EVALUATION OF HIGH PRESSURE WATER SPRAY SYSTEMS AS A CONTROL MEASURE TO REDUCE SILICA EXPOSURES IN UNDERGROUND GOLD MINES

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A Research report submitted to the Faculty of Health Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Public Health.

Johannesburg, September 2017.

DECLERATION

I, Hendrik Johannes Senekal, declare that this Research Report is my own, unaided work. It is being submitted for the degree of Master of Public Health at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

15th day of September 2017 in Johannesburg.

I dedicate this research report to my family and friends. The love, support and encouragement you provided carried me to the end of this road and to the beginning of the next.

Thank you all!

Abstract

Gold mining has always played a major role in the South African economy. Unfortunately, workers' health could be at risk as exposure to respirable quartz could cause silicosis. Silicosis has no cure or treatment and the only means to prevent silicosis is to reduce exposure to as low a level as possible. This study tested the effectiveness of a high-pressure water spray system as an engineering control measure, to reduce respirable dust and respirable quartz concentrations. This intervention produced a mean personal respirable quartz concentration reduction of 87% (p-value of 0.00003). In addition, a reduction of 53% (p-value of 0.04) was observed in the mean static dust concentration measurements taken upstream and downstream of the control measure. Significant improvement in respirable dust and respirable quartz concentrations was observed after the introduction of the high-pressure water spray system. The results from this study indicate that the health risk to underground mine workers could be reduced by implementing a high-pressure water spray system as an engineering control.

Acknowledgements

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Nomenclature

ACGIH - American Conference of Governmental Industrial Hygienists

BDL - Below detection limit

CDC - Centers for Disease Control and Prevention

DMR - Department of Mineral Resources

MHSC - Mine Health and Safety Council

MOSH - Mining Industry Occupational Safety and Health

NIOSH - National Institute for Occupational Safety and Health

OEL - Occupational Exposure Limit

REL - Recommended Exposure Limit

RQC Respirable Quartz Concentration

RV - Rock and Ventilation

SANAS - South African National Accreditation System

SIMRAC - Safety in Mines Research Advisory Committee

TLV - Threshold Limit Value

TWA - Time Weighted Average

XRD - X-Ray Diffraction

1 INTRODUCTION

"It is health that is real wealth and not pieces of gold and silver."- Mahatma Gandhi

Gold mining has played a major role in the economy of South Africa since 1886 when the first large gold mining company, Witwatersrand Gold Mining Company, was established (1). In 2013, the mining sector directly contributed 8.3% of the Gross Domestic Product (GDP) of South Africa, totalling R280 billion (2). Although lower than the industry peak value of 21% during 1970, mining still provides a valuable contribution to South Africa's GDP. The mining sector has contributed R2 401 billion to South Africa's GDP over the past decade (2).

The South African mining industry employed a total of 510 099 workers during 2013 (2). During the same time, South African gold mines employed 131 591 workers, a reduction over the years from 179 964 during 2004 (2).

Unfortunately, gold mining does not come without risks to workers' safety and health. Among these risks, a major concern is the health risk of exposure to respirable crystalline silica or also referred to as respirable quartz. As a naturally occurring substance in rock and sand, exposure is very likely during mining operations. Depending on the level of exposure, such exposure could have a negative impact on worker health (3).

An important health risk for exposure to respirable quartz is silicosis. A study conducted in the United States of America indicated that, with an increase in cumulative dose of exposure to respirable quartz, the risk of silicosis also increases (4).

A study conducted by Hnizdo and Sluis-Cremer [1993] considered the risk of silicosis amongst a cohort of white gold mine workers. The study found that if workers are exposed to respirable quartz at a concentration of 0.1 mg/m^3 over a period of 20 years, this exposure equates to a cumulative exposure of 2 mg/m^3-years and the cumulative exposure curve indicates a less than 10% risk of silicosis. If the respirable quartz concentration is increased to 0.2 mg/m^3, the cumulative exposure increases to 4 mg/m^3 and the cumulative exposure curve indicates a silicosis risk of greater than 50% (5).

The South African Department of Labour's National Programme for the Elimination of Silicosis states that dust control programmes are inadequate in the mining sector, as well as in the rest of industry (6). It furthermore states that a large burden of silicosis exists within previously exposed industry workers, and that silicosis is common in the industry especially in the gold mining industry (6).

A SIMRAC report (SIM020603), stated that during 1999 the National Centre for Occupational Health published data on 26 000 underground dust measurements from 48 gold mines in South Africa; of the 48 mines, only eight (17%) had an estimated time weighted average below the OEL of 0.1 mg/m^3 (7). In view of the burden to health, the researchers concluded that more effective control measures are required to reduce quartz concentrations in mines, other industries and particularly in gold mines.

Furthermore, the Mine Health and Safety Council (MHSC) presented new milestones for the mining industry related to preventing occupational diseases during the 2014 Mine Occupational Health and Safety Summit (8).

The milestone for the prevention of silicosis states that, "by December 2024, 95% of all exposure measurement results will be below the milestone level for respirable crystalline silica of 0.05 mg/m^3 (these results are individual readings and not average results)." In addition, the milestone specifies that, "using present diagnostic techniques, no new cases of silicosis will occur amongst *previously unexposed individuals* (*previously unexposed individuals* are those unexposed to mining dust prior to December 2008 i.e. equivalent to a new person who entered the industry in 2009)" (8).

1.1 LITERATURE REVIEW

1.1.1 Dust and crystalline silica (quartz)

Exposure to silica during mining operations is very likely as silica can be present in almost every mineral deposit and rock type. The silica content in rock may differ greatly; in some rock types such as sandstone and quartz it can be as high as 90% and more (9).

Airborne dust particulates are generated by various mining activities. Below are a few of these activities specific to underground mining operations (9):

1) Drilling and blasting of rock
2) Scraping and sweeping of ore

3) Barring and making safe
4) Primary and secondary support
5) Loading, transport and tipping of ore
6) Rock crushing, conveyor transport of ore and hoisting of ore
7) Backfill placement and spillage

1.1.2 Particle sizes

Figure 1 shows the ISO/ACGIH/CEN curve used internationally to classify particulate sizes in three categories (10).

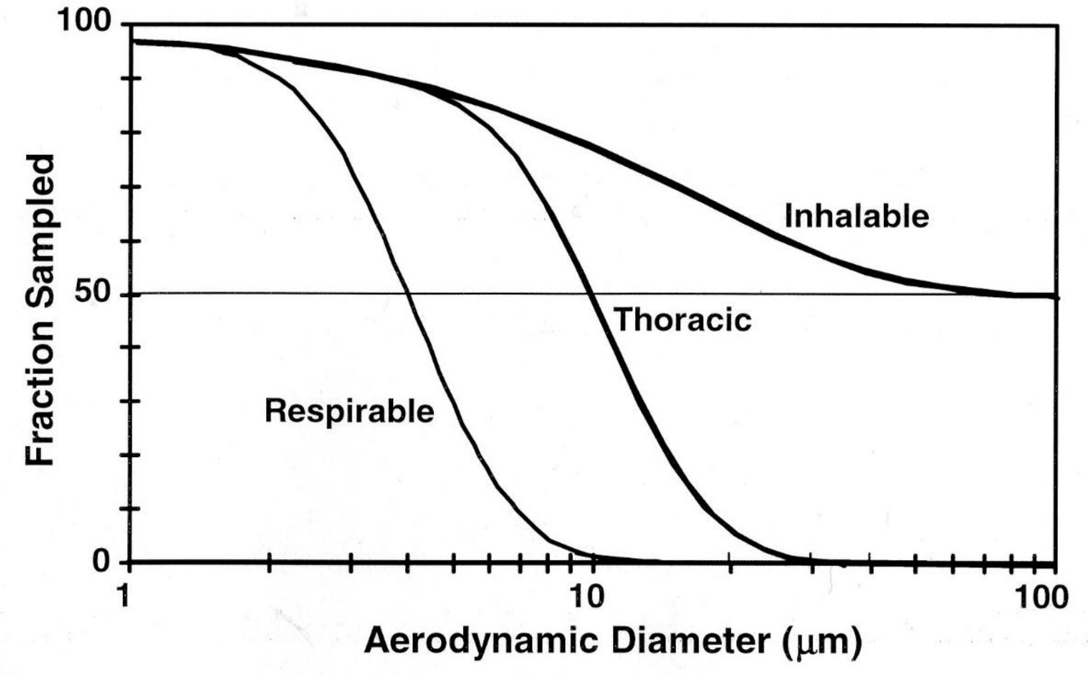

Figure 1: ISO/ACGIH/CEN sampling conventions [ISO 1995] (10).

Particulate sizes are categorised in three broad categories:

1) Inhalable particulate fraction has a 50% cut-point of 100 µm. Inhalable particulate is normally deposited in the nose, throat and trachea (10).
2) Thoracic particulate fraction has a 50% cut-point of 10 µm. Thoracic particulate can penetrate the lungs' airways (10).
3) Respirable particulate fraction has a 50% cut-point of 4 µm and is considered to be most dangerous as they can pass into the gas exchange region of the lungs (10).

1.1.3 Health risk

The Health and Safety Executive (UK) explains that extended periods of exposure to respirable quartz can cause fibrosis of lung tissue and lead to loss of lung function. Silicosis may have a significant impact on health, depending on severity. Sufferers of severe silicosis will experience shortness of breath, and will tire quickly. Affected individuals often become unable to work and even confined to their homes and beds. Premature death may occur (11).

The National Institute for Occupational Health and Safety (USA) describes three types of silicosis:

1) Simple chronic silicosis can occur after long-term exposure (20 years and more) to low concentrations of respirable quartz. This could cause swelling in the lungs and chest lymph nodes. Diseased persons may have difficulty with breathing. This is considered to be the most common form of silicosis (3).
2) Accelerated silicosis results from higher concentration exposure to respirable quartz over shorter exposure periods (5 - 15 years). Symptoms such as swelling in the lungs and others present faster than in simple chronic silicosis (3).
3) Acute silicosis results from very high concentration exposures to respirable quartz over short exposure periods. The lungs can become inflamed and also fill with fluid. Diseased persons could experience severe shortness of breath and also have low blood oxygen levels (3).

1.1.4 Prevalence of silicosis

During 2000 and 2001, a study was conducted amongst a sample of 520 black gold mine workers in South Africa. The study indicated that a high prevalence (18 - 19%) of radiological silicosis existed among gold mine workers still in-service and over the age of 37 years (12).

During 1975, three percent (3%) of deceased gold mine workers were found to have silicosis at autopsy (13). This proportion increased to 32% in 2007 (13). However, silicosis is not the only health risk associated with respirable quartz exposure. Silicosis is known to substantially increase the risk of contracting tuberculosis (14). In addition, tuberculosis is associated with respirable quartz exposure, even in the absence of silicosis (15).

There is no treatment available for silicosis. In the absence of treatment or a cure, silicosis can only be controlled by preventing exposure to respirable quartz (3).

1.1.5 Controls for the reduction of respirable crystalline silica exposure

The hierarchy of controls is summarised by the Centres for Disease Control and Prevention (CDC) as follows (16).

1) Elimination and Substitution

As quartz is part of the ore being mined in the gold mining industry, the elimination and substitution are not considered viable options in controlling quartz exposures in the South African mining industry. The next level of control to be considered is engineering controls (9).

2) Engineering controls

Engineering controls should be considered as the most important control measure, as these can play a major role in controlling and reducing quartz exposures. These controls include measures such as dust dilution by ventilation, dust filtration systems, local exhaust ventilation systems, water spray systems, dust scrubber systems and air-conditioned cabins for mechanised equipment (9).

3) Administrative controls

Administrative controls such as worker training and education, removal of workers from workings during blasting times and limiting of exposure time also assist in controlling and reducing exposure to respirable quartz (9).

4) Personal protective equipment

Personal protective equipment such as respirators can also play an important role in controlling respirable quartz exposures, but the effectiveness of respirators also depends on various factors that have to be managed. Respirators are considered to be the last line of defence and should only be considered once all else fails (9).

1.1.6 Use of water sprays as an engineering control measure

Water sprays are among the oldest and most commonly used methods of dust control. The principle of operation is that as the fine dust becomes wet, the weight increases and prevents dust from becoming airborne or airborne dust will settle from the air (17).

The effectiveness of water spray systems depends on factors such as nozzle type, spray pattern, nozzle placement, droplet size, water pressure, water quality, water and airflow rates and maintenance of equipment (17).

Smaller water droplet size is more efficient as it comes into contact with the dust particle. If water droplets are much greater than dust particles, dust particles do not make contact with water droplets and just flow around the water droplets. Figure 2 illustrates this concept.

