safety Executive, United Kingdom

¹³ OSHA - Occupational Safety and Health Administration, USA

22.9(2)(a) of the MHS Act defines an OEL as "The time-weighted average (TWA) concentration for an 8-hour workday and a 40-hour workweek to which nearly all workers may be repeatedly exposed without adverse health effects.". The OEL of 3 mg/m³ for respirable particles not otherwise specified (PNOS) is the benchmark for comparing exposure sampling results for general RD when the specific chemical components are not confirmed.

The calculated TWA exposure concentration was compared against the specified OEL to identify overexposures. This comparison contributed to evaluating the accuracy of the DustCount.

The primary aim of the qualitative analysis is to assess the results of the DustCount against the conventional gravimetric results and to draw meaningful conclusions regarding the accuracy, precision and sensitivity of the exposure monitoring equipment evaluated.

Table 3-3 Quantitative analysis parameters that were evaluated through the interpretation of statistical analysis results

Quantitative analysis parameter	Description
Accuracy	Accuracy should not be confused with reliability; it refers to the criterion validity of results, meaning how close the results are to the "true value" or the accepted gold standard. To evaluate the accuracy of the DustCount, quantitative analysis results were used to assess the agreement between the DustCount and the conventional gravimetric exposure monitoring method. A high level of agreement would demonstrate the ability of the DustCount to accurately measure RD exposure under the same conditions as the conventional method (Streiner & Norman, 2006). The qualitative analysis results showed poor agreement between the DustCount measurements and the conventional gravimetric exposure monitoring method, as indicated by the Bland-Altman analysis. This suggests a low level of accuracy in the DustCount measurements.
Precision	Precision should not be used synonymously with validity. It refers to the degree to which a result can be repeated, often referred to as test-retest or interrater reliability. The precision of the DustCount were evaluated by examining the variability in its measurement results to assess the device's ability to yield consistent readings under the same conditions as the conventional gravimetric equipment (Streiner & Norman, 2006). The DustCount results exhibited less variability compared to the conventional gravimetric exposure monitoring method. However, this does not imply that the DustCount is more precise. Instead, it highlights that the DustCount undersamples and its results may not accurately represent workplace exposure excursions. While the DustCount logs peaks during the shift, these are not reflected in the final mass concentration results at the end of the sampled shift.

Quantitative analysis parameter	Description
Sensitivity	<p>Sensitivity in exposure monitoring refers to the ability of a monitoring method or equipment to accurately measure low levels of exposure, particularly concentrations near or below the limit of detection of the equipment. The importance of high sensitivity lies in its ability to prevent false negatives, ensuring that exposure risks are not underestimated. Even small quantities of hazardous substances can pose significant health risks, and these risks may not be immediately apparent. This is crucial because exposure concentrations and constituents in work environments can vary depending on the activities and tasks being performed (Reese, 2018:216).</p> <p>The DustCount recorded a minimum value of 0.040 mg/m³ demonstrating the expected sensitivity in detecting low exposure levels.</p>

3.3.2.2 Qualitative Analysis

Qualitative analysis refers to the description of characteristics, qualities and objective experiences of the subject being studied rather than measuring or quantifying variables, aiming to gain a deeper understanding of the subject (Punch 2008,61). The parameters in Table 3-4 were used to evaluate the performance of the DustCount against the conventional gravimetric RD exposure sampling method:

Table 3-4 Qualitative analysis parameters used to evaluate the accuracy of the DustCount against the conventional gravimetric method and equipment

Qualitative analysis parameter	Description
Cost-effectiveness (Lemasters 1996; Faster Capital 2024)	A cost comparison was conducted to assess the cost-effectiveness of DustCount real-time versus conventional gravimetric exposure monitoring. The analysis focused on equipment costs (as a one-time investment) and running costs (sampling costs) to provide a high-level overview of the costs associated with each method. This comparison, however, does not include other aspects of exposure monitoring, such as the cost of biannual calibration of the pump flow calibrator, consultation fees for the person performing the sampling, or professional fees for time, result interpretation, and report writing, as a registered Occupational Hygienist must sign off exposure monitoring results.
Turnaround time (Harper 2020)	This evaluation considered all relevant variables for both exposure monitoring methods, including the entire process flow, such as sampling, transport time, laboratory analysis time, reporting, battery life, and data accuracy.
Ease of use (Claudio et al. 2015)	The ease of use was evaluated based on the physical handling of the exposure monitoring equipment, the knowledge required, and the level of training needed to perform sampling with each method.

Qualitative analysis parameter	Description
Robustness (De Vito et al. 2020)	Robustness was evaluated based on the design of the equipment for harsh environments, its sensitivity to environmental factors, portability, maintenance requirements, and overall versatility.

The qualitative analysis parameters were based on established factors relevant to exposure monitoring and the limitations of the equipment. These factors were drawn from the literature and applied to compare the DustCount with conventional gravimetric exposure monitoring methods and equipment.

3.4 Results

The methodology, as set out in Section 3.3 of Chapter 3, was applied. For readability, the results of the DustCount are hereafter referred to as DustCount real-time Respirable Dust Concentration (DRC real-time); DustCount gravimetric Respirable Dust Concentration (DRC gravimetric), and the results of the conventional gravimetric method as conventional gravimetric concentration (CGC).

3.4.1 Quantitative Analysis

The following sections present the quantitative analysis results comparing the Dustcount measurements with those obtained through the conventional gravimetric method.

3.4.1.1 Descriptive statistics

Descriptive statistics of RD concentrations in three areas at an opencast iron ore mine using two different exposure sampling equipment side-by-side are presented in Table 3-5.

Table 3-5 Descriptive statistics of RD concentrations in three areas on an opencast iron ore mine.

Measurement Method	Area of measurement	Number of measurements	(mg/m ³)										Coefficient of variation (%)
			Min	25 th Percentile	Median	75 th Percentile	Max	Range	Mean	Standard Deviation	Geometric Mean	Geometric SD	
CGC	1	11	0.110	0.143	0.174	0.195	0.245	0.137	0.168	0.041	0.163	1.277	24.2
	2	12	0.076	0.162	0.258	0.430	1.033	0.957	0.336	0.253	0.270	2.005	75.2
	3	12	0.123	0.554	2.314	3.435	9.226	9.103	2.664	2.618	1.517	3.574	98.3
	Total	35	0.076	0.149	0.250	1.033	9.226	9.150	1.081	1.894	0.416	3.597	175
DRC real-time	1	11	0.044	0.080	0.098	0.115	0.131	0.087	0.095	0.025	0.091	1.359	26.3
	2	12	0.040	0.093	0.157	0.257	0.363	0.323	0.175	0.099	0.147	1.905	56.5
	3	12	0.054	0.225	0.507	0.754	1.444	1.390	0.509	0.393	0.357	2.698	77.3
	Total	35	0.040	0.092	0.131	0.285	1.444	1.404	0.264	0.294	0.171	2.456	111
DRC gravimetric	1	11	0.055	0.083	0.115	0.142	0.158	0.103	0.111	0.032	0.107	1.374	28.6
	2	12	0.054	0.095	0.137	0.322	0.579	0.525	0.212	0.181	0.160	2.129	85.5
	3	12	0.057	0.290	0.912	1.432	2.584	2.527	0.942	0.741	0.595	3.321	78.7
	Total	35	0.054	0.095	0.142	0.540	2.584	2.530	0.431	0.575	0.221	3.039	134

CGC: conventional gravimetric concentration (obtained through collecting samples with equipment and the process according to MDHS14/4)

DRC gravimetric: DustCount concentration obtained through gravimetric analysis of the filters collected using the DustCount

Area 1 was the drum beneficiation plant

Area 3 was the primary and secondary crusher

DRC real-time: DustCount real-time concentration obtained through using the DustCount

Total: This refers to the analysis of all data points for all 3 areas sampled combined per sampling method

Area 2 was the tertiary crusher

The clustered column chart in Figure 3-4 indicates the paired data points for the results obtained from the DustCount real-time and the conventional gravimetric equipment and method.

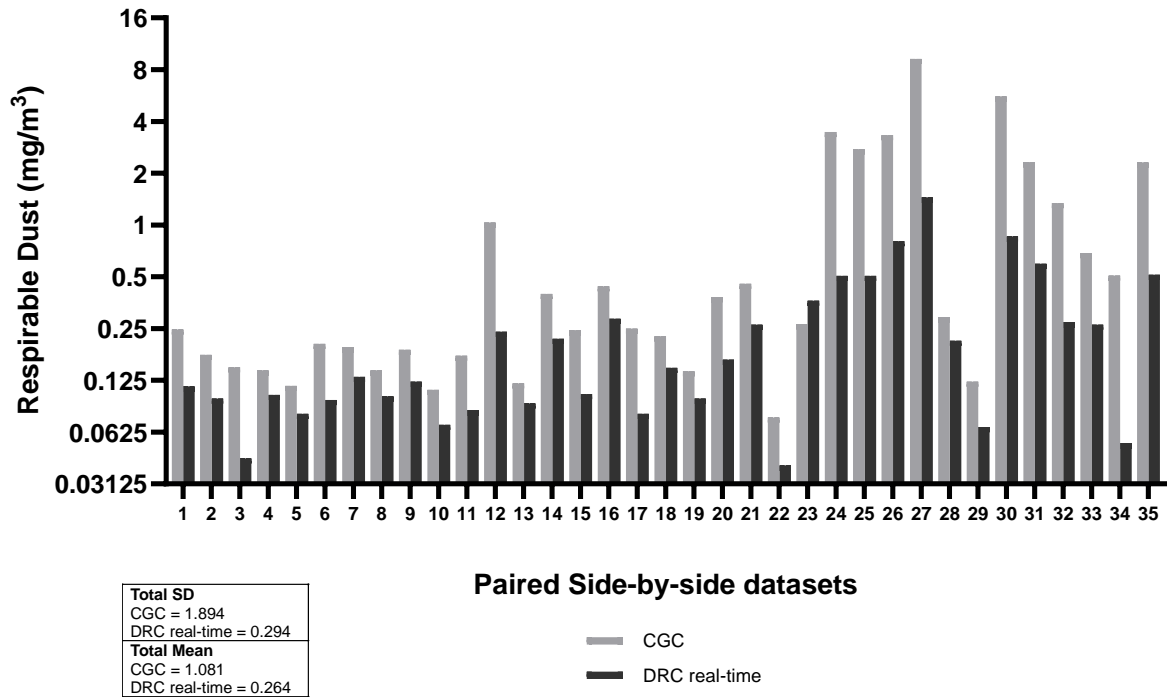


Figure 3-4 Paired data points for two exposure sampling methods

3.4.1.2 Outlier Testing

Considering that some CGC results in Figure 3-4 were much higher than the DRC real-time results, a ROUT outlier test was performed using a Q value of 1%. The Q value determines the aggression level with which the method will remove outliers (Motulsky & Brown, 2006). Several data points were indicated as possible outliers. The ROUT outlier test highlighted 13 data points for removal, which were indicated because they deviated from the rest of the dataset.

A Grubbs statistical test was performed ($\alpha = 0.05$) as paired data point T27 was suspected to be an outlier due to the significant deviation from all other results. Observation T27 was excluded from the dataset (CGC of 9.226 mg/m³ and DRC Real-time of 1.444 mg/m³) and is indicated in the box plot in Figure 3-5(b).

A Tukey box plot was drawn, including all the data points for both methods. The box plot in Figure 3-5 (a) provides an overview of the complete datasets' distribution, central tendency, and

variability. Outliers were retained in the dataset because they provide valuable information that may represent rare but important exposure scenarios. Removing them could distort the analysis by ignoring significant patterns or trends. Additionally, the dataset size and context suggest that outliers are not errors, but rather valid extremes that should be considered for a more accurate and comprehensive analysis.

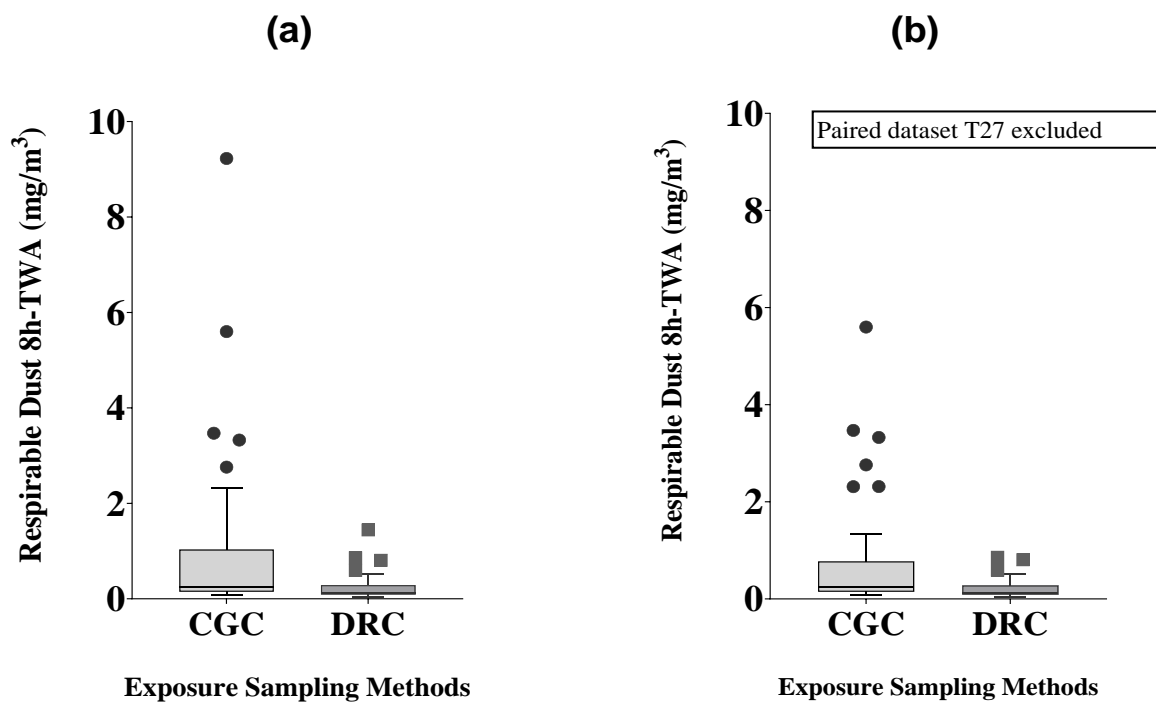


Figure 3-5 Box plots of (a) all DRC real-time vs CGC data points and (b) possible outliers excluded

The figure shows the box plots of (a) all CGC and DRC real-time data points indicating IQR and possible outliers (b) possible outlier data point excluded. Inside each box, the line represents the median (50th percentile). Due to the skewness of the data, the median line is close to the 1st quartile lines on the left side of both boxes. The box represents the interquartile range, spanning from the 1st quartile (Q1, or 25th percentile) to the 3rd quartile (Q3, or 75th percentile). The whiskers extend from the edges of the box to the smallest and largest values within a range defined as 1.5 times the IQR from the first and third quartiles. Any data points outside the whiskers can be considered as potential outliers and are marked as individual points.

GraphPad Prism 10 software provides several different BA plot options. Due to the presentation of the cluster chart in Figure 3-4, the percentage difference, and B-A difference, BA plot options were used as recommended by the GraphPad software statistical manual.

3.4.1.3 Bland-Altman (BA) analysis plot

These plots were used to determine the level of agreement between (1) the DRC real-time and the CGC with possible outliers excluded, (2) the DRC real-time and the CGC – all data points, (3) DRC gravimetric and CGC and (4) DRC gravimetric and DRC real-time

The results of the BA plots are summarised in Table 3-6 and the BA plots in Figure 3-6:

Table 3-6 Bland-Altman (BA) analysis results

Bland-Altman analysis	$BA = \%Difference \left(100x \frac{B - A}{Ave} \right) vs Ave$	$BA = Difference (DRC - CGC) vs Ave.$
	The percentage difference between the two measurement methods (y-axis) was plotted against the average of the two methods' results for each data point (x-axis)	The difference between the two measurement methods (y-axis) was plotted against the average of the two methods' results for each data point (x-axis)
1. DRC real-time vs CGC (Possible outliers excluded)	<ul style="list-style-type: none"> Bias: -57.89% Standard deviation: 35.17% 95% limits of agreement: -126.80% and 11.04% 	<ul style="list-style-type: none"> Bias: -0.11mg/m³ Standard deviation: 0.12 mg/m³ 95% limits of agreement: -0.34 mg/m³ and 0.11 mg/m³
2. DRC real-time vs CGC (All datapoints)	<ul style="list-style-type: none"> Bias: -77.41% Standard deviation: 45.53% 95% limits of the agreement: -166.6% and 11.84% 	<ul style="list-style-type: none"> Bias: -0.82 mg/m³ Standard deviation: 1.61 mg/m³ 95% limits of agreement: -3.98 mg/m³ and 2.35 mg/m³
3. DRC gravimetric vs CGC	<ul style="list-style-type: none"> Bias was -57.95% Standard deviation: 44.73% 95% limits of agreement: -145.60% and 29.72% 	<ul style="list-style-type: none"> Bias: -0.65 mg/m³ with Standard deviation: 1.36 mg/m³ 95% limits of agreement: -3.32 mg/m³ and 2.02 mg/m³
4. DRC gravimetric vs DRC real-time	<ul style="list-style-type: none"> Bias: -25.02% Standard deviation: 47.47% 95% limits of agreement: -118.10% and 68.02% 	<ul style="list-style-type: none"> Bias: -0.17 mg/m³ Standard deviation: 0.30 mg/m³ 95% limits of agreement: -0.75 mg/m³ and 0.42 mg/m³.

Bias: The average difference between the results of the two measurement methods.