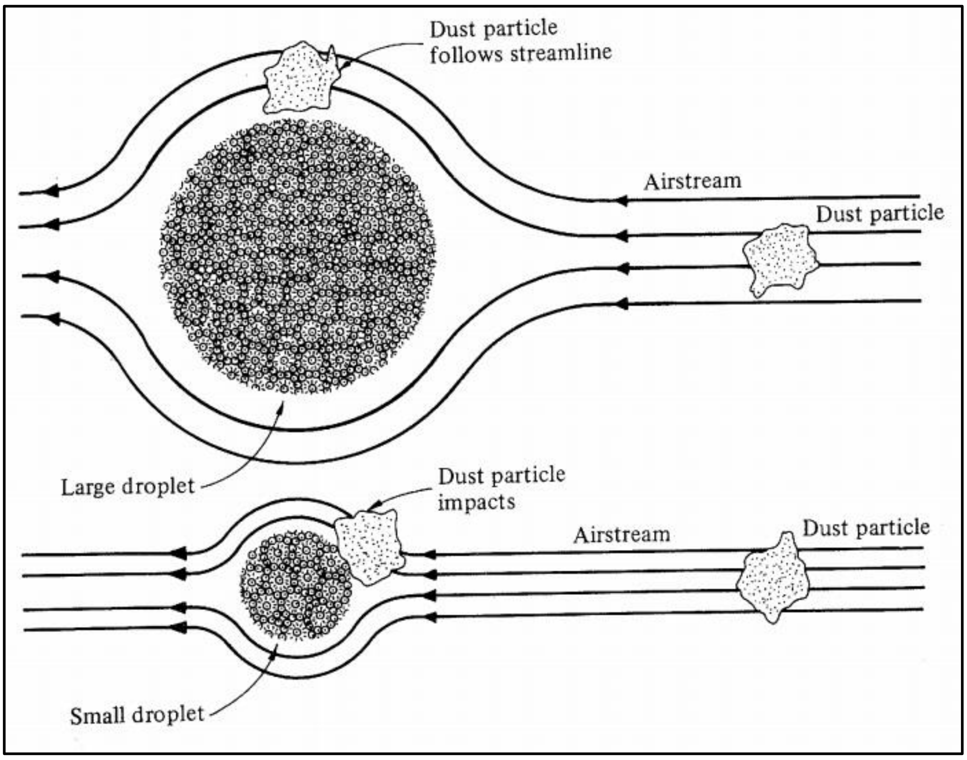

Figure 2: Airflow around large and small water droplet (18).

A study conducted in a gold mine during 2008 evaluated the effectiveness of a high-pressure water spray system installed at a tipping point. The study concluded that an improvement of between 89% and 91% was observed in respirable quartz concentration (19).

The water spray system evaluated during this study, sprayed water into the airstream to suppress and remove the dust and quartz from the air. The system comprised nine spray heads, each spray head was fitted with seven spray nozzles. The water flowrate was 0.3 litres per second at 30 bar, thus 160 litres per minute. Figure 3 shows the spray heads utilised for this system.

Figure 3: Spray heads utilised for the spray system.

1.2 STUDY MOTIVATION

In order to reduce respirable quartz exposures, effective control measures will be required to assist in bulk scrubbing of intake air to mine workings. This study was designed to evaluate a control measure being considered in reducing respirable quartz exposures.

This study was conducted to review data collected during an experimental study, conducted during 2010; the data comprises pre- and post-intervention personal and static gravimetric measurements for respirable dust and respirable quartz. The intervention is a high-pressure water spray system installed in a major intake airway and evaluated for its effectiveness, as a possible dust suppression engineering control.

Should this system be sufficiently effective in reducing respirable dust and respirable quartz concentrations, it could be installed in mine intake airways within the mining and especially the gold mining industry, as part of a respirable quartz control strategy. Ultimately, the system has the potential to reduce worker exposure to respirable quartz and eventually reduce the incidence and prevalence of silicosis.

1.3 OBJECTIVES

The aim of this study is to assess the effectiveness of a high-pressure water spray system, as a possible respirable quartz engineering control. To achieve this aim, four objectives were identified:

1) To describe the respirable quartz exposures among workers in the sub-shaft bank area of a gold mine during 2010.
2) To assess the effectiveness of the engineering control measure by comparing pre- and post-control personal respirable quartz exposures at the sub-shaft bank area in a gold mine during 2010.
3) To assess the effectiveness of the engineering control measure by comparing pre-and post-control static respirable quartz concentrations at the sub-shaft bank area in a gold mine during 2010.
4) To assess to what extent, the respirable quartz exposures have been reduced (at the sub-shaft bank area in a gold mine during 2010), by comparing respirable quartz exposures to national and international limits of exposure.

2 METHODOLOGY

2.1 STUDY DESIGN

The study is a secondary analysis of data collected from an experimental study concluded during 2010, with pre- and post-intervention personal and static gravimetric measurements for respirable quartz exposures. Results from the previous study were reported only as descriptive statistics with minimums, maximums and means.

For this review of data, results for pre- and post-intervention measurements were compared to establish if the reduction in both the personal and static respirable quartz exposures observed is statistically significant. The intention was to assess if the dust suppression engineering control measure was effective by comparison to baseline exposure, as well as to national and international limits.

2.2 STUDY SETTING

The primary study was conducted at a gold mine in the West Witwatersrand area close to Carletonville during September 2010. The workplace identified for this study was the sub-shaft bank area. This specific workplace was suggested by the mine because there were concerns about high respirable quartz exposures. Measurements conducted prior to this study confirmed that this workplace did indeed pose a high risk in terms of respirable quartz exposures.

This area serves as a major intake of fresh air to the rest of the mine as approximately 160 m^3/s of air passes through this area. Any contamination of this fresh intake air could affect the rest of the mine, exposing the rest of the workforce to high levels of respirable dust and respirable quartz. The high concentration of respirable dust and quartz is generated by shaft activities such as rock hoisting and backfill spillages, which then contaminates the intake air.

A high-pressure water spray system was installed on the bank of the rock and ventilation shaft, in the intake air to the rest of the mine. The purpose of the system was to scrub hazardous respirable quartz from the intake air. See Figure 4 for a pictorial representation.

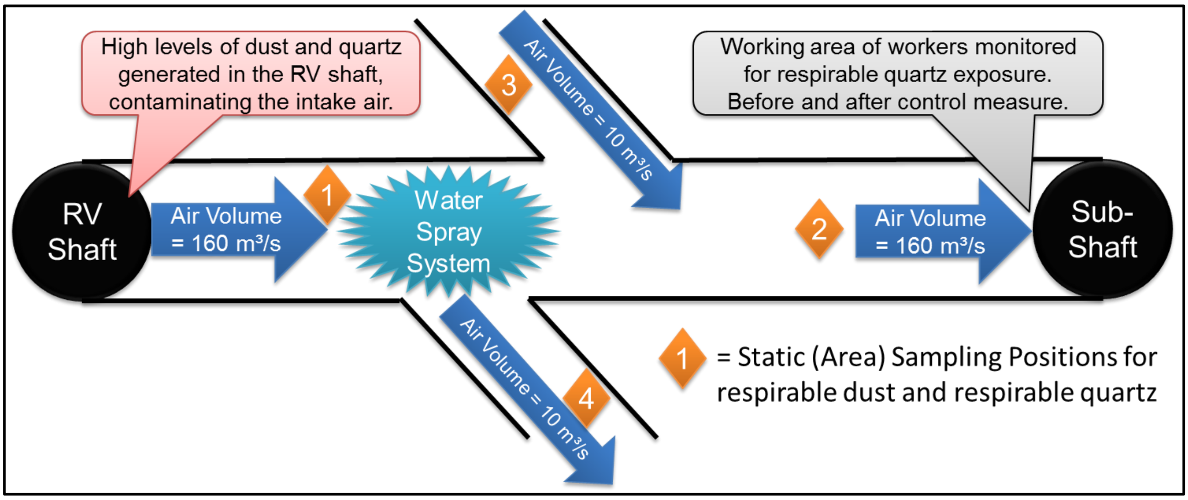

Figure 4: Indicating the position of the water spray system, sampling positions of static sampling and position of workers sampled.

The 10 m^3/s of air from position 3 was considered to have little effect on the total 160 m^3/s at position 4; in fact, from the results observed during measurement the mean dust load from position 3 was higher (0.1 mg/m^3) than that of position 4 (0.068 mg/m^3); indicating that the expected reduction in respirable dust and associated respirable quartz across the water spray system might be even greater.

2.3 SAMPLING STRATEGY

There were five employees working at the sub-shaft bank area. All employees were fitted with personal samplers in this working area. Sampling was conducted for six full shifts, thus a total of 30 samples for pre-intervention/control measurements were taken. The same procedure was followed for the post-intervention/control measurements. A total of 60 personal samples were collected for measuring respirable quartz exposure.

In addition to the personal sampling, static (area) samples were also collected. Static sampling consisted of four samples being taken over six shifts; thus, a total of 24 samples were collected for the pre-control measurements. The same procedure was carried out for the post-control measurements. Thus, a total of 48 static (area) respirable quartz concentration samples were collected.

2.4 MEASUREMENT PROCEDURES

Sampling was conducted as per national and international standards i.e. the Department of Mineral Resources Guidelines and the Health and Safety Executive

(HSE) Methods for the Determination of Hazardous Substances (MDHS) 14/4 (20).

Full shift personal gravimetric sampling was conducted to determine respirable quartz exposures. Calibrated gravimetric sampling pumps were issued to workers at the working place at the start of the shift, and collected at the end of the shift.

Gravimetric samplers were attached to the worker within the breathing zone of the worker for a full shift. Figure 5 shows how the pump is attached to the worker.

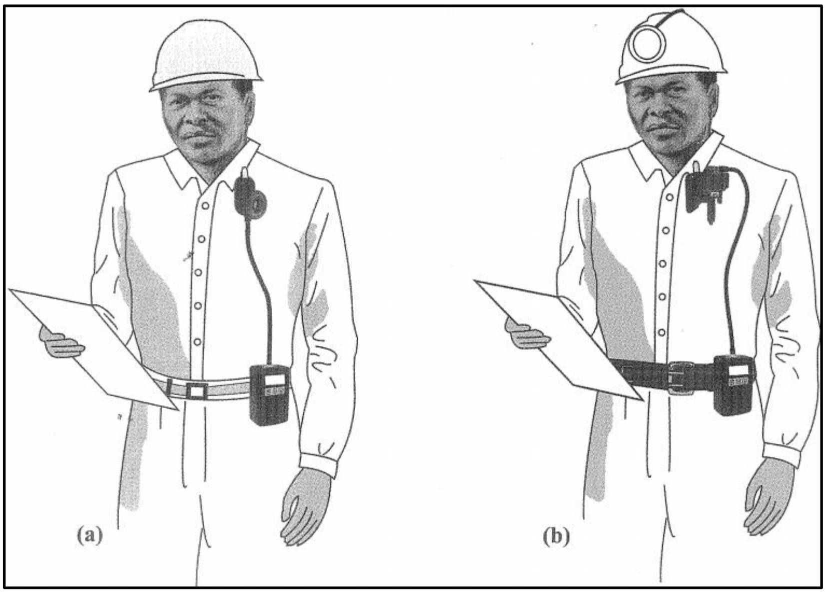

Figure 5: Worker with sampling pump and filter unit in the breathing zone (21).

Full shift static (area) gravimetric sampling was conducted to determine respirable quartz concentrations. Calibrated gravimetric sampling pumps were placed at identified positions by a competent person, in possession of a Certificate in Mine Environmental Control. Pumps were placed at the start of the shift and collected at the end of the shift.

Filters used for sampling were weighed before and after sampling to establish the weight and calculate the Time Weighted Average (TWA) for the respirable quartz concentration. Analysis for silica was performed, using X-Ray Diffraction (XRD).

2.5 QUALITY CONTROL

All gravimetric samplers' flow rates were calibrated to 2.2 (± 5%) litres per minute before sampling, and all gravimetric samplers' flow rates were checked after sampling to be within ± 5% of the calibrated value. All calibrations were conducted with a calibrated Gilibrator within its calibration interval.

All calibration was conducted by a competent person, in possession of a Certificate in Mine Environmental Control. Flow rates from calibrations and checks were recorded and used to assess measurements' validity and accuracy.

Filters used for sampling were weighed before and after sampling by a South African National Accreditation System (SANAS) accredited laboratory. Sample Analysis for silica was performed at the same accredited laboratory, using X-Ray Diffraction (XRD) analysis. XRD analysis was performed as prescribed in Health and Safety Executive (HSE) Methods for the Determination of Hazardous Substances (MDHS) 101/2 (22).

The detection limit for XRD analysis was determined as three times the standard deviation of the response of 145 unused filters and was calculated as 8 µg. This method represents a 99% confidence level.

2.6 DATA ANALYSIS

All data obtained from the primary study was captured in Microsoft Excel. This study also utilized Microsoft Excel 2016 and the added data analysis tool pack to analyse data and produce box and whisker graphs, as well as tables to summarize and graphically present the results. All other tests such as F-tests and T-tests were also done in Microsoft Excel 2016.

2.6.1 Objective one

Workers' respirable quartz time weighted average exposures were assessed and compared to the South African Occupational Exposure Limit (OEL) of 0.1 mg/m³ to establish the extent of worker exposure. Measurements were categorised in ranges relative to the South African Occupational Exposure Limit.

2.6.2 Objectives two and three

Descriptive statistics were used to describe the personal respirable dust and respirable quartz exposures of the exposed workers. This includes pre- and post-control measurement data. The same statistical analysis was applied to the static measurements collected during this study.

In addition to the basic descriptive statistics (mean, minimum and maximum) of data described in the 2010 study, the following statistics were also calculated and described:

- Number of samples
- Minimum
- Maximum
- Geometric Mean
- Geometric standard deviation
- Inter-quartile range
- 90th percentile

Box and whisker graphs were used to indicate descriptive statistics such as means, minimums, maximums and inter-quartile range to compare pre- and post-control measurement data.

For objective two, the descriptive statistical data for the personal respirable dust and respirable quartz exposures was used to establish if the difference between pre- and post-control data was statistically significant. This was done by means of a T-Test by comparing the pre- and post-control data sets. The null hypothesis assumed that there is no difference in comparing the means from pre- and post-control data sets, and an alpha value of 0.05 was used. The alternate hypothesis is that there is a difference in comparing the means from pre- and post-control data sets, and an alpha value of 0.05 was used. An F-test was conducted to establish equal or unequal variance of the data set.

For objective three, the descriptive statistical data for the static respirable dust concentrations was used to establish if the difference between pre- and post-control data was statistically significant. This was done by means of a T-Test by comparing the pre- and post-control data sets. The null hypothesis assumed that there is no difference in comparing the means from pre- and post-control data sets, and an alpha value of 0.05 was used. The alternate hypothesis is that there is a difference in comparing the means from pre- and post-control data sets, and an alpha value of 0.05 was used. An F-test was conducted to establish equal or unequal variance of the data set.

2.6.3 Objective four

To assess the extent of the control measure effectiveness for respirable quartz, the descriptive statistical data was compared to national and international limits of exposure. The specific limits are listed below:

- South African Occupational Exposure Limit (OEL) of 0.1 mg/m³ (23),
- The National Institute for Occupational Safety and Health's (NIOSH) Recommended Exposure Limit (REL) of 0.05 mg/m³ (24), and
- The American Conference of Industrial Hygienist's (ACGIH) Threshold Limit Value (TLV) of 0.025 mg/m³ (25).

2.7 STUDY LIMITATIONS

One limitation not considered during the study is other sources of respirable quartz downstream of the control measure. It is hypothesised that this does not play a major role, as activities in this area remained similar during the pre- and post-control measurements.

Another limitation for the study was the fact that real-time dust measurements could not be collected. For this reason, gravimetric sampling was conducted over a full shift of 8 hours. This is in fact an averaged measurement over a full shift of 8 hours.

In addition, only one test site was available, it would have been helpful if the study could have been repeated at other sites.

As this study is a secondary data analysis of a primary study conducted during 2010, the site cannot be revisited to answer any unanswered questions.

3 RESULTS

3.1 SUB-SHAFT BANK AREA WORKERS EXPOSURES

Table 1 contains data of respirable dust and respirable quartz exposures obtained from personal measurements of workers at the sub-shaft bank area. Measurements were done before any engineering control measure was introduced, and they were conducted over all shifts (morning, afternoon and night). Respirable dust and respirable quartz exposures are expressed as a Time Weighted Average over 8 hours (TWA,8h) expressed in units of mg/m^3.

Respirable quartz exposure measurements indicated in red exceed the South African Occupational Exposure Limit of 0.1 mg/m^3. An interesting observation is that all the respirable quartz exposures that exceeded the South African Occupational Exposure Limit were measured during afternoon and night shifts. These are normally the shifts when most rock hoisting is conducted.

Table 1: Respirable dust and respirable quartz exposure measurements of workers at the sub-shaft bank area.

Occupation	**Shift**	**Respirable Dust Exposures [TWA,8h] (mg/m³)**	**Respirable Quartz Exposures [TWA,8h] (mg/m³)**
Banksman	Morning	0,076	0,013
Assistant	Morning	0,047	0,016
Assistant	Morning	0,038	0,017
Assistant	Morning	0,038	0,015
Assistant	Morning	0,056	0,017
Assistant	Morning	0,302	0,060
Banksman	Morning	0,271	0,066
Assistant	Morning	0,336	0,089
Assistant	Morning	0,281	0,078
Assistant	Morning	0,297	0,089
Onsetter	Afternoon	0,290	0,056
Banksman	Afternoon	0,283	0,064
Assistant	Afternoon	0,097	0,015
Assistant	Afternoon	0,270	0,059
Assistant	Afternoon	0,137	0,026
Banksman	Afternoon	0,389	0,077
Assistant	Afternoon	0,660	0,122*
Assistant	Afternoon	0,781	0,166*
Onsetter	Afternoon	1,662	0,302*
Assistant	Afternoon	1,637	0,277*
Banksman	Night	0,801	0,121*
Onsetter	Night	0,858	0,122*
Assistant	Night	0,835	0,125*
Assistant	Night	0,747	0,111*
Assistant	Night	0,839	0,153*
Banksman	Night	0,088	0,009
Assistant	Night	0,114	0,010
Assistant	Night	0,077	0,008
Assistant	Night	0,142	0,013
Onsetter	Night	0,086	0,008

** Values exceeding the South African Occupational Exposure Limit (OEL) of 0.1 mg/m³ indicated in red.*

A total of 30 measurements were obtained. The mean respirable quartz exposure TWA was 0.076 mg/m³; this is greater than 50% of the South African Occupational Exposure Limit of 0.1 mg/m³. The 90th percentile of 0.154 mg/m³ exceeded the South African Occupational Exposure Limit by approximately 50%.

The distribution in range of the measurements, compared to the South African Occupational Exposure Limit, is shown in Table 2.

Table 2: Range distribution of exposure measurements.

Range	**Percentage of measurements**
Greater than 100% of SA OEL	30% (9 measurements)
Greater than 50%, but less than 100% of SA OEL	30% (9 measurements)
Greater than 10%, but less than 50% of SA OEL	30% (9 measurements)
Less than 10% of SA OEL	10% (3 measurements)

Note: The South African Occupational Exposure Limit (OEL) for respirable quartz is 0.1 mg/m³.

3.2 PERSONAL RESPIRABLE DUST AND RESPIRABLE QUARTZ EXPOSURES

Table 3 and Table 4 include descriptive statistics to summarise the data for personal respirable dust and respirable quartz exposure, for pre- and post-control measurements. Respirable dust and respirable quartz exposures are expressed as a Time Weighted Average over 8 hours (TWA,8h) expressed in units of mg/m³.

Table 3: Personal respirable dust exposure including pre- and post-control measurements taken for all shifts.

	All Shifts		**Morning Shift**		**Afternoon Shift**		**Night Shift**	
	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control
Number of samples	30	27	10	9	10	9	10	9
Minimum (mg/m³)	0,038	0,009	0,038	0,019	0,097	0,019	0,077	0,009
Maximum (mg/m³)	1,662	0,009	0,336	0,019	1,662	0,019	0,858	0,009
Geometric mean (mg/m³)	0,418	0,061	0,174	0,050	0,621	0,057	0,459	0,075
Geometric standards deviation (mg/m³)	0,436	0,044	0,131	0,023	0,582	0,019	0,378	0,070
Inter-quartile range (mg/m³)	0,635	0,029	0,243	0,029	0,478	0,019	0,732	0,128
90th percentile (mg/m³)	0,841	0,137	0,305	0,073	1,639	0,071	0,841	0,159
P value	0,0001		0,0159		0,0058		0,0104	
Percentage reduction of mean	85%		71%		91%		84%	

Table 4: Personal respirable quartz exposure including pre- and post-control measurements taken for all shifts

	All Shifts		**Morning Shift**		**Afternoon Shift**		**Night Shift**	
	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control
Number of samples	30	21	10	8	10	8	10	5
Minimum (mg/m³)	0,0076	0,0076	0,0133	0,0076	0,0155	0,0076	0,0076	0,0076
Maximum (mg/m³)	0,3018	0,0076	0,0892	0,0076	0,3018	0,0076	0,1529	0,0076
Geometric mean (mg/m³)	0,0768	0,0096	0,0460	0,0076	0,1165	0,0076	0,0679	0,0160
Geometric standards deviation (mg/m³)	0,0750	0,0043	0,0332	0,0001	0,1012	0,0000	0,0624	0,0051
Inter-quartile range (mg/m³)	0,1025	0,0001	0,0583	0,0000	0,0981	0,0000	0,1122	0,0021
90th percentile (mg/m³)	0,1542	0,0173	0,0890	0,0077	0,2794	0,0076	0,1281	0,0200
P value	0,00003		0,00524		0,00364		0,02804	
Percentage reduction of mean	87%		83%		93%		77%	

Based on the descriptive statistics, a series of box and whisker graphs were prepared to compare pre- and post-control measurement data.

Box and whisker graphs describe and indicate the distribution of a dataset. The two boxes represent 50% of the data set (2nd and 3rd quartiles), with the median indicated by the line between the two boxes. The mean is indicated by the “X”, and the whiskers (lines extending from the boxes) represent the 1st and 4th quartile respectively. The outer limits of the lines indicate the minimum and maximum values for the data set. The box and whisker graphs also include the number of quantifiable measurements (n) and the number of measurements below the detection limit (BDL).

Figure 6 compares the workers’ level of exposure to respirable dust during all shifts, and includes pre- and post-control measurements. A reduction in mean respirable dust exposure concentrations of 85% was noted, from 0.418 mg/m³ to 0.061 mg/m³ (p-value of 0.0001).

Figure 7 compares the workers’ level of exposure to respirable quartz during all shifts, and includes pre- and post-control measurements. A reduction in mean respirable quartz exposure concentrations of 87% was noted, from 0.0768 mg/m³ to 0.0096 mg/m³ (p-value of 0.00003).

Figure 8 compares the workers’ level of exposure to respirable dust during morning shift, and includes pre- and post-control measurements. A reduction in mean respirable dust exposure concentrations of 71% was noted, from 0.174 mg/m³ to 0.050 mg/m³ (p-value of 0.01).

Figure 9 compares the workers’ level of exposure to respirable quartz during morning shift, and includes pre- and post-control measurements. A reduction in mean respirable quartz exposure concentrations of 83% was noted, from 0.0460 mg/m³ to 0.0076 mg/m³ (p-value of 0.005).

Figure 10 compares the workers’ level of exposure to respirable dust during afternoon shift, and includes pre- and post-control measurements. A reduction in mean respirable dust exposure concentrations of 91% was noted, from 0.621 mg/m³ to 0.057 mg/m³ (p-value of 0.005).

Figure 11 compares the workers' level of exposure to respirable quartz during afternoon shift, and includes pre- and post-control measurements. A reduction in mean respirable quartz exposure concentrations of 93% was noted, from 0.116 mg/m³ to 0.007 mg/m³ (p-value of 0.003).

Figure 12 compares the workers' level of exposure to respirable dust during night shift, and includes pre- and post-control measurements. A reduction in mean respirable dust exposure concentrations of 84% was noted, from 0.459 mg/m³ to 0.075 mg/m³ (p-value of 0.01).

Figure 13 compares the workers' level of exposure to respirable quartz during night shift, and includes pre- and post-control measurements. A reduction in mean respirable quartz exposure concentrations of 77% was noted, from 0.067 mg/m³ to 0.015 mg/m³ (p-value of 0.02).

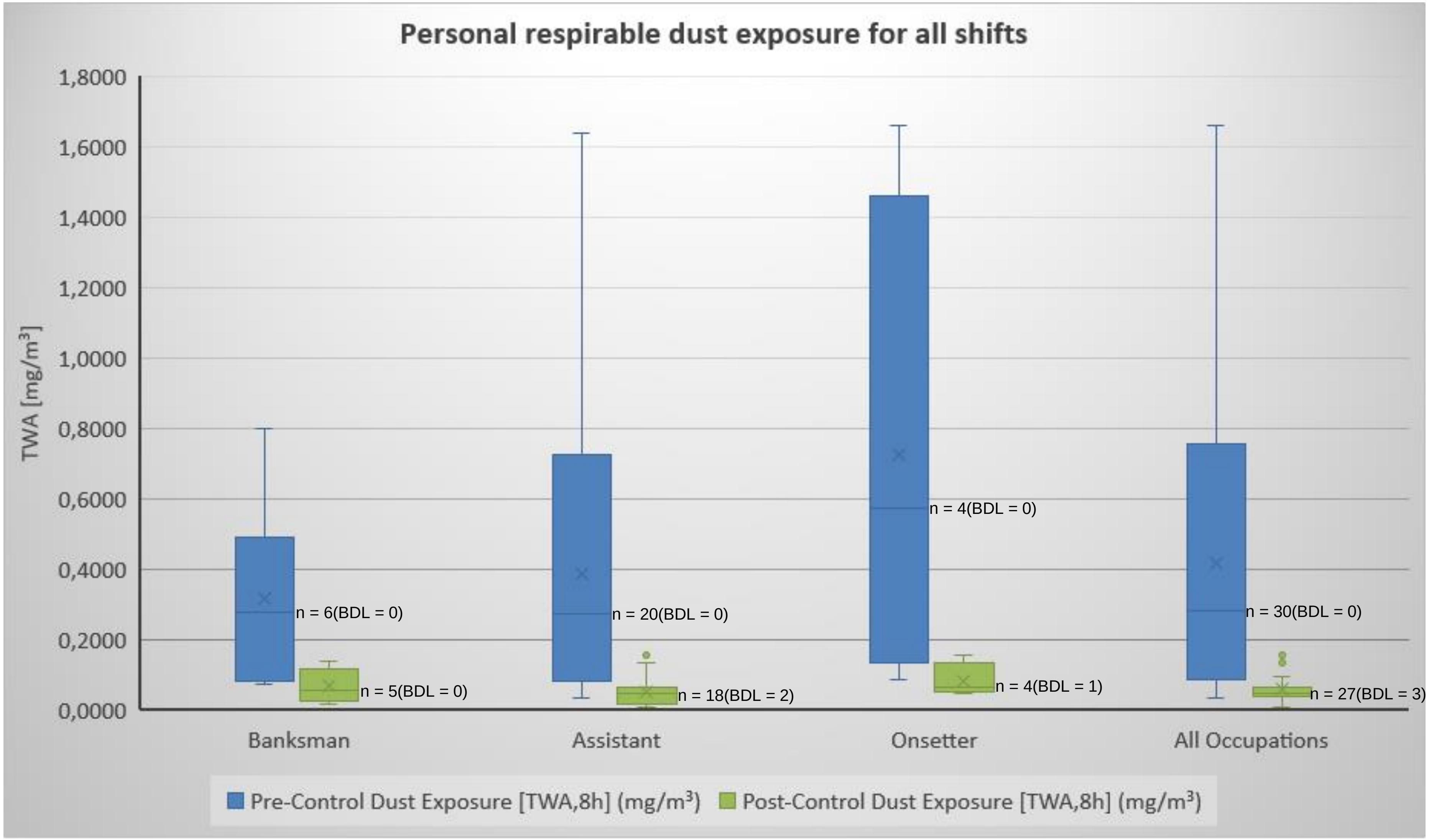

Figure 6: A “box and whisker” plot to summarise the personal respirable dust exposure for all shifts