Standard deviation: The variability of the differences between the results of the two methods around the average bias.

95% Limits of agreement: Range within which 95% of the sample results are, and 5% can be outside of this range.

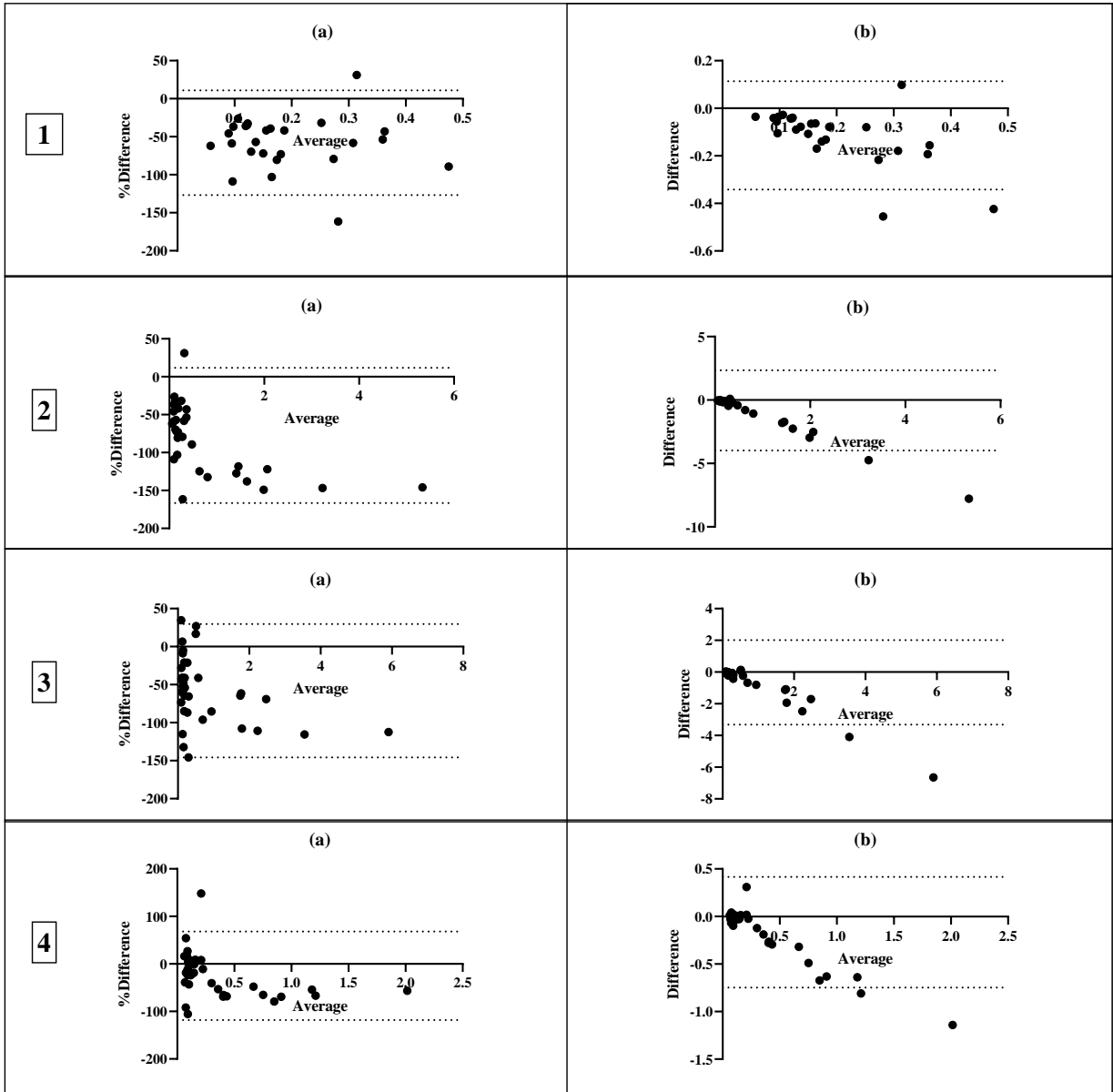


Figure 3-6 BA plots of the results of Table 3-6

1. The first set of BA plots the DRC real-time vs CGC paired data points, with possible outliers excluded.
2. The second set of BA plots was created using all DRC real-time vs CGC paired data points.
3. The third set of BA plots was created using all DRC gravimetric vs CGC paired data points.
4. The fourth set of BA plots was created using all DRC real-time vs DRC Gravimetric paired data points.

3.4.1.4 Comparison of Distribution

The Kolmogorov-Smirnov Test results, included in Table 3-7, were used to compare the overall distributions of the results of the two exposure sampling methods while the Anderson-Darling test was applied to compare the distributions of the results of the two exposure sampling methods. It was used as it is often more sensitive in the tails of the distributions. A p-value obtained when performing the Kolmogorov-Smirnov and Anderson-Darling tests indicates the normality of the data distribution. A value of $p < 0.05$ indicates that the data is not normally distributed.

Table 3-7 Distribution comparison between results of CGC and DRC

Distribution Test	Measurement method	p-value
Kolmogorov-Smirnov	CGC	<.001
	DRC real-time	0.026
Anderson-Darling	CGC	<.001
	DRC real-time	<.001

3.4.1.5 Comparison of Means

- A Wilcoxon independent nonparametric samples t-test was used to compare the mean differences between the results of the two measurement methods and determine whether there was a significant difference. All data points were included in the analysis, and possible outliers were not excluded. The two-tailed P value of < 0.0001 was below the specified significance level of 0.05.
- The Mann-Whitney U test for effect size had an r-value of 0.83, where r is the effect size and a p-value of < 0.001 . An r-value of 0.5 or higher indicates a significant effect. This means that the results of the two measurement methods differ statistically significantly.
- The coefficient of variation (CV) of the DRC real-time dataset was 111%, the CV of the CGC dataset was 175% and the CV of the DRC gravimetric was 134%.

3.4.1.6 Additional Data Provided by the DustCount

As the DustCount has data logging capabilities, it provides more data points, which can enable the identification of key tasks and activities during a shift that cause peak exposures that may even momentarily exceed the OELs. The added value of the DustCount is that it provides an indication of exposure variation over a shift, provided through the peak intensity, frequency and duration of exposures logged, which can be tied to the time and location of exposure. According to information provided on the field sheets accompanying the specific samples in the examples in Figure 3-7, the spikes in the peaks of exposure concentration logged can be ascribed to specific activities and occurrences:

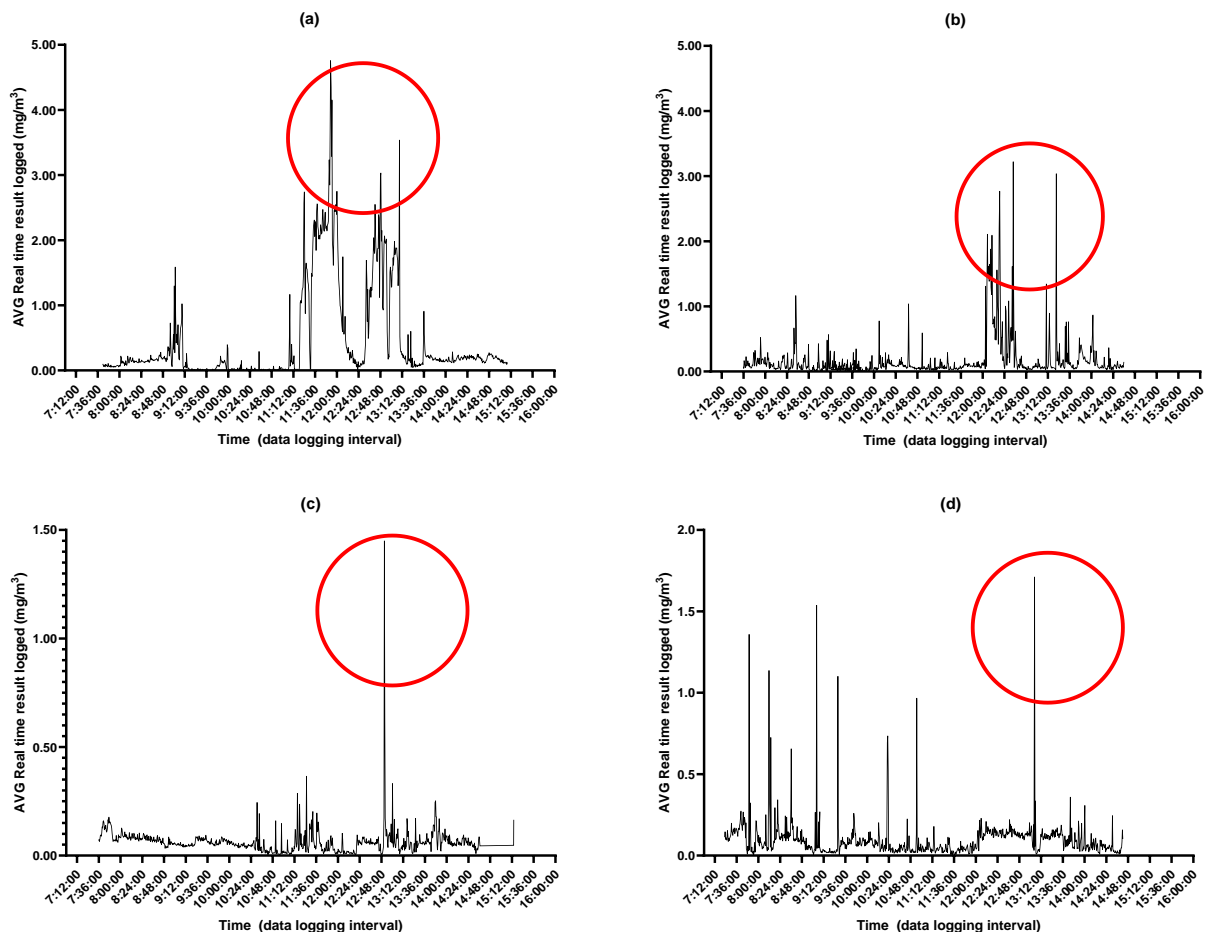


Figure 3-7 Data logged by DustCount monitors indicating peak exposure excursions:

- (a) In the first instance of the increased peak at around 09:00, ore was being dumped at the primary crusher (measurement area 3).
- (b) the plant was not running until 10:00 which can be seen in the low levels of the concentration peaks. The peak at around 12:00 was due to a large rock of ore in the crusher that was being crushed, causing a plume of dust in the primary and secondary crusher areas (measurement area 3).
- (c) the plant was running “idle” between 10:00 and 14:00, which can be seen in the low levels of the concentration peaks, the peak seen at around 12:50. There was a breakdown in the plant equipment due to a blocked gutter at the tertiary crusher (measurement area 2).
- (d) notes indicate that the day on which sampling was conducted was humid, with light rain from 12:00. All plant areas were wet during the operation of the drum beneficiation plant (measurement area 1).

The DustCount detects and counts particles, displaying their mass concentration in $\mu\text{g}/\text{m}^3$, and provides real-time information on particle number concentration distributions for the $\text{PM}_{2.5}$, PM_4 , and PM_{10} fractions of the particle size range (Rasmussen et al. 2019). Figure 3-8 illustrates the particle count and size distribution bins of a set of real-time data logged by a DustCount during a shift. The optical particle counter technology used in the DustCount determines particle counts based on particle sizes, which are detectable depending on their diameters (Schmoll et al. 2010). The device operates within a detectable mass concentration range of $1 \mu\text{g}/\text{m}^3$ to $21.50 \text{ mg}/\text{m}^3$. Particles are counted across 20 size ranges and categorised into particle size bins from $0.3 \mu\text{m}$ to $20 \mu\text{m}$ (Rasmussen et al. 2019). Humidity is a known confounder of real-time monitors such as the DustCount (Dinh et al. 2023) This factor was considered during data analysis, particularly as some sampled employees, such as cleaners, used high-pressure water equipment to clean areas. This scenario applied to 9 samples within the dataset.

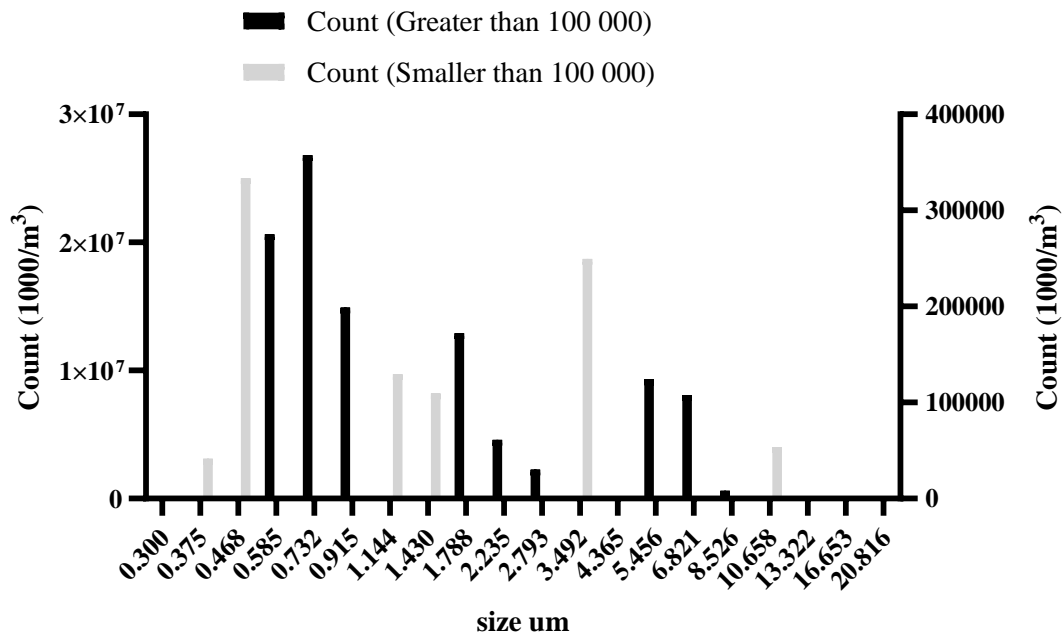


Figure 3-8 Particle count vs size distribution of a single DustCount unit, measuring a worker’s exposure during the shift

3.4.2 Qualitative Analyses

Table 3-8 below summarises an overview of the different exposure sampling and analysis methodologies/techniques used to quantify RD and their limitations and advantages. A visual representation of the qualitative analysis results is depicted in Figure 3-9.

Scores were arbitrarily assigned to the parameters, ranging from 0 to 15 on a matrix where 0 represented poor performance and 15 represented excellent performance. Based on available information, subjective scores were assigned to the DustCount and conventional exposure monitoring equipment. Input from Occupational Hygiene professionals who frequently use these devices was also considered.

Table 3-8 Qualitative analysis results

Qualitative analysis parameter	Conventional Gravimetric	DustCount
1. Cost-effectiveness	<p>The CGC initial investment (once-off cost of purchasing sampling equipment) is a roughly calculated average of R76 350.</p> <p>The ongoing sampling cost is around R550 per sample (which includes laboratory analysis).</p>	<p>The DRC initial investment (once-off cost of purchasing sampling equipment and calibration set up) is a roughly calculated amount of R238 100. The sampling cost (if laboratory analysis is included) works out to about R380 per sample. The CGC is cheaper to buy than the DRC, but more costly per sample. To reach a break-even point to justify the cost of the DRC, you would need to take more than 950 CGC samples if all the DustCount filters are gravimetrically analysed. If the DustCount filters are not analysed and only real-time TWA results of the optical particle counter are considered, the break-even point is at ±294 samples if the sample cost of the DustCount is assumed to be R0.</p>
2. Turnaround time	<p>Exposure monitoring results are critical for promptly identifying overexposures and enabling timely interventions with control measures. However, conventional gravimetric analysis can take days to weeks to yield results due to the time-consuming nature of both the gravimetric procedure and laboratory analysis.</p>	<p>In contrast, real-time monitoring provides results instantly or at the end of the shift, facilitating quicker decision-making and more immediate corrective action.</p>
3. Ease of use	<p>Well-established, and training and information are readily accessible.</p>	<p>The DustCount cassette is tightly sealed, lacking a handling tool such as what is available for conventional gravimetric cassettes, which may result in potential sample loss if the cassette is opened incorrectly by an inexperienced user. DustCount data is accessed by connecting the device to a computer and using the accompanying software. The user interface requires at least basic computer skills, which may pose a learning curve for some users.</p>
4. Robustness	<p>CGC was made for industrial environments, but the equipment is vulnerable to damage. However, this is mitigated by the fact that conventional gravimetric sampling equipment is widely available, meaning easy access to maintenance. Damage can be prevented through proper care.</p>	<p>DRC sensors are sensitive to humidity, making them susceptible to damage in harsh environments and where water vapour is present. Humidity can cause interference with readings, resulting in inaccurate results while damage can reduce the sensor's lifespan.</p>

Qualitative analysis parameter	Conventional Gravimetric	DustCount
5. Advantages	<p>Accepted in many countries to measure exposure to respirable dust.</p> <p>CGC has been validated by various regulatory agencies such as NIOSH and OSHA and is accredited by various international bodies.</p>	<p>Instantaneous exposure results</p> <p>The DustCount enables the determination of the particle size distribution of the airborne contaminant sampled and provides a visual overview of the duration and concentration of the exposure during real working conditions. This information aids risk assessment (Rasmussen et al., 2019). The sensitivity of the DustCount may enable investigations of ultrafine particulate matter</p> <p>Sample collection filter inside the instrument for optional subsequent chemical analysis, DRC might be valuable for ongoing exposure monitoring and not necessarily compliance-related sampling.</p>
6. Limitations	<p>Time delay in results, impacts the timely implementation of control measures in case of over-exposures.</p> <p>Only one data point per sampling session.</p>	<p>Costly</p> <p>Not accredited by international bodies.</p>
7. Covariates	<p>Particle mass concentration.</p> <p>Electrostatic charge.</p> <p>Wind speed and direction.</p>	Humidity