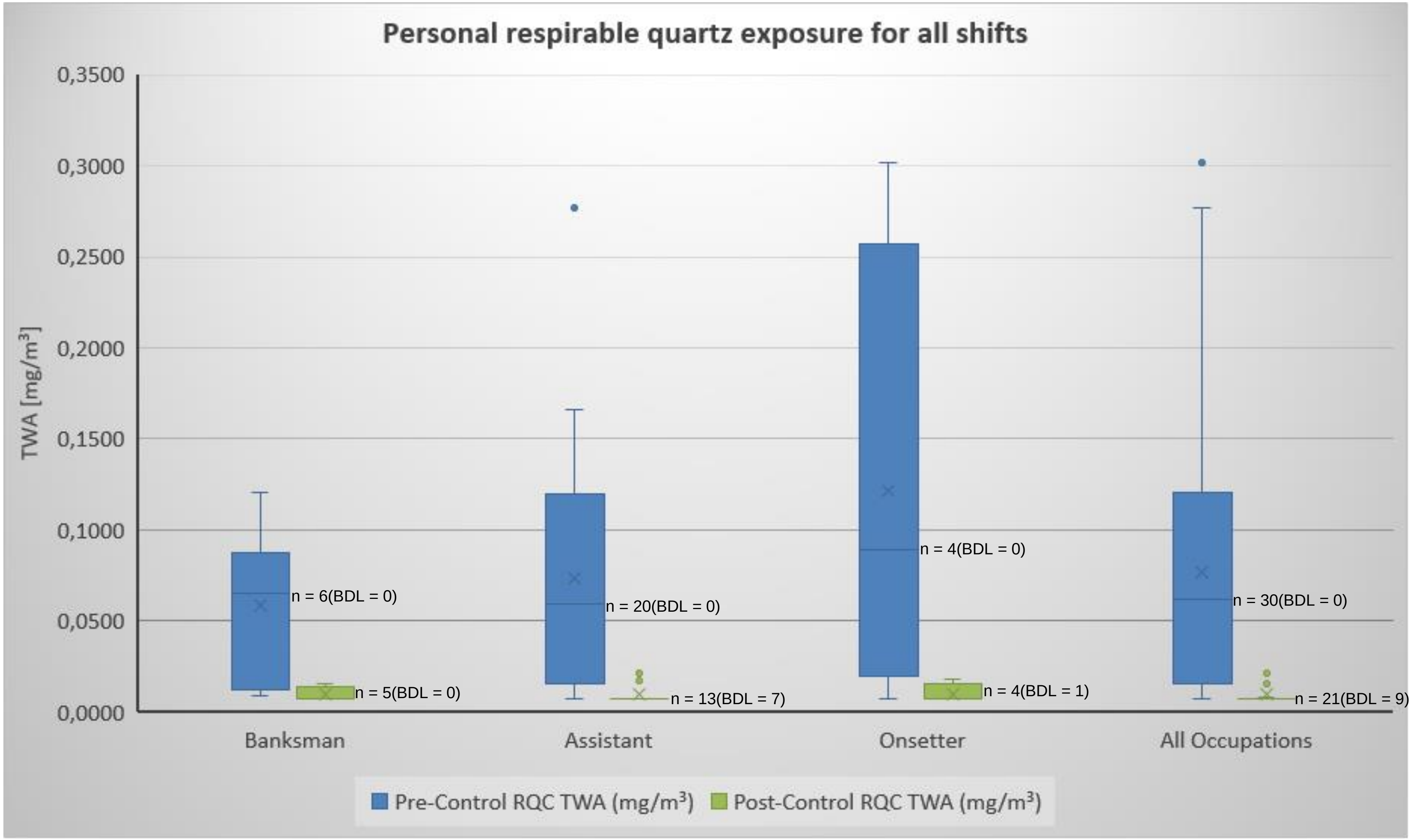

Figure 7: A “box and whisker” plot to summarise the personal respirable quartz exposure for all shifts

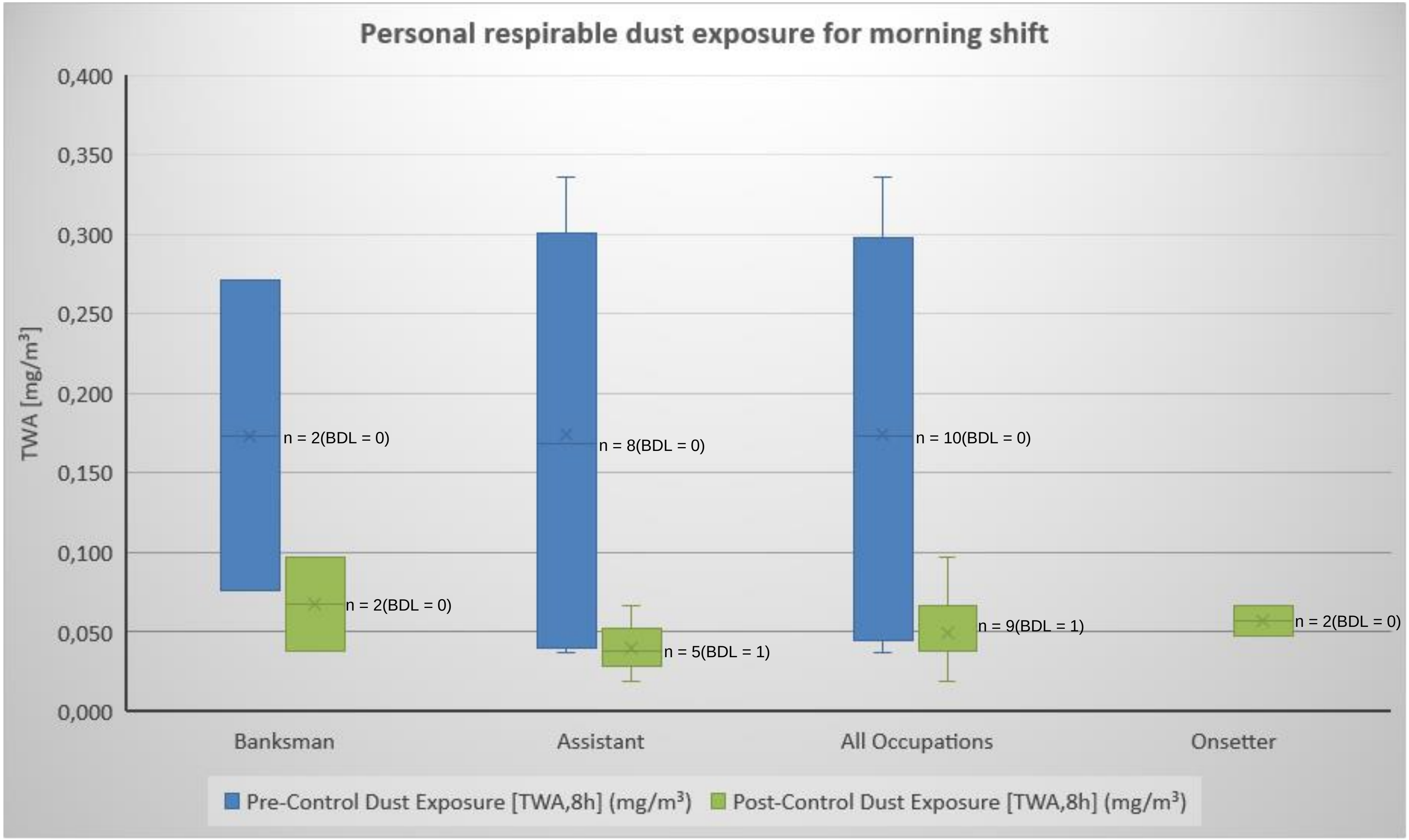

Figure 8: A "box and whisker" plot to summarise the personal respirable dust exposure for morning shifts

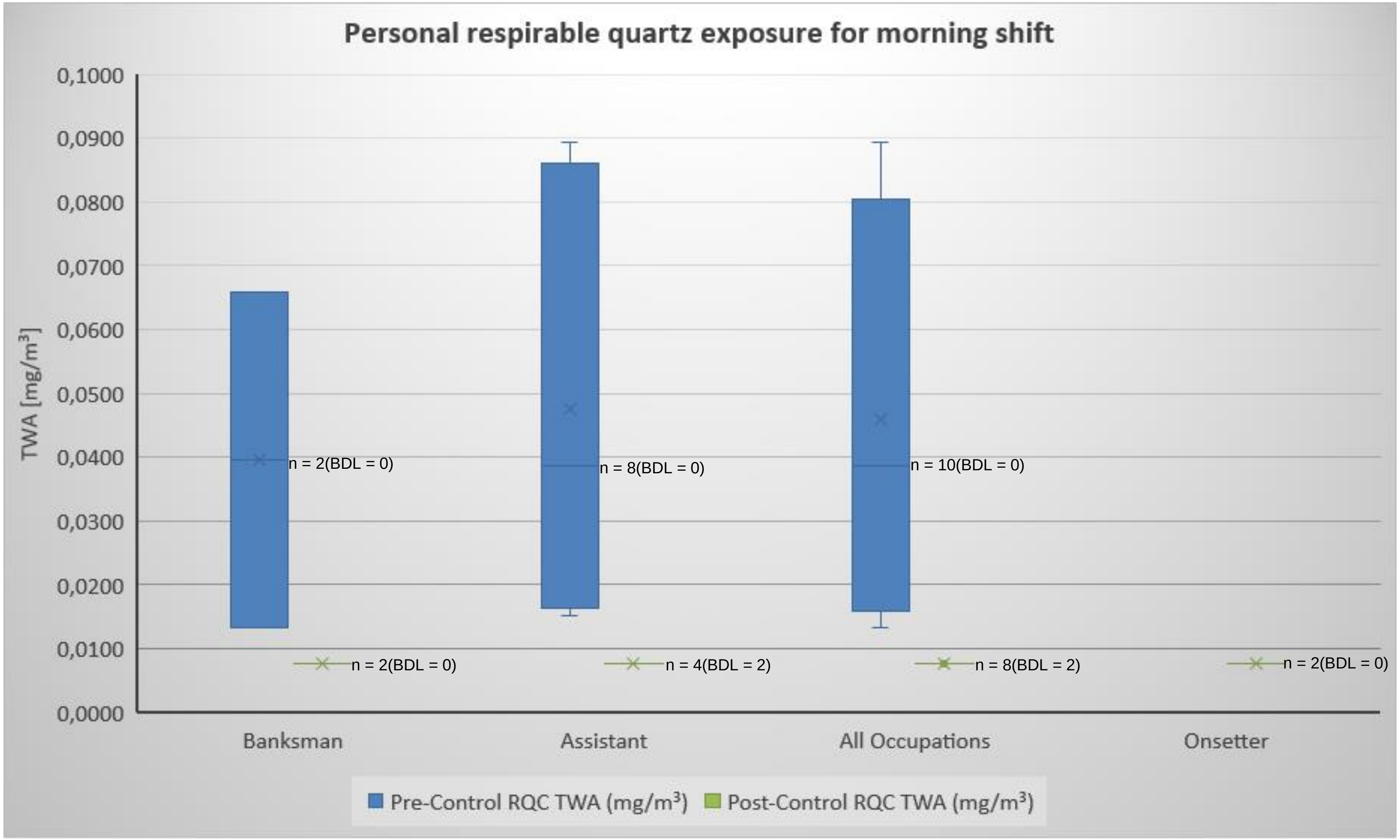

Figure 9: A "box and whisker" plot to summarise the personal respirable quartz exposure for morning shifts

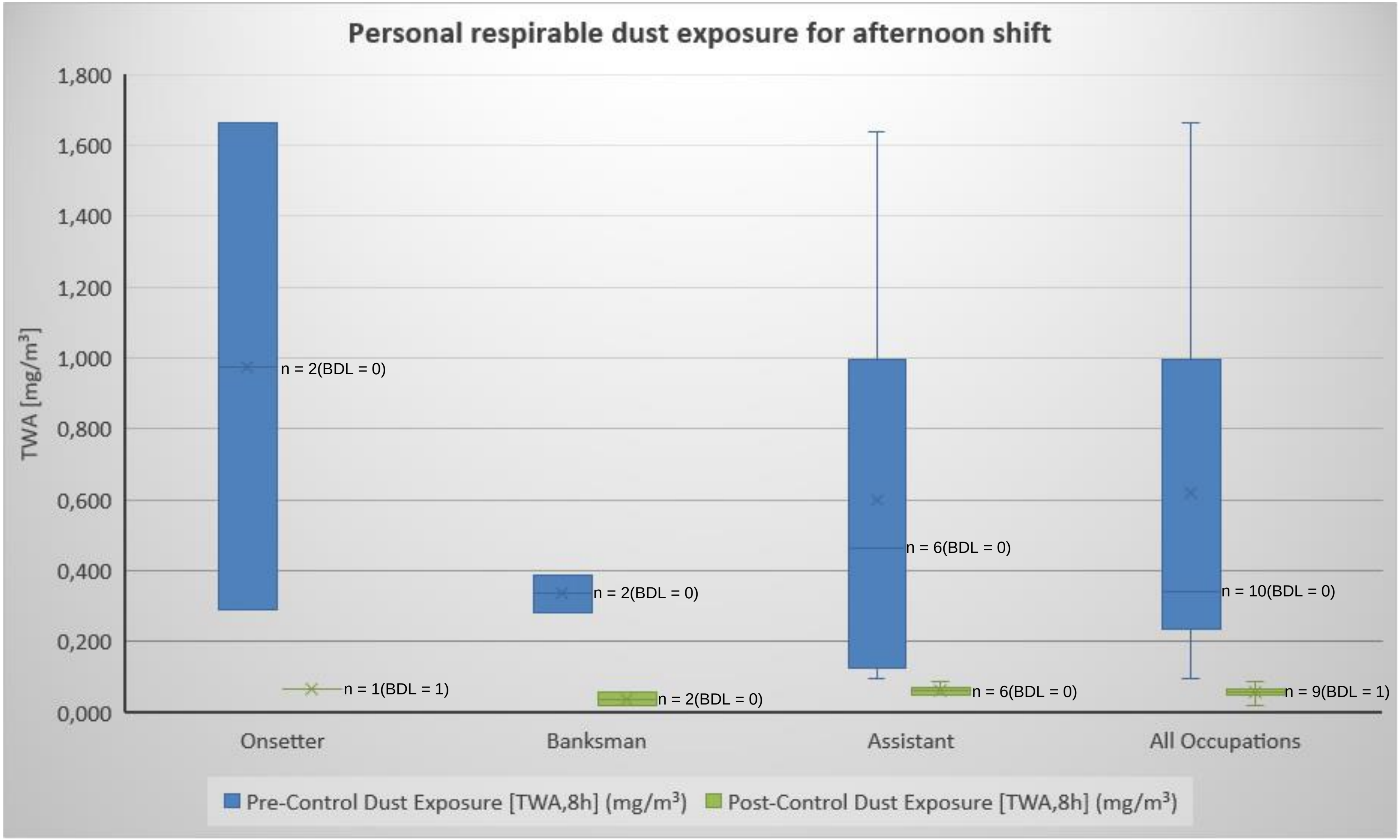

Figure 10: A "box and whisker" plot to summarise the personal respirable dust exposure for afternoon shifts

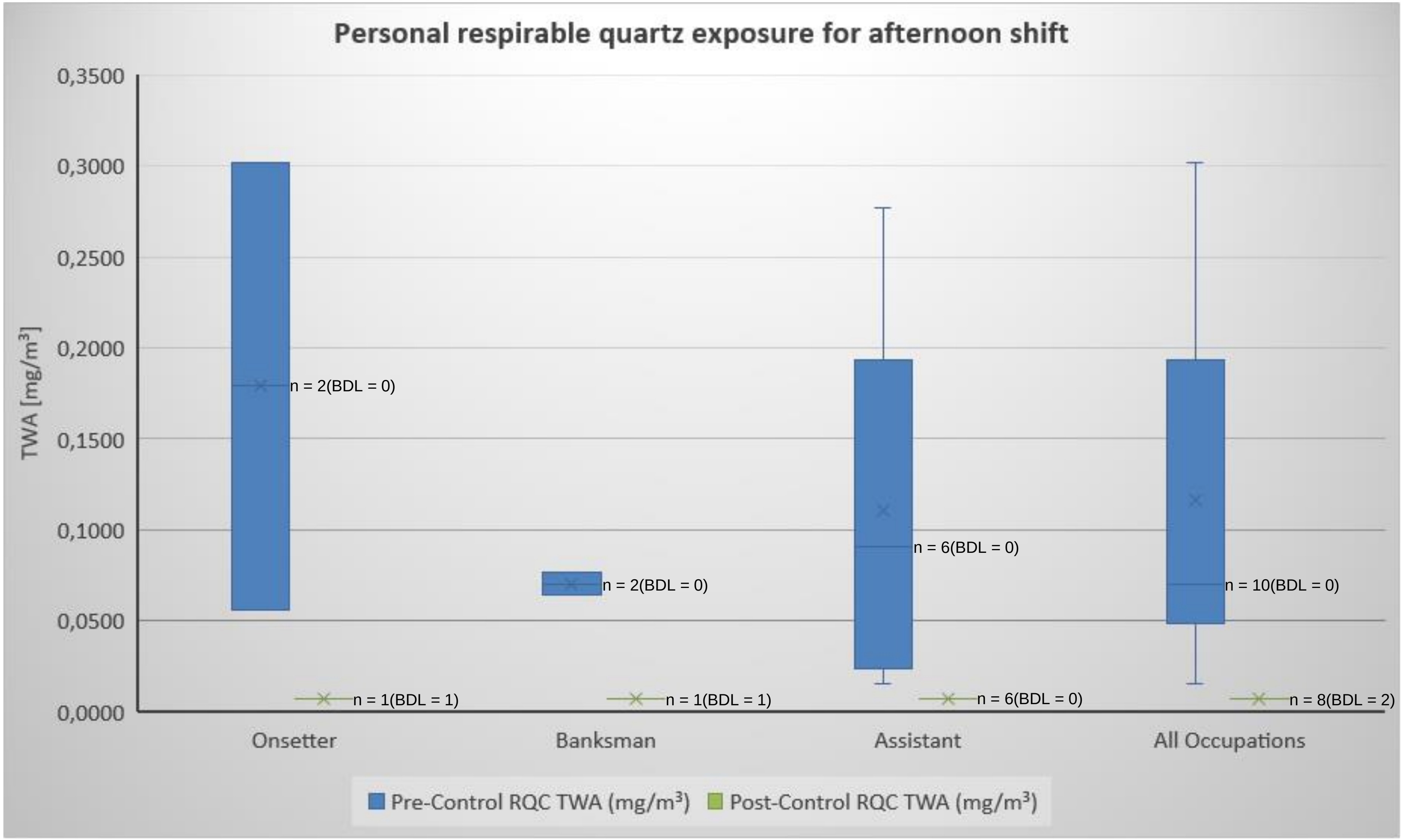

Figure 11: A "box and whisker" plot to summarise the personal respirable quartz exposure for afternoon shifts

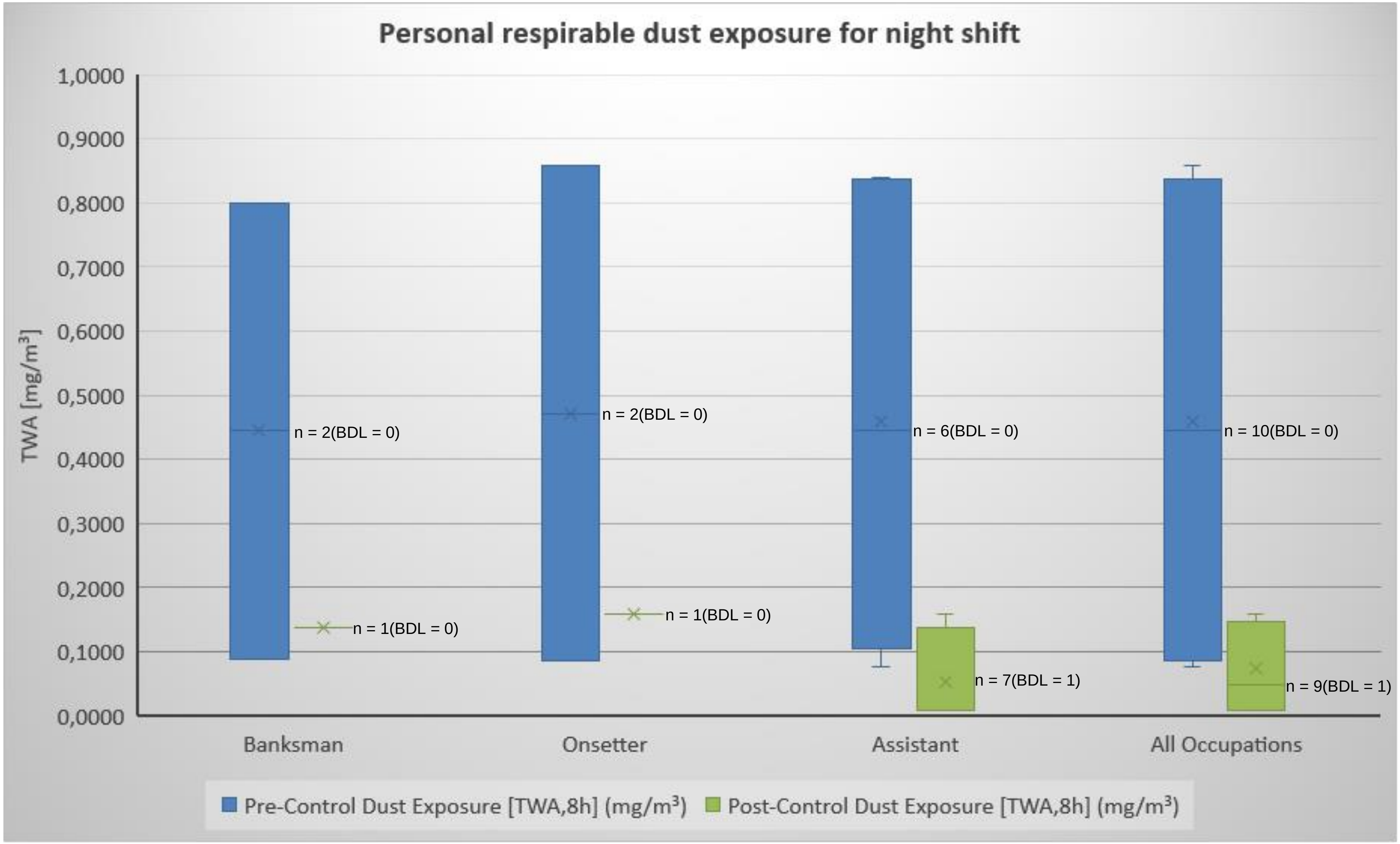

Figure 12: A "box and whisker" plot to summarise the personal respirable dust exposure for night shifts

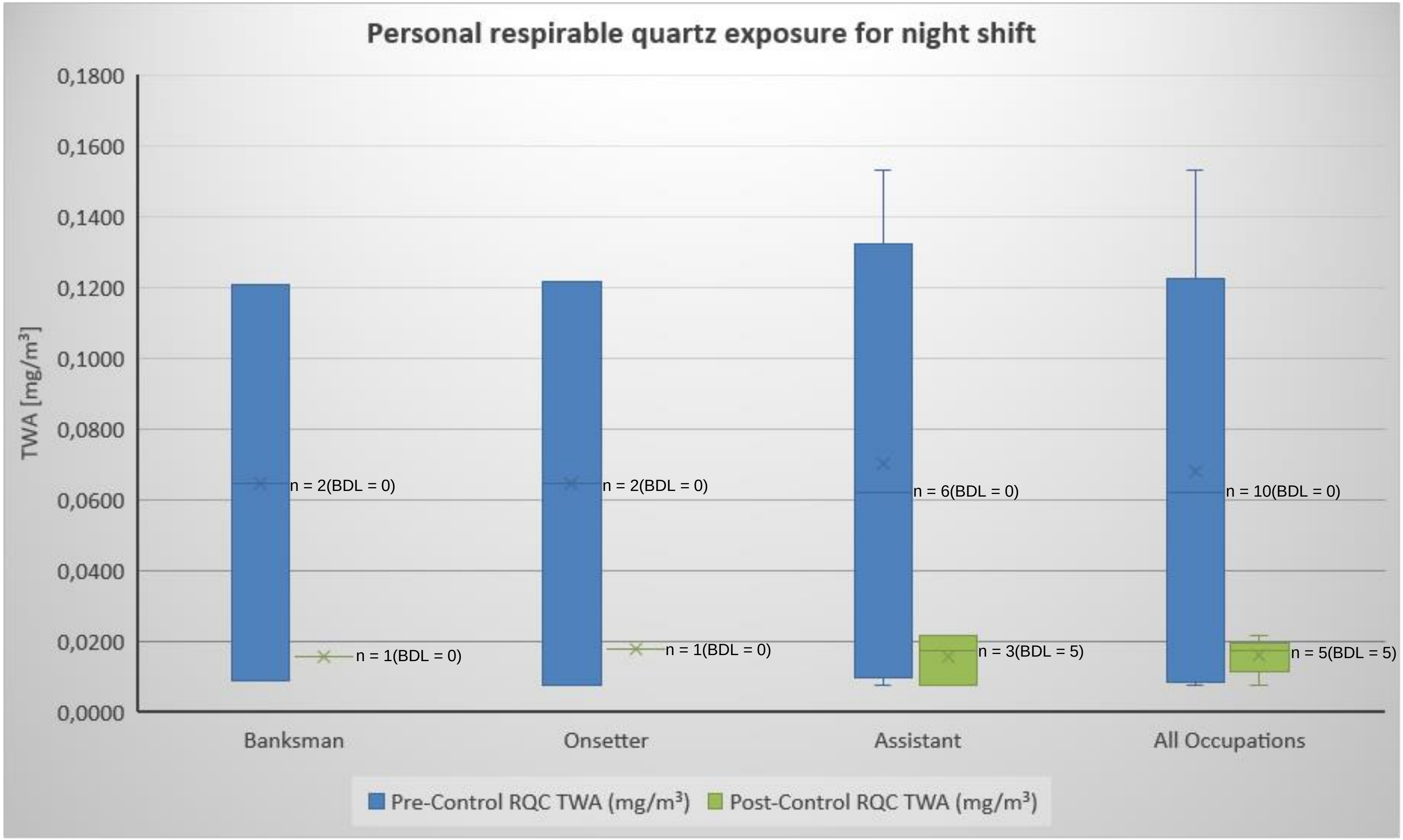

Figure 13: A "box and whisker" plot to summarise the personal respirable quartz exposure for night shifts

3.3 STATIC RESPIRABLE DUST CONCENTRATIONS

Table 5 summarises the data for static respirable dust measurements collected at the selected measuring positions (Figure 4), for pre- and post-control measurements and expressed in units of mg/m³.