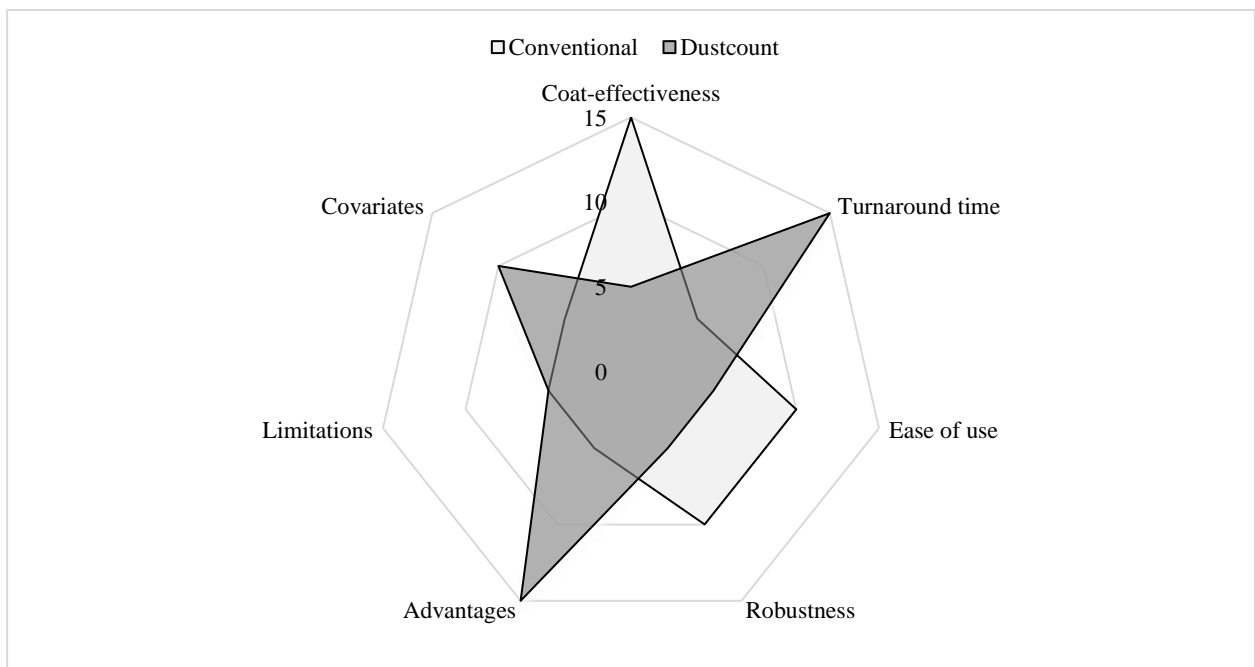


Figure 3-9 DustCount real-time vs conventional gravimetric exposure sampling equipment qualitative analysis results summary

3.5 Discussion

3.5.1 Quantitative analysis

Various statistical tests were performed to evaluate the agreement, variability, and reliability of the two methods. These tests helped identify whether the DustCount can produce data comparable to gravimetric monitoring, the accepted reference method.

The descriptive statistics summarised in Table 3-5 reveal that the CGC method (median = 0.25 mg/m³) reported higher exposure sampling results compared to the DRC real-time method (median = 0.13 mg/m³). A visual inspection of the data, represented in the clustered column chart (Figure 3-4), demonstrates that the difference between the results of the two methods increases as the average concentration measured rises. Specifically, CGC values were consistently higher than DRC real-time values for many paired data points, suggesting that the CGC method measured higher exposure assessment values, while the DRC real-time method tended to underestimate exposure concentrations.

The clustered column chart (Figure 3-4) and the Bland-Altman (BA) plots (Figure 3-6) indicate that DRC real-time results exhibit lower variability compared to CGC. The DustCount demonstrated poor agreement with the conventional gravimetric exposure monitoring method, as shown by the Bland-Altman analysis. This indicates a low level of accuracy in DustCount measurements. This finding suggests that while the DustCount may provide real-time data, its results may not reliably represent the true exposure levels as measured by the reference standard method. Consequently, the DustCount might require calibration or adjustment to ensure its results are comparable to conventional methods. This is further supported by the standard deviation and geometric standard deviation presented in Table 3-5. The lower variability observed in the DRC real-time data suggests greater precision, as the DRC real-time data points display smaller peaks and greater consistency. However, while precision is essential, the accuracy of exposure measurements is crucial in assessing airborne concentrations. The tendency of the DRC

real-time equipment to undersample may indicate that it fails to capture airborne concentrations adequately, potentially missing critical exposure events in the work environment. For instance, while the DustCount logs peaks during a shift, these peaks are not reflected in the final mass concentration results. This discrepancy highlights the need for careful consideration when using the DustCount to assess occupational exposures, especially during activities with significant fluctuations in dust levels. Specific paired data points, such as T27 and T30, stood out as potential outliers due to their notably higher values. Outlier tests were conducted to determine whether these data points should be excluded from the analysis. It is important to note that outliers in exposure data often represent rare but significant events, making their exclusion inappropriate without careful consideration (Motulsky and Brown 2006; Wallfish 2006).

The ROUT outlier testing identified 13 data points in the paired dataset as potential outliers. However, excluding these points solely based on statistical methods risks introducing bias and altering the true underlying distribution of the data. Outliers identified by the ROUT method may reflect meaningful variability or exposure events that are contextually important. Similarly, Tukey box plots flagged additional potential outliers, with points lying beyond the whiskers requiring further investigation. After careful consideration, it was decided to retain all data points in the paired dataset for the Bland-Altman analysis to preserve the integrity and representativeness of the data.

A normality test was conducted using the Kolmogorov-Smirnov and Anderson-Darling tests. Both tests yielded p-values below 0.05, indicating that the datasets significantly deviate from a normal distribution. This result necessitates the use of non-parametric statistical methods for comparing the data points of the two exposure sampling methods. Because of the results of the Kolmogorov-Smirnov and Anderson-Darling tests which indicated that the data was not

normally distributed, a non-parametric Mann-Whitney test was performed to analyse the differences between the two independent groups of the continuous variable.

The Mann-Whitney U test was performed to compare the means of the datasets. The high r-value obtained demonstrated a significant difference between the results of the CGC and DRC real-time methods, reinforcing the observation that the methods produce systematically different exposure measurements. The coefficients of variance (CV) of 111% and 134% for the DRC real-time and DRC gravimetric datasets shows high variability, with the standard deviations larger than the means. This significant CV highlights substantial inconsistencies in the data collected by the DustCount.

Table 3-9 Summary of the performance evaluation of the DustCount unit against the conventional gravimetric equipment in terms of accuracy, precision and sensitivity

Qualitative analysis parameter	Conventional Gravimetric	DustCount
1. Accuracy	CGC is accepted as the golden/reference standard. CGC proved reliable, and the results aligned with historical exposure monitoring data.	The DRC real-time results were significantly lower and less comparable, raising concerns about its agreement with established methods. A different calibration factor may improve the accuracy of the RD measured with the DustCount. The DustCount was calibrated using ultrafine Arizona Road Dust. A calibration factor derived from an aerosolized dust sample taken directly from the site could be applied to improve its accuracy.

Qualitative analysis parameter	Conventional Gravimetric	DustCount
2. Precision	CGC results indicated a higher level of variability compared to the DRC results. Higher variability of CGC results reflects actual environmental conditions better, making it more representative in fluctuating work environments. The CGC results demonstrated the expected variability, as the end-of-shift mass concentration values reflected both high and low exposure levels. However, it was observed that the DustCount device logged significant peak exposure events during the shift, which were not proportionately reflected in the cumulative mass concentration results at the shift's conclusion.	The DRC real-time results had lower variability than the CGC. While DRC is more consistent, its undersampling challenges the representativeness of its data, particularly in dynamic conditions. The DustCount undersamples and possibly underestimates exposures across all measurements for all three areas sampled. If the DustCount fails to capture particles accurately compared to CGC, it affects the interpretation of results. Undersampling affects the interpretation of exposure results as it can lead to underestimating the health risks posed by the exposure.
3. Sensitivity	The lowest CGC exposure result measured was 0.058 mg (laboratory gravimetric result), which is typical for this method. This value aligns with the expected sensitivity range outlined by the MDHS 14/4 method, where the limit of detection (LOD) typically ranges from 0.001 mg to 0.005 mg of dust. The CGC result, being above the LOD, is not an outlier and can be accepted as valid, ensuring the method's reliability for standard monitoring.	The lowest DRC real-time exposure results were 0.014 mg (digital result) and 0.038 mg (laboratory gravimetric result for the same sample). This demonstrates that the DRC is more sensitive to low concentrations of respirable dust (RD) than the CGC method and equipment, as expected based on the advanced technology utilized by the device.