Table 5: Static respirable dust concentration measurements obtained from all shifts

	Position 1		**Position 2**		**Position 3**		**Position 4**	
	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control	Pre-Control	Post-Control
Number of measurements	6	6	6	5	5	6	6	6
Minimum (mg/m³)	0,063	0,070	0,091	0,025	0,125	0,051	0,078	0,025
Maximum (mg/m³)	2,141	0,196	1,463	0,108	1,752	0,195	1,883	0,110
Geometric mean (mg/m³)	0,678	0,117	0,573	0,055	0,634	0,100	0,755	0,068
Geometric standards deviation (mg/m³)	0,742	0,055	0,535	0,032	0,639	0,052	0,663	0,031
Inter-quartile range (mg/m³)	0,242	0,082	0,665	0,017	0,050	0,042	0,647	0,037
90th percentile (mg/m³)	1,401	0,185	1,191	0,087	1,232	0,159	1,536	0,101
P value	0,12		0,04		0,13		0,05	
Percentage reduction of mean	83%		90%		84%		91%	

Figure 14 compares the static respirable dust measurements collected pre- and post-control. The graph contains results of measurements collected during morning, afternoon and night shift.

At measurement position 1, a reduction in mean respirable dust concentration of 83% from 0.678 mg/m³ to 0.117 mg/m³ was noted (p-value of 0.12).

For measurement position 2, a reduction in mean respirable dust concentration of 90% from 0.573 mg/m³ to 0.055 mg/m³ was noted (p-value of 0.04).

For measurement position 3, a reduction in mean respirable dust concentration of 84% from 0.634 mg/m³ to 0.100 mg/m³ was noted (p-value of 0.13).

For measurement position 4, a reduction in mean respirable dust concentration of 91% from 0.755 mg/m³ to 0.068 mg/m³ was noted (p-value of 0.05).

Figure 15 compares the static respirable dust concentration measurements collected pre- and post-control. The graph contains results of measurements collected during morning shift.

Figure 16 compares the static respirable dust concentration measurements collected pre- and post-control. The graph contains results of measurements collected during afternoon shift.

Figure 17 compares the static respirable dust concentration measurements collected pre- and post-control. The graph contains results of measurements collected during night shift.

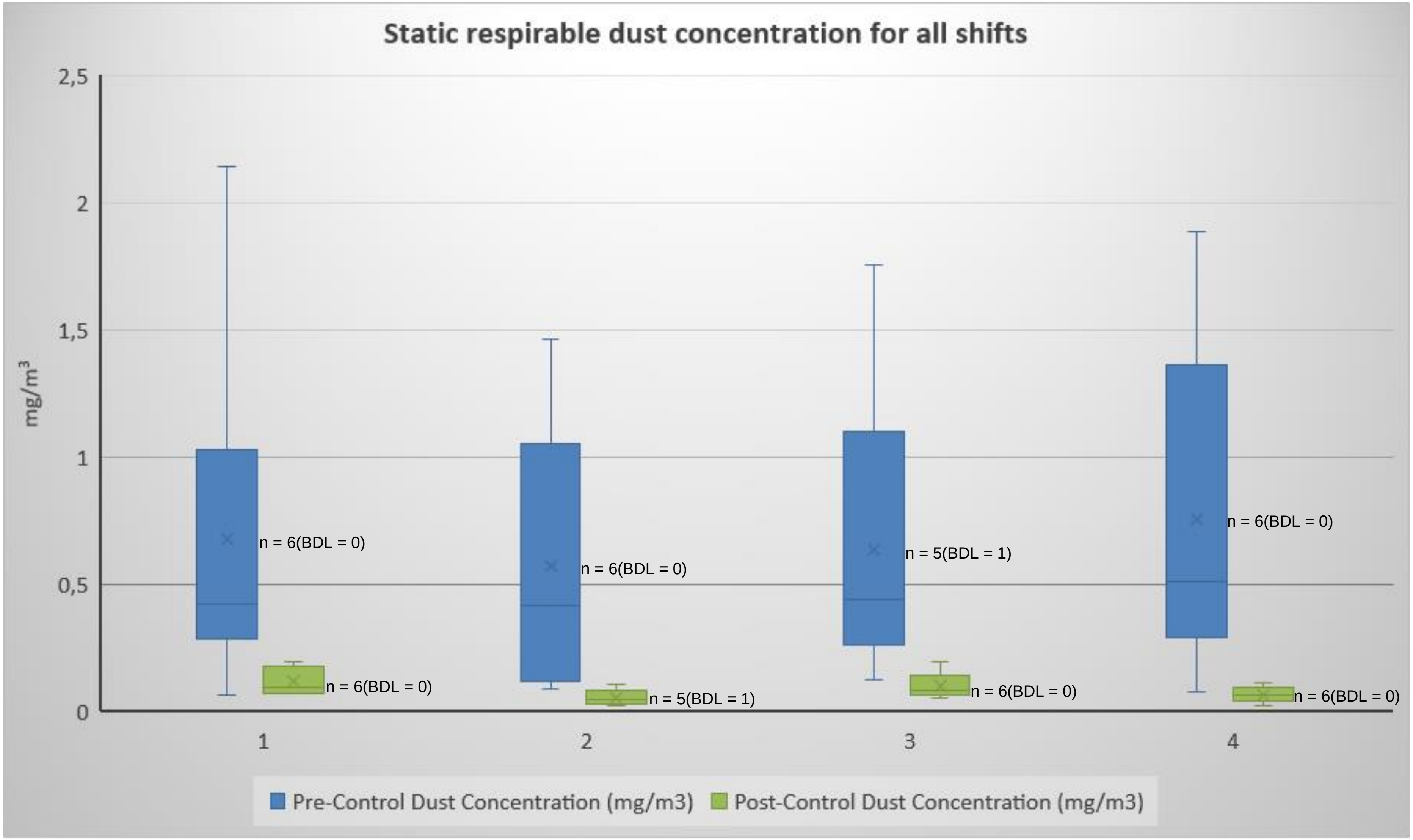

Figure 14: A “box and whisker” plot to summarise the static respirable dust concentration for all shifts

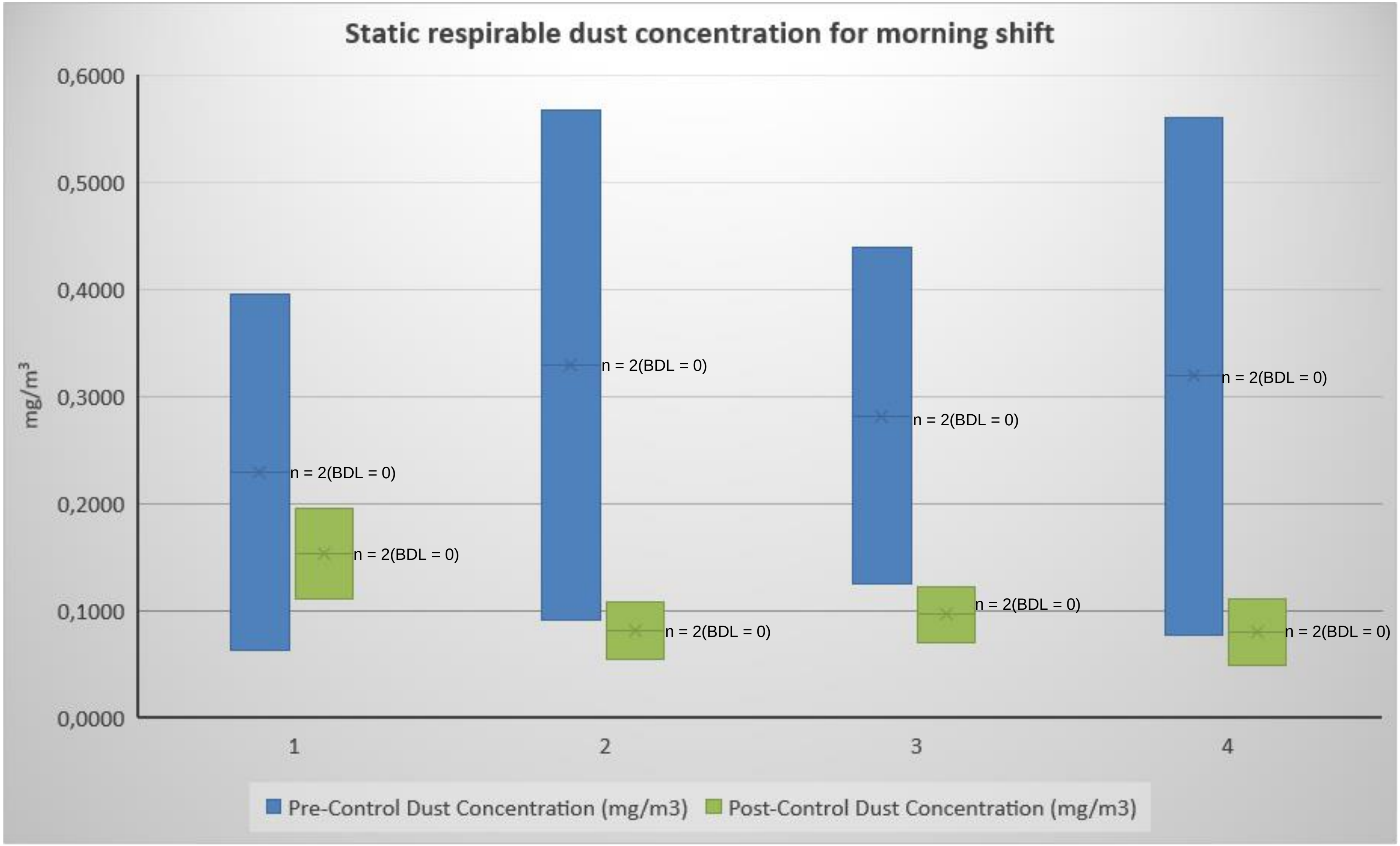

Figure 15: A “box and whisker” plot to summarise the static respirable dust concentration for morning shifts

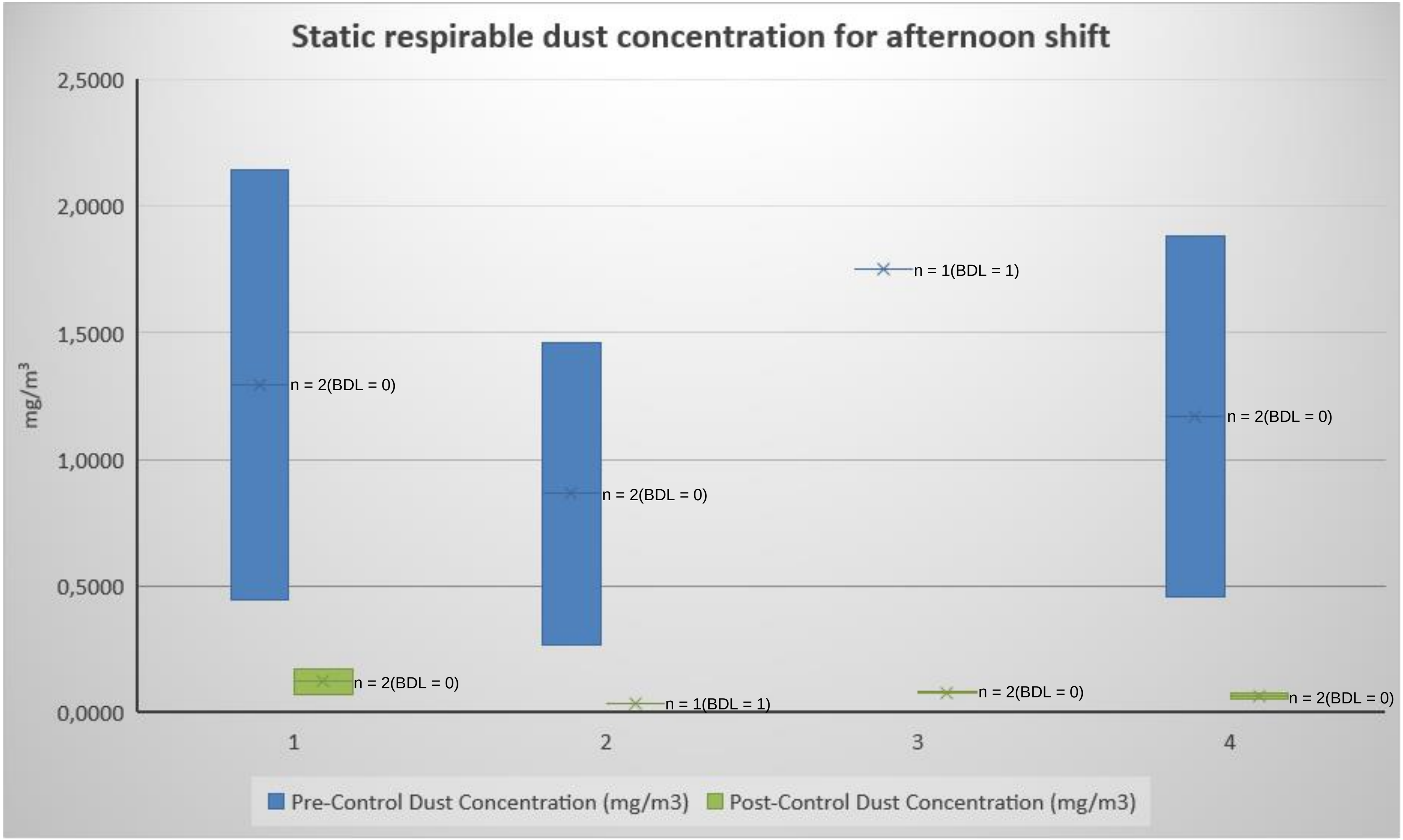

Figure 16: A "box and whisker" plot to summarise the static respirable dust concentration for afternoon shifts