3.5.2 Qualitative analysis

The radar chart with parameters 1 to 7 is visually represented in Figure 3-9. Arbitrary scores were assigned to the parameters based on the interpretation of the results in Table 3-8 Qualitative analysis results. The chart aims to emphasise the key strengths of the DRC and CGC visually.

Conventional gravimetric exposure sampling equipment: Stronger in cost-effectiveness and robustness, but slower, more limited, and potentially less user-friendly.

DustCount: Faster, easier to use, with more advantages and fewer limitations, but it may lack cost-effectiveness and robustness.

Overall, the accuracy of the DustCount is questionable as the results obtained from the DustCount are significantly different than the CGC results obtained. The DustCount offers valuable capabilities which can be considered in risk assessment when investigating workers' exposure to hazardous airborne particles.

3.6 Conclusion

The primary aim of the study was to evaluate the performance of DustCount real-time monitors for personal exposure sampling of RD. This objective was addressed through a detailed qualitative and quantitative analysis of secondary data results. The findings indicate that the DustCount device consistently undersamples compared to conventional methods, confirming the study's hypothesis. Despite this limitation, the DustCount still holds potential as a useful tool for providing valuable exposure information. The DustCount is a technically advanced tool suitable for specific research-focused tasks, especially if a suitable calibration factor is created and applied to the results. In contrast, the conventional gravimetric exposure sampling method and equipment provide more practical advantages for routine compliance monitoring and cost-conscious applications. Finally, DustCount logging capabilities provided valuable data linked to specific activities. This feature offers insights into exposure profiles, enhancing the understanding of exposure dynamics and supporting investigative efforts into exposure patterns and causes. The DustCount demonstrated high sensitivity by recording a minimum value of 0.040 mg/m³, showing its ability to detect low exposure levels effectively. This sensitivity is crucial for identifying small but potentially hazardous quantities of airborne contaminants, which might pose significant health risks over time. However, the practical implications of this sensitivity should be balanced against the device's limitations in accuracy and precision to ensure effective workplace monitoring.

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CHAPTER 4 CONCLUSION

4.1 Introduction

Real-time personal exposure monitoring devices, developed to enhance exposure sampling, have been used in several industries such as mining, construction, and manufacturing, as well as for applications like indoor air quality, environmental monitoring, and occupational exposure monitoring (Negi *et al.*, 2010:419; Thorpe & Walsh, 2007:679). Given the range of applications, the measurement accuracy of these devices should be evaluated (Ruiter, *et al.*, 2020:1). This study was the first to evaluate the performance of the Nanozen DustCount® 9000-Z1 personal real-time monitor (Nanozen Industries Inc., Vancouver, Canada) against a conventional gravimetric sampling method, method MDHS14/4¹⁴, at an opencast iron ore mine in South Africa. This chapter includes four primary sections: the main findings, limitations, recommendations and future studies. The aim, objectives and hypothesis outlined in Chapter 1 were revisited and addressed according to the conclusions of the study. From here onwards, the Nanozen DustCount® 9000-Z1 will be called DustCount for brevity and improved readability.

4.2 Main Findings

This study aimed to evaluate the performance of DustCount real-time monitors. This was done by assessing the exposure sampling results obtained by a contracted company that performed side-by-side sampling with the DustCount and conventional exposure sampling equipment in accordance with the MDHS14/4 method, similar to what was done by Lemke (2021). The aim of the study was reached through the completion of the objectives set out in Chapter 1, which were:

- (1) Evaluating real-time DustCount respirable dust (RD) exposure concentration results against conventional gravimetric MDHS14/4 method results revealed that the DustCount consistently undersampled. This was evidenced by the differences in the geometric mean (GM) and geometric standard deviation (GSD). The GM for the DustCount real-time results was 0.171 mg/m³, with a standard deviation (SD) of 2.456 mg/m³, while the GM for the conventional gravimetric results was 0.416 mg/m³ with an SD of 3.597 mg/m³. The coefficient of variance of the DustCount real-time dataset was 111%, indicating a significant variability. A bias of -77.41% indicated a statistically significant difference between the results of the DustCount real-time equipment and conventional gravimetric equipment.

¹⁴ Methods for the determination of hazardous substances 14/4: General methods for sampling and gravimetric analysis of respirable and inhalable dusts – Health and Safety Executive.

Bland-Altman (BA) plots revealed a systemic bias in the DustCount results. These plots indicated that the two methods were in closer agreement at low dust concentrations (0–0.2 mg/m³). However, at higher concentrations (>0.2 mg/m³), the gravimetric method consistently measured higher RD levels than the DustCount, showing a concentration-dependent disparity in agreement. Similar results were reported by Borghi et al. (2018:10), who found that the measurement error increased as particle concentration rose when comparing a direct-reading monitor to conventional gravimetric equipment.

When comparing DustCount real-time results to conventional gravimetric results, the bias was –0.82 mg/m³. In contrast, when comparing DustCount gravimetric results to conventional gravimetric results, the bias was between –0.65 and –0.82 mg/m³. The bias between the DustCount real-time and DustCount gravimetric results ranged from –0.17 to –0.82 mg/m³. These findings are consistent with those reported by Lemke (2021), who observed a bias of 0.14 mg/m³ when comparing DustCount real-time to conventional gravimetric results, indicating poor agreement between DustCount real-time and conventional gravimetric results.

- (2) Assessing RD gravimetric analysis results of DustCount filters against the MDHS14/4 conventional gravimetric equipment, the bias of –57.95% was lower than that of DustCount real-time results when compared to conventional equipment results, but still indicates poor agreement. The mean of the DustCount gravimetric results was 0.431 mg/m³ with an SD of 0.575 mg/m³, whereas the mean of the conventional gravimetric results was 1.081 mg/m³, and the SD was 1.894 mg/m³. The limits of agreement were relatively broad, –3.32 mg/m³ and 2.02 mg/m³, which emphasised the poor agreement and reflected significant discrepancies in the results provided by the two types of exposure sampling equipment. This indicated that the results of the gravimetric analysis of the DustCount filters deviated significantly from the results obtained with the conventional gravimetric equipment. The SD of BA analysis was 1.61 mg/m³, a concerning value in light of the Occupational Exposure Limit (OEL) of 3 mg/m³ for respirable particles not otherwise specified (PNOS) as stipulated by the Mine Health and Safety Act 29 of 1996. This implies that conventional gravimetric results could alert that a sample exceeds the OEL, whereas the DustCount result may have reported the contrary due to the notable undersampling.
- (3) Comparing DustCount real-time RD results—obtained using OPC technology—with gravimetric analysis of DustCount filter results—obtained via its impactor-based particle size separation method—revealed a bias of –0.17 mg/m³ with a standard deviation of 0.30 mg/m³.

The hypothesis for the study was that the DustCount results would show a statistically significant difference and poor agreement compared to the conventional gravimetric sampling method and equipment. In light of the quantitative analysis results, the hypothesis postulated for this study is accepted.

The qualitative analysis revealed that conventional gravimetric exposure sampling equipment was more cost-effective and robust but was slower in providing results and potentially less user-friendly. In contrast, the DustCount offered faster results and greater ease of use, though its higher cost poses a barrier. Calibration plays a critical role in the effective use of sensor technologies for exposure monitoring, and improved and easier assessable calibration factors can enhance the accuracy of DustCount real-time results and increase the feasibility of its use.

The study consistently found that the DustCount undersampled respirable dust (RD) concentrations compared to conventional gravimetric equipment. In all instances, the gravimetric method recorded higher RD mass concentrations than the real-time readings obtained from the DustCount. Bias refers to a consistent or systematic error in measurement (Cullen & Frey, 1999:51). In exposure monitoring, bias is considered significant if it exceeds 10% of the true exposure values as measured by a reference method (Higgins *et al.*, 2024:2). In this study, a significant bias was observed when comparing the gravimetric analysis results of the DustCount filters to the real-time readings generated by the optical particle counter (OPC) of the DustCount. This significant difference was also noted when comparing the DustCount gravimetric filter analysis with the conventional gravimetric results, confirming the hypothesis that DustCount measurements consistently diverged from those of the conventional gravimetric equipment. The advantages and limitations of the DustCount were elaborated on in the following paragraphs.

The DustCount uses OPC technology and includes a built-in filter cassette, enabling subsequent sample composition analysis (Nanozen Industries Inc., 2020). The DustCount has configurable functions such as data logging and alarm settings. Data was logged at pre-set intervals throughout the exposure sampling session, providing multiple exposure data points. The value of this functionality was demonstrated in Figure 4-1 below.

This capability is especially useful for tracking short-term exposure trends. For example, while the DustCount reported an average RD mass concentration lower than the conventional gravimetric equipment during the shift, it logged exposure spikes around 12:00 and 14:00, exceeding both the gravimetric readings and the OEL of 3 mg/m³. This data can be used to identify exposure trends and inform the implementation of effective control measures.

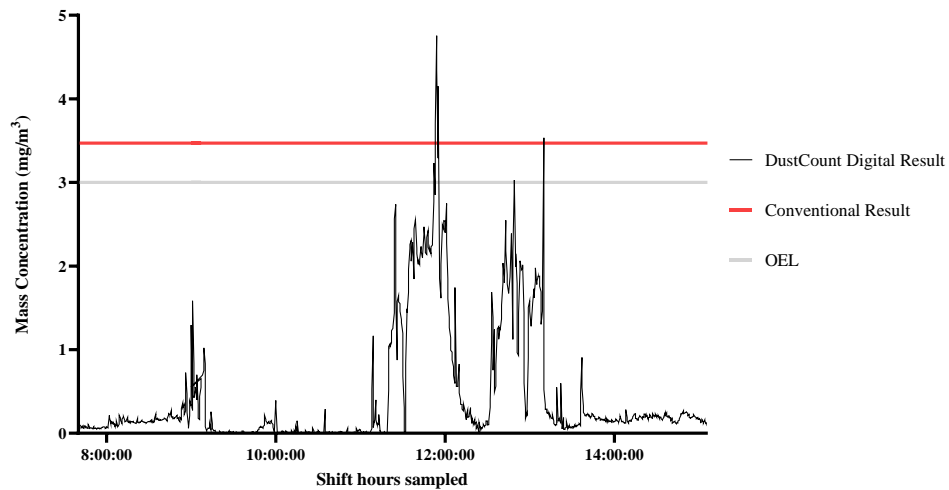


Figure 4-1 DustCount real-time results, logged every 30 seconds during the shift, compared to conventional gravimetric measurements and the PNOS ¹⁵OEL of 3 mg/m³ as specified in the Mine Health and Safety Act 29 of 1996

The DustCount is highly effective for analysing short-duration exposures to airborne particles, particularly in environments where concentrations are low. This capability makes it a valuable tool for assessing exposure in future studies (Wei, 2020:72). The DustCount’s particle size detection range spans from 1.00 µg/m³ to 21.50 mg/m³, and its sensitivity may also facilitate investigations into ultrafine particulate matter (Rasmussen *et al.*, 2019:2).

In addition to the abovementioned capabilities, the DustCount is robust and user-friendly, offering a relatively quick turnaround for exposure monitoring results. It allows for the determination of the particle size distribution of airborne contaminants and provides a visual overview of exposure duration and concentration during real-world working conditions. This information is instrumental for comprehensive risk assessments. An example of this was shown in Figure 4-2.

¹⁵ PNOS – particles not otherwise specified, the exposure concentration value to be used for exposure to dust of which the chemical constituents are not classified.

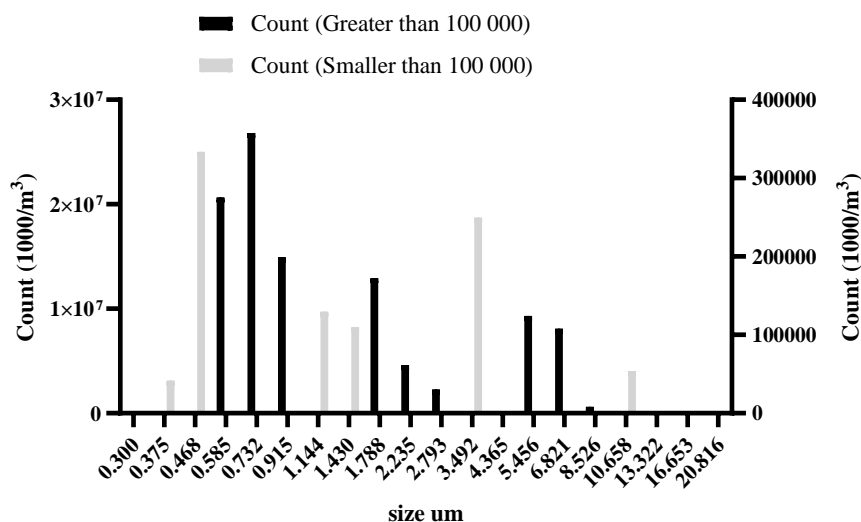


Figure 4-2 Particle count vs size distribution of a single DustCount unit, measuring a worker’s exposure during the shift

4.3 Limitations of the study

4.3.1 Size of the dataset

This study was limited to the data points provided in the dataset received from the contracted company. The dataset only included 35 paired samples, which constrained the scope of the analysis. A larger sample size could enhance the evaluation of the equipment by providing more robust data, enabling more meaningful conclusions with improved statistical reliability. The dataset size can influence the statistical power of the analysis; however, with $n=35$, the application of the Central Limit Theorem (CLT) is justified, as the data was not excessively skewed (Kwak & Kim, 2017:145).

4.3.2 Real-Time Exposure Monitoring Confounding Factors

One potential cause of discrepancies in the accuracy of readings was that DustCount devices inherently rely on light-scattering (photometric) technology. This method is sensitive to various factors that can influence the results, including particle size, type, and environmental conditions like humidity and temperature. Humidity and temperature, for example, can affect the refractive index of particles and influence the way they scatter light, potentially leading to deviations from the results obtained using gravimetric methods (Haltermann *et al.*, 2018:64). These influences may have resulted in deviations compared to gravimetric methods (Javed & Guo, 2021:2).

In this study, one of the sampled job categories included plant cleaners, who used high-pressure water equipment to clean plant areas for significant portions of their shifts. The fine water vapor

generated during these tasks likely interfered with the DustCount sensors, potentially affecting their accuracy. Specifically, fine mist or aerosolized water may have altered the light scattering by dust particles, hindering the device's ability to accurately measure airborne dust concentrations (Patts *et al.*, 2019:744). This issue was particularly evident in 9 out of the 35 sample pairs, where discrepancies between DustCount and gravimetric methods were observed. However, the consistent undersampling observed in the DustCount results cannot be solely attributed to this interference.

Additionally, interpreting real-time data posed challenges due to spikes in readings that did not always indicate actual exposure levels. These fluctuations could be attributed to non-exposure factors, such as equipment interference or temporary environmental changes, that resulted in brief but significant changes in the light-scattering measurements. For example, if the sensor was exposed to sudden airflow changes, vibrations, or changes in particle density unrelated to actual worker exposure, it could lead to misleading spikes in the data. Equipment interference, such as electromagnetic noise or mechanical vibrations from nearby machinery, could also have influenced the DustCount readings (Ioar, *et al.*, 2017:2). This variability in the real-time data highlights the need for caution when interpreting spikes as indications of hazardous exposure levels.

4.4 Recommendations

Based on the findings of this study, the following sections outline key recommendations aimed at addressing the identified issues and guiding future actions.

4.4.1 Worker Exposure

Of the 70 samples in the side-by-side 35-paired dataset, six conventional gravimetric samples exceeded the TWA OEL of 3 mg/m³. It is recommended that control measures in this area be reassessed in line with the hierarchy of controls.

Since dust is an inherent part of the mining environment, it cannot always be eliminated. Workers' exposure is influenced by their movement within work areas. Engineering controls are considered the most effective method for managing exposure to respirable dust in mining environments (Blackley & Halldin, 2017:18). These controls rely heavily on the specific operations and equipment generating the exposure. Measures such as dust suppression systems, dust extraction systems, enclosed cabins, and physical barriers can reduce exposure at the source or limit the spread of airborne dust (NIOSH, 2021:42).

Administrative controls can also play a significant role in protecting worker health. Examples include implementing work rotations, providing training to increase awareness of occupational

hazards, managing traffic flow to minimise dust generation, and ensuring effective housekeeping practices.

While personal protective equipment (PPE) is generally regarded as a last resort due to its reliance on proper usage for effectiveness, it can serve as a critical line of defence when other controls are insufficient. Respiratory protection and protective clothing can help reduce individual exposure to respirable dust.

4.4.2 Data Collection

A standardised sampling strategy for a side-by-side approach and analysis is recommended to ensure accurate data collection when comparing exposure sampling methods (Siegel *et al.*, 2019:11; Borghi *et al.*, 2018:17). To establish an accepted standardized approach, detailed sampling plans must be designed to account for multiple work environments, developed through collaboration between research bodies and occupational hygiene professionals (Kromhout, 2002). A critical component requiring further detail is the calibration of equipment, as there is currently no publicly available step-by-step guideline for calibrating the DustCount to ensure the most accurate data. A comprehensive sampling protocol should also be developed, accounting for the variability of work environments and representative exposure ranges through appropriate sampling durations. Additionally, documenting conditions such as humidity, temperature, and airflow during each sampling event is essential for understanding the impact of environmental factors on real-time monitors. Measurements should be compared to occupational exposure limits (OELs) to assess the practical implications of any discrepancies. Detailed guidelines on quality control must be established, including calibration checks, field blanks, and data validation procedures (Chow *et al.*, 2002). Finally, standardized reporting formats should be implemented to ensure consistency and comparability across studies.

Current studies indicate that real-time data monitors are moderately accurate compared to conventional exposure sampling, devices like the DustCount can be integrated into existing exposure sampling strategies if appropriately applied (Brouwer & Lavoue, 2020:106). Direct-reading monitors can reveal short-term temporal variations, making them helpful in augmenting filter-based conventional sampling approaches, which require an extended sample collection period (to meet the detection limits of gravimetric analysis). Averaging measurements over a longer period than the actual duration of the exposure could result in a significant underestimation of airborne hazardous particle concentrations. Direct-reading measurement technologies could, therefore, be recommended to assist in evaluating short-duration exposure, which is required to address existing uncertainties in assessing risks of aerosol exposure.

4.5 Future Studies

Potential future studies identified could include the following:

- Before incorporating real-time data-capturing equipment into exposure sampling strategies, ethical considerations should be addressed. Privacy and data security are critical when using sensor technology for exposure monitoring (Evans, 2023). Employees must be assured that the sensor technology is used to protect their health and not for punitive purposes, as workers may be resistant to real-time monitoring if their concerns are not addressed through training and transparent communication. The primary goal of improving exposure sampling is to control exposure risks better, and any increase in data availability should not be used to discipline employees. A research study is recommended to investigate the ethics associated with using real-time personal exposure monitors, such as improved training programmes and adjusted PPE.
- Building on the ethical considerations of real-time monitoring, the DustCount's capability to track worker behaviour and health, provides a unique opportunity to enhance exposure management strategies (Wang *et al.*, 2024). A study could use the DustCount to investigate the link between worker behaviour and health, as the DustCount exposure monitoring coupled with health monitoring of workers, such as spirometry results and compliance with PPE, could provide valuable insight into patterns that could predict adverse health outcomes and inform preventative mitigations (Laskaris *et al.*, 2019).
- Future research could consider using the DustCount in non-commercial agricultural settings such as smaller-scale crop farms to assess respirable dust levels as it is a less-studied environment. A non-commercial environment is suggested as infrastructure to control or monitor exposure is likely limited. An agricultural setting may pose the opportunity to investigate dust from various sources (Aiello *et al.*, 2022). This information could then be compared to established industries to highlight potential gaps in exposure standards.
- For future studies, it is recommended to compare the inlet efficiencies and particle size-separation equipment to assess their impact on sampling results (Vinson *et al.*, 2007:710). There is no published study on the DustCount inlet (Wei *et al.*, 2020:3).
- Additionally, the possibility of heteroscedasticity in the DustCount results should be considered, as the variance in the dataset may not be constant at different levels. Heteroscedasticity means the variability of the residuals is not constant across all levels of the independent variables when performing regression analysis. This can occur when the scatter or spread of data points increases or decreases as the value of the independent variable changes (Rosopa & Schaffer, 2013:335). In the context of exposure monitoring or environmental data analysis, heteroscedasticity can arise when the variability in measurements (e.g., dust concentrations) differs depending on the exposure level or the work

environment's characteristics. For instance, measurement variability may be greater in areas with very high dust concentrations than in areas with lower concentrations. This could be observed in the differences in RD exposure measured by the DustCount across three distinct work areas. Variance in dust exposure levels may arise due to various factors impacting the exposure level, such as proximity to dust-generating activities. Heteroscedasticity could impact the process when deciding on control strategies, and the effect of this should thus be investigated. A study investigating the relationship between heteroscedasticity and the work environment and exposure levels could be considered.

- While the DustCount filter gravimetric analysis demonstrated less bias than the real-time counterpart, it still exhibited poor alignment with the conventional MDHS14/4 method, and this discrepancy should be investigated. The broad limits of agreement suggest the limited reliability of DustCount's gravimetric filter measurements in environments requiring high precision.

Currently, there is a limited body of peer-reviewed and published academic research studies on the DustCount. Given the advantages offered by the DustCount, further research is necessary to validate the capabilities of the DustCount. By conducting these studies, the occupational hygiene and safety industry can gain valuable insights and tools to manage workplace exposures and improve health outcomes proactively.

4.6 Conclusion

While the DustCount was effective in detecting exposure in low-concentration environments, it tended to undersample at higher dust concentrations. As a result, its reliability in accurately measuring higher levels of RD exposure is compromised unless a revised correction factor is established. This highlights the importance of regular correction and validation to ensure the DustCount provides accurate data across varying exposure levels. One of the key benefits of the DustCount is its potential to serve as a surveillance tool for evaluating the effectiveness of control methods. As a risk assessment tool, it is especially useful for quickly investigating remote areas or locations with low dust concentrations. If the use of an accurate correction factor was possible, the DustCount results could be extrapolated to predict the results obtained from conventional gravimetric equipment used for compliance monitoring (Borghi *et al.*, 2018:16).

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ANNEXURES A:



Private Bag X1290, Potchefstroom
South Africa 2520

Tel: 086 016 9698
Web: <http://www.nwu.ac.za/>

**North-West University Health Research Ethics
Committee (NWU-HREC)**

Tel: 018 299-1206
Email: Ethics-HRECApply@nwu.ac.za (for human
studies)

26 October 2023

ETHICS APPROVAL LETTER OF STUDY

Based on approval by the North-West University Health Research Ethics Committee (NWU-HREC) on 26/10/2023, the NWU-HREC hereby approves your study as indicated below. This implies that the NWU-HREC grants its permission that, provided the general conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Performance comparison of the Nanozen DustCount personal real-time monitor with a conventional respirable dust exposure sampling method																															
Principal Investigator/Study Supervisor/Researcher: Mr CJ van der Merwe																															
Student: V Jansen - 27334546																															
Ethics number:	<table border="1"><tr><td>N</td><td>W</td><td>U</td><td>-</td><td>0</td><td>0</td><td>2</td><td>0</td><td>9</td><td>-</td><td>2</td><td>2</td><td>-</td><td>A</td><td>1</td></tr><tr><td colspan="3">Institution</td><td colspan="5">Study Number</td><td colspan="2">Year</td><td colspan="5">Status</td></tr></table>	N	W	U	-	0	0	2	0	9	-	2	2	-	A	1	Institution			Study Number					Year		Status				
N	W	U	-	0	0	2	0	9	-	2	2	-	A	1																	
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Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation																															
Application Type: Single study	Risk: <table border="1"><tr><td>Minimal</td></tr></table>	Minimal																													
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Commencement date: 26/10/2023																															
Expiry date: 31/10/2024																															
Approval of the study is provided for a year, after which continuation of the study is dependent on receipt and review of an annual monitoring report and the concomitant issuing of a letter of continuation. A monitoring report is due at the end of October annually until completion of the study.																															

General conditions:
<i>While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:</i>
<ul style="list-style-type: none">• <i>The principal investigator/study supervisor/researcher must report in the prescribed format to the NWU-HREC:</i><ul style="list-style-type: none">- <i>Annually on the monitoring of the study, whereby a letter of continuation will be provided annually, and upon completion of the study; and</i>- <i>without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.</i>• <i>The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the principal investigator/study supervisor/researcher must apply for approval of these amendments at the NWU-HREC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.</i>• <i>Annually a number of studies may be randomly selected for active monitoring.</i>• <i>The date of approval indicates the first date that the study may be started.</i>• <i>In the interest of ethical responsibility, the NWU-HREC reserves the right to:</i><ul style="list-style-type: none">- <i>request access to any information or data at any time during the course or after completion of the study;</i>

- to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;
- withdraw or postpone approval if:
 - any unethical principles or practices of the study are revealed or suspected;
 - it becomes apparent that any relevant information was withheld from the NWU-HREC or that information has been false or misrepresented;
 - submission of the annual monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and/or
 - new institutional rules, national legislation or international conventions deem it necessary.
- NWU-HREC can be contacted for further information via Ethics-HRECApply@nwu.ac.za or 018 299 1206

The NWU-HREC would like to remain at your service and wishes you well with your study. Please do not hesitate to contact the NWU-HREC for any further enquiries or requests for assistance.

Yours sincerely,



Chairperson NWU-HREC

Current details:(23239522) G:\My Drive\9. Research and Postgraduate Education\9.1.5.4 Templates\9.1.5.4.2_NWU-HREC_EAL.docm
20 August 2019
File Reference: 9.1.5.4.2

ANNEXURES B:



Venita de Kock

BA HONS. · PEG

☎ 084 588 5008

✉ venita.dekock@gmail.com

27 November 2024

LANGUAGE EDITING STATEMENT

I, Jannetje Levina De Kock hereby declare that the thesis

Performance comparison of the Nanozen Dustcount
personal real-time monitor with a
conventional respirable dust exposure sampling method

by

Veruschka Wagner

Student number: 27334546

for submission to the OHHI, NWU.

- has been edited for language correctness and spelling.
- has been edited for consistency (repetition, long sentences, logical flow)

No changes have been made to the document's substance and structure (nature of academic content and argument in the discipline, chapter and section structure and headings, order and balance of content, referencing style and quality).

J L DE KOCK