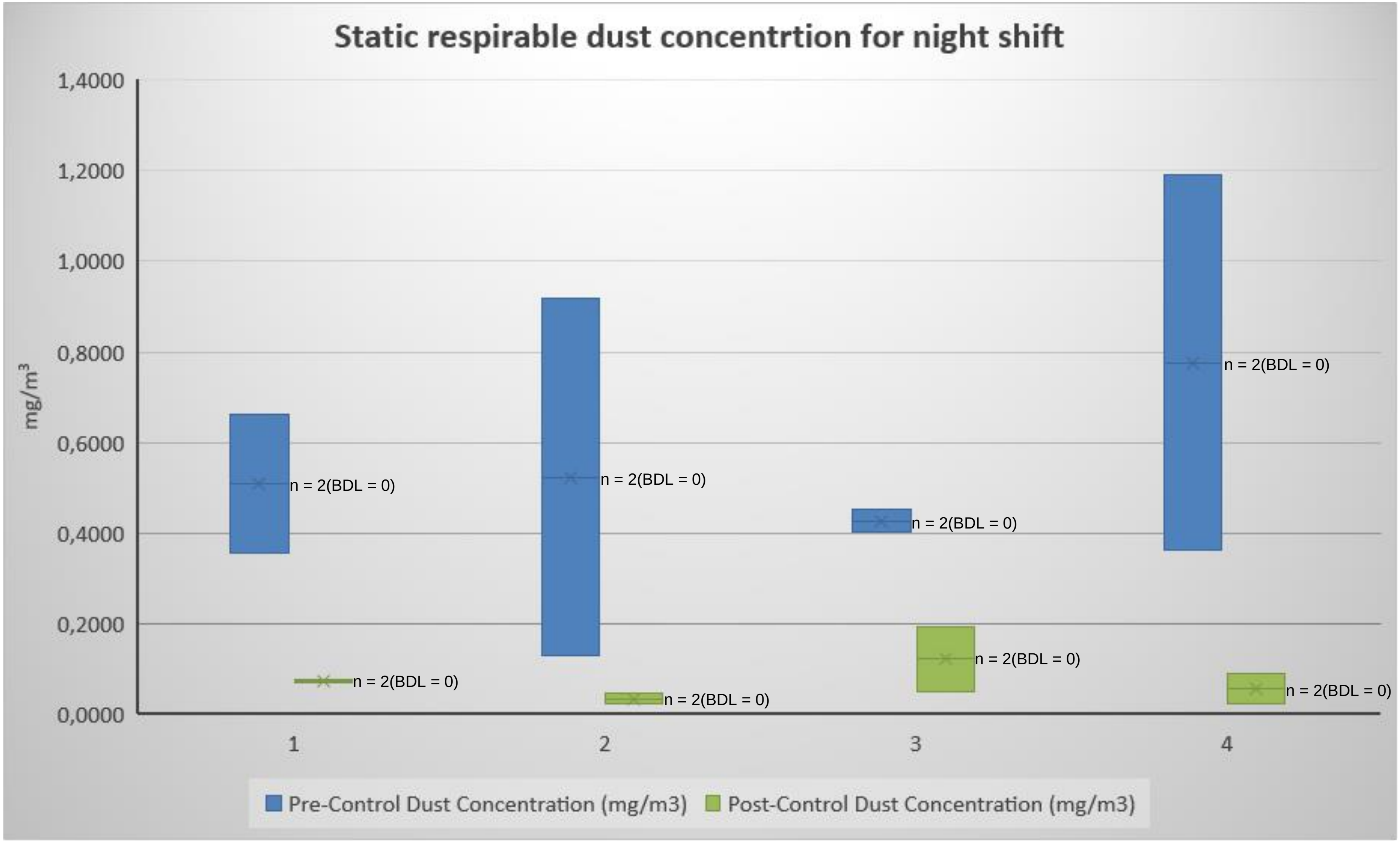

Figure 17: A "box and whisker" plot to summarise the static respirable dust concentration for night shifts

Table 6 summarises the data for static respirable dust concentration measurements collected at measurement positions 1 and 2 (Figure 4), during post-control measurements (with water spray system operating) and expressed in units of mg/m³.

Table 6: Compare measurement position 1 and 2 during post-control measurements

	Position 1	**Position 2**
	Post-Control	Post-Control
Number of measurements	6	5
Minimum (mg/m³)	0,070	0,025
Maximum (mg/m³)	0,196	0,108
Geometric mean (mg/m³)	0,117	0,055
Geometric standards deviation (mg/m³)	0,055	0,032
Inter-quartile range (mg/m³)	0,082	0,017
90th percentile (mg/m³)	0,185	0,087
P value	0,04	
Percentage reduction of mean	53%	

Figure 18 compares the static respirable dust concentration measurements collected post-control (after installation of water spray system). Results of measurements collected during morning, afternoon and night shift are included. When comparing dust concentration measurements between position 1 (after installation of water spray system as control measure) and position 2 (after installation of water spray system as control measure), a reduction in mean of 53% from 0.116 mg/m³ to 0.054 mg/m³ was noted (p-value of 0.04).

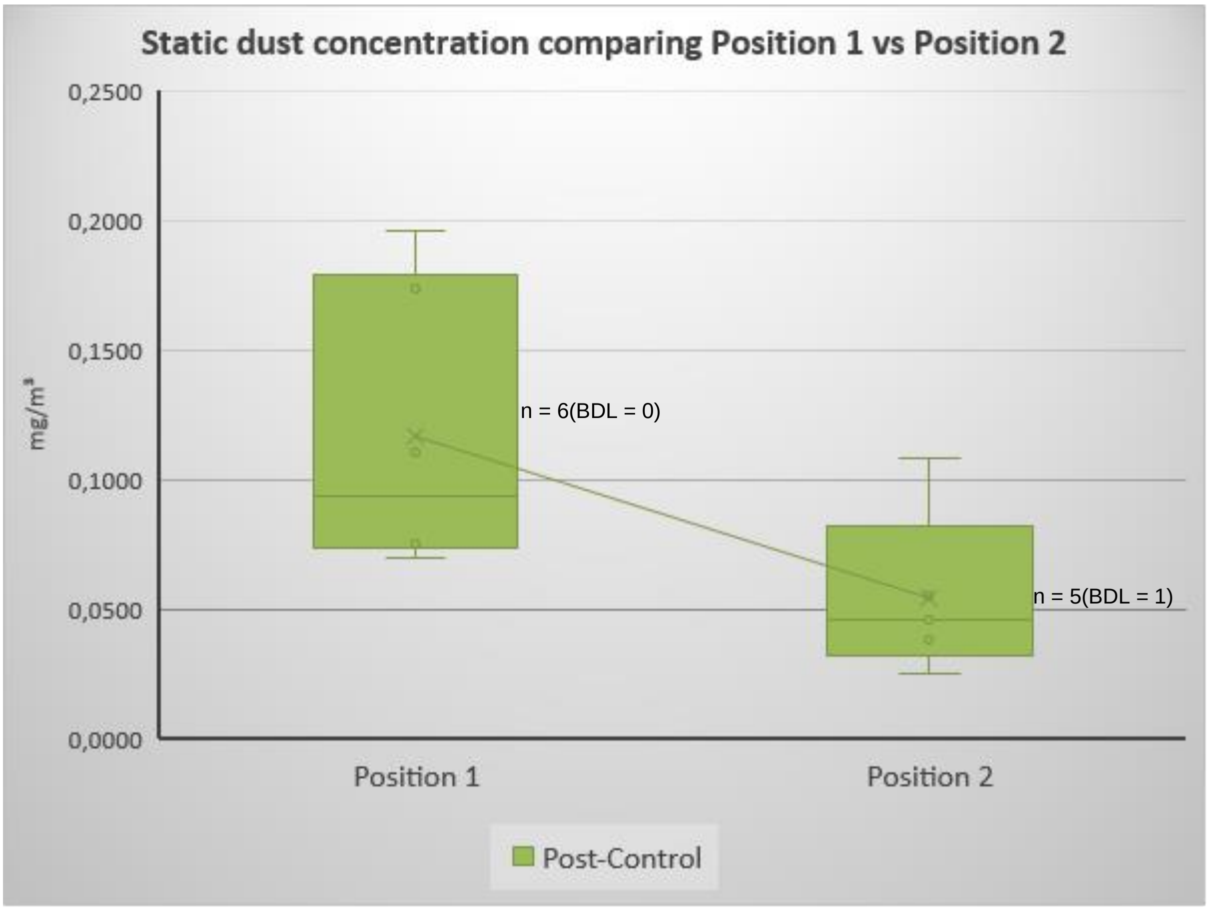

Figure 18: A “box and whisker” plot to summarise the static respirable dust concentration for positions 1 and 2 for all shifts (after introduction of the water spray system)

3.4 COMPARING EXPOSURE TO NATIONAL AND INTERNATIONAL LIMITS

Figure 19 compares the measurement results to national and international limits of exposure. From this figure, it is evident that the mean pre-control personal respirable quartz exposure measurements in most cases exceed the majority of the limits of exposure, with the exception of the South African occupational exposure limit (OEL). This value was exceeded only during the afternoon shift.

Mean personal respirable quartz exposure levels, measured post-control, however, did not exceed any of the limits of exposure. Mean personal respirable quartz exposure levels measured over all shifts were reduced by 90% to 0.010 mg/m^3, which is 10% of the South African occupational exposure limit of 0.1 mg/m^3.

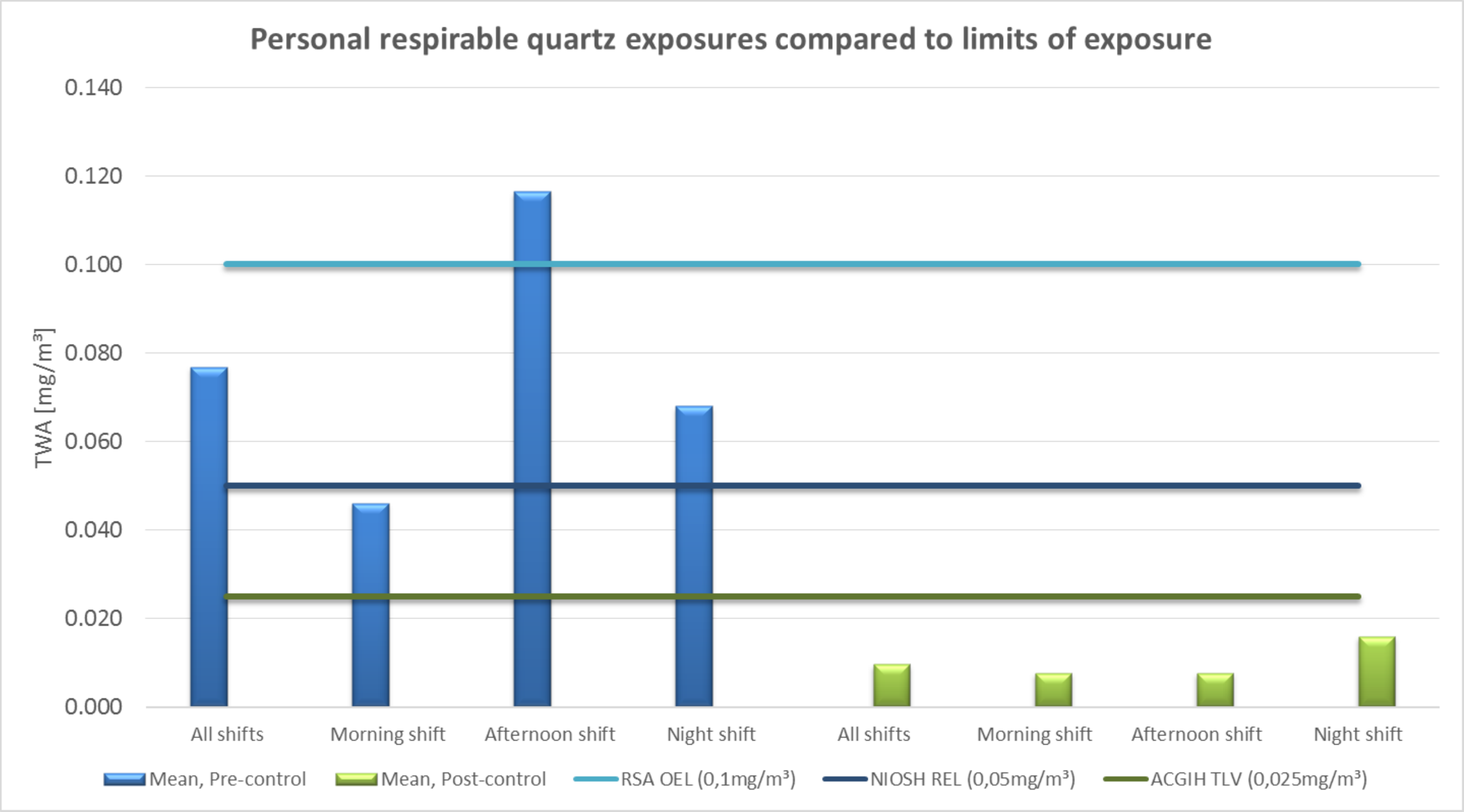

Figure 19: Comparing personal respirable quartz exposures to limits of exposure

4 DISCUSSION

The aim of this study was to assess the effectiveness of a high-pressure water spray system, as a possible respirable quartz engineering control. Four objectives were identified as mentioned earlier and the results will be discussed in this section.

4.1 WORKERS EXPOSURE TO DUST AND QUARTZ

Workers at the sub-bank area were exposed to high levels of respirable quartz. The mean personal respirable quartz exposure of 0.076 mg/m³ exceeded 50% of the South African Occupational Exposure Limit of 0.1 mg/m³. The 90th percentile of 0.15 mg/m³ exceeds the South African Occupational Exposure Limit by 50%. This indicates that workers are exposed to respirable quartz concentrations exceeding the allowable limits and this provides a serious risk to the health and safety of the workers, not only in this area but also downstream as the sub-shaft area is part of the main intake air infrastructure.

The current industry milestone states that, “by December 2024, 95% of all exposure measurement results will be below the milestone level of 0.05 mg/m³ for respirable crystalline silica”.

4.2 EFFECTIVENESS OF ENGINEERING CONTROL

In order to assess the effectiveness of the engineering control measure, pre- and post-control data sets were compared to establish if a statistically significant reduction in respirable quartz exposures was observed.

During post-control measurements, the levels of respirable quartz exposure were found to have reduced significantly. The mean personal respirable quartz exposure of the workers reduced by 87% from 0.076 mg/m³ to 0.0096 mg/m³, less than 10% of the South African Occupational Exposure Limit of 0.1 mg/m³. The 90th percentile reduced from 0.15 mg/m³ to 0.017 mg/m³ reducing by a factor of 10 to approximately 17% of the South African Occupational Exposure Limit. In comparing pre- and post-control measurements for personal respirable quartz exposures, a significant reduction in mean of 87% was achieved. This reduction is very significant and does seem to indicate that the system was highly effective.

In addition, static measurements were also collected and compared. Although the objective stated that in order to assess the effectiveness of the high-pressure water spray system as a control measure, pre- and post-control respirable quartz concentrations would be compared, during the study it was decided to rather make use of respirable dust concentrations to assess the effectiveness of the control measure.

The reason for this is that the respirable quartz concentration is dependent on the respirable dust concentration as dust contains quartz. Since the primary focus of the control measure implemented is to reduce dust concentrations, as a secondary effect quartz concentration will also be reduced.

During the analysis of the results obtained from the static measurements, it was observed that there had been a change in the dust concentrations upstream of the sampling positions between the pre-control (before installation of the water spray system) and post-control (after installation of the water spray system) measurement periods. The reason for this reduction is unknown and we can only speculate on a possible cause for this observation.

However, static measurements collected from measurement position 1 (upstream of the high-pressure spray system) support this hypothesis. With this measurement position being upstream of the high-pressure water spray system, it theoretically should not have been affected by the high-pressure water spray system.

The results indicated that the mean respirable dust concentration levels reduced by 83%, although not statistically significantly (P=0.12), between pre- and post-control measurements (at measurement position 1). This does complicate the study analysis and highlights concerns that the system may not be as effective as the personal respirable dust and respirable quartz exposure measurements indicate.

Further analysis of the static respirable dust measurements, however, provided a positive indication of the control measure effectiveness. A direct comparison between static measurement positions 1 and 2 after the installation of the water spray system (post-control) revealed that there was indeed a reduction in mean respirable dust concentrations.

The reduction was observed when comparing the mean dust concentrations post-control (after installation of the water spray system) between static measurement position 1 and static measurement position 2. With the high-pressure water spray system between these two points, this can provide a directly comparable variable to determine the system effectiveness.

By comparing the mean respirable dust concentrations between static measurement positions 1 and static measurement position 2, a significant reduction in mean of 53% was observed (P=0.04). Refer to Figure 18 for greater detail.

4.3 NATIONAL AND INTERNATIONAL LIMITS OF EXPOSURE

Results from the measurements obtained post-control introduction were compared against three limits of exposure, as listed below:

- South African Occupational Exposure Limit (SA-OEL) of 0.1 mg/m³,
- The National Institute for Occupational Safety and Health's Recommended Exposure Limit (NIOSH-REL) of 0.05 mg/m³, and
- The American Conference of Industrial Hygienist's Threshold Limit Value (ACGIH-TLV) of 0.025 mg/m³.

Mean pre-control personal respirable quartz exposures exceed the ACGIH-TLV and the NIOSH-REL across all shifts, as well as the SA-OEL during night shift.

Analysis of the post-control personal respirable quartz exposures indicated that the mean respirable quartz exposure did not exceed any of the exposure limits listed above and used for comparison. The shift with the highest mean respirable quartz exposure was night shift, which was also below the ACGIH-TLV of 0.025 mg/m³.

From this study conducted, indications are that the bulk scrubbing of intake air from shafts with high-pressure water spray systems does show potential. Significant improvement in personal respirable quartz exposures was observed after introduction of the high-pressure water spray system. This is also supported by the decrease in respirable dust concentrations observed across the high-pressure water spray system.

Other studies have also shown that significant reduction in dust and the associated quartz concentrations can be achieved by using water spray systems as an engineering control measure.

A study by Jayaraman and Jankowski [1988] conducted full scale airborne capture tests on a continuous miner face of a coal mine. Results showed a reduction of 30% in respirable dust concentrations. This was achieved by fitting the continuous miner with a conventional water spray system operating at 100 Bar with a flowrate of 72 litres per minute. When a high-pressure water spray system was used, the dust concentration also reduced by 30% but with a flowrate of only 11 litres per minute. When using the two systems together a reduction in respirable dust concentration of 59% was observed (26).

The National Institute of Occupational Safety and Health tested the effectiveness of water spray systems to reduce airborne dust concentrations in the breathing zone of construction workers while breaking concrete with jackhammers (27). Water sprayed by a nozzle at a flowrate of 0.3 litres per minute reduced airborne dust concentration between 69% and 71% (27). Reducing the water flowrate to 0.25 litres per minute reduced airborne dust concentrations by 42% and 43% (27).

Studies conducted as part of the Mine Health and Safety Council Project on Engineering and Engineering Controls (SIM 030603 B), tested the effectiveness of water spray systems to reduce respirable quartz concentrations from identified sources of respirable dust and respirable quartz (28)

Efficiency tests done at the shaft ore pass system indicated that respirable quartz concentration increase between upstream and downstream measurements (without a spray system as an engineering control) was 37%. Once the water spray system was introduced (as engineering control) the increase between upstream and downstream was reduced to 7.3% (28).

Efficiency tests done at an underground stope indicated that respirable quartz concentration increase between upstream and downstream measurements (without a spray system as an engineering control) was 165%. Once the water spray system was introduced (as engineering control) the increase between upstream and downstream was reduced to 1.6% (28).

4.4 CONCLUSION

Significant improvement in personal respirable dust and respirable quartz exposures was observed after the introduction of the high-pressure water spray system. This is also supported by the decrease in dust concentrations observed between upstream and downstream of the high-pressure water spray system.

The results from this study and the results of the other studies discussed previously, indicate that the health risk to underground mine workers could be reduced by implementing a high-pressure water spray system as an engineering control measure.

During this study the null hypothesis assumed that there was no difference in comparing the means from pre-control and post-control data sets, and an alpha value of 0.05 was used. The alternate hypothesis is that there was a difference in comparing the means from pre-control and post-control data sets, and an alpha value of 0.05 was used. The results from this report suggest that the null hypothesis can be rejected, as the p-values proved that there is a difference in the mean exposure values.

Considering the information contained in this document, it is suggested that it would be worth introducing high-pressure water spray systems as an engineering control measure to reduce respirable dust and respirable quartz concentrations.

Mines from all commodities should consider high-pressure water spray systems as engineering control measure. Particularly mines that have problems with contamination of intake air with high concentrations of respirable dust and respirable quartz, from especially (but not limited to) activities such as:

- Loading, tipping and hoisting of ore.
- Scraping, sweeping and cleaning of ore
- Drilling and blasting of rock
- Primary and secondary support
- Rock crushing, conveyor transport of ore

- Backfill spillage in shafts

Certain commodities (diamond mines) can, unfortunately, not use water as a dust control measure due to water and ore incompatibility concerns; Kimberlite is known to be hygroscopic and will absorb any water resulting in the decomposition of Kimberlite (29).

This study did however not consider the cost effectiveness of the water spray system as an engineering control measure, and this should be considered before implementation.

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Appendix A – Plagiarism declaration

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

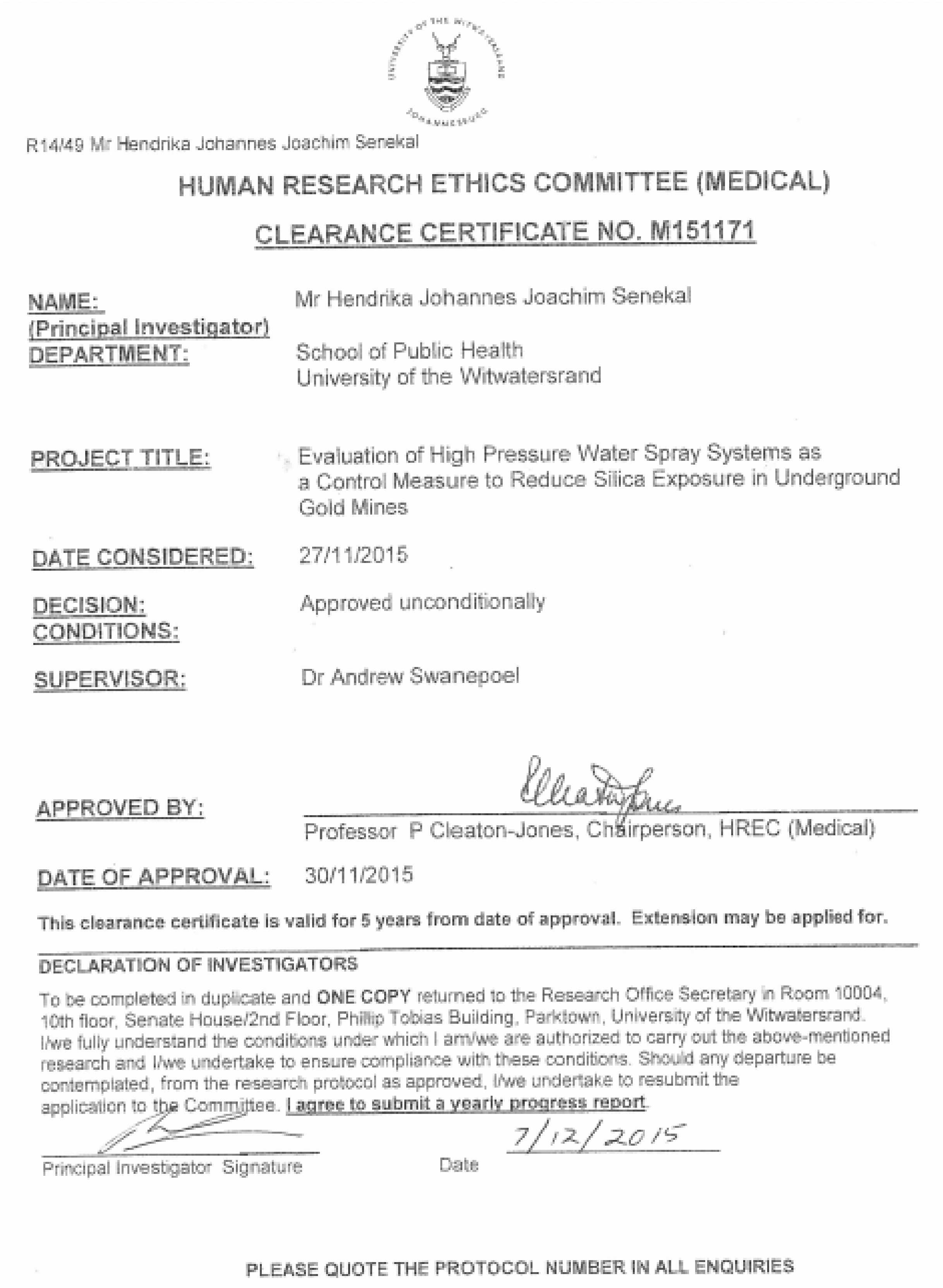
I Hendrik Johannes J Senekal (Student number: 678572) am a student registered for the degree of Masters in Public Health in the academic year 2016.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.

Signature: __________________________ Date: 15/09/2017

Appendix B – Ethics clearance certificate



R14/49 Mr Hendrika Johannes Joachim Senekal

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

CLEARANCE CERTIFICATE NO. M151171

NAME: **(Principal Investigator)**	Mr Hendrika Johannes Joachim Senekal
DEPARTMENT:	School of Public Health University of the Witwatersrand
PROJECT TITLE:	Evaluation of High Pressure Water Spray Systems as a Control Measure to Reduce Silica Exposure in Underground Gold Mines
DATE CONSIDERED:	27/11/2015
DECISION: **CONDITIONS:**	Approved unconditionally
SUPERVISOR:	Dr Andrew Swanepoel
APPROVED BY:	Professor P Cleaton-Jones, Chairperson, HREC (Medical)
DATE OF APPROVAL:	30/11/2015

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary in Room 10004, 10th floor, Senate House/2nd Floor, Phillip Tobias Building, Parktown, University of the Witwatersrand. I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated, from the research protocol as approved, I/we undertake to resubmit the application to the Committee. **I agree to submit a yearly progress report.**

Principal Investigator Signature

7/12/2015

Date

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES