

Safety in Mines Research Advisory Committee

Evaluation of Real-time and Gravimetric-type Monitoring Instruments for Use in Underground Mines

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Executive Summary

Monitoring of dust in the mines is an important task and requires reliable dust-monitoring instruments. Information on routine worker dust-exposure levels using reliable dust monitors can assist both workers' and operators' awareness of the need to protect their respiratory health. However, uncertainty regarding the accuracy of measurement of dust-monitoring instruments weakens the validity of efforts aimed at monitoring and determining workers' personal exposures.

Against this background, the search for an improved or alternative instrument that will be able to measure dust-exposure levels more accurately and more reliably is continuing. In order to be able to react quickly when an unhealthy dust exposure level occurs, a near-real-time personal monitoring instrument for mineworkers is undoubtedly required. Therefore, the principal aim of this research project is to evaluate the newly available, near-real-time and respirable dust gravimetric monitoring instruments for personal sampling purposes under various South African mining conditions with regard to their feasibility as alternative/potential instruments. It is expected that this will further enhance the health and safety of the South African mine labour force by providing effective personal monitoring.

The specific objectives of the project were as follows:

- To evaluate the newly available, near-real-time and respirable dust gravimetric monitoring instruments for personal exposure assessment in order to determine whether they meet the requirements of conditions in the South African mining industry.
- To evaluate six different instruments for monitoring the respirable dust fraction, both in the laboratory and in typical underground mine conditions, viz. in coal, gold, platinum and diamond mines.
- To compare the performance of the identified instruments in terms of accuracy, the option for quartz analysis, intrinsic safety issues, and practical implications such as portability, ease of use and wearability underground.

In order to achieve the set objectives, an initial worldwide literature review was carried out on the availability of newly developed instruments and their use as personal samplers. The findings of the literature review are discussed in Section 2.9. Based on these findings, six dust monitors were selected for evaluation. They were: (1) a locally

manufactured sampler, (2) the Dorr-Oliver 10 mm sampler, (3) the NIOSH RDD tube, (4) the IOM sampler, (5) the PDR and (6) the Split-2 dust monitor. All the instruments were operated according to the new CEN/ISO/ACGIH size-selective curve and the SA sampler was used as a reference sampler.

Laboratory evaluation of the instruments as area samplers was carried out in the Polley dust duct. Side-by-side comparison of the identified instruments with the SA gravimetric sampler indicated that there was a significant difference in the measured dust levels between them and the SA sampler, except for the PDR near-real-time dust monitor. Based on the criteria set for the selection of a suitable instrument and statistical analysis of the laboratory data, it was found that the PDR is potentially the best near-real-time personal dust monitor for underground applications.

Field evaluation of the instruments as personal dust-monitoring instruments, side by side in the breathing zone, was carried out in gold, platinum, coal and diamond mines. In all, eleven weeks were spent underground in these mines. It was not the intention of this study to exclude or recommend any particular type of dust-monitoring instrument for industrial use, but rather to evaluate their comparative performance, under broadly the same conditions, as personal samplers in the field and area samplers in the laboratory.

Main findings

The following overall conclusions were drawn from this study:

- From both the laboratory and field studies, it was noted that when two samplers (the SA sampler and the Dorr-Oliver sampler) were operated according to the ACGIH/ISO/CEN size-selective curve, there was a significant difference in the measured respirable dust concentrations. From this it can be inferred that either the SA sampler overestimates or the Dorr-Oliver sampler underestimates the "true" concentration. In the USA, the Dorr-Oliver sampler is considered to give a "true" measured concentration and in South Africa, the locally manufactured Higgins-Dewell-type sampler is considered to give a "true" measured concentration. Surprisingly, when the SA sampler and the BGI sampler were compared in the coal mines as area samplers according to the ACGIH/ISO/CEN curve, it was found that there was an insignificant difference in the measured dust levels (Belle *et al.*, 2001).
- The portable near-real-time dust monitor (PDR) proved to have the highest potential as a personal dust monitor for exposure assessment. Nevertheless, all

the near-real-time instruments can be used for engineering control or for a quick estimation of dust levels, but using a near-real-time monitoring instrument as a stand-alone unit for compliance is not recommended. However, modifying the current PDR unit (by adding a micro-size-selective device and improving the battery life and intrinsic safety) is likely to turn the monitor into a unique near-real-time compliance instrument for personal monitoring specially suited to South African mining conditions.

- From the laboratory and field trials, it was found that the responses of most of the newly developed dust monitors were linear compared with the SA sampler over a wide range of concentrations and aerosol distributions of various dust types. These variations in the dust monitors' performance are not surprising given the wide correction factors that have to be applied since the performance of a monitor is dependent on the size characteristics of the environmental aerosol, the density of environmental dust, the wind factor, the orientation of the sampler (sensing chambers in the case of real-time monitors) and the micro environment of the workers' breathing zone.
- The RDD near-real-time dust monitor was easy to use and wear as a personal sampler under extremely harsh environmental conditions such as in hard rock mines. However, in view of the poor relationship between pressure drop and mass of dust collected on the filter, the RDD needs further fine-tuning. Further, the RDD is not recommended for use in an environment where diesel particulate matter (DPM) is present. Also, there is no confirmed procedure for evaluating the quartz content of the RDD foam dust sample.
- From the field experience, it was noted that personal sampling in the harsh conditions of underground hard rock mines is extremely difficult. Drawing rational conclusions as to the reasons for the variations in the measured dust levels is notoriously complex. It is therefore suggested that in future evaluations and comparisons of the performance of personal dust samplers in the workplace should be carried out on a rotating 'mannequin'.
- The study has gathered a large amount of data on personal dust-monitoring instruments and built up considerable expertise on the subject. The identified instruments were successfully evaluated and new research directions that should be pursued for developing a near-real-time monitoring instrument have been determined. The project has led to technical knowledge and to know-how on the feasibility and practicality of providing information on the use of personal samplers in some of the harsh conditions underground.

- Finally, this study has generated a wealth of unique information and experience related to the evaluation of newly available dust-monitoring instruments for personal sampling purposes and to the difficulties encountered in some of the deepest and hottest mines in the world.

Main recommendations

The following recommendations are made based on the extensive laboratory and field study:

- The ACGIH, CEN and ISO have called for a harmonised approach worldwide to dust sampling in accordance with the same international size-selective sampling conventions. This study has shown that when the two size-selective samplers were operated according to the new ISO/CEN/ACGIH curve, the result was a significant difference in the respirable dust concentration level measured. It is against this background that the South African mining industry and allied industries should resolve to carry out basic and pragmatic research into defining the detailed penetration characteristics (aspiration efficiency) of the SA sampler for the size fractions of respirable dust. Side-by-side comparison of the BGI cyclone and the Dorr-Oliver cyclone according to the new respirable dust curve may lead to an understanding of why the SA sampler's measurements vary from the "true" concentration.
- In past decades, researchers used the MRE 113a, which followed the Johannesburg (BMRC) curve, as a benchmark "true sampler" because it was based on health studies. Ideally, samplers with penetration characteristics that "exactly" follow the respective size-selective curves should provide "true" concentrations (Vincent, 2002). However, there is no single physical sampler that precisely duplicates the theoretical size-selective curve. Owing to the differences observed, the study identifies the need for consensus on a "true SA sampler" which will operate according to the proposed new size-selective curve for international sampling harmonisation.
- In South Africa, no study has yet been carried out to determine how closely non-ideal SA samplers conform to either the BMRC or ISO/CEN/ACGIH size-selective curves when used in the field. Furthermore, the DME (1997) does not provide any guidelines as to which of the samplers conform to the specified collection efficiencies of either the BMRC or the ISO/CEN/ACGIH curve. Also, a draft guideline should be developed for the South African mining industry based on the results of recommended research and investigations into acceptance

criteria for overseas instruments and, if necessary, the development of "secondary acceptance parameters" for specific samplers should be pursued.

- The study highlights the lack of infrastructure for applied aerosol research for the mining industry. What is lacking in this field at present is a well-established state-of-the-art centre for aerosol sampler testing to cater for the needs of the local mining industry and allied industries. This need is emphasised by the considerable current research outputs in the field of aerosol sampling research from various universities, laboratories and research institutes in European, North American and some South East Asian countries. In view of the needs of the local mining industry, southern Africa needs to take a quantum leap in this area. Such a centre would acquire various sampling instruments, which could be used for comparing the test results from a wide range of manufactured dust-monitoring instruments and would facilitate the calibration of these instruments. Informal exchanges between dust experts have demonstrated that the "need for worldwide interaction" still exists. Therefore, the establishment of this centre would lift South Africa's and the region's capacity in dust research and should be regarded as a national priority. This should be the strategic aim of the Advisory Committee for the future of dust measurement and control research.
- (Belle – I have moved this to "Findings") Use of area sampling as an alternative to personal sampling in extremely harsh conditions such as deep gold mines should be reviewed, based on the practicality of such sampling and the quality of the exposure data obtained.
- Further work is needed to develop suitable test facilities and methods in consultation with overseas research agencies (Vincent, J., NIOSH, MSHA). Some of the shortcomings identified in this study should be regarded as pointing a way forward for better understanding of personal sampling in mines.

Glossary of abbreviations, symbols and terms

Abbreviations

ACGIH	American Conference of Governmental Industrial Hygienists
ANOVA	Analysis of Variance
BMRC	British Medical Research Council
CM	Continuous Miner
CV	Coefficient of Variation
DME	Department of Minerals and Energy
DO	Dorr-Oliver
DPM	Diesel Particulate Matter
HSE	Health and Safety Executive
HSL	Health and Safety Laboratory
IOM	Institute of Occupational Medicine
IS	Intrinsically Safe
ISO	International Standards Organization
LCL	Lower Confidence Limit
MMCRDM	Machine-mounted Continuous Respirable Dust Monitor
MRE	Mine Research Establishment
MSHA	Mine Safety and Health Administration
NIOSH	National Institute of Occupational Safety and Health
PDM	Personal Dust Monitor
PDR	Personal Data Ram
PRL	Pittsburgh Research Laboratory
RDD	Respirable Dust Dosimeter
RHS	Right-hand Side
RSD	Relative Standard Deviation
SA	South Africa
SABS	South African Bureau of Standards
SCSR	Self-contained Self-rescuer
SIMRAC	Safety in Mines Research Advisory Committee
STEL	Short-term Exposure Level
TEOM	Tapered Element Oscillating Microbalance
TWA	Time-Weighted Average
UCL	Upper Confidence Level
UK	United Kingdom

USA

United States of America

Symbols

%	percentage
μm	micrometres/microns
L/min	litres per minute
m	metre
m/s	metres per second
m^2	square metre
m^3/s	cubic metres per second
mg/m^3	milligrams per cubic metre
mm	millimetre

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1 Introduction

The monitoring of dust in the mines is an important task and requires reliable dust-monitoring instruments. There are various ways of measuring dust, viz. personal sampling, area sampling and engineering sampling. Area samplers are free-standing collection devices, whereas samplers mounted on workers' bodies are called personal samplers. Mainly in the USA, the need for the development of a real-time continuous respirable dust monitor, which can provide an assessment of the miner's exposure on a continuous basis, has been apparent for a long time and was identified in several reports by the Mine Safety and Health Administration (MSHA, 1992), the National Institute for Occupational Safety and Health (NIOSH, 1995), and the Secretary of Labor's Dust Advisory Committee (MSHA, 1996). Knowledge of routine dust-exposure levels can help mine workers and mine operators focus on the protection of workers' respiratory health.

In South Africa, there have been a number of Safety in Mines Research Advisory Committee (SIMRAC) projects that have focused on the issues pertaining to the assessment of the hazards posed by dust in mining operations (Unsted, 1996; Unsted, 1997a; Unsted, 1997b; Biffi *et al.*, 2000). The research work has shown that the use of direct-reading light-scattering instruments is not reliable due to their inherent sensitivity to particulate matter other than dust (diesel soot and water droplets, for example). The level of uncertainty regarding the accuracy of measurement of dust-monitoring instruments weakens the validity of efforts aimed at monitoring and determining workers' personal exposures.

Against this background, the search for an improved or alternative instrument that will be able to measure occupational dust exposure more accurately and more reliably is continuing. In order to be able to react quickly when an unhealthy dust-exposure level occurs, a personal monitoring instrument is undoubtedly required. Therefore, the primary aim of this research project is to evaluate the newly available near-real-time respirable dust-monitoring instruments and gravimetric sampling instruments for personal exposure assessment (personal sampling) under various South African mining conditions with regard to their feasibility as alternative/potential instruments.

The main objectives of the project are to evaluate the newly available instruments for personal exposure assessment to determine whether they meet the requirements of

conditions in the South African mining industry and to enhance the health and safety of the South African mine labour force through effective personal monitoring. It was proposed to evaluate six different instruments in the laboratory, as well as under conditions typical of South African mines. The instruments were evaluated in typical South African underground mines, viz. coal, gold, platinum and diamond mines.

In order for the introduction of the new dust-monitoring instruments for personal sampling in underground mines to be accepted by the stakeholders, they should meet the basic requirements (criteria) as outlined below:

- They must be intrinsically safe for use in South African underground mines.
- They must sample according to the size-selective criteria (ISO/CEN/ACGIH curve) at specified flow rates.
- They must meet the $\pm 25\%$ NIOSH or CEN 50% accuracy criterion.
- They should preferably use a different quick analysis procedure to the weighting method that is currently used.
- They must give real-time concentration values, cumulative shift exposure and sampling time.
- They must be robust enough to withstand the harsh conditions prevailing in South African mines.
- They must be compact and portable for personal sampling.
- They must be cost-effective in terms of personal sampling.
- They must offer the possibility of collecting dust samples for further quartz analysis.

2 Literature Review: Monitoring Instruments

In order to determine which real-time dust-monitoring instruments are newly available, an extensive literature review was carried out and international research organisations were contacted. The following section summarises the available instruments and the status of their availability for evaluation in South African mines for personal sampling.

2.1 Machine-mounted continuous respirable dust monitor (MMCRDM)

The machine-mounted continuous respirable dust monitor (MMCRDM), which was developed by NIOSH (USA), measures dust with a tapered element oscillating microbalance (TEOM) (Cantrell *et al.*, 1997) for area sampling purposes. TEOM-based monitors are used around the world to measure combustion particulate and ambient air quality levels (Patashnick and Rupprecht, 1991). The TEOM operating principle uses a replaceable filter cartridge mounted on the narrow end of a hollow tapered tube. The wide end of the tube is fixed. Air passes through the filter and down through the tube to a pump. The tapered tube with the filter on the end is maintained in oscillation. The oscillation frequency is controlled by the characteristics of the tube and the filter mass at its end. As dust collects on the filter, the mass change is measured as a frequency change in the oscillation of the tube. The exact mass of dust collecting on the filter is then determined directly and accurately. The dust particle pre-selector of the MMCRDM consists of three components. Sample air enters an omni-directional inlet cap, and then passes through a central tube to an elutriator, which removes particles larger than about 15 µm in size, and finally enters a virtual impactor, which passes only respirable size particles to the tapered element filter.

2.1.1 MMCRDM results

The MMCRDM was compared (Kissell and Thimmons, 2001) with three co-located dust compliance samplers under several different test conditions in the Pittsburgh Research Laboratory (PRL). The results of the test conditions, where the accumulated mass on the MMCRDM filter was compared with the average mass collected on the three compliance sampler filters, indicated a very good correlation ($r = 0.99$). The MMCRDM was also tested underground in six different mines and the results are summarised in Table 2.1.

Table 2.1: MMCRDM compared with Dorr-Oliver sampler (Kissell and Thimmons, 2001)

Total shifts	Section	Mean	Precision	Bias	Accuracy
16	CM	1,052	0,130	+ 0,052	29%
10	Longwall	1,93	0,641	+0,930	> 25%
8	CM	0,951	0,226	- 0,049	40%
38	CM	0,888	0,159	- 0,011	34%
9	CM	1,40	0,110	+0,400	> 25%
1	Longwall	Failed			

2.1.2 MMCRDM conclusions

- Preliminary laboratory results on the MMCRDM were positive. However, in the underground trials, none of the tests met the $\pm 25\%$ NIOSH criterion.
- During the field tests, the MMCRDM had many operational shortcomings, viz. long warm-up times, rock dust interference, failure due to moisture and, particularly, a lack of reliability.
- Finally, the study (Kissell and Thimmons, 2001) concluded that the MMCRDM cannot be used to represent worker exposure levels to respirable dust and that the reliability of the MMCRDM needs to be vastly improved for the monitors to be considered mine-worthy. The instrument is under development at this stage and was not available for evaluation purposes (Kohler, 2002).

2.2 Respirable Dust Dosimeter (RDD)

The Respirable Dust Dosimeter (RDD) is a new near-real-time dust-monitoring instrument developed by NIOSH which gives a close estimate of the worker's exposure. The laboratory performance of a detector tube made from glass and brass that had good correlation between differential pressure and mass has been described by the NIOSH researchers (Volkwein *et al.*, 2000; Page *et al.*, 2000). A commercially available, intrinsically safe, low flow rate air-sampling pump with integral pressure transducer is used to monitor the pressure increase with mass loading. Figure 2.2a shows both parts of

a complete RDD. The increasing pressure differential across the filter created by mass accumulation is measured and correlated with respirable mass.



Figure 2.2a: Respirable dust dosimeter (RDD) showing sampling pump and dust tube (Source: Volkwein et al., 2000)

Dust enters the inlet of the detector tube, as illustrated in Figure 2.2b, through a 6,3 mm diameter by 8,0 mm length of polyurethane open-cell foam with a density of 50 ppi (pores per inch). This segment filters out oversized non-respirable particulates and protects the main classifier from being plugged with oversize material. The tube narrows to a 4,0 mm diameter section which contains a 25,0 mm length of 90 ppi open-cell urethane foam; this collects the non- respirable dust and passes the respirable fraction of the dust.

The flow path of the classified respirable fraction of the dust gradually expands in the detector tube to 6,3 mm diameter, and travels 55 mm to uniformly deposit onto the collection filter. The respirable dust deposits onto an 8 mm diameter fluorocarbon-coated glass fibre filter, supported by a porous fibre back-up pad. The respirable classification section and the filter holder are made of conductive plastic which is ultrasonically welded together. At the recommended flow rate of 250 ml/min, the instrument samples according to the new ISO/CEN/ACGIH respirable curve, with a D_{50} of 4 microns.

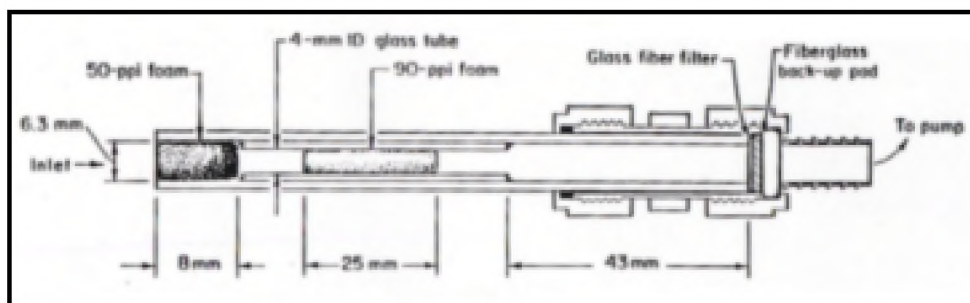


Figure 2.2b: Dust detector tube portion of dust dosimeter (Source: Volkwein et al., 2000)

2.2.1 RDD – laboratory and in-mine results

The RDD described by Volkwein *et al.* (2000) appears to be a promising development in dust exposure measurement. The measurements using the RDD and the Dorr-Oliver cyclone (operated at a flow rate of 1,7 L/min according to the ISO/CEN/ACGIH curve) were compared in both state-of-the-art laboratory and field trials. Both studies were based on a static or area sampling method. The RDD dust values were compared with standard Dorr-Oliver cyclone samples. Figure 2.2c shows the area sampling basket with two Dorr-Oliver cyclones and one respirable dust dosimeter (Source: Ramani *et al.*, 2001).

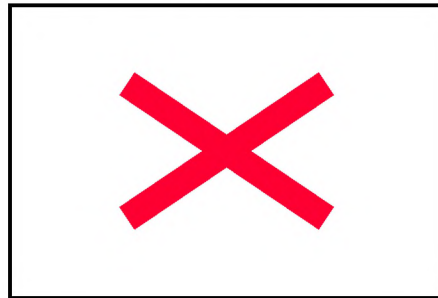


Figure 2.2c: Area sampling photograph showing two gravimetric samplers and one respirable dust dosimeter (Source: Ramani et al., 2001)

The averages of the combined set of laboratory and mine data reveal that the predictive linear relationship between the RDD and the gravimetric sampler data was strong (95%). The preliminary evaluation results have indicated that the RDD reading is a good surrogate for the mass of dust on a gravimetric filter, and can be used to approximate the cumulative dust exposure, calculated as either a mass or a time-weighted concentration. The detector tube approach to personal dust monitoring offers many advantages. Estimates of cumulative shift dust exposure can be made easily and quickly, at low cost, in a small and lightweight package. The RDD was therefore evaluated for personal sampling purposes in South African underground mines.

2.3 CIP10 Sampler

The CIP10 was developed for respirable dust sampling in mines by a French institute and has been used in South African mines for a while. The approximate cost of the unit is R13

000-00. Due to its low weight (300 g), the instrument is preferred in the mines. However, its use as a personal sampler by an unsupervised workforce is a concern. One of the observations made in the mines was that many face workers keep the instrument inside their pockets, resulting in low or almost no dust on the foam matrix. Therefore, the use of the instrument requires careful attention and training. Several investigations have been carried out both locally and overseas regarding the instrument's performance and accuracy when compared with those of gravimetric dust samplers (Gorner and Fabries, 1997). A study of the use of the CIP10 as a personal monitoring instrument has been carried out in the laboratory in South Africa (Rowe, 2001) and this instrument is currently being used in both coal and non-coal mines in South Africa.

In a recent study (Kenny, 2001) by the Health and Safety Executive (HSE), various dust-monitoring instruments were identified and selected for laboratory and underground evaluation purposes. The instruments evaluated for personal and area monitoring purposes in the UK mines were: MRE 113a, CIP10, NIOSH RDD and HSE Electret. The main aim of the UK evaluation study was to test the reliability and performance of these instruments and the practicality of using them for personal sampling in underground mines. The study recommended the CIP10 sampler as an alternative to the MRE 113a sampler for personal exposure measurement. Further, it concluded that the NIOSH detector tube is a less precise instrument. However, it was reported that the RDD could be used for screening or background measurements of respirable dust, especially for assessment purposes.

As a part of this research project, the results from the study (personal and area sampling) were plotted and the accuracy of the instruments was determined. Figure 2.3a shows the CIP10 and NIOSH RDD area concentration values measured side-by-side in the UK mines. Figure 2.3b shows the dust concentration values measured with the CIP10, the NIOSH RDD and the MRE 113a used as static/area samplers. Figure 2.3c shows the dust concentration values measured with the CIP10 and the NIOSH RDD as personal samplers.

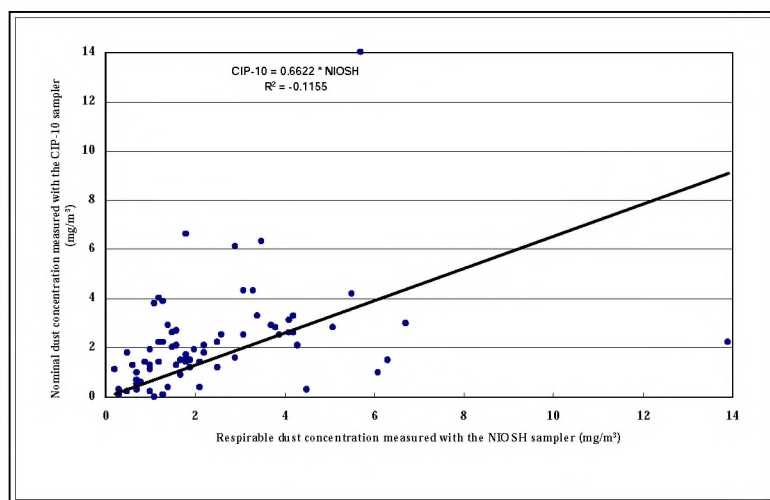


Figure 2.3a: Comparison of CIP10 and NIOSH RDD area concentrations

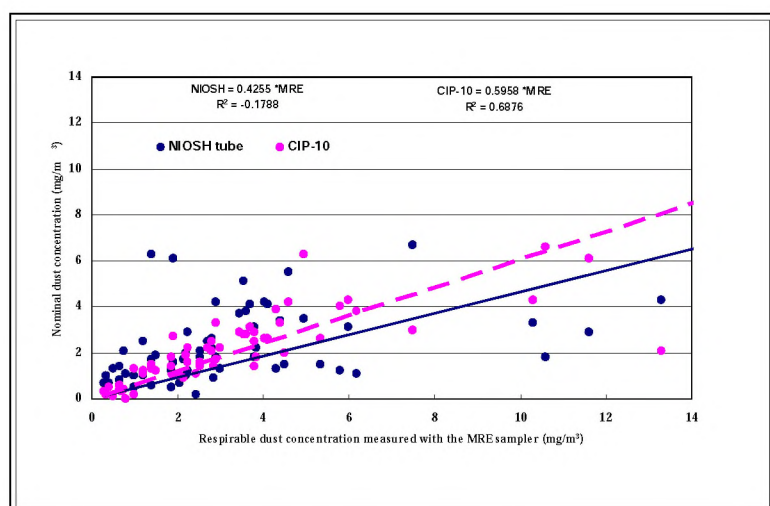


Figure 2.3b: Comparison of CIP10, NIOSH RDD and MRE 113a area concentration data

From the above plots, the following inferences were made:

- When the dust monitoring was carried out with static samplers in fixed locations, the CIP10 concentrations (follows CEN respirable definition) were on average 40% lower than those measured using the MRE 113a (follows BMRC respirable definition).

- When the dust monitoring was carried out with static samplers in fixed locations, the NIOSH RDD concentrations (follows CEN respirable definition) were on average 52% lower than those measured using the MRE 113a.

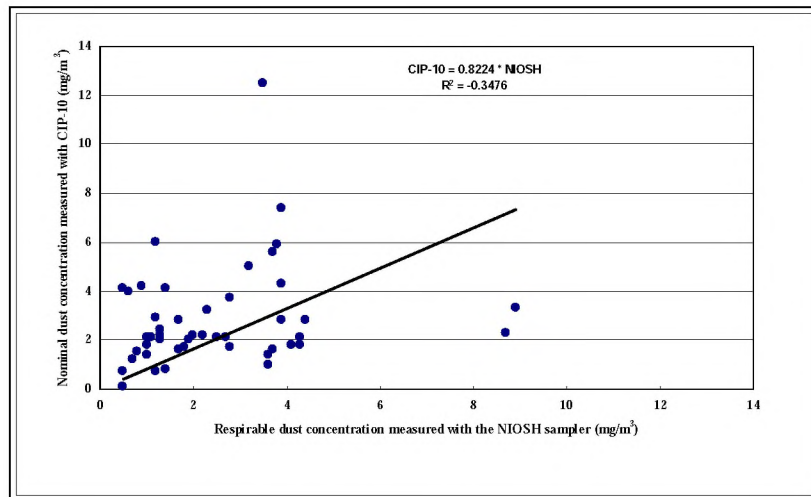


Figure 2.3c: Comparison of CIP10 and NIOSH RDD personal dust concentration data

- When the dust monitoring was carried out with static samplers in fixed locations, the CIP10 concentrations were on average 35% lower than those measured using the NIOSH RDD.
- When the dust monitoring was carried out as personal samplers in the worker's breathing zone, the CIP10 concentrations were on average 18% lower than those measured using the NIOSH RDD. There was a poor linear relationship between the measured CIP10 and RDD dust levels.

Table 2.3: *Accuracy of the new dust samplers evaluated in the UK field study*

Concentration ratio	Sample pairs	Mean	Precision	Bias	Accuracy
CIP10/MRE113a	62	0,715	0,397	- 0,285	> 50%
NIOSH/MRE113a	62	0,991	0,849	- 0,009	> 50%
MRE-1/MRE-2	44	1,094	0,607	+ 0,094	> 50%
CIP10/NIOSH	62	1,230	0,839	+ 0,230	> 50%
CIP10/NIOSH*	47	1,642	0,979	+ 0,642	> 50%

* Personal sampling data

The concentration ratios between the side-by-side static samplers were calculated from the underground field data. Table 2.3 compares the mean concentration ratio, precision, bias and accuracy for the field data, between the side-by-side fixed samplers. The results indicate that none of the samplers (even the MRE 113a) met the NIOSH accuracy criterion, both during area sampling and in the personal sampling technique.

2.4 TEOM-based Personal Dust Monitor (PDM-2)

The Personal Dust Monitor consists of two modules (hence the designation PDM-2). The instrument is based on miniaturised TEOM (Tapered Element Oscillating Microbalance) technology, combined with an electronic momentum-compensation device for personal use. A prototype PDM-2 is shown in Figure 2.4. The weight of the total unit is 1,95 kg. The lapel module contains the inlet to a Dorr-Oliver nylon cyclone, a U-shaped air heater section, the filter connected to a momentum-compensated tapered element microbalance, and a computer. The belt module contains a flow-controlled pump, batteries and the data display. The inlet of the cyclone has a custom-fabricated shield to protect the inlet from direct water spray action and to reduce the sensitivity of the inlet to wind direction.

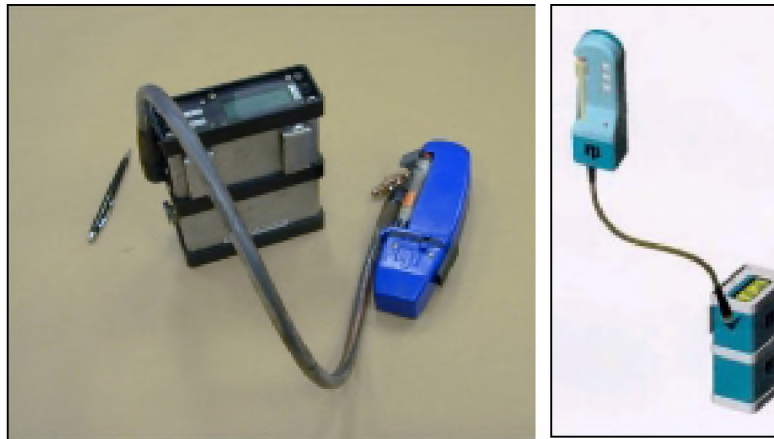


Figure 2.4: Person wearable samplers (PDM-2) showing the lapel and belt pack modules (Source: NIOSH, 2001)

2.4.1 Preliminary results for the PDM-2

Preliminary laboratory trials were conducted in both the Marple dust chamber and in a full-scale model longwall dust gallery (Volkwein *et al.*, 2000) at the Pittsburgh Research Laboratory (PRL). The Marple chamber results were positive and showed a very high correlation coefficient R^2 value of 0,99 over the mass ranges tested. Also, it was observed that the PDM-2 prototypes were not sensitive to shock or to the tilt of the unit, as might be experienced when they are worn by a person.

From communication with the NIOSH researcher (Volkwein, 2002) it was ascertained that further tests are being conducted by NIOSH in four underground coal mines to confirm the laboratory results. NIOSH hopes to build on this technology to develop a one-piece dust monitor combined with a cap lamp, which will be even more convenient for miners to wear and will allow them to monitor their environments while working. To date, the TEOM-based personal wearable dust-monitoring instrument is still in the prototype stage and is not available for evaluation purposes. NIOSH is expected to test the instruments during 2002 and only on attaining success in the field (USA) is the instrument likely to be manufactured. NIOSH has also expressed interest in participating with CSIR Miningtek in further tests in South Africa once the instrument becomes available.

2.5 HSE Passive Sampler (HSE Electret)

The HSE Electret sampler (Figure 2.5a) developed at the Health and Safety Laboratory (HSL – UK) operates without a pump (passive sampling), collecting particles onto a charged plastic film by means of electrostatic attraction (Brown *et al.*, 1995). The fraction of dust collected does not conform to any of the standardised fractions.

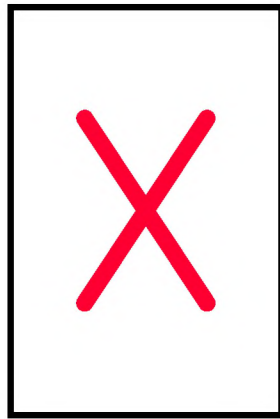


Figure 2.5a: HSE passive sampler

This restricts the use of passive samplers in South African underground mines for either area or personal sampling purposes, unless they are approved by the DME. Calibration requires a limited side-by-side sampling exercise using both conventional and passive samplers, and the function may vary both within and between mines (Hemingway, 1996). The calibration would also need to be updated periodically within a single mine. The likely cost per unit is in the region of R400-00, although subsidiary apparatus is required at a central laboratory to prepare and analyse the samples. In principle, the passive sampler could be used for quartz analyses, although in practice the very small quantity of dust collected (a few hundred micrograms) will make analyses more difficult, albeit well above the limit of detection. The passive sampler has already been subjected to comparative trials in some UK collieries as a fixed-point sampler, and has shown reasonable agreement with the MRE 113a (Hemingway, 1996).

The field data from two mines were analysed as a part of this research study. The relationship between MRE 113a (which follows BMRC) and the HSE passive sampler placed side by side is shown in Figure 2.5b. Table 2.5 summarises the poor performance of the HSE Electret when compared with the MRE 113a. As the instrument does not conform to any size-selective sampling curve, it was not considered for underground evaluation as a personal compliance sampler. Similar to other available gravimetric

samplers currently used underground, the HSE Electret will be useful for research and investigative purposes but the mines will not add gain any additional value by replacing the existing gravimetric samplers with HSE Electret samplers.

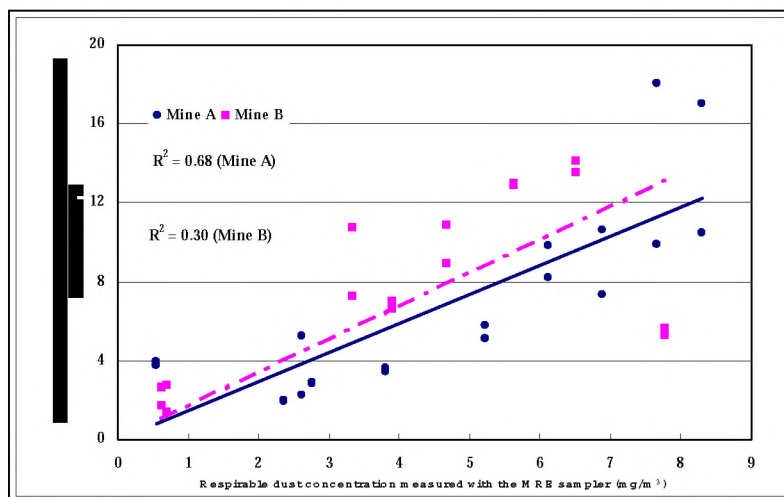


Figure 2.5b: Relationship between MRE and HSE passive sampler area concentration data

Table 2.5: Field results of HSE Electret sampler compared with MRE 113a

Mine	Sample pairs	Mean	Precision	Bias	Accuracy
A	20	1,846	0,982	+ 0,846	> 50%
B	16	2,257	0,418	+1,257	> 50%
A and B	36	2,028	0,733	+ 1,028	> 50%

2.6 Institute of Occupational Medicine (IOM) sampler

The standard IOM sampler, as shown in Figure 2.6, was designed by Mark and Vincent (1986) and collects dust samples by the gravimetric method. It has a 15 mm diameter inlet orifice. Aerosol is aspirated into the IOM sampler at a flow rate of 2,0 L/min. Particles aspirated into the inlet are either collected by a 25 mm filter or deposited on the inside surfaces of an internal two-piece cassette. The original IOM sampler that was modified by HSL is already in widespread use above ground for sampling inhalable dust (MDHS 14/2,1997). The cassette of the sampler has been modified to incorporate two size-selective foams in front of the usual filter; this means that the sampled inhalable dust is further subdivided into thoracic and respirable dust fractions, i.e. all three fractions are sampled simultaneously. The three dust fractions can be quantified by analysing the

foams and filter separately. The respirable dust collected on the filter can be further analysed for quartz content.



Figure 2.6: Standard IOM sampler

Kenny *et al.* (1997) found that at low air movement environments, the personal sampling performance of the IOM sampler agreed very well with human inhalability. Area sampling performance of six inhalable aerosol samplers was studied using monodisperse, solid particles by Li *et al.* (2000). The study reported that the area sampling performance of the IOM sampler is highly dependent on wind orientation, wind speed and particle size. When the measured sampling efficiency was compared with the inhalable convention, the IOM sampler oversampled the large particles ($>20\ \mu\text{m}$). The IOM sampling head weighs only 20 g and costs around R 900-00 but, as in the case of the cyclone, an intrinsically safe pump is required. As no study had been carried out in South Africa, the IOM respirable foam sampler was considered for evaluation in this study as a personal sampler.

2.7 Respicon sampler

The Respicon sampler shown in Figure 2.7, designed by Koch *et al.* (1999), has a circular inlet-head perimeter and samples are collected by the gravimetric sampling method. Because of this circular inlet design, dust is aspirated into the inlet from all wind directions (360°) at the same time. Therefore, unlike the other samplers, the Respicon sampler does not have different inlet wind orientations. Dust is aspirated into the Respicon (Figure 2.7) inlet at a flow rate of 3,10 L/min and then separated into three fractions by two virtual impacters. Particles on these three filters allow the determination of particle concentration for the inhalable, thoracic and respirable fractions. The laboratory study using the Respicon sampler as an area sampler provided a reasonable match for the inhalable convention (Li *et al.*, 2000).



Figure 2.7: Respicon sampler

Similar to other available gravimetric samplers currently used underground, the Respicon sampling instrument will be useful for research and investigative purposes but the mines will not gain any additional value by replacing them the existing gravimetric samplers with Respicon samplers. The Respicon sampler could potentially be used for fixed-point area or personal sampling of respirable dust concentrations with the approval of the DME.

2.8 Real-time dust-monitoring instruments

Near-direct-reading instruments based on light scattering are available to estimate personal exposure to dust in underground mines, but independent studies to support the manufacturers' performance claims are not available. In many of the studies carried out the instruments were evaluated on surface as an area sampling technique. Real-time direct-reading instruments for mine dust have been used for routine engineering control and risk assessment purposes for some years. Some of the instruments with potential for the personal exposure assessment of workers for compliance sampling are discussed below.

2.8.1 Mini-Ram (PDR)

The Mini-Ram system (Figure 2.8.1a) was developed in the USA. The units are expensive (R50 000/unit) but allow near-real-time readout of respirable dust levels and are therefore important diagnostic tools for the detailed study of dust sources and dispersal. Instruments of this kind are usually used for area sampling purposes in the section return airway in underground coal mines. The units are portable and weigh approximately 600 g. The instruments are tuned to respond to dust in the respirable size range, but

interferences can occur, such as during stone dusting in the coal mines, which cause erroneously high readings if they are not maintained daily.



Figure 2.8.1a: Personal Data Ram (Mini-Ram)- Near-real-time dust monitor

For quantitative measurements, the instruments require calibration by means of side-by-side comparisons with a standard respirable dust sampler (Baldwin *et al.*, 1997). A study by Tarkington *et al.* (1997), comparing two direct-reading aerosol instruments (LD-1H Laser Dust Monitor and Mini-Ram) with respirable gravimetric samplers indicated that the Mini-Ram was a better instrument for industrial hygiene screening than the LD-1H because it gave a higher (conservative) reading. However, this study was not based on personal exposure assessment.

The reliability of the concentration data measured with an earlier version of the RAM-1 monitor was analysed using the data collected in the NIOSH longwall gallery dust-control studies (Belle and Ramani, 1997). The results of the data were plotted as shown in Figure 2.8.1b. From the plot we observe that the use of a near-real-time instrument as a stand-alone unit is not recommended for personal exposure assessment purposes but rather it is more suited to the identification of dust trends during a working shift. The PDR near-real-time monitor displays concentration in mg/m^3 in addition to TWA, Max, Min, STEL and sampling time on the display readout. Due to the PDR's portability and desired features, it was considered for evaluation in underground mines. The instrument has a preliminary Intrinsically Safe (IS) certificate obtained from the SABS (Gruppung, 2001).

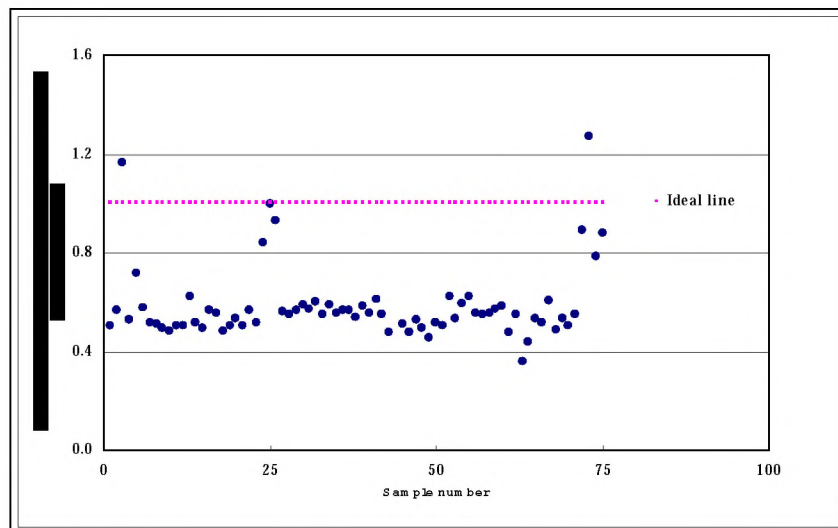


Figure 2.8.1b: Relationship between RAM-1 real-time concentration and gravimetric sampler concentration (Data Source: Belle and Ramani, 1997)

2.8.2 SKC Split-2 real-time monitor

This is a near-real-time flexible particulate monitoring instrument developed in the USA by SKC Inc., PA. The Split-2 dust monitor (Figure 2.8.2) is designed for personal or area monitoring for respirable, thoracic or inhalable dust. Similar to the PDR dust monitor, the Split-2 is a passive dust monitor which can become an active monitor by combining it with a 2,0 L/min sample pump and a GS cyclone or IOM sampling head for dust monitoring and concurrent dust sampling according to a specific size-selective curve. The Split-2 displays concentration in mg/m^3 in addition to TWA, Max, Min, STEL and sampling time on the display readout.



Figure 2.8.2: Personal SKC SPLIT-2 near-real-time dust monitor

No literature information on the instrument's performance in either laboratory or field studies was available. This potential instrument had never been tested in South Africa before and was considered for evaluation as a part of this study. However, the instrument

does not have an Intrinsically Safe certificate for either surface or underground operations (Grabe, 2001).

2.8.3 Respicon light-scattering dust monitor

The Respicon light-scattering monitor is a new sampler, recently available commercially, one version of which combines aerodynamic size selection with three light-scattering detectors (Koch, 1999). Hence, with the use of size-selective filters, real-time readout of inhalable, thoracic and respirable dust concentrations simultaneously can be obtained. Furthermore, the particles collected on filter substrates can be either weighed or analysed for quartz, and the gravimetric results used to calibrate the light-scattering response.

The light-scattering Respicon is an expensive instrument (costing approximately R80 000). The sampling head is a little bulky for personal sampling and requires an intrinsically safe pump. Versions of Respicon monitoring instruments have potential for fixed-point monitoring of respirable dust. Whether the instrument is intrinsically safe for underground evaluations is not known.

2.8.4 Hund tyndallometer

The Hund tyndallometer (Figure 2.8.4a) is an intrinsically safe photometric size-selective (BMRC) dust-monitoring instrument. It is being widely used in South Africa for dust control applications. The instrument gives the operator an indication of the dust trend in the workplace, but must be used in conjunction with a gravimetric sampler due to its unreliability as a stand-alone measurement device. Figure 2.8.4b shows a plot of the relationship between the average coal dust concentration measured using a Hund Tyndallometer and a gravimetric sampler, positioned side by side, during various underground operations as a fixed or area-monitoring instrument.

From the plot we observe the Hund tyndallometer is not reliable for use as a near-real-time, stand-alone instrument for either personal or area sampling purposes ($r = 0,32$), but rather it is more suited for the identification of dust trends during a working shift. This can be attributed to the different size-selective sampling curves of the two instruments. Currently, the instrument does not follow the new ISO/CEN/ACGIH respirable curve for particle size fractionation. Due to its design features, the instrument was not considered for further evaluation.



Figure 2.8.4a: Hund tyndallometer (real-time dust monitor)

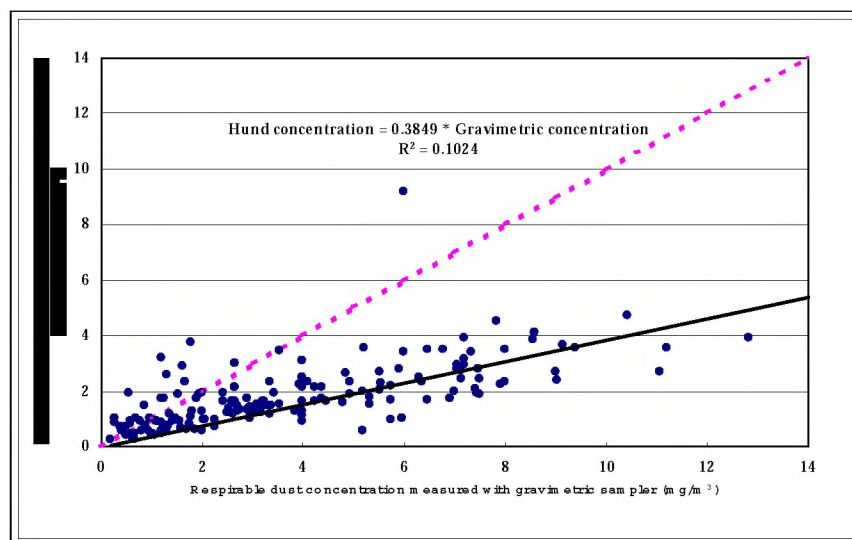


Figure 2.8.4b: Relationship between average Hund tyndallometer and gravimetric dust sampler concentration measurements in coal mines (Data Source: Belle, unpublished report, 2001)

2.9 Conclusions of literature review

Past and current studies, and the available research reports, make conflicting recommendations on the use of the newly available dust-monitoring instruments for personal sampling and or area sampling purposes. There are merits to and limitations on the particular sampling method chosen (personal or area), depending on the type of sampling instrument used. However, the personal sampling method is the most suitable method for assessing, and most representative of, the worker's dust exposure (Leidel *et al.*, 1977, Kissell and Sacks, 2002).

The following conclusions were drawn from the review of available worldwide literature on newly developed gravimetric sampling and near-real-time monitoring instruments, and their evaluation by overseas researchers:

- The available real-time instruments are not yet fully portable or applicable for underground operations. Several developments have taken place but only limited field studies have been carried out overseas on the use of near-real-time monitoring instruments for personal sampling. The newly available instruments have been evaluated as area/fixed-point dust-monitoring instruments in the mines but only a few (RDD, CIP10 and Electret) have been evaluated as personal monitoring instruments.
- A variety of near-real-time dust-monitoring instruments are available on the market which claim to assist with personal exposure assessment. All the available instruments are calibrated using "mono-disperse" particles (Arizona road dust) in the laboratory. However, each instrument requires a user-determined "correction factor" obtained from a side-by-side gravimetric size-selective sampler, evaluated with "poly-disperse" dust having wide size-distribution curves appropriate to the specific mine. There is no "absolute correction factor" available for individual sampling instruments. The "correction factor" changes with the history of the sampling data obtained in side-by-side comparisons of the near-real-time monitoring instrument and the type of gravimetric size-selective sampler used.
- Except for the NIOSH RDD tube, none of the newly developed near-real-time monitoring instruments is "intrinsically safe" for underground use (the PDR has a partial IS certificate).
- Some of the "new" gravimetric-type instruments (such as the IOM sampler) do not yield any additional information on respirable dust or help the mining industry as the existing gravimetric samplers are capable of collecting the necessary personal exposure data. The CIP10 dust monitor recommended (Kenny, 2002) by the HSE in the UK for "potential underground usage for personal sampling" is already in use in South African mines.
- In order to determine the quartz content of the exposed respirable dust, the near-real-time monitoring instruments must be used in conjunction with gravimetric dust samplers in active sampling mode.
- The errors associated with personal sampling are usually the result of the worker's body movements, instrument portability and other sampler-handling mistakes.

Therefore, ultimately, an accurate sampling instrument that would be able to cope with the worker's usual production demands is required for the harsh environment of the mining industry.

- Nowhere in the literature study were evaluations carried out using two or more near-real-time instruments of similar type, either in surface industrial or mining operations. Potential use of the currently available, stand-alone real-time instruments for personal exposure assessment has been researched on many occasions and the results on area sampling indicate that they are not reliable for this purpose.
- Currently, there is a wide variety of real-time monitoring instruments available on the market specifically for area sampling purposes. However, it is difficult to compare the manufacturers' specifications. Also, currently there is no consensus standard on the selection of a suitable instrument.

In order for the introduction of newly developed dust-monitoring instruments for personal sampling purposes in underground mines to be accepted by the stakeholders, the following criteria were set for the study:

- They must be intrinsically safe for use in South African underground mines. (For surface use, the IS criteria are not applicable unless they a specific requirement.)
- They must sample according to the size-selective criteria (ISO/CEN/ACGIH curve) at specified flow rates.
- They must meet the $\pm 25\%$ NIOSH accuracy criterion.
- They should preferably use a different quick analysis procedure to the weighting method that is currently used.
- They must give real-time concentration values, cumulative shift exposure and sampling time.
- They must be robust enough to withstand the harsh conditions prevailing in South African mines.
- They must be compact and portable for personal sampling.
- They must be cost-effective in terms of personal sampling.
- They must offer the possibility of collecting dust samples for further quartz analysis.

However, it is important to keep in mind that an instrument that is found to be highly accurate (more so than the existing instruments) should still be evaluated for its ease of use underground, which may be the main culprit in causing inaccuracies.

3 Laboratory Study

3.1 Introduction

This section of the report discusses the results of the laboratory evaluation of the newly developed near-real-time and gravimetric-type dust-monitoring instruments in the Polley duct. Detailed descriptions of the Polley dust duct, the experimental design, the sampling plan, the laboratory tests and the data analysis procedures are given in the Laboratory Test Protocol document attached as Appendix A.

The following table (Table 3.1) summarises the features of the various dust-monitoring instruments (near-real-time and gravimetric type) that are currently available on the market. The instruments' potential suitability for use in mines is claimed by various instrument manufacturers. However, only a few of these instruments have been used in underground mines over the past few years in South Africa (e.g. the CIP-10), but they are being recommended for use in European mines (Kenny, 2002).

Table 3.1: Intrinsically safe dust samplers potentially suitable for South African mines

Name	Sampling method	Quartz?	Fraction	Personal	Area	Size-selective curve	Weight (g)	IS	Status
MRE113A	G	Y	R	N	Y	BMRC	4 250	Y	C
Cyclone	G	Y	R, T	Y	Y	ISO/CEN/ACGIH	550	Y	C
CIP10	G	Y	R, T, I	Y	Y	ISO/CEN/ACGIH	300	Y	C
IOM foam	G	Y	R, T, I	Y	Y	ISO/CEN/ACGIH	530	Y	New
Electret	G	N	NS	Y	Y	None	150	Y	New
Hund	RT	N	R	Y	Y	BMRC	1 000	Y	C
Dust track	RT	N	R	Y	Y	ISO/CEN/ACGIH	800	N	C
TEOM	RT	Y	R	Y	Y	ISO/CEN/ACGIH	-	-	NA
NIOSH RDD	RT	Y	R	Y	Y	ISO/CEN/ACGIH	200	Y	New
Mie-PDR	RT	N	R	Y	Y	ISO/CEN/ACGIH	600	N	C
Respicon	RT	N	R, T, I	Y	Y	ISO/CEN/ACGIH	800	N	C
Split-2	RT	N	R, T, I	Y	Y	ISO/CEN/ACGIH	800	N	C

G: Gravimetric; RT: Real-time; Y: yes; N: no; R: respirable; T: Thoracic; I: Inhalable; NS: not specified; IS: intrinsically safe; NA: not available

For all laboratory comparison purposes, the South African cyclone (GME#GE05) was used as a standard sampler. The precision is determined from the concentration ratio between the sampler pairs. Based on the criteria set for the study and in consultation with the stakeholders, the following instruments were selected for laboratory evaluation:

- Personal gravimetric respirable samplers:
 1. SA cyclone
 2. Dorr-Oliver 10 mm cyclone
 3. IOM foam sampler
- Personal real-time monitoring instruments:
 1. SKC Split-2 dust monitor
 2. Mie-PDR
 3. NIOSH RDD tube
 4. Hund tyndallometer.

3.2 Methodology

For the laboratory study, the identified monitoring instruments were exposed to two types of dust, viz. coal and sandstone briquette dust. The quartz content of the sandstone briquette dust, as analysed in the CSIR Miningtek laboratory, indicated that the average (three samples) was 50,63%.

The locally manufactured and widely used gravimetric sampler (cyclone), which is similar to the Higgins-Dewell-type cyclone in terms of performance, was operated at 2,2 L/min. This conforms to the new ISO/ACGIH/CEN curve with a D_{50} of 4 microns (Kenny *et al.*, 1998). The study by Liden and Kenny (1993) suggests that operating Dorr-Oliver 10 mm cyclone at a flow rate of 1,7 L/min is actually most appropriate for sampling according to the new ISO/CEN/ACGIH definition of respirable dust with a D_{50} of 4 microns. Sampler inlets faced the direction of the airflow in order to avoid the effect of nozzle inlet orientation on sampler performance. New Gillian pumps were used for the tests and were calibrated to three digits after the decimal point, using a digital Gillibrator. Figure 3.2 shows a typical side-by-side positioning of samplers in the test chamber. Tests were carried out with various pairs of identified dust monitors exposed to coal and sandstone briquette dust.

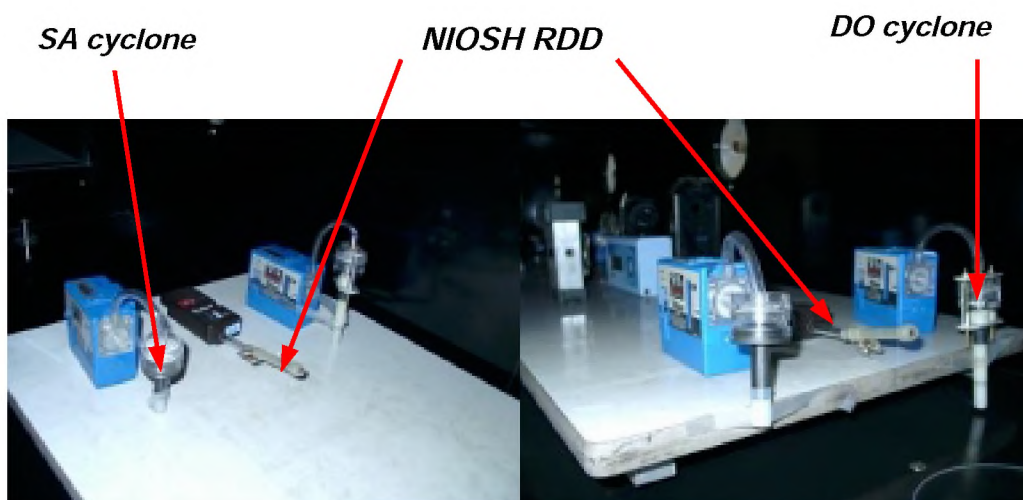


Figure 3.2: Typical side-by-side positioning of samplers in the test chamber

3.3 Laboratory results

3.3.1 Pair-wise comparison of Dorr-Oliver and South African cyclones

Initially tests were carried out to determine the concentration levels across the Polley duct. Both Dorr-Oliver (DO) cyclones and SA samplers were used in the dust chamber and tests were conducted for both coal and sandstone briquette-generated dust. Preliminary studies indicated that there is no significant difference in the measured dust levels across the chamber. Table 3.3.1a shows a summary of the respirable dust concentration values obtained in the side-by-side comparisons of similar types of sampler. The relationship between the concentration values obtained from the two side-by-side cyclones, during the laboratory trials, is shown in Figures 3.3.1a and 3.3.1b. The correlation coefficient (r) between the two side-by-side Dorr-Oliver cyclones is 0,993. Similarly, the correlation coefficient (r) between the two side-by-side SA cyclones is 0,998.

Table 3.3.1: Summary statistics of side-by-side comparison of dust samplers

Statistic	C _{DO-1}	C _{DO-2}	C _{SA-1}	C _{SA-2}
Mean	5,706	5,541	10,899	10,706
Variance	4,668	4,729	120,15	122,15
Median	7,096	6,941	7,413	7,038
Minimum	2,65	2,496	3,294	3,026
Maximum	7,376	7,376	32,708	33,347
Size	12	12	15	15

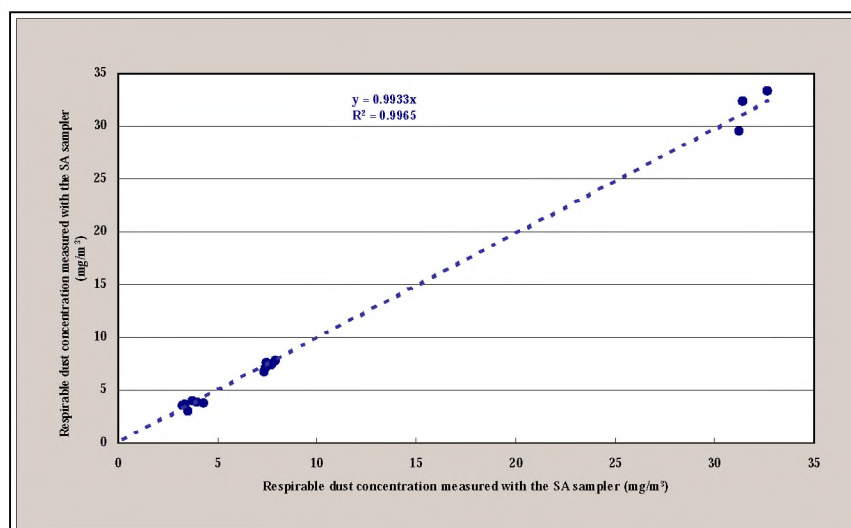


Figure 3.3.1a: Relationship between two side-by-side SA cyclones in the test chamber

A combined plot of the two data ($r = 0.993$) sets is shown in Figure 3.3.1c, indicating that the linear relationship between the two side-by-side samplers is very strong. The two data sets of concentration values indicate that concentration across the chamber is reasonably uniform for the test conditions.

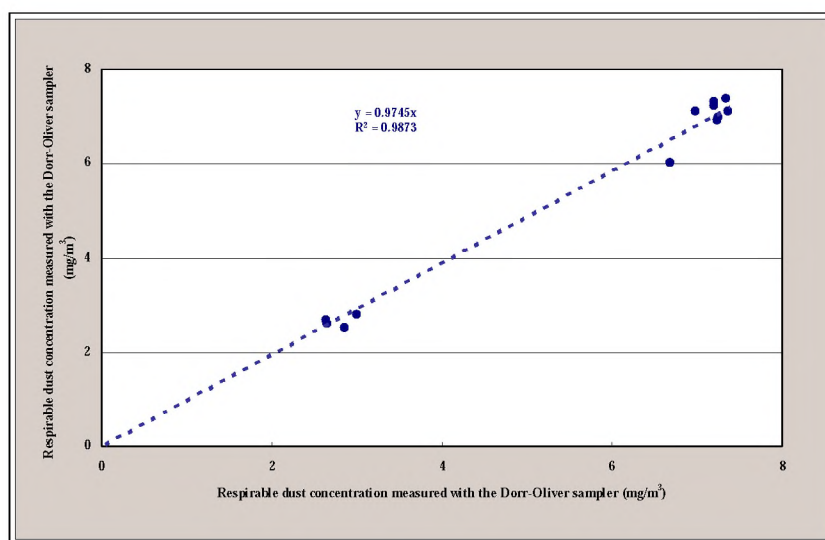


Figure 3.3.1b: Relationship between two side-by-side Dorr-Oliver cyclones in the test chamber

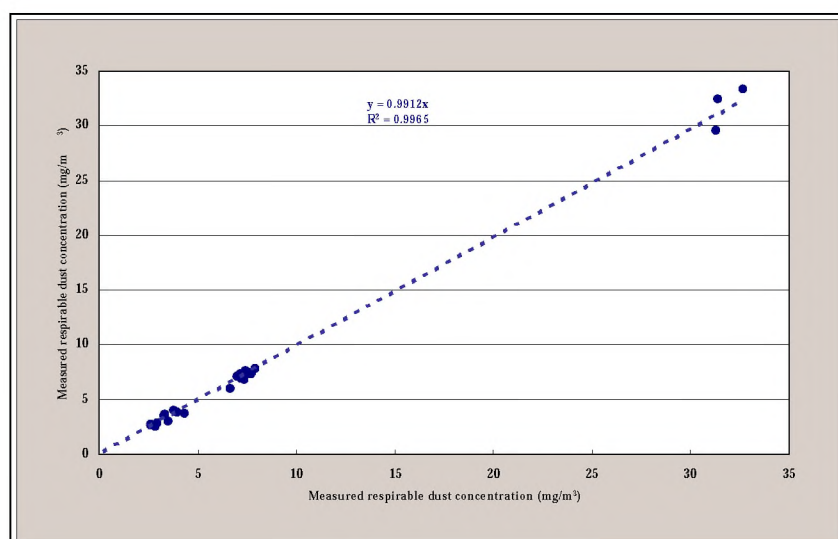


Figure 3.3.1c: Combined data of two side-by-side cyclones in the test chamber

The data were analysed to determine the difference in measured concentration levels from a Dorr-Oliver cyclone, an SA cyclone and a NIOSH RDD sampler positioned side by side (Figure 3.3.1d) using coal and sandstone briquette dust.



Figure 3.3.1d: Dorr-Oliver cyclone (right), SA cyclone (left) and NIOSH RDD sampler

Table 3.3.1b shows summary statistics of the respirable dust concentration values obtained during the side-by-side comparison of the DO and SA samplers. The relationship between the concentration values (95 pair-wise sample data sets) obtained from side-by-side DO and SA samplers during the laboratory tests for coal and sandstone briquette dust is shown in Figure 3.3.1e. The correlation coefficients (r) between the SA cyclone and the DO cyclone for coal and sandstone dust are 0,957 and 0,901 respectively. A combined plot of the two data sets ($r = 0,938$) is shown in Figure 3.3.1f.

Table 3.3.1b: Summary statistics of side-by-side SA and DO samplers

	Coal		Sandstone dust		Combined	
Statistic	C _{DO}	C _{SA}	C _{DO}	C _{SA}	C _{DO}	C _{SA}
Mean	3,551	4,627	5,627	7,092	4,556	5,820
Variance	3,764	6,054	5,664	8,556	5,721	8,721
Median	2,809	3,602	4,853	6,055	4,357	5,986
Minimum	0,962	0,555	2,049	3,043	0,962	0,555
Maximum	7,724	8,753	12,05	16,77	12,05	16,77

Size	49	49	46	46	95	95
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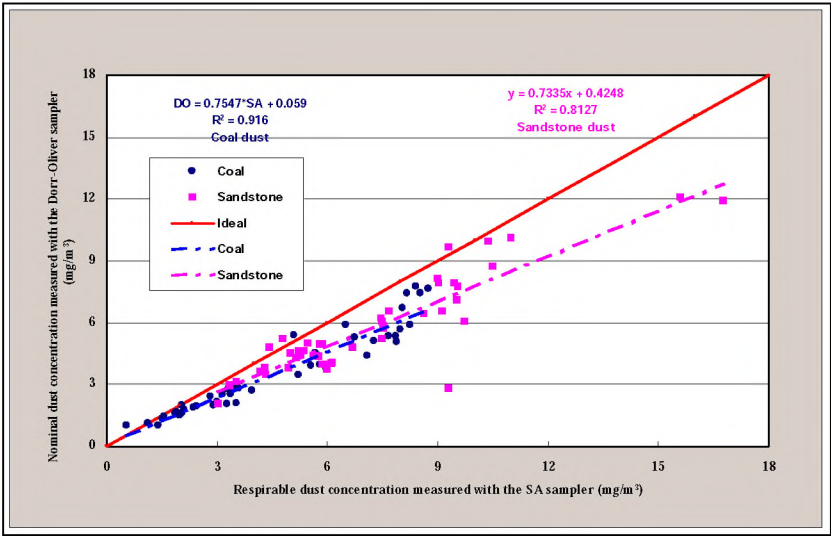


Figure 3.3.1e: Relationship between DO and SA cyclones

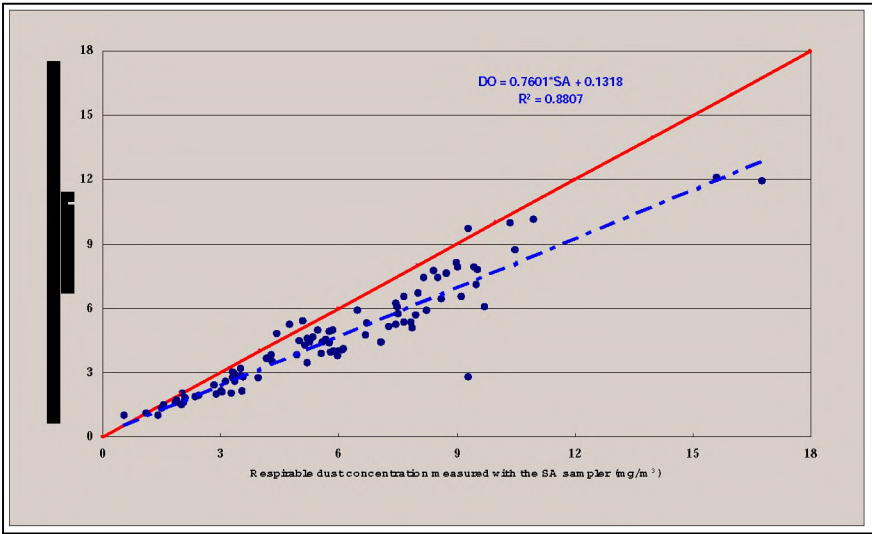


Figure 3.3.1f: Relationship between DO and SA cyclones (combined data)

From the plot we notice that when the two samplers were operated according to a specific size-selective curve (ACGIH/CSN/ISO), there was a significant difference in the measured respirable dust concentrations. During the trials, both samplers were positioned in the direction of the airflow. The 95 pair-wise data set for the samplers positioned side by side indicates that the measured concentrations using the DO and SA samplers were

4,556 mg/m³ and 5,820 mg/m³ respectively when the samplers were exposed to the same dust cloud. From this we infer that either the SA sampler overestimates the "true" concentration by 27,74% or the DO sampler underestimates it by 21,72%. In the USA, the DO sampler is considered to give a "true" measured concentration, and in South Africa, the locally manufactured Higgins-Dewell-type SA sampler is considered to give a "true" measured concentration.

It is expected that if the SA sampler had operated according to the BMRC size-selective curve, it would have yielded higher dust concentrations due to higher collection efficiency at most respirable sizes. In South Africa, no study has yet been carried out to determine how closely non-ideal SA samplers conform to either the BMRC or ISO/CEN/ACGIH size-selective curves when used in the field. Furthermore, the DME does not provide any guidelines as to which of the samplers conform to the specified collection efficiencies for either the BMRC or the ISO/CEN/ACGIH curve.

In past decades, researchers used the MRE 113a, which followed the Johannesburg curve (BMRC) curve, as a benchmark "true sampler" as it was based on health studies. Ideally, samplers with penetration characteristics that "exactly" follow the respective size-selective curves will provide a "true" concentration (Vincent, J, NIOSH, 2002). However, there is no single physical sampler that duplicates the theoretical size-selective curve. Owing to the differences observed, the study identifies the need for consensus on a "true sampler" which operates according to the proposed new size-selective curve for international sampling harmonisation.

One of the major sources of variations in measured sampler dust concentrations could be the size distribution of the parent dust (Soderholm, 1991, Volkwein, J., 2002). However, the size distribution of the parent mine aerosol dust varies with time and the type of mining operation. Furthermore, the effect of air velocity on the cyclone inlet (the DO 10 mm cyclone has a small rectangular opening, while the SA sampler has a narrow slit opening) may constitute another reason, as the aspiration efficiency of the various cyclones will be different. Therefore, it is possible that with improved and portable size-characterisation instruments, the respirable dust fractions of the parent dust, as well as the bias for a given size and standard deviation, could be calculated for SA samplers. In addition, the results point to possible ambiguity in the "true" measured concentration when operated according to a specific size-selective criterion. There is a need for research into defining the detailed penetration characteristics (aspiration efficiency) of the

SA sampler for the size fractions in the respirable dust range. Also, a draft guideline should be developed for the South African mining industry based on the outcome of the above-recommended research.

Unlike in many of the laboratory studies, SA sampler penetration curves were not determined for mine atmospheric dust (poly-disperse) and the harsh, turbulent conditions underground. Therefore, it is difficult to obtain definite and conclusive evidence to clear up the uncertainties. What can be said with certainty is that the results presented here indicate that under the conditions of this study, there were significant differences between the measured respirable dust concentrations using two samplers, measured according to a specified size-selective curve.

It is worth mentioning that a recent study (Belle *et al.*, 1999) in which the performance of two different gravimetric samplers (BGI sampler and SA sampler), conforming to the same size-selective curve (ISO/CEN/ACGIH) and used as area samplers, was compared in the field, yielded insignificant differences in measured levels. This further validates continued usage of local samplers in our mines. In conclusion, the SA sampler yielded the higher average concentration, followed by the D-O sampler, in spite of them both being exposed to similar test conditions.

3.3.2 Pair-wise comparison of IOM sampler and South African cyclones

During the laboratory trials, the IOM sampler operated at 2,0 L/min and the SA cyclone operated at 2,2 L/min were positioned side by side inside the dust chamber and exposed to coal and sandstone briquette dust. The relationship between the concentration values obtained from the side-by-side IOM and SA samplers during the laboratory evaluation for both types of dust is shown in Figure 3.3.2. The solid black line represents a 1:1 relationship.

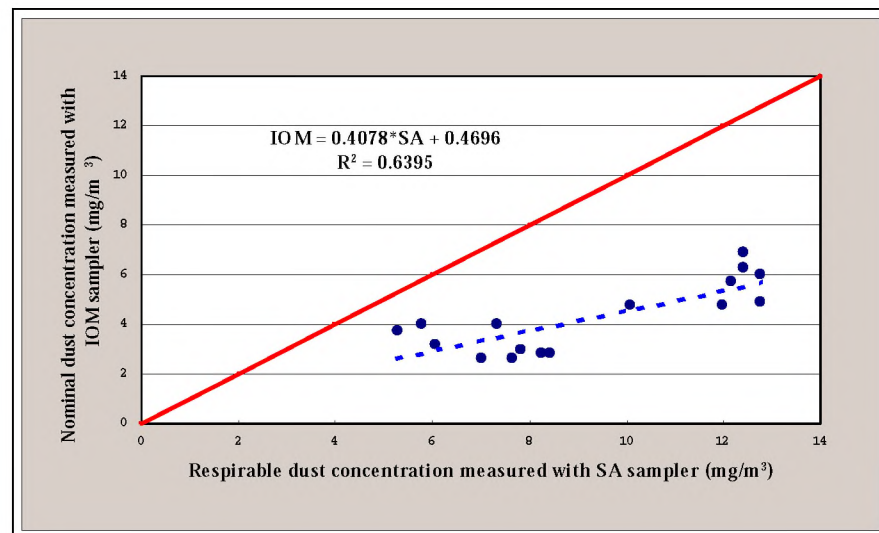


Figure 3.3.2: Combined plot of the relationship between side-by-side IOM and SA samplers

The correlation coefficient (r) between the two samplers is 0,7984. The plot shows a good linear relationship between the sampler results and clearly indicates the underestimation by the IOM sampler for various measured dust concentrations. From the laboratory data, we note that there is a significant difference between the measured dust concentrations using the two samplers. For coal dust, the average measured concentration levels using the SA and IOM samplers are $7,232 \text{ mg/m}^3$ and $3,088 \text{ mg/m}^3$ respectively for the test conditions. Similarly, for sandstone dust, the average measured concentration levels using the SA and IOM samplers are $11,293 \text{ mg/m}^3$ and $5,407 \text{ mg/m}^3$ respectively. From the regression line we can calculate that the IOM sampler underestimates the respirable dust concentration levels by about 36% at a compliance level of 2 mg/m^3 , but at greater dust levels the underestimation is much higher.

3.3.3 Relationship between the NIOSH Respirable Dust Dosimeter (RDD) and South African cyclones

The NIOSH RDD was positioned side by side inside the dust chamber with the SA sampler and the DO sampler, as shown in the Figure 3.3.1d. The operating principle of the RDD is discussed elsewhere in this report (Section 2.2). During the laboratory trials, it was initially assumed that the variability from tube to tube was negligible and it was expected that the SKC dosimeter pump would calculate the differential pressure directly. However, the older-version dosimeter pump (which was used in the test) did not have the

feature that would give the pressure drop with increase in mass loading directly. Therefore, the variability from tube to tube was incorporated into the laboratory results.

In order to determine the variability, the RDD tubes were tested in a clean weighing room – 30 seconds for each tube – and the initial pressure was measured. The average of the initial RDD tube pressures was subtracted from the final laboratory-measured pressure data. Figure 3.3.3a shows the histogram of the initial pressures of the RDD tubes. The summary statistics of the initial pressures measured for the RDD tubes is shown in Table 3.3.3a. From the latter table and the distribution plot (Figure 3.3.3a) it can be seen that the initial pressures of the RDD tubes were normal, with minimum and maximum initial measured pressures of 2,786 mmHg and 4,571 mmHg respectively. The mean initial pressure for the 168 tubes measured was 3,507 mmHg.

The scatter plot and the least-squares regression of the gravimetric sample mass versus the dosimeter pressure increases for the side-by-side comparisons with both coal and sandstone dust are shown in Figures 3.3.3b and 3.3.3c respectively.

Table 3.3.3a: Summary statistics of initial RDD pressures

Statistic	RDD pressure
Mean	3,507
Variance	0,052
Standard deviation	0,227
Median	3,482
Minimum	2,786
Maximum	4,571
Size	168

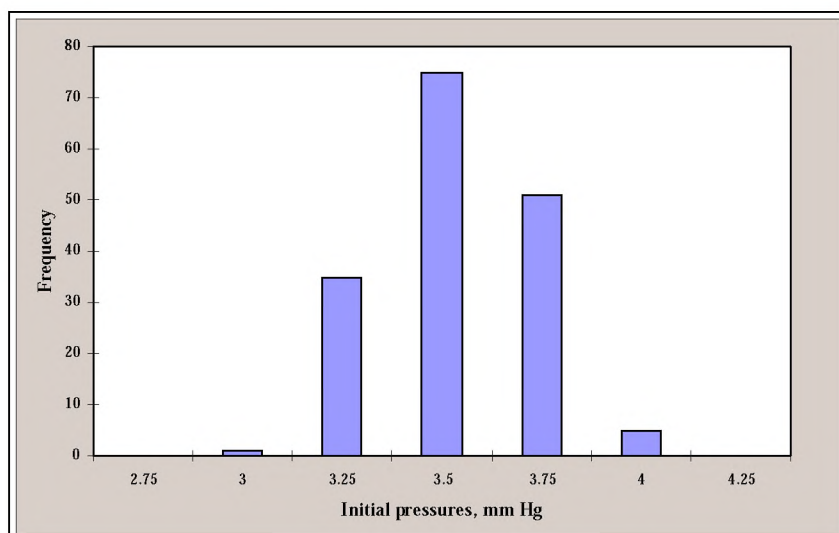


Figure 3.3.3a: Variability of initial pressures of RDD tubes

Overall, the plots show the linear relationship between the RDD and SA samplers. The scatter was wide for all levels of respirable coal dust, but it was narrow for the respirable sandstone dust, with a power relationship giving the best fit. The linear relationship between the RDD and SA samplers was plotted for the combined dust data and it was found that the relationship between the two samplers was comparatively strong (Figure 3.3.3d).

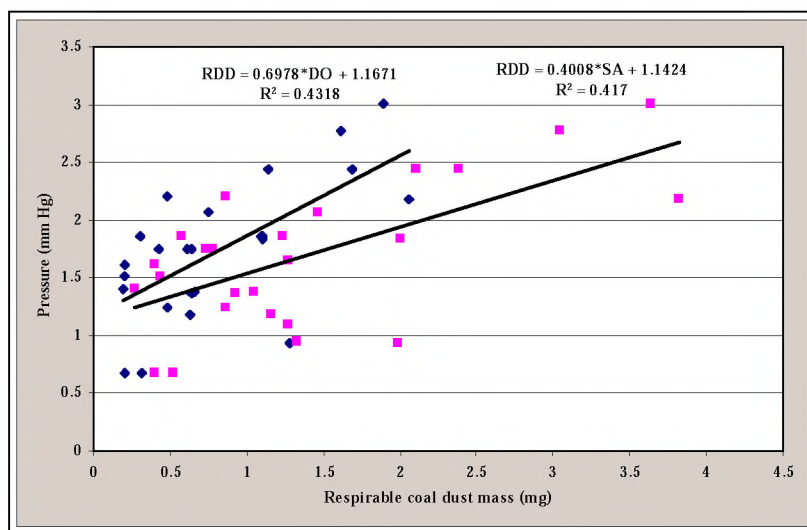


Figure 3.3.3b: Relationship between RDD and cyclones for coal dust

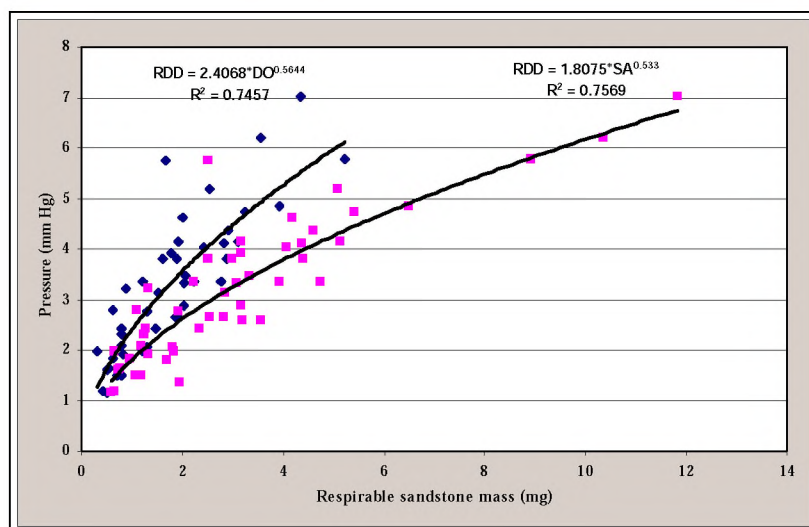


Figure 3.3.3c: Relationship between RDD and cyclones for sandstone dust

The combined data for the plot of both coal and sandstone dust indicate a good coefficient of determination. From the laboratory trials, it can be concluded that the relationship between the RDD and SA gravimetric samplers was average. The differences could be due to the variations in initial pressure between the RDD tubes. In conclusion, the laboratory study shows the potential of the RDD sampler as a screening tool for engineering sample purposes.

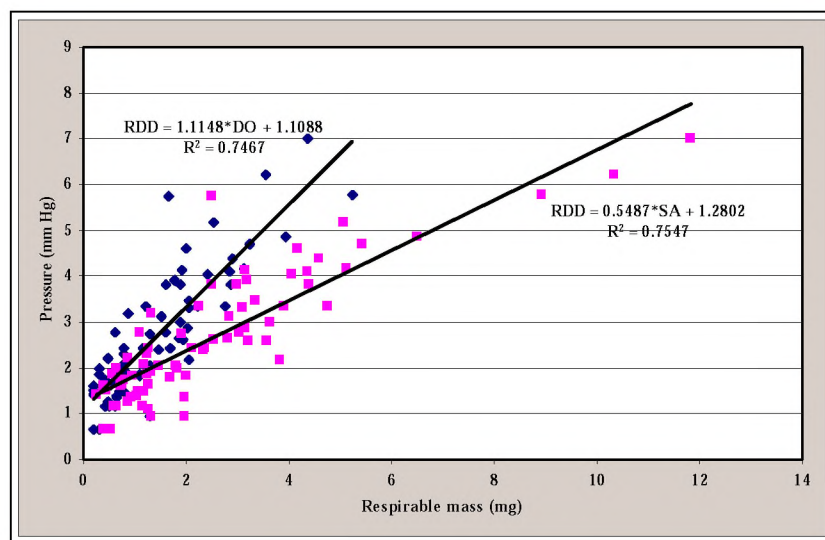


Figure 3.3.3d: Combined data plot of relationship between RDD and SA cyclones

3.3.4 Comparison of near-real-time dust monitors (Hund, PDR, Split-2) and SA sampler

A photographic view of the real-time dust-monitoring instruments evaluated in the Polley duct is shown in Figure 3.3.4a. During the study, all the near-real-time monitors were used in the passive sampling mode (they can be operated in the active mode as well). The SA gravimetric sampler was operated at a flow rate of 2,2 L/min according to the ISO/CEN/ACGIH size-selective curve.

The average real-time Hund respirable dust concentration level and the SA sampler concentration level for coal and sandstone dust is shown in Figure 3.3.4b. From the plot we observe that there is a strong linear relationship ($r = 0,972$) between the Hund and the SA sampler. The laboratory data (59 pairs) shows that there is a significant difference between the measured dust concentrations between the Hund and the SA sampler (see Figure 2.8.4b).

For coal dust, the average measured concentration levels using the SA sampler and the Hund tyndallometer were $3,365 \text{ mg/m}^3$ and $1,708 \text{ mg/m}^3$ respectively. Similarly, for sandstone dust, the average measured concentration levels using the SA sampler and the Hund tyndallometer were $7,953 \text{ mg/m}^3$ and $3,854 \text{ mg/m}^3$ respectively. The combined data indicate that on average for the test conditions, the measured concentration levels using the SA sampler and the Hund were $5,447 \text{ mg/m}^3$ and $2,300 \text{ mg/m}^3$ respectively.

The linear regression equation and the results suggest that the Hund seriously underestimates the measured dust levels when operated in a passive sampling mode. This can be partly attributed to the operating characteristics of the Hund. Also, the Hund approximately follows the BMRC size-selective curve, whereas the SA sampler was operated according to the ACGIH/CEN/ISO curve, with a higher particle size cut-off. Overall, it can be concluded that the use of the real-time Hund on a stand-alone basis in passive mode will seriously underestimate the personal respirable dust exposure.

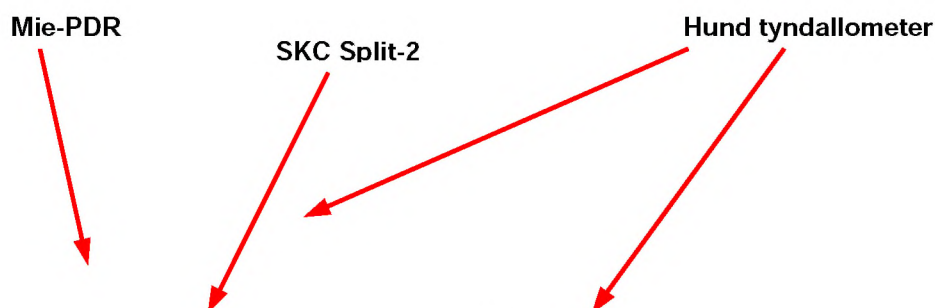




Figure 3.3.4a: Split-2, PDR and Hund dust monitors in the test chamber

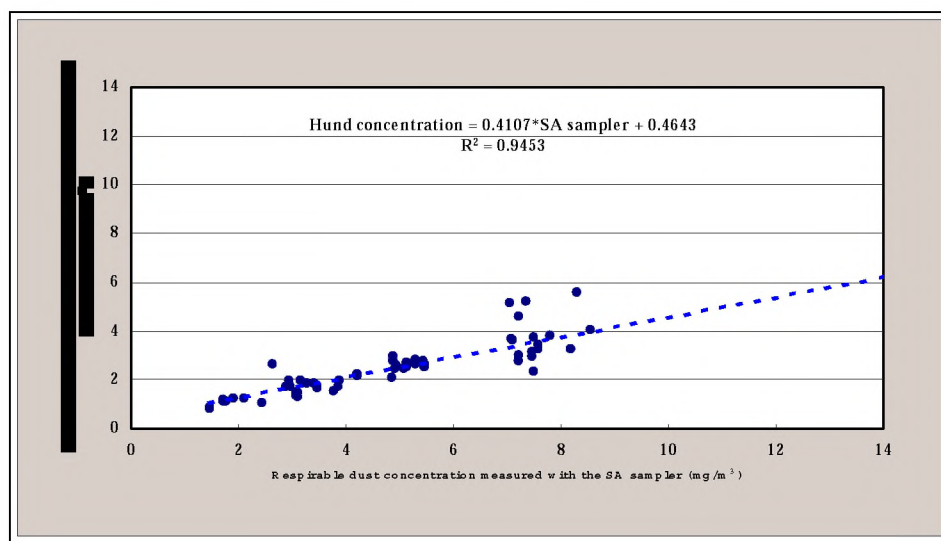


Figure 3.3.4b: Relationship between average real-time and gravimetric dust levels

As a part of the laboratory study, the difference in the measured dust levels when the real-time instruments (Hund, PDR and Split-2) and the SA gravimetric sampler were positioned side by side and exposed to the same dust cloud was determined. Figure 3.3.4c shows the maximum display concentration recorded by the real-time instruments positioned side by side in the test chamber. The plot (Figure 3.3.4c) shows that the PDR dust monitor yielded the highest recorded maximum dust concentration levels, followed by the Hund and Split-2 dust monitors. For engineering dust control strategies, the PDR could be the preferred instrument as it would give the occupational hygienist or the environmental supervisor conservative measurement levels.

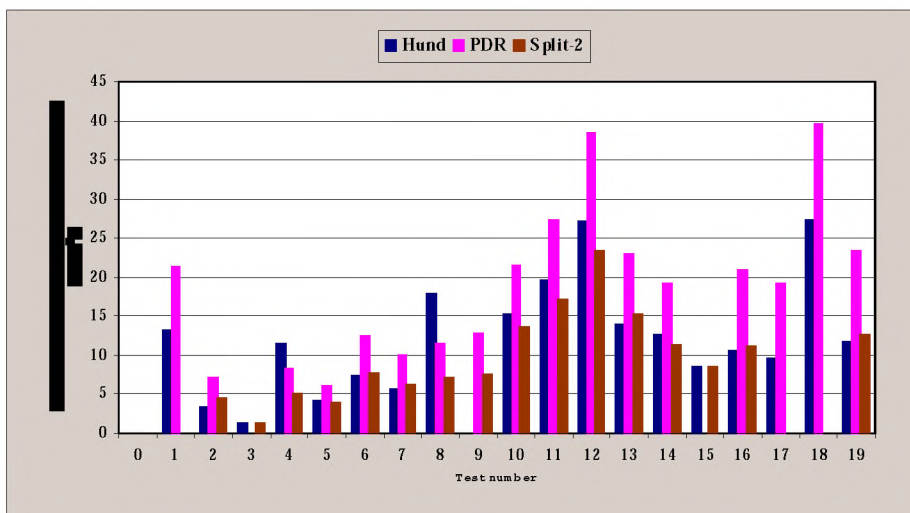


Figure 3.3.4c: Maximum display concentration recorded by real-time monitoring instruments (Hund, PDR and Split-2) positioned side by side

Figure 3.3.4d shows the average respirable dust concentration recorded by the real-time instruments positioned side by side along with the SA gravimetric sampler in the test chamber. From the plot (Figure 3.3.4d), we note that there is a significant difference between the measured average dust concentrations using the gravimetric and near-real-time dust monitors. For coal dust, the average ratios of real-time dust monitor and gravimetric sampler concentration levels for the Hund, PDR and Split-2 samplers are 0,52, 0,859 and 0,544 respectively. Similarly, for sandstone dust, the average ratios are 0,506, 0,95 and 0,55 respectively. The combined data indicate that the average ratios are 0,513, 0,906 and 0,546 respectively. Overall, it can be seen that PDR dust monitor yielded dust levels closest to those of the gravimetric sampler, followed by the Split-2 and the Hund.

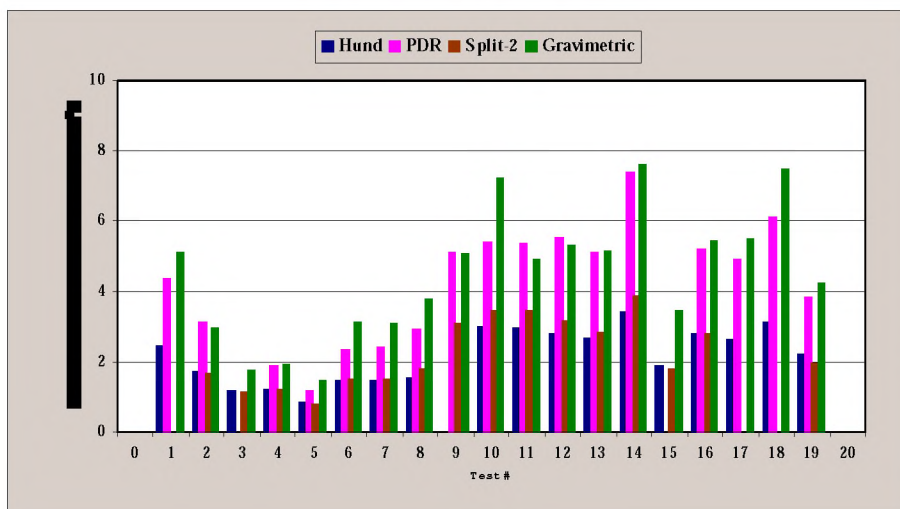


Figure 3.3.4d: Relationship between average SA gravimetric sampler and average real-time dust concentration levels (Hund, PDR and Split-2)

3.3.4.1 Variations between three Split-2 instruments positioned side by side

In order to determine the variation between near-real-time dust-monitoring instruments of a similar type, three Split-2 near-real-time dust monitors were positioned side by side. A photographic view of the near-real-time monitoring instruments tested in the chamber is shown in Figure 3.3.4.1a. The results of the variation between instruments of the same type are discussed below. Figures 3.3.4.1b to 3.3.4.1d show the average, maximum STEL and maximum display concentration levels recorded by the Split-2 instruments positioned side by side, randomly, in the test chamber using sandstone briquette dust.

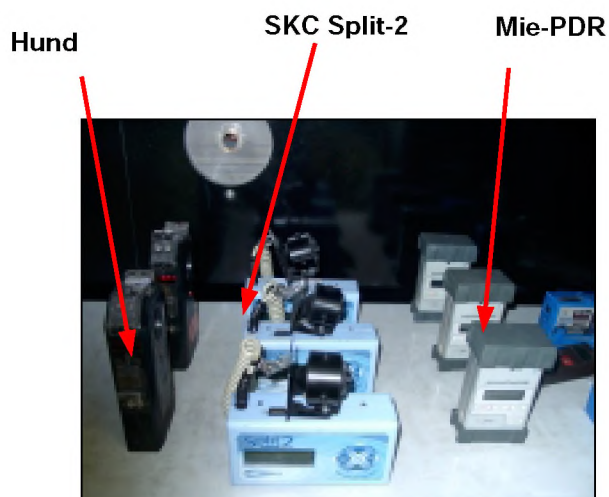


Figure 3.3.4.1a: Split-2, PDR and Hund monitors in the test chamber

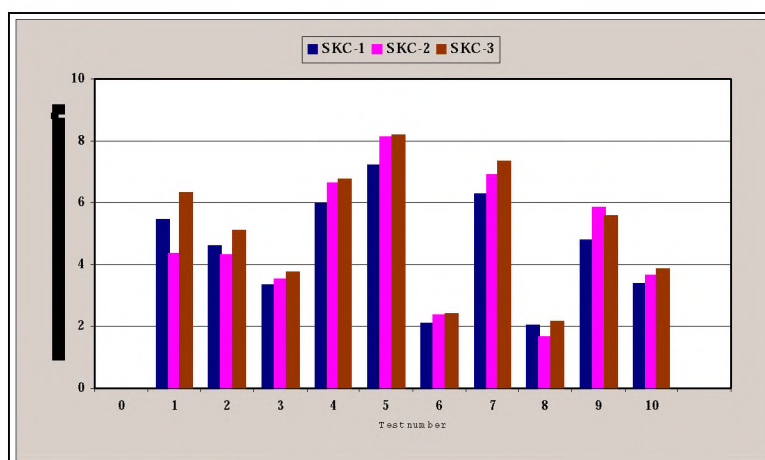


Figure 3.3.4.1b: Average real-time concentration levels recorded by the Split-2 using sandstone dust

Similarly, Figures 3.3.4.1e to 3.3.4.1g show the average, maximum STEL and maximum display concentration levels recorded by the Split-2 instruments positioned side by side, randomly, in the test chamber using coal dust. Table 3.3.4.1a shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the Split-2 real-time dust monitors using both coal and sandstone dust.

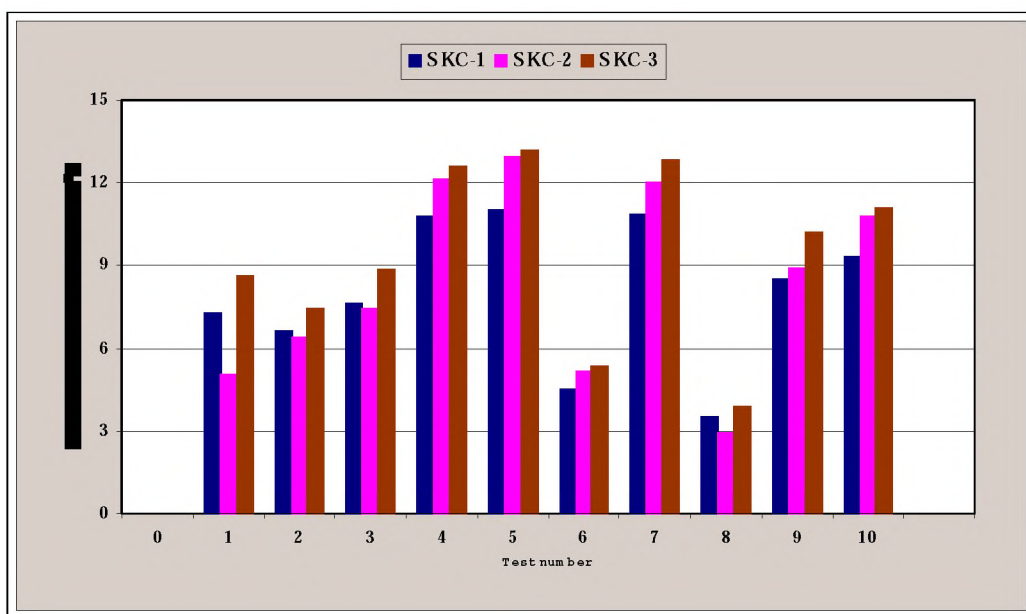


Figure 3.3.4.1c: Maximum-STEEL real-time concentration levels recorded by the SKC Split-2 using sandstone dust

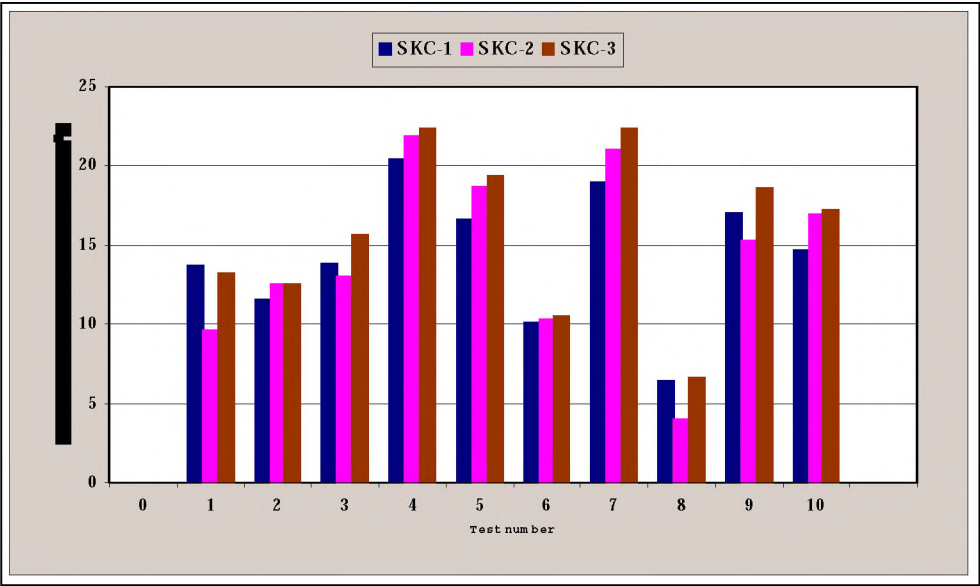


Figure 3.3.4.1d: Maximum display real-time concentration levels recorded by the SKC Split-2 using sandstone dust

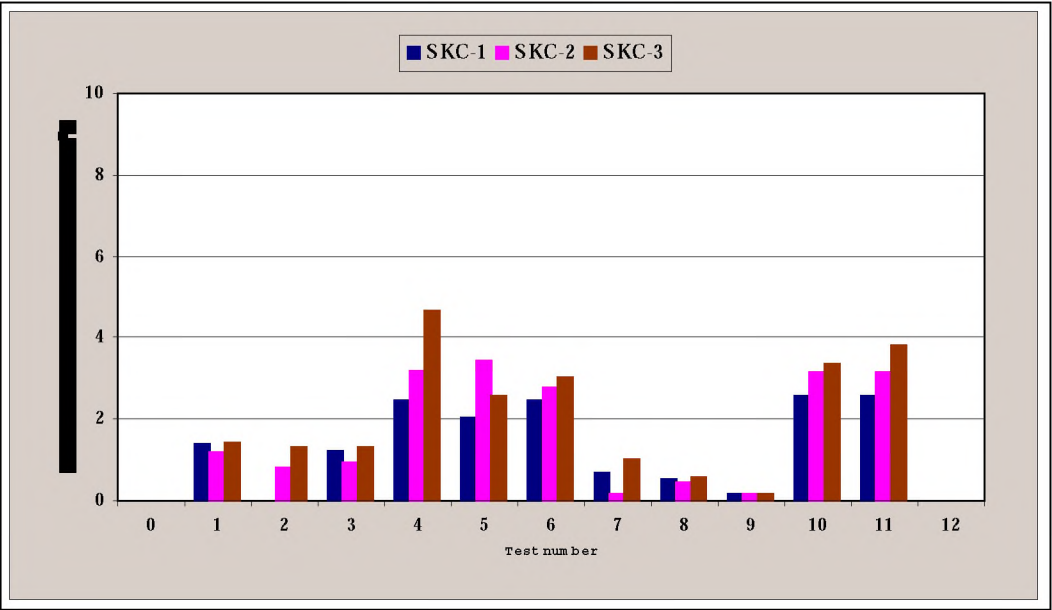


Figure 3.3.4.1e: Average real-time concentration levels recorded by the SKC Split-2 using coal dust

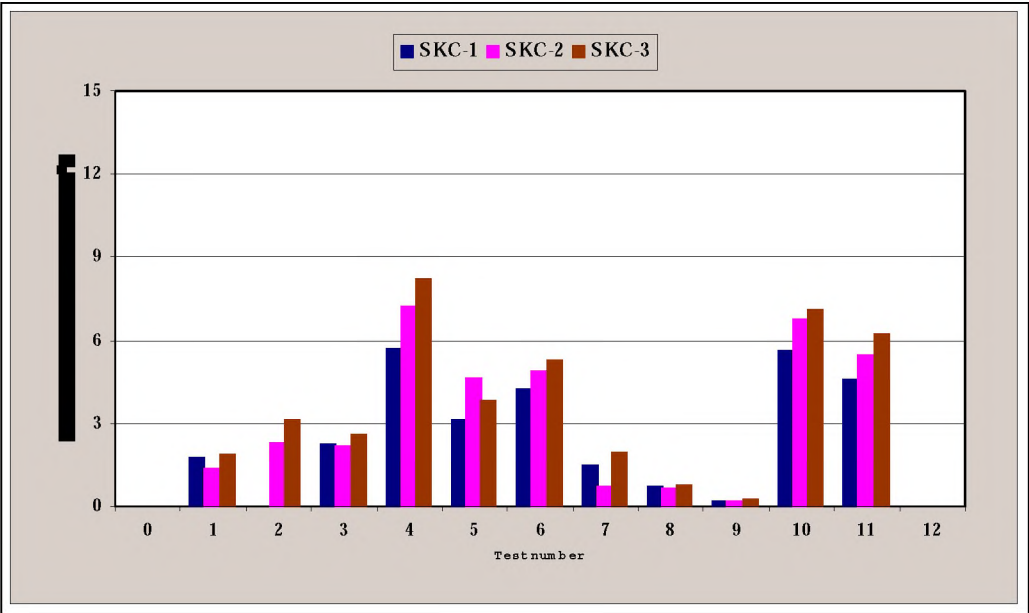


Figure 3.3.4.1f: Maximum STEL real-time concentration levels recorded by the SKC-Split-2 using coal dust

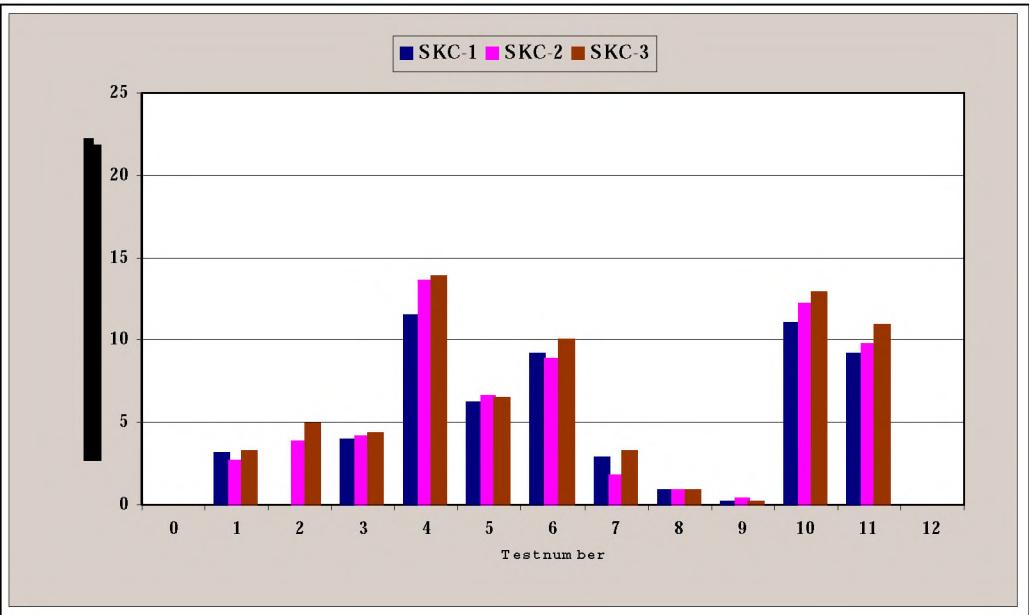


Figure 3.3.4.1g: Maximum display real-time concentration levels recorded by the SKC Split-2 using coal dust

From the plots we observe that the average, maximum STEL and maximum display concentrations recorded by the three Split-2 near-real-time dust-monitoring units positioned side by side would differ when the instruments were exposed to the same dust

cloud. This is not surprising, as the dust levels recorded are greatly influenced by the micro dust environment of the sensing zone of each unit.

Table 3.3.4.1a: Summary statistics of dust concentrations (av.) using the Split-2

Statistic	Average dust levels, mg/m ³					
	Sandstone dust			Coal dust		
	Split ₁	Split ₂	Split ₃	Split ₁	Split ₂	Split ₃
Mean	4,51	4,733	5,143	1,617	1,862	2,199
Variance	3,11	4,341	4,259	0,875	1,961	2,261
Median	4,685	4,33	5,33	1,725	1,985	2,005
Minimum	2,05	1,64	2,14	0,16	0,15	0,18
Maximum	7,20	8,13	8,19	2,6	3,45	4,66
Size	10	10	10	10	10	10
	Maximum STEL, mg/m ³					
	Split ₁	Split ₂	Split ₃	Split ₁	Split ₂	Split ₃
Mean	8,005	8,373	9,398	2,945	3,384	3,791
Variance	6,882	12,27	10,12	3,947	7,135	7,656
Median	8,055	8,17	9,52	2,645	3,405	3,175
Minimum	3,52	2,93	3,87	0,18	0,17	0,21
Maximum	11,04	12,96	13,17	5,67	7,18	8,19
Size	10	10	10	10	10	10
	Maximum dust levels, mg/m ³					
	Split ₁	Split ₂	Split ₃	Split ₁	Split ₂	Split ₃
Mean	14,342	14,336	15,848	5,811	6,089	6,61
Variance	17,814	30,927	26,366	17,35	23,40	24,84
Median	14,255	14,16	16,345	5,03	5,38	5,41
Minimum	6,4	3,96	6,65	0,22	0,35	0,24
Maximum	20,38	21,91	22,38	11,48	13,61	13,86
Size	10	10	10	10	10	10

3.3.4.2 Variation between three PDR monitors positioned side by side

The results of the variation between the dust levels measured by three PDR dust monitors positioned side by side and exposed to the same dust cloud are discussed below. Figures 3.3.4.2a to 3.3.4.2d show the average, maximum STEL and maximum display

concentration levels recorded by three PDR dust monitors positioned side by side, randomly, in the test chamber using sandstone briquette dust.

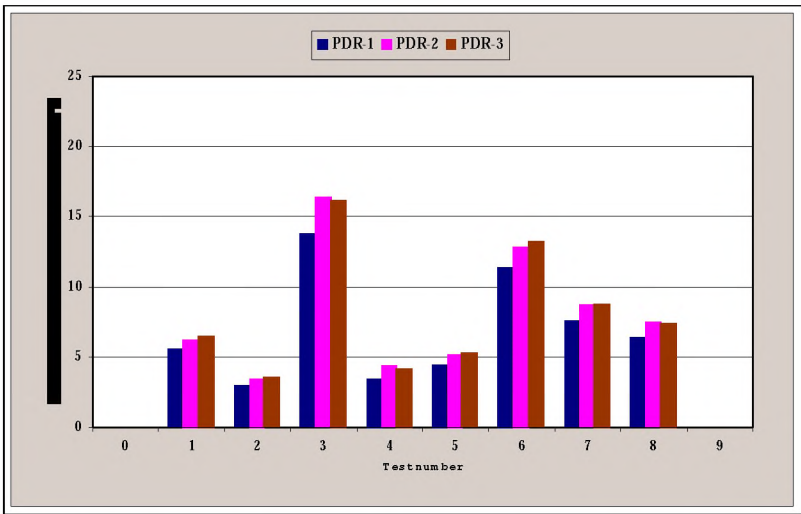


Figure 3.3.4.2a: Average real-time concentration levels recorded by the PDR using sandstone dust

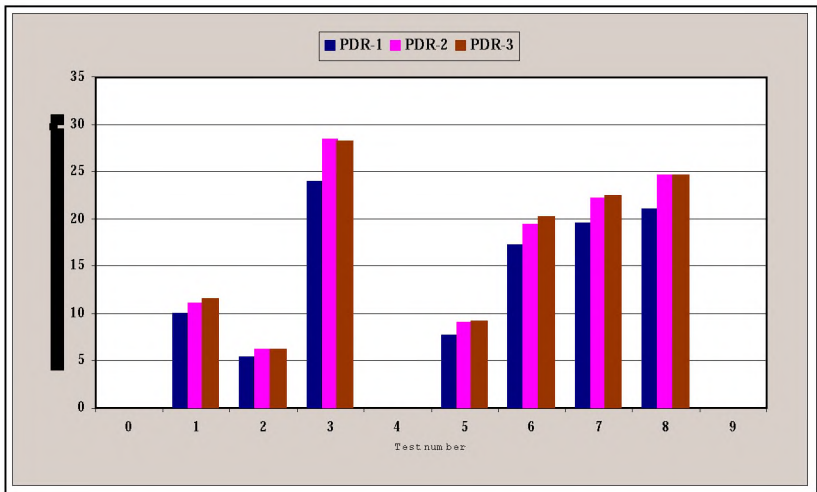


Figure 3.3.4.2b: Maximum-STEL real-time concentration levels recorded by the PDR using sandstone dust

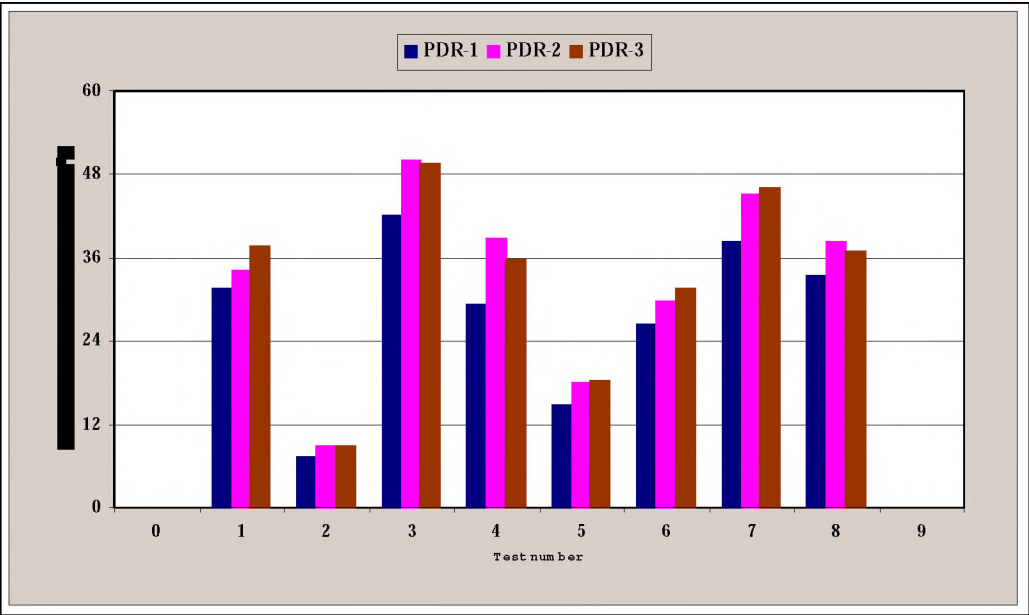


Figure 3.3.4.2c: Maximum display real-time concentration levels recorded by the PDR using sandstone dust

Figures 3.3.4.2d to 3.3.4.2f show the average, maximum STEL and maximum display concentration levels recorded by the PDR instruments positioned side by side, randomly, in the test chamber using coal dust.

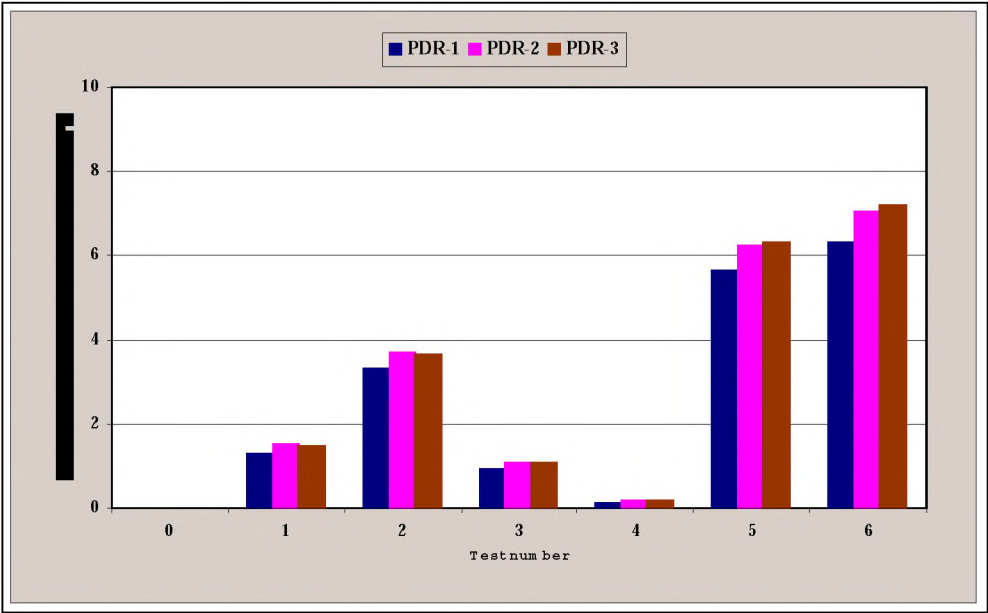


Figure 3.3.4.2d: Average real-time concentration levels recorded by the PDR using coal dust

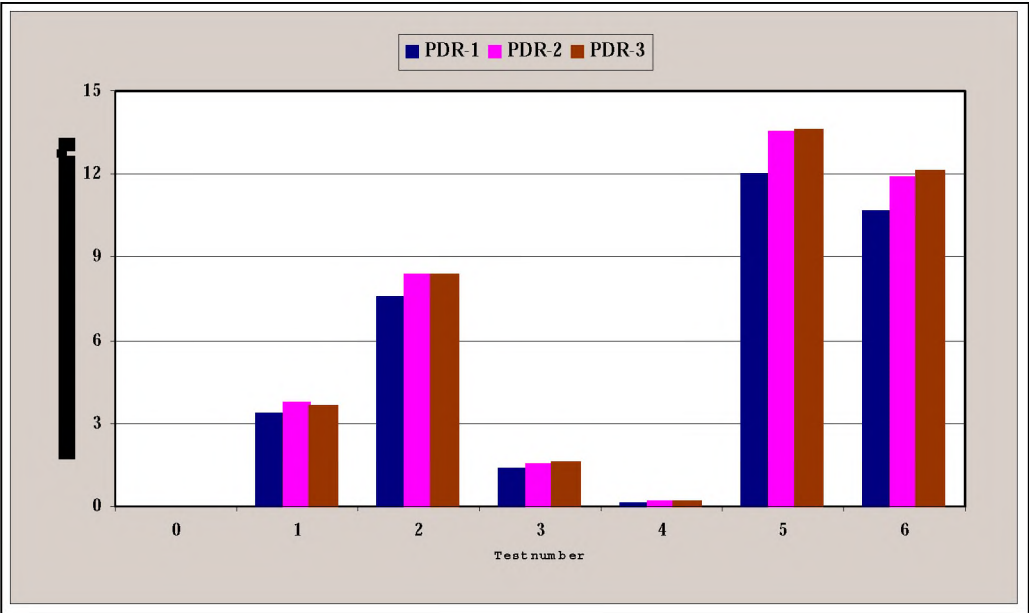


Figure 3.3.4.2e: Maximum STEL real-time concentration levels recorded by the PDR using coal dust

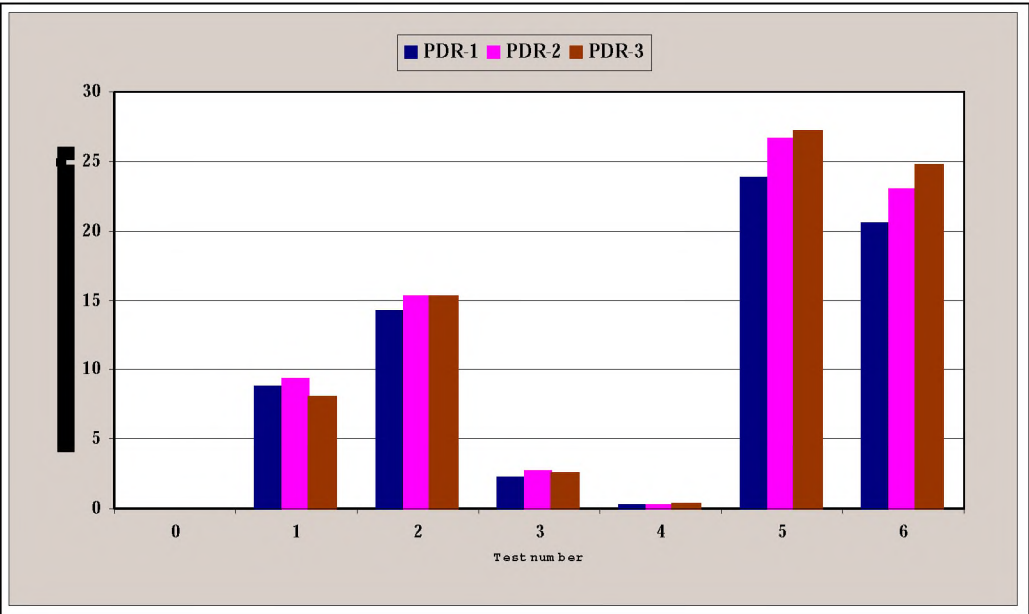


Figure 3.3.4.2f: Maximum display real-time concentration levels recorded by the PDR using coal dust

Table 3.3.4.2 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of three PDR real-time dust monitors using both coal and sandstone dust.

Table 3.3.4.2: Summary statistics of dust concentrations (av.) using the PDR

Statistic	Average dust levels, mg/m ³					
	Sandstone dust			Coal dust		
	PDR ₁	PDR ₂	PDR ₃	PDR ₁	PDR ₂	PDR ₃
Mean	7,439	8,573	8,670	2,938	3,286	3,316
Variance	14,759	20,715	20,314	6,695	8,188	8,443
Median	6,411	7,452	7,411	2,32	2,60	2,57
Minimum	2,99	3,427	3,502	0,125	0,172	0,187
Maximum	13,755	16,368	16,182	6,315	7,044	7,188
Size	7	7	7	6	6	6
	Maximum STEL, mg/m ³					
	Sandstone dust			Coal dust		
	PDR ₁	PDR ₂	PDR ₃	PDR ₁	PDR ₂	PDR ₃
Mean	14,967	17,25	17,46	5,843	6,541	6,58
Variance	52,409	73,16	71,22	24,74	30,76	31,47
Median	17,213	19,38	20,22	5,45	6,06	6,02
Minimum	5,314	6,155	6,211	0,137	0,182	0,204
Maximum	23,956	28,47	28,1	35,032	39,25	39,48
Size	7	7	7	6	6	6
	Maximum dust levels, mg/m ³					
	Sandstone dust			Coal dust		
	PDR ₁	PDR ₂	PDR ₃	PDR ₁	PDR ₂	PDR ₃
Mean	27,629	31,949	32,687	11,638	12,863	13,053
Variance	157,72	214,07	212,53	92,57	114,357	127,41
Median	31,507	34,017	36,99	11,503	12,863	11,708
Minimum	7,333	8,777	8,951	0,233	0,257	0,329
Maximum	41,987	49,948	49,605	23,844	26,616	27,175
Size	7	7	7	6	6	6

From the plots and the summary statistics table it can be seen that there is a significant difference between the dust levels measured by the three PDR monitors positioned side by side under the same dust cloud.

3.3.5 Establishing an accuracy criterion

As indicated earlier, for all comparison purposes, the dust level measured by the SA sampler was considered the "true" concentration. Therefore, the concentration ratio of the "evaluation instrument" to the reference instrument (in this study, the SA sampler) was calculated. If the variability in the concentration ratio is small, then one can consider accepting the "evaluation instrument" for further use. The concentration ratio is analogous to the bias as described by Kennedy *et al.* (1995). Bias is the relative discrepancy between the mean of normally distributed measurements and the true concentration. The relative standard deviation (RSD) was calculated from the standard deviation and the mean concentration ratio. Two accuracy criteria, $\pm 25\%$ and $\pm 50\%$, were used. These are analogous to the NIOSH instrumentation accuracy criterion (Kennedy *et al.*, 1995) and the European Community standard for "screening measurements" (CEN, 1993). For normally distributed data, 95% of the measurements fall within the range $\pm 1,96s$, where s is the standard deviation. For example, assuming that the mean is 100, for the criterion of $\pm 25\%$, then $1,96s = 25$ or $s = 12,7$. Because the mean is 100, the standard deviation divided by the mean (called RSD or CV) is 0,127. Thus, the $\pm 25\%$ accuracy criterion (NIOSH) is met at $RSD = 0,127$ or less and the $\pm 50\%$ accuracy criterion (CEN) is met at $RSD = 0,25$ or less.

Table 3.3.5 shows summary statistics of respirable dust concentration values obtained from the side-by-side comparison of the potential samplers and the SA sampler measured in the laboratory Polley dust duct when exposed to coal and sandstone briquette dust. The CV is the ratio of standard deviation and mean value expressed as a percentage. Therefore, the lower the CV of the correction factor, the more linear the response of the monitor.

From the summary statistics table (Table 3.3.5) it can be seen that there is no clear relationship between the accuracy of an instrument and its measured concentration levels. Overall, the CV of the ratio between the sampler dust concentrations was above the NIOSH and CEN accuracy criteria (except in three cases out of a total of 18). Generally, the identified potential instruments failed to meet the NIOSH and CEN accuracy criteria. The fact that the instruments failed to meet the criteria will not automatically exclude their usage in the industry for dust-monitoring purposes since researchers worldwide seldom agree when evaluating the accuracy and performance of newly developed samplers. However, it would be interesting to pursue a research project

in which the accuracy factors from various countries were compared. A new approach to the selection of instruments may also be necessary. The study indicates that a "secondary" acceptance parameter may be necessary for accepting the claims made by manufacturers with regard to dust monitoring instruments for the mining industry.

Table 3.3.5: Summary of the correction factors for dust monitors

Dust type	Instrument pair	Mean SA conc., mg/m ³	Mean ratio of concentrations	No. of readings	SD	RSD or CV (%)
Coal-Sandstone	DO-DO	5,624	1,038	12	0,053	5,11
Coal-Sandstone	SA-SA	10,803	1,035	15	0,074	7,15
Overall	DO-SA	8,501	1,036	27	0,064	6,18
Coal	DO-SA	4,627	0,795	49	0,173	21,76
Sandstone	DO-SA	7,092	0,803	46	0,133	16,56
Overall	DO-SA	5,821	0,799	95	0,154	19,27
Coal	IOM-SA	7,232	0,442	8	0,133	30,09
Sandstone	IOM-SA	11,293	0,493	8	0,098	19,87
Overall	IOM-SA	9,263	0,468	16	0,116	24,78
Coal	Hund-SA	3,365	0,535	28	0,12	22,43
Sandstone	Hund-SA	7,954	0,505	31	0,09	17,83
Overall	Hund-SA	5,446	0,519	59	0,11	21,19
Coal	PDR-1-SA	3,306	0,859	9	0,118	13,74
Sandstone	PDR-1-SA	5,694	0,959	8	0,088	9,18
Overall	PDR1-SA	0,464	0,906	17	0,114	12,58
Coal	Split2-1-SA	3,306	0,544	9	0,071	13,05
Sandstone	Split2-1-SA	5,148	0,549	7	0,077	14,02
Overall	Split2-1-SA	4,148	0,546	16	0,072	13,19
Coal*	PDR-1-SA	3,828	1,010	6	0,414	40,99
Sandstone*	PDR-1-SA	8,509	0,826	8	0,196	23,73
Overall*	PDR-1-SA	6,503	0,905	14	0,309	43,09
Coal	PDR-2-SA	3,828	1,193	6	0,555	46,52
Sandstone	PDR-2-SA	8,509	0,952	8	0,208	21,85
Overall	PDR-2-SA	6,503	1,058	14	0,397	37,52
Coal	PDR-3-SA	3,828	1,234	6	0,608	49,27
Sandstone	PDR-3-SA	8,509	0,965	8	0,222	23,00
Overall	PDR-3-SA	6,503	1,080	14	0,433	40,09
Coal*	Split2-1-SA	4,324	0,543	11	0,451	83,05
Sandstone*	Split2-1-SA	10,02	0,448	10	0,079	17,63
Overall*	Split2-1-SA	7,038	0,498	21	0,327	65,66
Coal	Split2-2-SA	4,324	0,525	11	0,416	79,20
Sandstone	Split2-2-SA	10,02	0,464	10	0,107	23,06

Overall	Split2-2-SA	7,038	0,496	21	0,305	61,49
Coal	Split2-3-SA	4,324	0,683	11	0,478	69,98
Sandstone	Split2-3-SA	10,02	0,508	10	0,093	18,30
Overall	Split2-3-SA	7,038	0,599	21	0,355	59,27

* 2nd series of tests

3.3.5.1 Statistical analyses

An analysis of the frequency distribution of the concentration values obtained by the samplers yielded a set of histograms. Comparing the sample distributions with a normal distribution leads to the rejection of the hypothesis that the sample distribution was normal. Therefore, plotting the histogram of the $\log_e$ transform of the dust concentration data led to the conclusion that the measurements were $\log_e$ normally distributed.

A paired t -test was performed on the set of sample pair data to determine whether there was a statistical difference in the $\log_e$ -transformed (normally distributed) concentration levels between the sampler pairs. A paired t -test of hypotheses was developed to compare the mean concentration levels measured with two sampling instruments (μ_A and μ_B). A paired t -test analysis procedure would probably have a smaller error term than the corresponding unpaired procedure because it removes the variability due to differences between the pairs. The null and alternative hypotheses for the sample pairs tested were:

$$H_0: \mu_A = \mu_B$$

$$H_1: \mu_A \neq \mu_B$$

In the paired t -test, hypothesis H_0 states that the mean dust concentration levels from both samples (μ_A and μ_B) are equal. On the other hand, the alternative hypothesis states that the two samplers in fact measure different mean concentration levels. It is therefore necessary to use hypothesis testing to accept or reject H_0 . For this work, a standard 95% confidence level was chosen. As the hypotheses stated were $\mu_A = \mu_B$ and $\mu_A \neq \mu_B$, all analyses were two-tailed to account for both conditions $\mu_A < \mu_B$ and $\mu_A > \mu_B$. Therefore, the critical t -values were determined by $t_{0,025}$ rather than $t_{0,05}$. Hypothesis tests were carried out for the data set. The results of the paired t -test statistical analyses are given in Table 3.3.5.1a.

In this study, a cut-off p-value of 0,05 was used (95% confidence level). From the analysis table we observe, with various degrees of freedom, the large p-value ($>0,05$) suggesting that the measured mean concentration levels are consistent with the null hypothesis, $H_0 =$

$\mu_A = \mu_B$, that is, the dust concentration measured by pairs of newly developed instruments and the SA sampler are not affected at the 95% level of confidence. From Table 3.3.5.1a we observe that, for both dust types, there was a significant difference in the measured dust concentration levels between the SA, the Dorr-Oliver (USA) and the IOM samplers. Similarly, the measured mean personal dust concentration levels from each pair of SA and PDR real-time dust monitors (all three units) were not significantly different and the null hypothesis is accepted for both dust types. Comparison of the Split-2 and the SA sampler concentration levels indicate that there was a significant difference in measured levels for both dust types for all three units.

Table 3.3.5.1a. Results of paired t-test (on transformed values)

Sampler pair	Dust type	Total pairs	95% LCL	95% UCL	T-value	p-value	Hypothesis
DO-SA	Coal	49	-0,298	-0,196	-9,72	0,000	Reject
DO-SA	Sandstone	46	-0,295	-0,177	-8,06	0,000	Reject
DO-SA	Total	95	-0,279	-0,203	-12,58	0,000	Reject
SA-IOM	Coal	8	0,618	1,08	8,63	0,000	Reject
SA-IOM	Sandstone	8	0,566	0,880	10,90	0,000	Reject
SA-IOM	Total	16	0,660	0,915	13,17	0,000	Reject
SA-Hund	Coal	28	0,567	0,728	16,56	0,000	Reject
SA-Hund	Sandstone	31	0,633	0,765	21,80	0,000	Reject
SA-Hund	Total	59	0,625	0,725	26,91	0,000	Reject
Split ₁ -SA	Sandstone	10	-0,946	-0,688	-14,30	0,000	Reject
Split ₂ -SA	Sandstone	10	-0,949	-0,631	-11,22	0,000	Reject
Split ₃ -SA	Sandstone	10	-0,824	-0,559	-11,83	0,000	Reject
Split ₁ -SA	Coal	11	-1,174	-0,419	-4,71	0,001	Reject
Split ₂ -SA	Coal	11	-1,310	-0,405	-4,22	0,002	Reject
Split ₃ -SA	Coal	11	-0,860	-0,186	-3,46	0,006	Reject
Split ₁ -SA	Total	21	-0,995	-0,617	-8,90	0,000	Reject
Split ₂ -SA	Total	21	-1,053	-0,598	-7,56	0,000	Reject
Split ₃ -SA	Total	21	-0,779	-0,428	-7,18	0,000	Reject
PDR ₁ -SA	Coal	6	-0,455	0,348	-0,34	0,747	Accept
PDR ₂ -SA	Coal	6	-0,360	-0,557	0,55	0,604	Accept
PDR ₃ -SA	Coal	6	-0,369	0,603	0,62	0,564	Accept
PDR ₁ -SA	Sandstone	8	-0,495	0,040	-2,02	0,084	Accept
PDR ₂ -SA	Sandstone	8	-0,078	0,285	-0,78	0,464	Accept
PDR ₃ -SA	Sandstone	8	-0,325	0,186	-0,65	0,539	Accept
PDR ₁ -SA	Total	14	-0,352	0,046	-1,66	0,121	Accept
PDR ₂ -SA	Total	14	-0,206	0,202	-0,02	0,981	Accept
PDR ₃ -SA	Total	14	-0,207	0,228	0,10	0,921	Accept

A paired *t*-test was performed on the combined data for both dust types to determine whether there was a statistical difference in the results obtained between the SA sampler and the near-real-time dust monitors. The result of the paired *t*-test was a test statistic with 15 degrees of freedom (high p-value), indicating that there is no significant difference

between the measured mean concentration levels using the SA sampler and the near-real-time PDR dust monitor side by side. However, for the Split-2 real-time dust monitor and SA sampler pair, with 20 degrees of freedom, $p = 0,000$, indicating a significant difference between the gravimetric and Split-2 samplers. Except in the case of the PDR dust monitor, there was a significant difference between the measured dust levels of the newly developed dust monitors and the SA sampler, showing rejection of the null hypothesis. In other words, the dust readings measured by the two samplers side by side are significantly affected at the 95% level of confidence.

Analysis of Variance (ANOVA)

The measured dust concentration ratio between the real-time dust monitors' data (PDR and Split-2) and the reference sampler (SA sampler) data was used to perform an analysis of variance (ANOVA). A discussion of the ANOVA models and their underlying assumptions can be found in any of the standard books on statistics.

In order to quantify statistically the influence of dust type (coal and sandstone), dust monitor type (Split-2 and PDR), monitoring units of the same type (unit 1, unit 2 and unit 3) and the position of the real-time dust-monitoring units in the dust chamber on the ratio of measured dust concentration levels between the instruments, a factorial analysis was carried out. Essentially, the measured dust concentration ratio data that were used for analysis were in the form of C_{ijkl} (mg/m^3). The subscripts have the following definitions:

i = dust type (DT), $i = 0$ is a coal dust, $i = 1$ is a sandstone dust

j = monitoring unit (MU), $j = 0$ is unit-1, $j = 1$ is unit-2, and $j = 2$ is unit-3

k = dust monitor type (DM), $k = 0$ is Split-2 monitor, $k = 1$ is PDR monitor

l = unit position (UP), $l = 0, 1$, and 2 indicate the sampling positions (randomly selected) across the dust chamber respectively.

The results of the analysis of variance (ANOVA) on the data are summarised in Table 3.3.5.1b.

Table 3.3.5.1b: Results of analysis of variance (ANOVA) for laboratory data

Sources of variation	Df	SS	MS	F-value	Pr > F
Dust type (DT)	1	0,04837	0,04837	0,87	0,352
Monitoring unit (MU)	2	0,20264	0,10132	1,83	0,166
Dust monitor type (DM)	1	5,7026	5,70266	103,11	0,000

Unit position (UP)	2	0,02967	0,01483	0,28	0,759
DT*MU	2	0,00839	0,00419	0,08	0,927
DT*DM	1	0,07872	0,07872	1,42	0,236
MU*DM	2	0,05783	0,02891	0,52	0,595
DT*MU*DM	2	0,01047	0,00524	0,09	0,910
Higher-order interactions	85	4,68171			
Total	98	10,8204			

The main factors of the statistical analysis were: dust type, monitoring unit, dust monitor type and sampling position. The ANOVA table gives, for each term in the model, the degrees of freedom, the sums of squares (SS), the adjusted mean squares (MS), the F-statistic from the adjusted mean squares and its p-value. In the ANOVA table, some p-values were less than 0,05, indicating that these factors are significant. Individual two-factor, three-factor or multi-factor interactions were also calculated and are shown in the table.

From the results of the ANOVA, the following conclusions were reached:

- The effect of dust type on the dust concentration ratio between the two monitors positioned side by side is insignificant.
- There is strong evidence (p-value of 0,000) of the effect of the type of dust-monitoring unit on the measured dust levels when the units are exposed to the same dust, for all dust types (the MS value for dust monitor type is 5,7026).
- The dust-monitoring instrument's performance is not significantly affected by the position of the monitoring unit within the chamber. Also, there is less evidence of a significant difference in the concentration levels measured by different units of the same type of dust monitor (p = 0,166).
- From the magnitude of each test parameter, the dust monitor type, monitoring unit (1 or 2 or 3), dust type and position of the monitoring units within the chamber can be arranged in descending order of importance. As we note from the table, the interactions between the main factors do not have any significant effect on the measured dust concentration levels.
- Overall, the ANOVA demonstrates very well that the main factor – dust-monitoring type (Split-2 or PDR) – greatly influenced the dust levels measured in the laboratory study.

3.4 Conclusions from the laboratory study

The following conclusions can be drawn from the laboratory evaluation of the identified potential instruments:

- There is a significant difference in the measured dust levels between SA sampler and Dorr-Oliver sampler when operated according to the same size-selective curve (ACGIH/ISO/CEN).
- There is a significant difference in measured dust levels between the IOM sampler and SA sampler
- NIOSH RDD can be potentially used as a screening tool and there was a linear relationship between increase in pressure of RDD and mass collected on the gravimetric filter
- There is a significant difference in dust levels between gravimetric samplers and near-real-time dust monitors when operated in passive mode
- From the statistical analysis of all side-by-side comparison of newly developed dust monitors and SA sampler indicate that there is a significant difference in measured dust levels except in the case of PDR near-real-time dust monitor. This indicates that the PDR is potentially closest dust sampler that can be used for estimating personal near-real-time dust exposure. However, the use of near-real-time instruments as a stand-alone instrument for compliance purposes is not recommended.

4 Underground Study

4.1 Introduction

This section of the report discusses the results of the underground evaluation of the newly developed near-real-time and gravimetric-type dust-monitoring instruments as personal sampling devices. Table 4.1 summarises the various dust-monitoring instruments (real-time and gravimetric type) that are available on the market. The potential instruments are claimed by the instrument manufacturers to be suitable for use in mines. However, only a few of these instruments are already used in underground mines in South Africa (e.g. the CIP-10), but several are being considered for recommended use in overseas mines (Kenny, 2000).

Table 4.1: Intrinsically safe dust samplers potentially suitable for South African mines

Name	Sampling method	Quartz?	Fraction	Personal	Area	Size-selective curve	Weight g	IS	Status
MRE 113a	G	Y	R	N	Y	BMRC	4 250	Y	C
Cyclone	G	Y	R, T	Y	Y	ISO/CEN/ACGIH	550	Y	C
CIP10	G	Y	R, T, I	Y	Y	ISO/CEN/ACGIH	300	Y	C
IOM foam	G	Y	R, T, I	Y	Y	ISO/CEN/ACGIH	550	Y	New
Electret	G	N	NS	Y	Y	None	150	Y	New
Hund	RT	N	R	Y	Y	BMRC	1 000	Y	C
Dust track	RT	N	R	Y	Y	ISO/CEN/ACGIH	800	N	C
NIOSH TEOM	RT	Y	R	Y	Y	ISO/CEN/ACGIH	-	-	NV
NIOSH RDD	RT	Y	R	Y	Y	ISO/CEN/ACGIH	150	Y	New
Mie-PDR	RT	N	R	Y	Y	ISO/CEN/ACGIH	600	N	C
Respicon	RT	N	R, T, I	Y	Y	ISO/CEN/ACGIH	800	N	C
Split-2	RT	N	R, T, I	Y	Y	ISO/CEN/ACGIH	1 200	N	C

G: gravimetric; RT: real-time; Y: yes; N: no; R: respirable; T: thoracic; I: inhalable; NS: not specified; IS: intrinsically safe; NV: not available

In order for the introduction of newly developed dust-monitoring instruments for personal sampling purposes in underground mines to be accepted by the stakeholders, a number of criteria were set during the study (see Section 2.9). To study the performance of the identified dust monitors (both gravimetric and near-real-time sampling types) under various underground test conditions, they need to be compared with a standard method for determining airborne respirable dust concentrations. In this study, they were compared with Higgins-Dewell-type South African cyclones. It was assumed that the cyclone

samplers gave negligible errors and a "true" measurement of personal dust concentration. Therefore, for all underground comparisons of personal dust levels, the South African cyclone was used as the standard sampler. The bias and accuracy were determined from the concentration ratios between the sampler pairs. For the underground evaluation, the following instruments were tested in this study:

Personal gravimetric respirable samplers:

- SA cyclone (GME # G05)
- Dorr-Oliver 10 mm cyclone
- IOM foam sampler.

Personal real-time monitoring instruments:

- SKC Split-2 dust monitor
- Mie-PDR
- NIOSH Dosimeter.

At the time of the underground evaluation, the Split-2 dust monitor did not have any IS certificate and the PDR had only partial SABS clearance. Therefore, during the underground trials, two methane monitors were used in order to detect the presence of methane in the sampling areas in the mines.

4.2 Test mines and instrumentation

In order to carry out the personal sampling in underground mines, a sampling harness was prepared and the dust monitors were worn in a specific position consistently in all the test mines (Figure 4.2a). Each sampling harness had the six identified instruments positioned side by side as shown in Figure 4.2b. The left lapel of the harness contained the SA cyclone, the IOM sampler and the PDR, while the right lapel of the harness contained the Split-2, the NIOSH RDD tube, and the Dorr-Oliver cyclone. The sampling harness with instruments weighed approximately 4,80 kg. During the underground trials, the individual carried a total weight of approximately 15 kg, which included the self-contained self-rescuer (SCSR), cap lamp and carrying bags. The sampling team was supervised underground by an experienced dust-monitoring/sampling expert to ensure consistency of the measurements. During a few trials, the near-real-time monitoring instruments (Split-2 and PDR) failed due to internal instrument problems and were sent for repairs.



Figure 4.2a: Underground team wearing six personal dust monitors

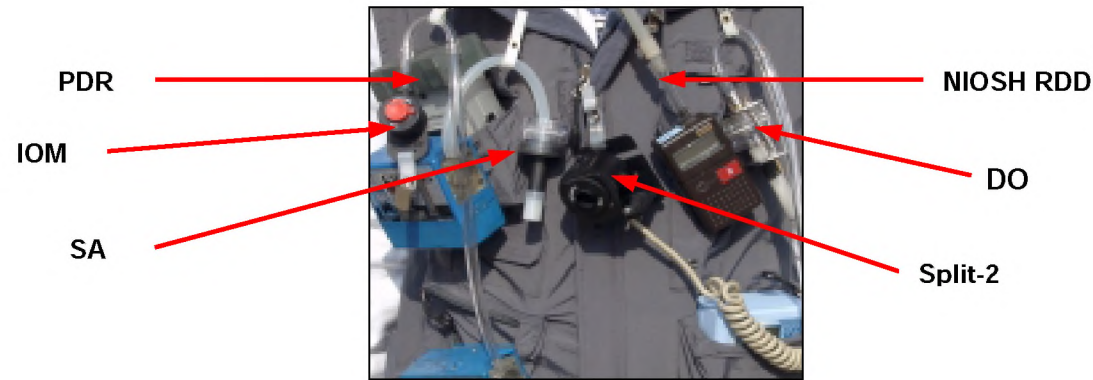


Figure 4.2b: Sampling harness with six personal dust monitors

The details of the sampling instruments are discussed in Section 2. While sampling and monitoring of the dust was taking place underground, a number of key practical issues were also observed, viz. robustness, ease of wearing, sampling environment, workforce, sampling strategy, etc. A summary of the sampled mines and individual sampling locations is given in Table 4.2. The sampled gold, platinum, coal and diamond mines are unique with regard to their extremely challenging environmental conditions. Some of the mines used diesel-operated equipment and machinery. The test procedure is described in the underground test protocol attached in Appendix A.

Table 4.2: Summary of underground mines and mining operations sampled

Mine type	Mine symbol	Sampled operations
Gold	K	Reef and waste tips; shaft levels
		Ore tips along the haulage
		Development heading and stopes
	GN	Reef and waste tips; shaft levels
		Ore tips along the haulage
		Development heading and stopes
Platinum	IP	Reef and waste tips; shaft levels
		Ore tips along the haulage
		Development heading and stopes
	NM	Reef and waste tips; shaft levels
		Ore tips along the haulage
		Development heading and stopes
Coal	GP	Coal face
		Face, out-bye
		Feeder-breaker and intake
	BC	Coal face
		Face, out-bye
		Transfer points; shaft intake
Diamond	C	Ore pass
		Haulage way
		Development heading
		Crusher and transfer points

4.3 Underground results

4.3.1 Pair-wise comparison of Dorr-Oliver and SA cyclones

The SA cyclone (GE-05), which is widely used in South African mines and is similar to the Higgins-Dewell-type cyclone in terms of performance, was operated at 2,2 L/min. This conforms to the new ISO/ACGIH/CEN curve with a D_{50} of 4 microns (Kenny *et al.*, 1998). The Dorr-Oliver (DO) cyclone sampler, extensively used in the USA, was operated at 1,7 L/min, which conforms to the new ISO/CEN/ACGIH curve with a D_{50} of 4 microns. During the underground trials, it was ensured that the cyclone nozzle inlets faced the direction of the airflow (or approximately 90 degrees to the wearer's body surface) in order to avoid the effect of nozzle inlet orientation on sampler performance.

During the underground trials, the DO and SA cyclones were positioned on the left and right lapels of the wearer respectively in the breathing zone. The relationship between the concentration values obtained from the side-by-side D-O and SA cyclones during the underground field trials in coal mines is shown in Figure 4.3.1a.

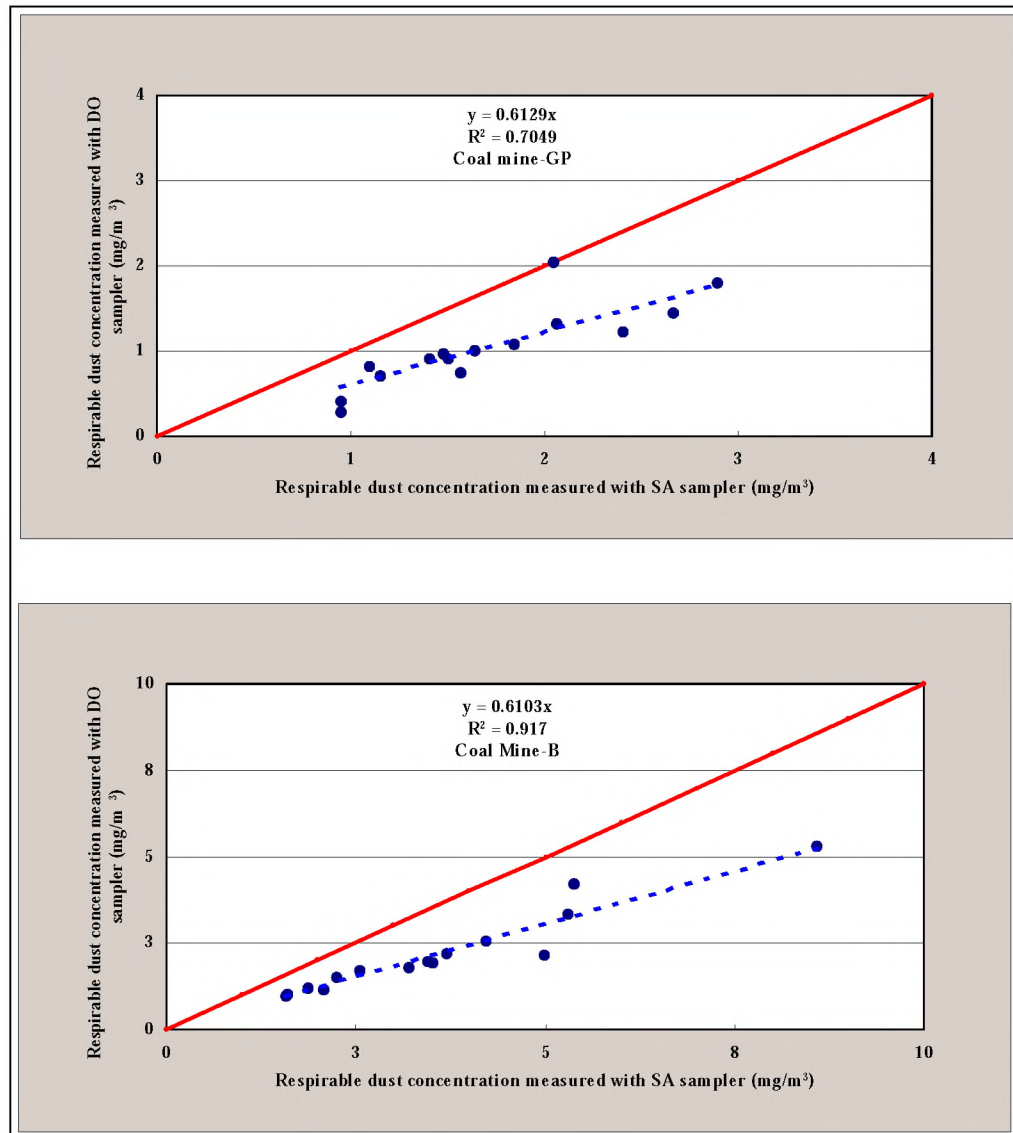


Figure 4.3.1a: Relationship between measurements of side-by-side personal DO and SA cyclones in coal mines (Top: coal mine GP; bottom: coal mine B)

The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two cyclones in coal mine GP and coal mine B are 0,839 and 0,957 respectively. A combined plot of the data set from the two coal mines ($r = 0,960$) is shown in Figure 4.3.1b. The cyclones' measurements show reasonable linearity when deployed in coal mines, but there was much scatter in coal mine GP. One of the possible reasons for

this could be the high air velocities (approximately 2,0 m/s) and the resulting spatial variations in the sampled dust cloud. The plot (Figure 4.3.1b) indicates that, on average, the DO sampler underestimates the measured respirable coal dust concentration by approximately 39%.

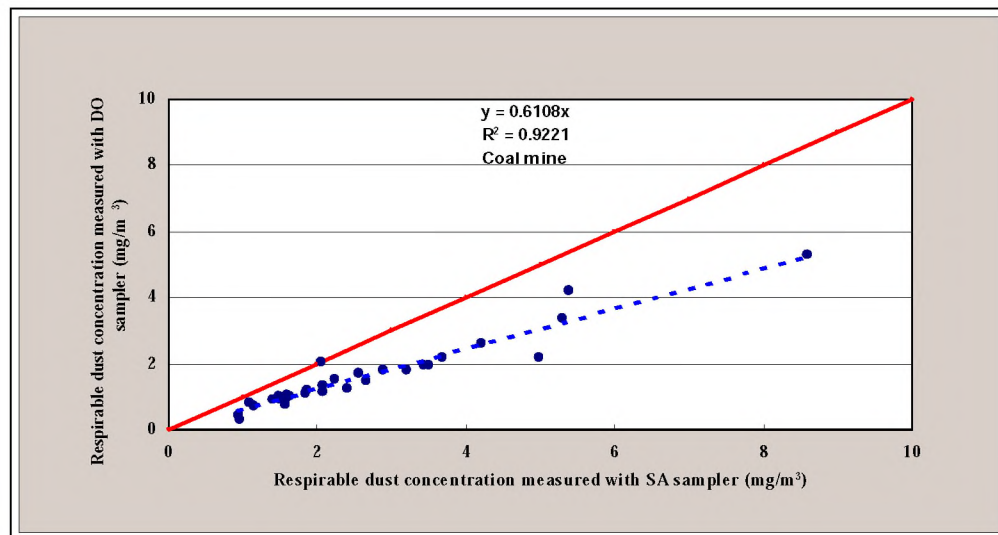


Figure 4.3.1b: Combined plot of the relationship between the measurements of side-by-side personal DO and SA cyclones in coal mines

The relationship between the concentration values obtained from the side-by-side DO and SA cyclones during the field trials in two gold mines is shown in Figure 4.3.1c. The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two cyclones in gold mine K and gold mine GN are 0,788 and 0,896 respectively. A combined plot of the two gold mine data sets ($r = 0,742$) is shown in Figure 4.3.1d. The two samplers show comparatively reasonable linearity when measured, with wide scatter. Some of the possible reasons could be environmental conditions such as humidity, temperature, air velocity and the orientation of the samplers to the dust cloud. The plot (Figure 4.3.1d) indicates that, on average, the DO sampler underestimates the measured respirable coal dust concentration by approximately 30%.

Similarly, the relationship between the concentration values obtained from the side-by-side DO and SA cyclones during the field trials in a platinum mine is shown in Figure 4.3.1e. The correlation coefficient (r) between the two cyclones in the platinum mine is 0,583. The two samplers show poor linearity when measured, with wide scatter. Also, we note that the measured respirable dust concentrations were below the $1,0 \text{ mg/m}^3$

level. The plot (Figure 4.3.1e) indicates that, on average, the DO sampler underestimates the measured respirable coal dust concentration by approximately 17% at low concentration levels; this is difficult to explain.

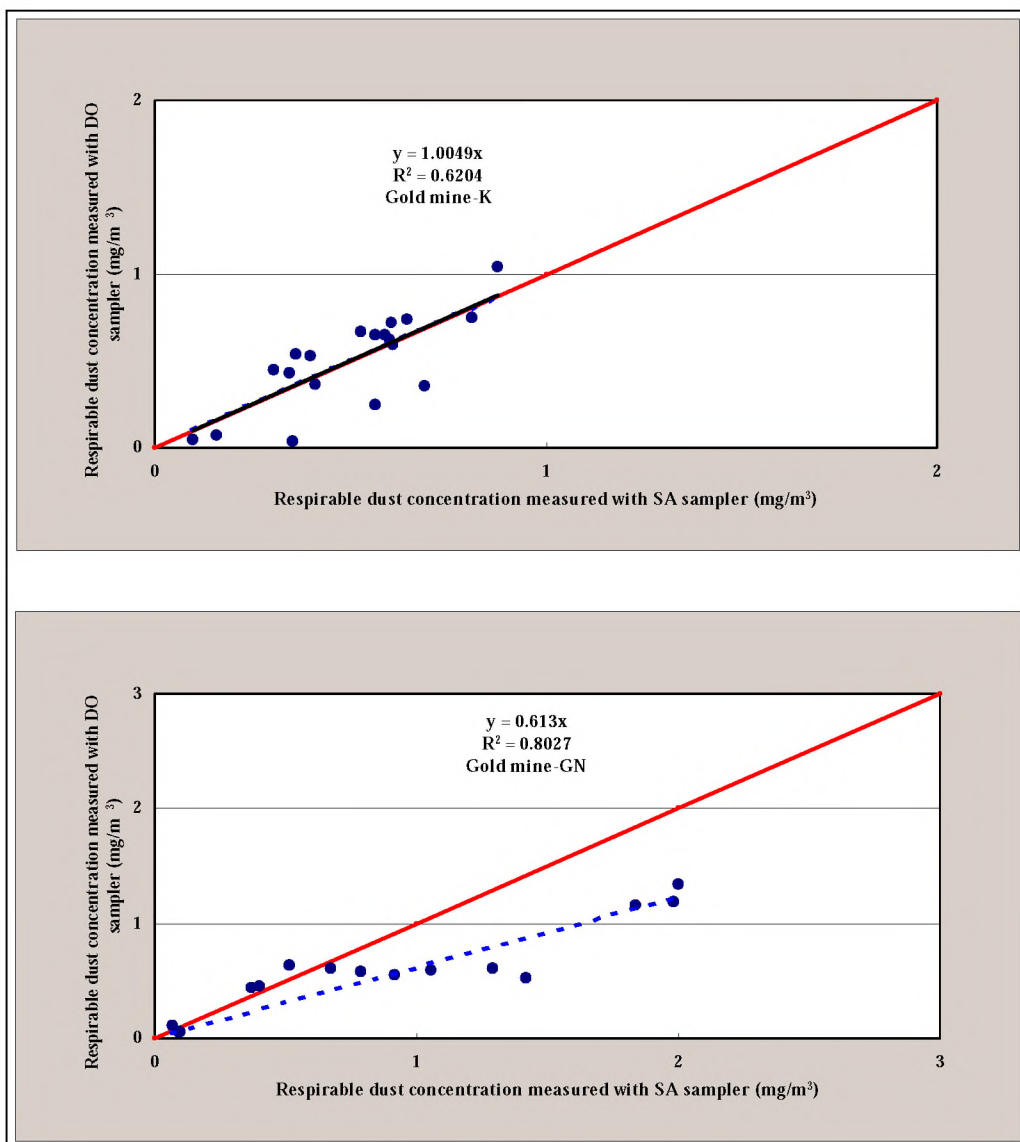


Figure 4.3.1c: Relationship between side-by-side personal DO and SA cyclones in gold mines (Top: gold mine K; bottom: gold mine GN)

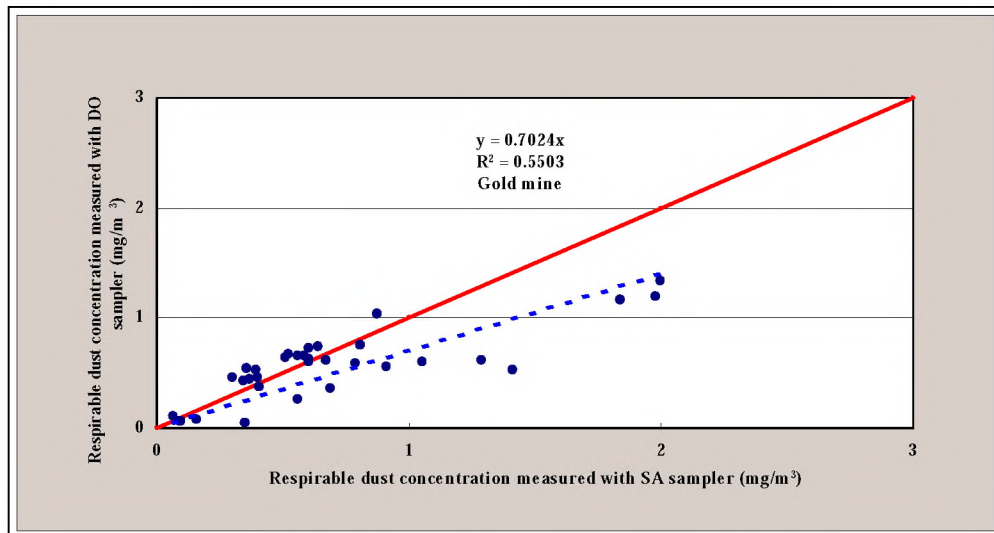


Figure 4.3.1d: Combined plot of the relationship between side-by-side personal DO and SA cyclones in gold mines

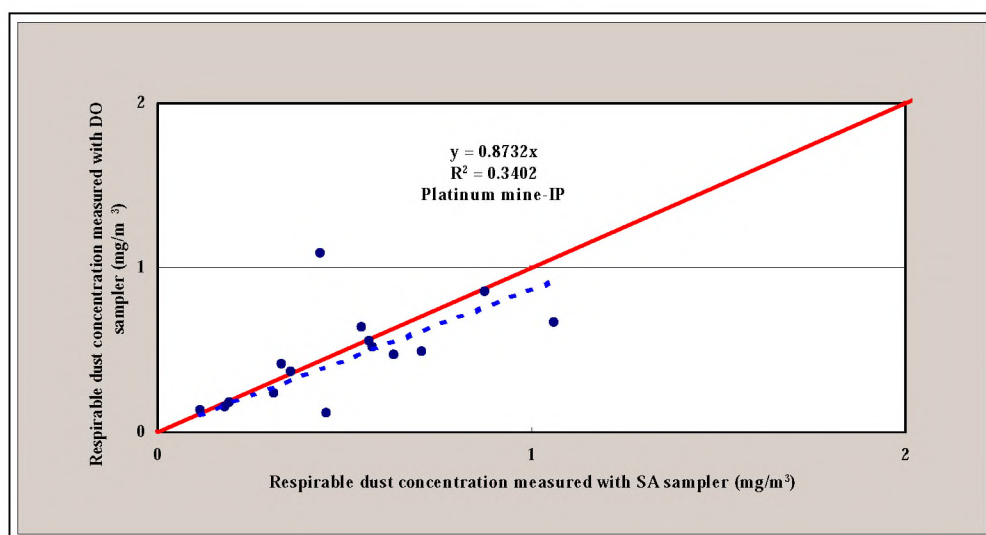


Figure 4.3.1e: Relationship between side-by-side personal DO and SA cyclones in a platinum mine

Similarly, the relationship between the concentration values obtained from the side-by-side DO and SA cyclones during the field trials in a diamond mine is shown in Figure 4.3.1f. The correlation coefficient (r) between the two cyclones in the diamond mine is 0,908. The plot (Figure 4.3.1f) indicates that the measured dust levels had a wide range and, on average, the DO sampler underestimates the measured respirable coal dust concentration by approximately 37,5%. From the plot we observe that there was a wide scatter for the higher measured dust concentrations.

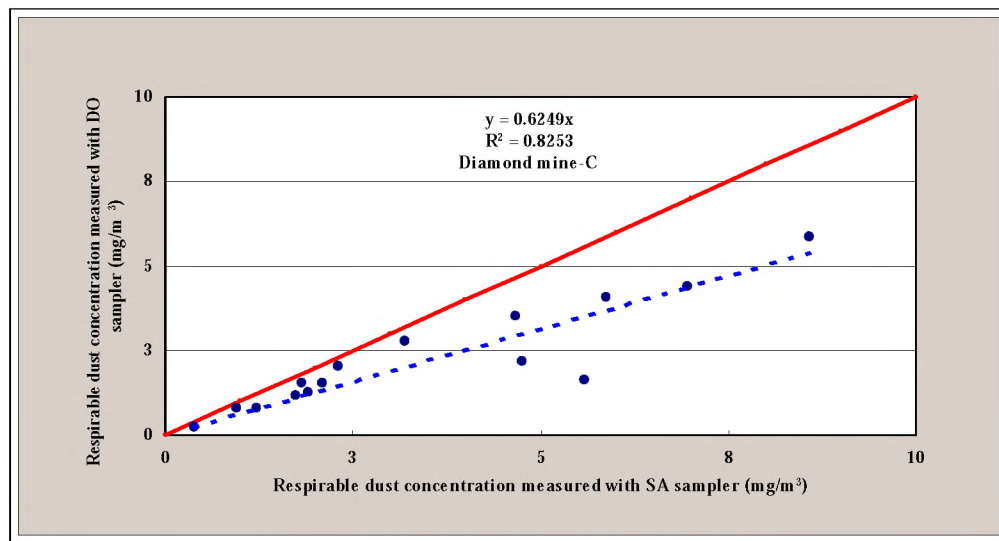


Figure 4.3.1f: Relationship between side-by-side personal DO and SA cyclones in a diamond mine

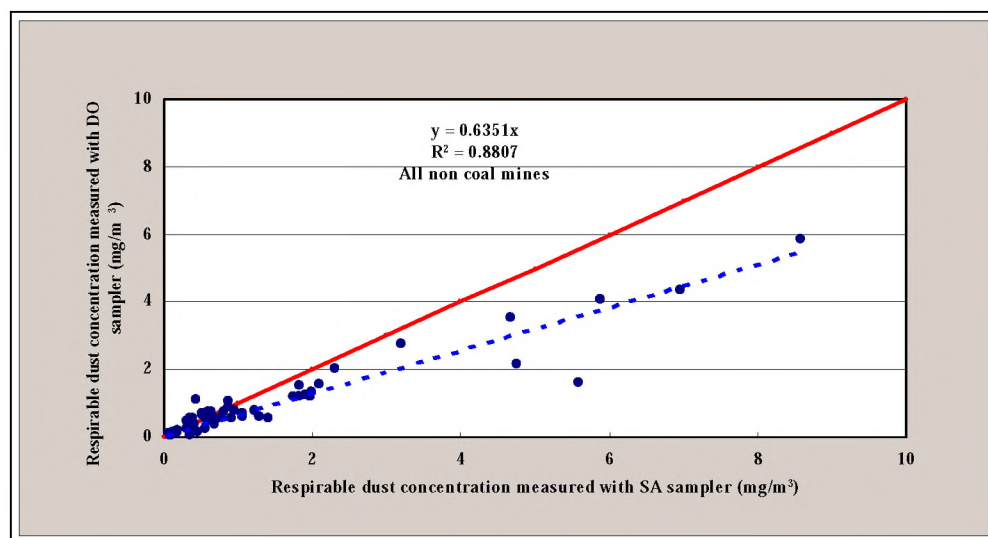


Figure 4.3.1g: Relationship between side-by-side personal DO and SA cyclones in all non-coal mines (gold, platinum, diamond)

In order to determine the relationship between the concentration values obtained from the side-by-side personal DO and SA cyclones during the field trials in hard rock mines (gold, platinum and diamond), the data were plotted as shown in Figure 4.3.1g. The correlation coefficient (r) between the two cyclones in all hard rock mines is 0,938, which shows a good linear relationship between the samplers. The plot in Figure 4.3.1h shows a good linear relationship ($r = 0,949$) between the DO and SA cyclones measured in various

types of mine, indicating a wide range of measured dust levels. From the linear regression equation we can deduce that, on average, the DO sampler underestimates the measured respirable dust concentration by approximately 38%. All underground measurement values included both compliance and non-compliance levels for the sampling period and the scatter was wide for both low and high dust concentrations. Another reason for the difference in the measurements could be the non-alignment of the samplers with the airflow as it is practically impossible to position a sampler facing the wind underground.

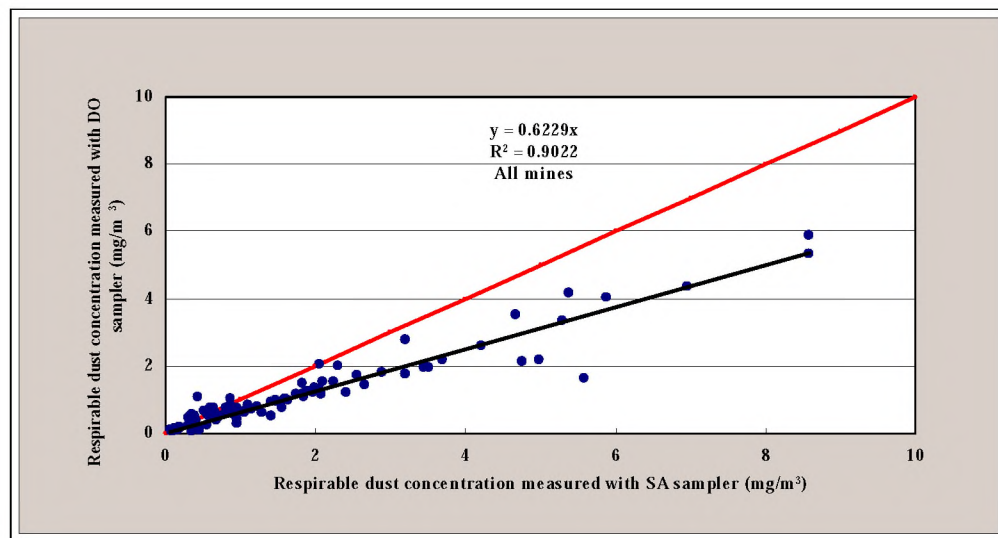


Figure 4.3.1h: Relationship between side-by-side personal DO and SA cyclones in all mines (gold, platinum, diamond and coal)

4.3.1.1 Accuracy criteria

As discussed before, for all comparison purposes, the SA sampler value was considered the true concentration. For this reason the concentration ratio of the "evaluation instrument" to the reference instrument (in this study, the SA sampler) was calculated. If the variability in the concentration ratio is small, then one can consider the "evaluation instrument" for further usage. The concentration ratio is analogous to the bias as described by Kennedy *et al.* (1995). Bias is the relative discrepancy between the mean of normally distributed measurements and the true concentration. The relative standard deviation (RSD) was calculated from the standard deviation and the mean concentration ratio. Two accuracy criteria, $\pm 25\%$ and $\pm 50\%$ were used. These are analogous to the NIOSH instrumentation accuracy criterion (Kennedy *et al.*, 1995) and the European Community standard for "screening measurements" (CEN, 1994). For normally distributed

data, 95% of the measurements fall within the range $\pm 1,96s$, where s is the standard deviation. For example, assuming that the mean is 100, for the criterion of $\pm 25\%$, then $1,96s = 25$ or $s = 12,7$. Because the mean is 100, the standard deviation divided by the mean (called RSD or CV) is 0,127. Thus, the $\pm 25\%$ accuracy criterion (NIOSH) is met at $RSD = 0,127$ or less and the $\pm 50\%$ accuracy criterion (CEN) met at $RSD = 0,25$ or less.

Table 4.3.1.1: Summary of the correction factors for the personal DO and SA samplers in mines

Mine type	Person	Mean SA conc. mg/m ³	Mean ratio of DO/SA conc.	No. of readings	SD	RSD or CV (%)
Coal mine GP	B	2,005	0,657	5	0,195	29,68
	L	1,697	0,617	5	0,117	18,96
	J	1,431	0,512	5	0,160	31,25
	Total	1,711	0,596	15	0,155	26,00
Coal mine B	B	3,516	0,564	5	0,087	15,43
	L	4,836	0,615	5	0,041	6,67
	J	2,504	0,642	5	0,083	12,93
	Total	3,618	0,607	15	0,075	12,36
Overall	Total	2,665	0,601	30	0,120	19,96
Gold mine K	B	0,512	1,226	6	0,241	19,66
	L	0,461	0,942	6	0,361	38,32
	J	0,523	0,783	7	0,434	55,42
	Total	0,499	0,973	19	0,389	39,98
Gold mine GN	B	0,752	0,813	5	0,315	38,75
	L	0,953	0,915	5	0,510	55,73
	J	0,994	0,663	5	0,158	23,83
	Total	0,899	0,797	15	0,348	43,66
Overall	Total	0,676	0,895	34	0,376	42,01
Platinum mine	B	0,568	0,839	5	0,399	47,56
	L	0,402	0,912	5	0,099	10,86
	J	0,502	1,177	5	0,751	63,80
	Total	0,490	0,977	15	0,482	49,33
Diamond mine C	B	4,480	0,643	5	0,218	33,90
	L	3,733	0,680	5	0,166	24,41
	J	2,212	0,694	5	0,085	12,25
	Total	3,475	0,672	15	0,155	23,07
All non-coal mines	Total	1,288	0,862	64	0,379	43,96
All mines	Total	1,728	0,779	94	0,342	43,90

Table 4.3.1.1 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the two samplers measured in coal, gold, platinum and diamond mines by three personnel. The CV is the ratio of standard deviation and mean value expressed as a percentage. Therefore, the lower the CV of the correction factor ratio, the more linear the response of the monitor. From the summary table (Table 4.3.1.1) we observe that there is no clear relationship between the accuracy and the measured concentration levels. Overall, the CV of the ratio between the sampler dust concentrations was below the NIOSH and CEN accuracy criteria (except in 3 cases out of a total of 18). Interestingly, the measurement values in coal mine B indicate that the CV of the correction factor ratio decreases with a decrease in the measured concentration levels. Overall, the DO sampler failed to meet the NIOSH and CEN accuracy criteria.

4.3.2 Pair-wise comparison of IOM sampler and SA cyclones

During the underground trials, the IOM sampler, operated at 2,0 L/min, and the SA cyclones, operated at 2,2 L/min, were positioned side by side on the left lapel of the wearer in the breathing zone. The relationship between the concentration values obtained from the side-by-side IOM and SA samplers during the field trials in coal mines is shown in Figure 4.3.2a. The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two samplers in coal mine GP and coal mine B are 0,767 and 0,474 respectively. A combined plot of the two coal mine data sets ($r = 0,519$) set is shown in Figure 4.3.2b. The samplers show poor linearity when measured in coal mines, despite there being less scatter. The plot (Figure 4.3.2b) indicates that, on average, the IOM sampler underestimates the measured respirable coal dust concentration by more than 50%.

The relationship between the concentration values obtained from the side-by-side IOM and SA samplers during the field trials in two gold mines is shown in Figure 4.3.2c. The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two cyclones in gold mine K and gold mine GN are 0,863 and 0,951 respectively. A combined plot of the two gold mine data sets ($r = 0,755$) is shown in Figure 4.3.2d. The two samplers show comparatively reasonable linearity when measured, with wide scatter. The plot (Figure 4.3.2d) indicates that, on average, the IOM sampler underestimates the measured respirable dust concentration by approximately 35%.

Similarly, the relationship between the concentration values obtained from the side-by-side IOM and SA samplers during the field trials in a platinum mine is shown in Figure 4.3.2e. The correlation coefficient (r) between the two cyclones in the platinum mine is 0,583. The two samplers show poor linearity, with wide scatter. Also, we note that the measured respirable concentrations were below the $1,0 \text{ mg/m}^3$ level. The plot (Figure 4.3.2e) indicates that, on average, the IOM sampler underestimates the measured respirable coal dust concentration by approximately 13% at low concentration levels.

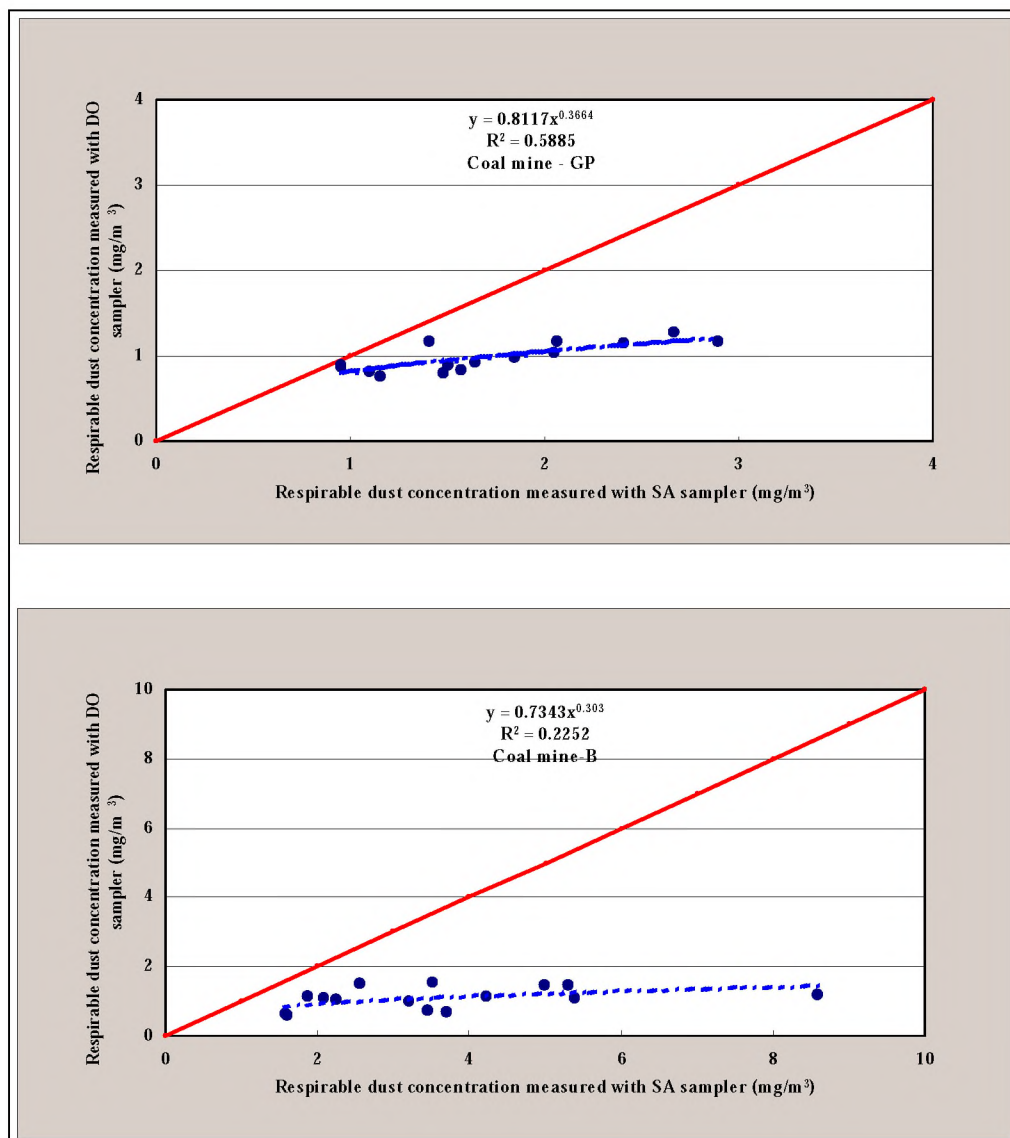


Figure 4.3.2a: Relationship between side-by-side personal IOM and SA samplers in coal mines (Top: coal mine GP; bottom: coal mine B)

The relationship between the concentration values obtained from the side-by-side IOM sampler and SA samplers during the field trials in a diamond mine is shown in

Figure 4.3.2f. The correlation coefficient (r) between the two cyclones in the diamond mine is 0,827. The plot (Figure 4.3.2f) indicates that the measured dust levels had a wide range and at compliance levels the IOM sampler underestimates the measured respirable coal dust concentration by more than 60%. From the plot we observe that at higher dust concentrations, the IOM sampler underestimates to a larger extent.

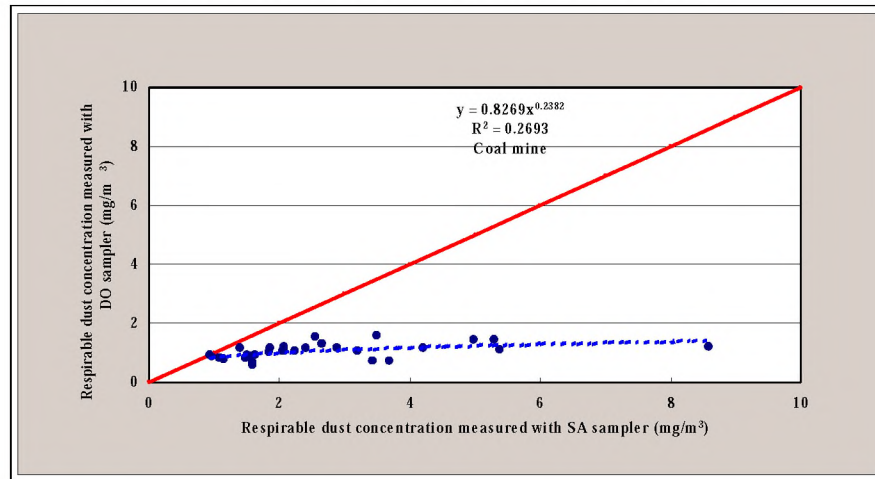


Figure 4.3.2b: Combined plot of side-by-side DO and SA cyclones in coal mines

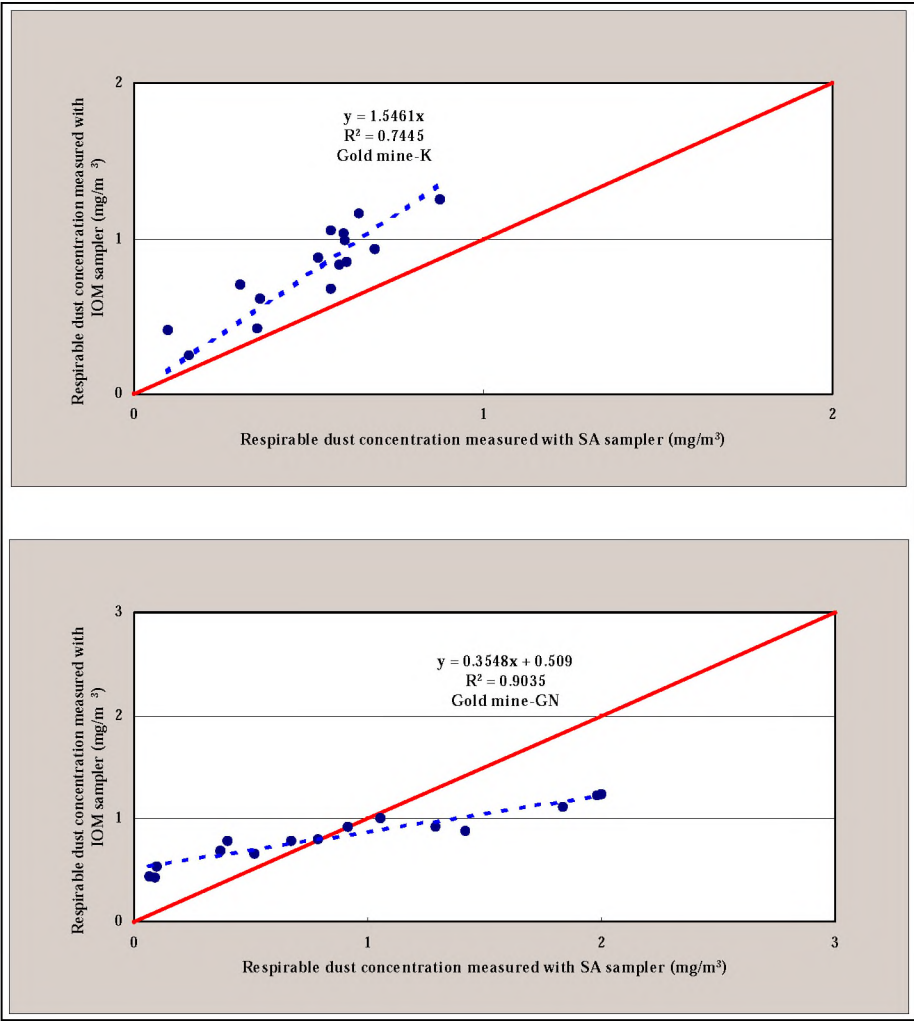


Figure 4.3.2c: Relationship between side-by-side personal IOM and SA samplers in gold mines (Top: gold mine K; bottom: gold mine GN)

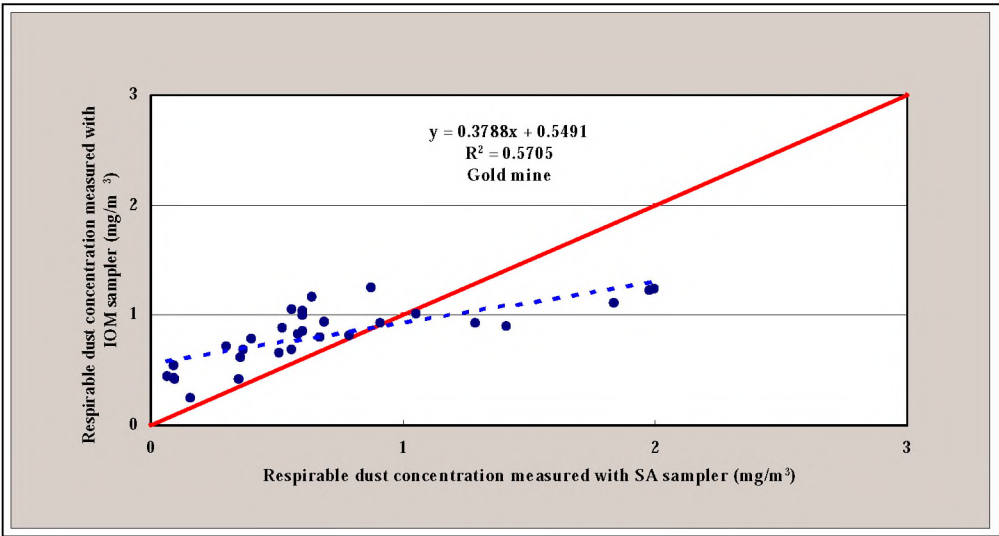


Figure 4.3.2d: Combined plot of the relationship between side-by-side personal IOM and SA samplers in gold mines

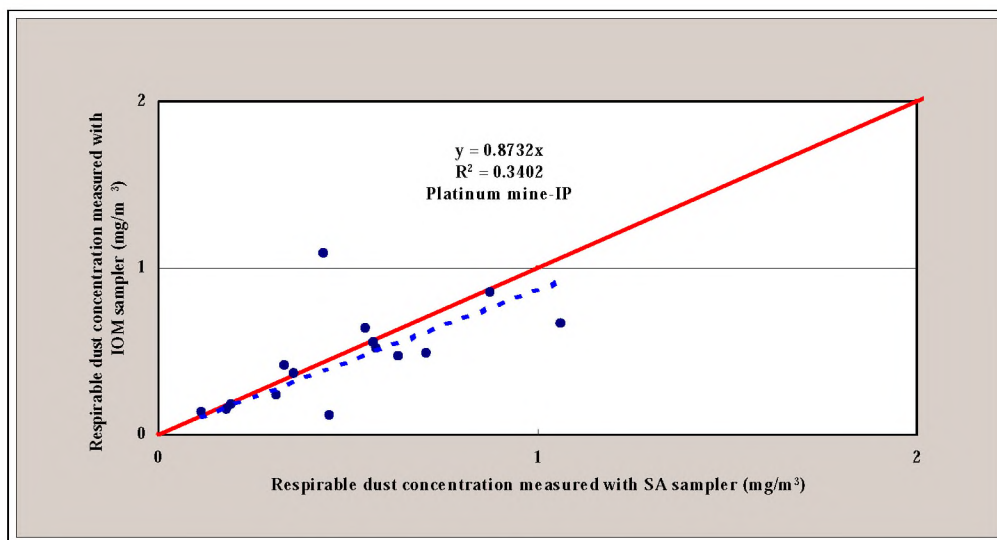


Figure 4.3.2e: Relationship between side-by-side personal IOM and SA samplers in a platinum mine

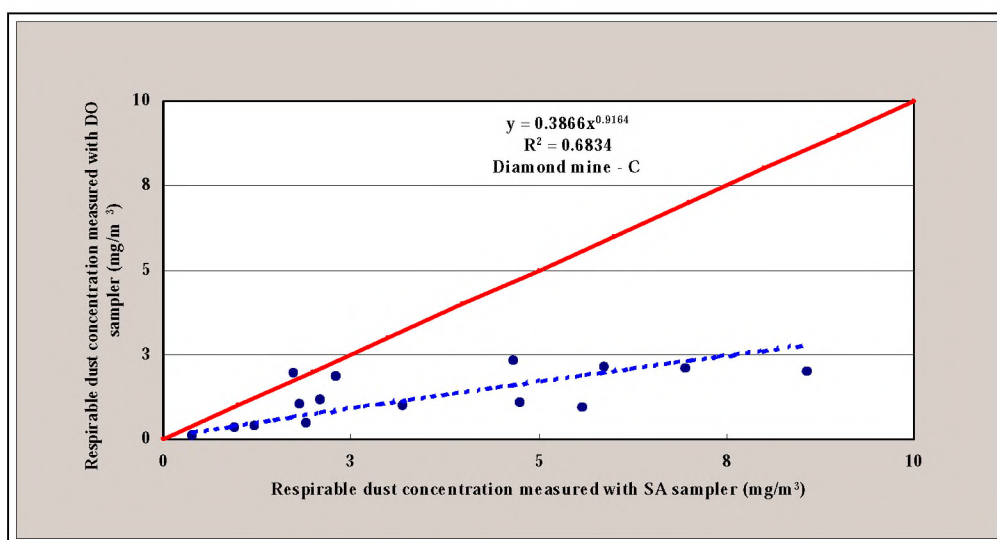


Figure 4.3.2f: Relationship between side-by-side personal IOM and SA samplers in a diamond mine

In order to determine the relationship between the concentration values obtained from the side-by-side personal IOM and SA samplers during the field trials in hard rock mines (gold, platinum and diamond), the relationship was plotted as shown in Figure 4.3.2g. The

correlation coefficient (r) between the two cyclones in all hard rock mines is 0,671, showing a poor non-linear relationship between the samplers. The combined scatter plot of all mine data (Figure 4.3.2h) again shows a poor non-linear relationship ($r = 0,671$) between the IOM and SA samplers measured in various mine types with a wide range of measured dust levels. From the non-linear regression equation we can deduce that, on average, the IOM sampler underestimates the measured respirable dust concentration by approximately 48% for a compliance level of 2 mg/m^3 . As the dust levels increase, the underestimation of the measured dust levels by the IOM sampler also increases, which makes the sampler unsuitable for use even for engineering control purposes. Also at low concentrations, the IOM sampler measures higher than the SA sampler. From the plot we can observe that all underground measurement values included both compliance and non-compliance levels for the sampling period and that the scatter was wide for both low and high dust concentrations.

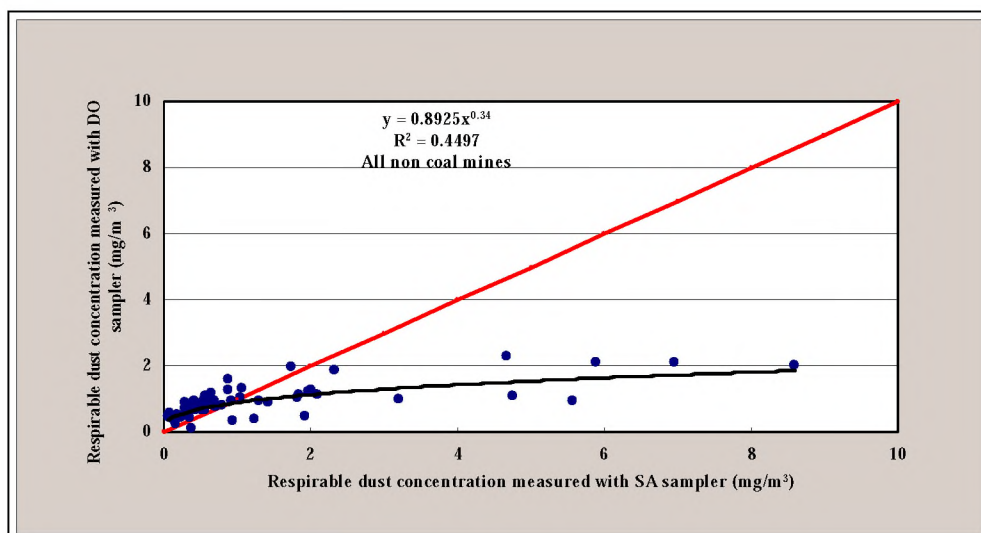


Figure 4.3.2g: Relationship between side-by-side personal IOM and SA samplers in all non-coal mines (gold, platinum, diamond)

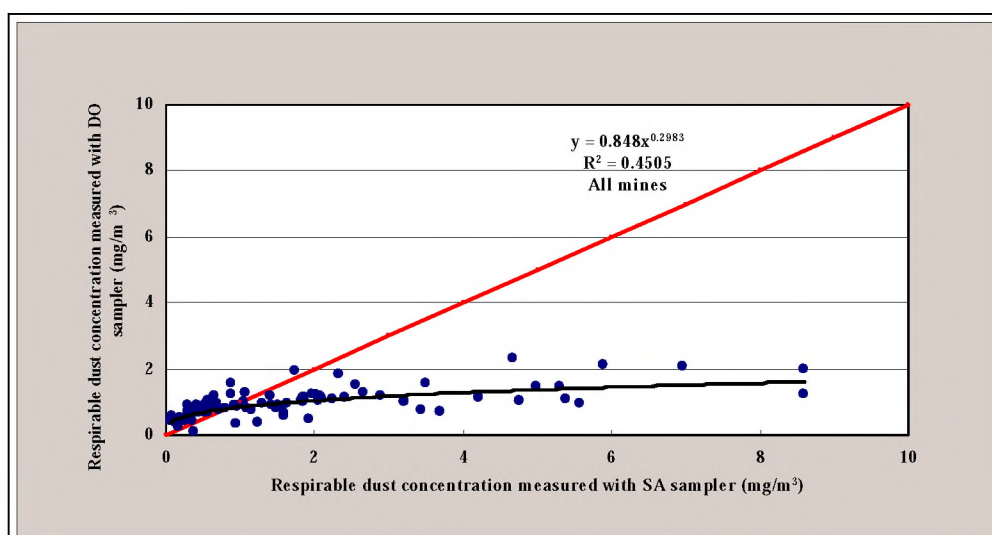


Figure 4.3.2h: Relationship between side-by-side personal IOM and SA samplers from all mines (gold, platinum, diamond and coal)

4.3.2.1 Accuracy criteria

Table 4.3.2.1 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the IOM and SA samplers measured in coal, gold, platinum and diamond mines by three personnel. The CV is the ratio of standard deviation and mean value expressed as a percentage. From the summary table (Table 4.3.2.1) we observe that there is no clear relationship between accuracy and the measured concentration levels. Overall, the CV of the ratio between the sampler dust concentrations was below the NIOSH and CEN accuracy criteria (except in 3 cases out of a total of 18). Interestingly, the measurement values in coal mine B indicate that the CV of the correction factor ratio decreases with a decrease in the measured concentration levels. Overall, the DO sampler failed to meet the NIOSH and CEN accuracy criteria.

Table 4.3.2.1: Summary of the correction factors for the IOM and SA samplers in all mines

Mine type	Person	Mean SA conc. mg/m ³	Mean ratio of IOM/SA conc.	No. of readings	SD	RSD or CV (%)
Coal mine GP	B	2,005	0,577	5	0,146	25,30
	L	1,697	0,634	5	0,206	32,49
	J	1,431	0,641	5	0,160	24,96
	Total	1,711	0,617	15	0,162	26,26
Coal mine B	B	3,516	0,297	5	0,112	37,71
	L	4,836	0,345	5	0,175	50,72

	J	2,504	0,421	5	0,155	36,73
	Total	3,618	0,354	15	0,149	42,09
Overall	Total	2,665	0,486	30	0,203	41,77
Gold mine K	B	0,533	1,763	5	0,333	18,89
	L	0,483	2,072	5	1,248	60,23
	J	0,721	1,457	5	0,233	15,99
	Total	0,502	1,764	15	0,748	42,40
Gold mine GN	B	0,752	2,219	5	2,057	92,69
	L	0,953	2,072	5	2,673	129,0
	J	0,994	1,642	5	1,724	104,9
	Total	0,899	1,978	15	2,041	103,2
Overall	Total	0,701	1,870	30	1,514	80,96
Platinum mine	B	0,450	2,221	8	0,886	39,89
	L	0,399	1,877	6	0,489	26,05
	J	0,434	1,876	7	0,692	36,88
	Total	0,431	2,008	21	0,712	35,46
Diamond mine-C	B	4,480	0,401	5	0,250	62,34
	L	3,733	0,324	5	0,137	42,28
	J	2,212	0,512	5	0,355	69,33
	Total	3,475	0,412	15	0,256	62,13
All non-coal mines	Total	1,245	1,583	66	1,267	80,03
All mines	Total	1,689	0,936	96	1,172	125,2

4.3.3 Relationship between NIOSH RDD, DO and SA samplers

During the underground trials, the RDD, DO and SA samplers were evaluated as personal samplers in gold, platinum, diamond and coal mines. The RDD and DO samplers were positioned on the left lapel of the wearer and the SA sampler on the right lapel of the wearer in the breathing zone. The pressure increase observed in each RDD from each individual wearer was noted down for a test shift. This pressure increase and the mass of dust on the respective filters of the DO and SA samplers were compared one to one. The scatter plots and regression analysis of the one-to-one relationship between the sampler measurements during the field trials in the gold mines are shown in Figure 4.3.3a.

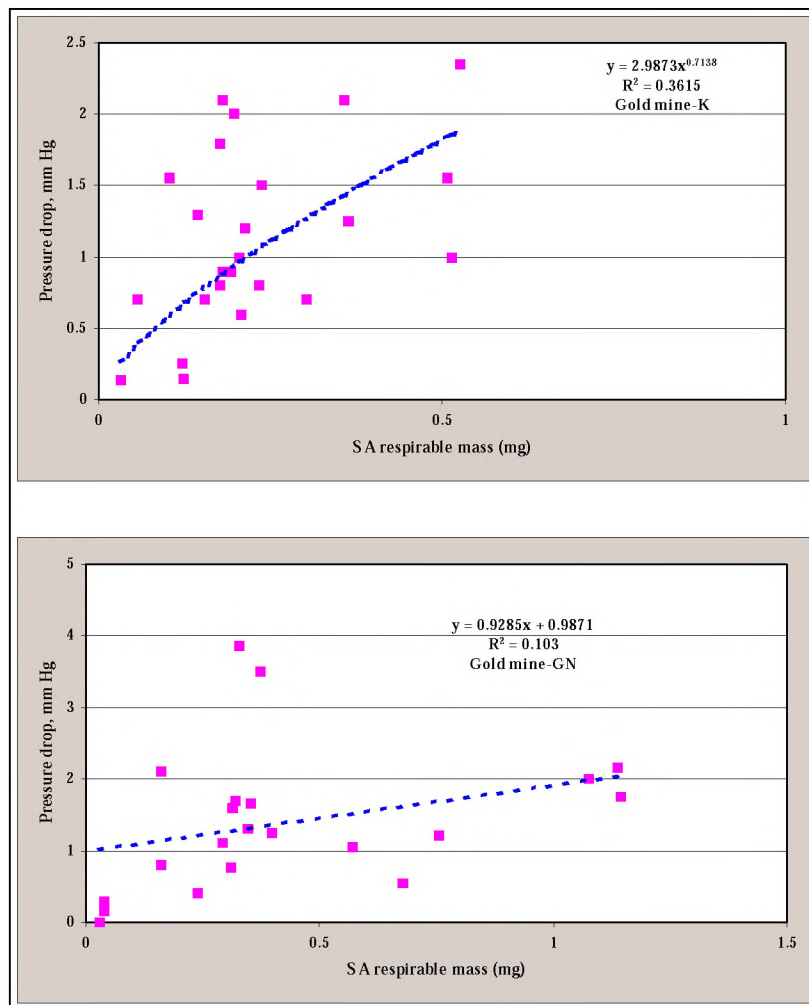


Figure 4.3.3a: Scatter plot of RDD pressure drops and SA sampler respirable dust mass in gold mines (Top: gold mine K; bottom gold mine GN)

In both mines, the scatter was wide and the relationship (linear or non-linear) was poor. This could be due to dusty air contaminated with diesel particulate material (DPM) or explosion fumes. In both mines, the use of diesel-operated equipment was common at the time of the evaluation. The mass of dust collected on the SA sampler filters in the mines was between 0,03 mg and 1,2 mg. The field evaluation in the coal mines yielded a good linear relationship between the gravimetric respirable dust mass and the pressure drop across the filter. However, this was not the case in the other mines.

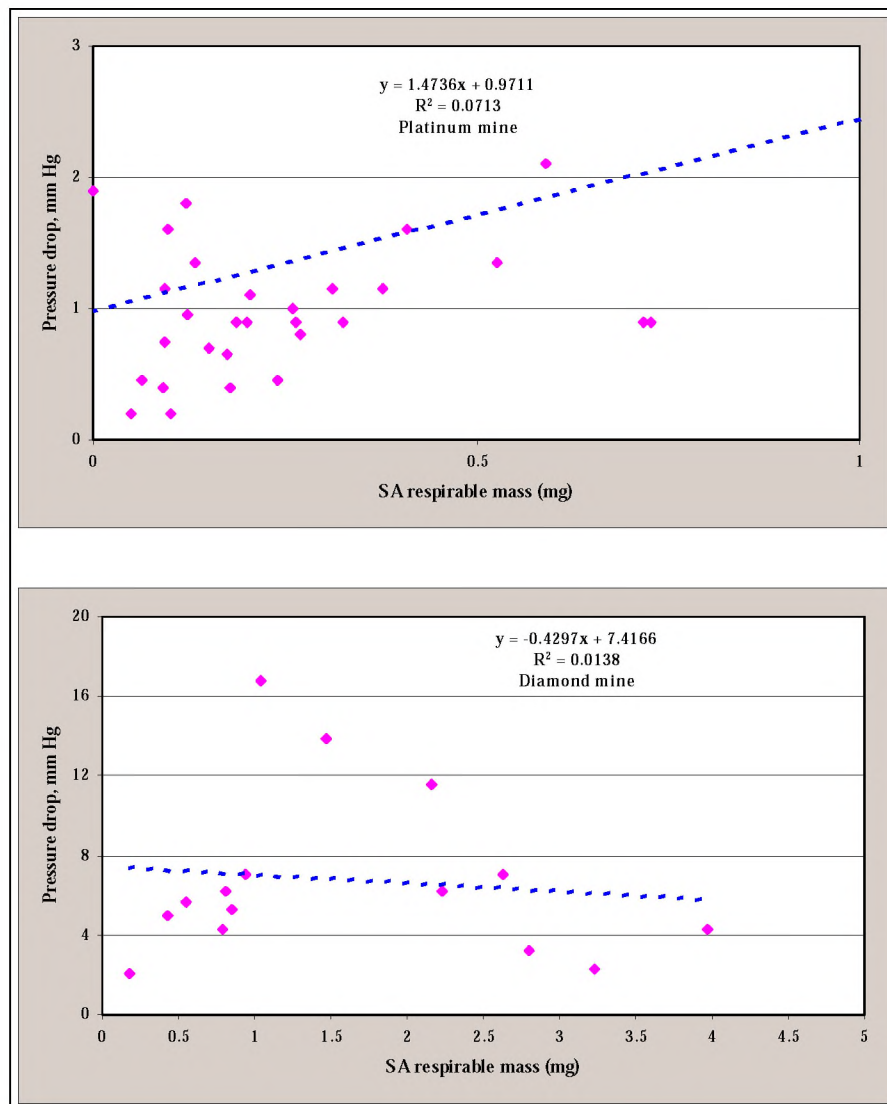


Figure 4.3.3b: Scatter plot of RDD pressure drop and SA sampler respirable dust mass in a platinum and a diamond mine (Top: platinum mine; bottom: diamond mine)

The scatter plots and regression analysis of the one-to-one relationship between the samplers during the field trials in the platinum and diamond mines are shown in Figure 4.3.3b. The scatter was wide in both the platinum and diamond mines and the relationship (linear or non-linear) was very poor. This could be due to dusty air contaminated with diesel particulate material (DPM) or explosion fumes. In both mines, the use of diesel-operated equipment was common at the time of evaluation. The mass of dust collected on the SA sampler filters in the platinum mine was between 0,03 mg and 1,0 mg. In comparison with the platinum mine, the respirable dust mass deposited on the filter in the diamond mine was between 0,03 mg to 4,2 mg. Also, the DPM resulted in a

much greater pressure drop than the mineral dust for a given mass of material on the filter.

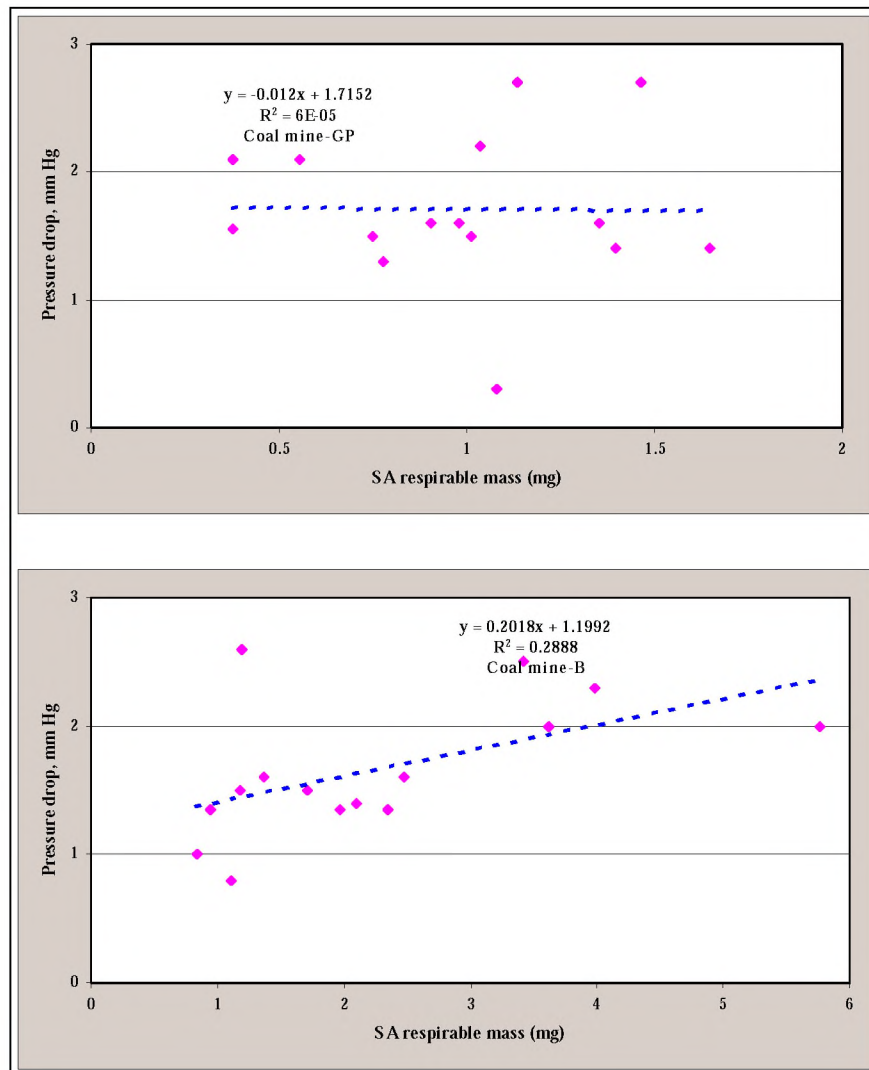


Figure 4.3.3c: Scatter plot of RDD pressure drop and SA sampler respirable dust mass in coal mines (Top: coal mine GP; bottom: coal mine B)

Although there was no diesel-operated machinery in the coal mines, the scatter was wide and there was no clear indication of a good linear or non-linear relationship between the samplers (Figure 4.3.3c). The field evaluation in US coal mines gave a good linear relationship between gravimetric respirable dust mass and the pressure drop across the filter, where these samplers were evaluated as area samplers. However, this was not the case in the South African mines. A combined plot of the two coal mine data sets is shown in Figure 4.3.3d.

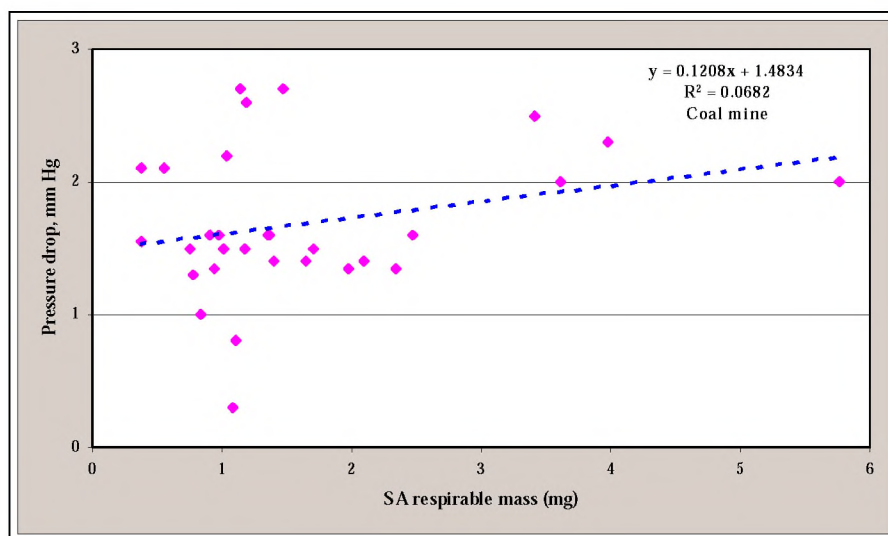


Figure 4.3.3d: Combined plot of RDD pressure drop and SA sampler respirable dust mass in coal mines

The two samplers show poor linearity and the least squares regression of the gravimetric sampler dust mass versus the dosimeter pressure drop increases for the side-by-side comparison of individual observations for the higher dust levels, as shown in Figure 4.3.3d.

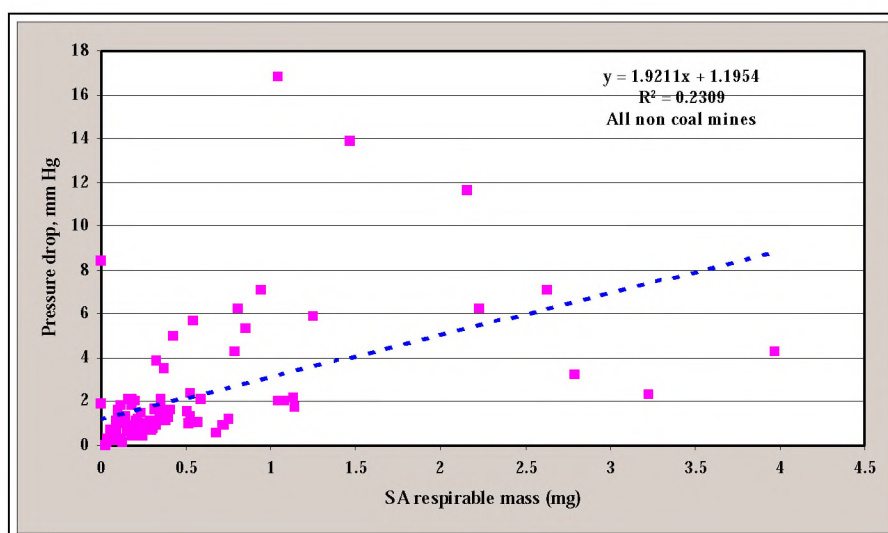


Figure 4.3.3e: Combined plot of RDD pressure drop and SA sampler respirable dust mass in non-coal mines

The data for non-coal mines (i.e. gold mines, platinum mines and diamond mines) were separated and are plotted in Figure 4.3.3e. From the plot we note that the relationship

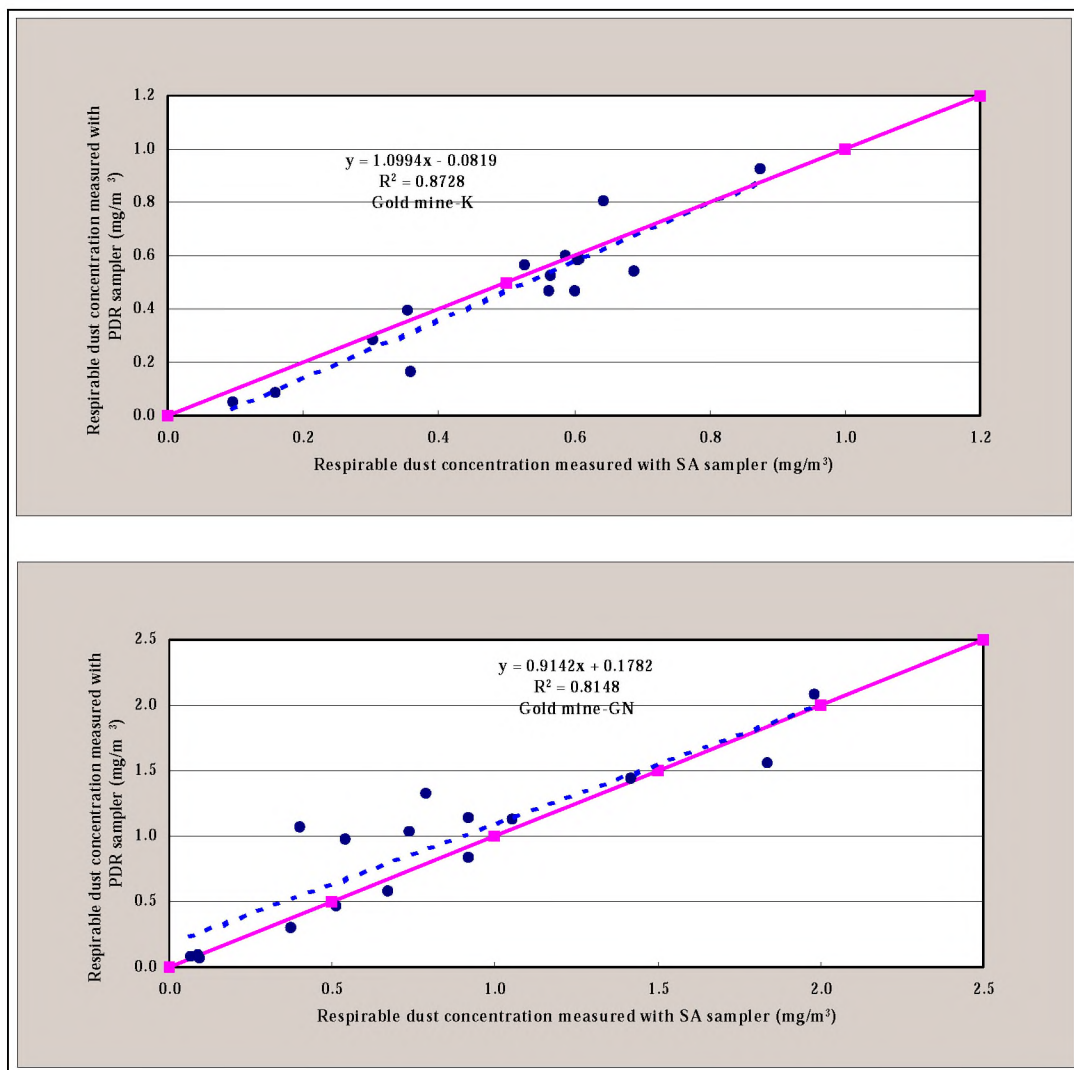
between the pressure drop and respirable dust mass was extremely poor ($r = 0,481$) and failed to support the hypothesis that pressure drop is a surrogate for the respirable dust mass collected. Even with the use of single or multiple correction factors for different dust types or for the same dust type, the RDD sampler is less accurate than the personal gravimetric dust sampler.

Unlike the laboratory evaluation results, no clear conclusion can be reached on the relationship between the SA sampler and the RDD. The hypothesis that the pressure increase across the RDD filters is a good surrogate for the mass of respirable dust collected by the SA sampler is not strongly supported by the field data. The uncertainty in the field measurements was high for each mine type and dust type. Whether the greater uncertainty was due to the size characteristics of the respirable dust or to spatial differences in the sample dust clouds could not be determined. Other observations from the study show greater variations in the dosimeter-to-dosimeter pressure measurements, requiring some effort from the manufacturer to correct this. Although the RDD offers completely new approaches to dust sampling and is simple and portable, great improvements are needed in terms of the instrument's accuracy before it can be recommended for use in South African mines.

4.3.4 Comparison of measured concentration levels using real-time PDR and SA gravimetric samplers

During the underground trials, the PDR near-real-time dust-monitoring instrument was evaluated as a passive personal sampler in gold, platinum, diamond and coal mines. During the underground trials, the PDR and SA samplers were positioned side by side on the right lapel of the wearer in the breathing zone. The average measured dust concentration level recorded by the PDR and the dust concentration level measured by the SA sampler from individual wearers were compared on a one-to-one basis. The scatter plots and regression analysis of the one-to-one relationship between the PDR and SA sampler measurements during the field trials in the gold mines are shown in Figure 4.3.4a.

The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two samplers in gold mine K and gold mine GN are 0,934 and 0,903 respectively. A combined plot of the two gold mine data sets ($r = 0,909$) is shown in Figure 4.3.4b. The dust monitors show good linearity when measured in gold mines, despite less scatter.



**Figure 4.3.4a: Scatter plot of PDR and SA dust concentration levels in gold mines
(Top: gold mine K; bottom: gold mine GN)**

The regression line from the plot (Figure 4.3.4b) indicates that, on average, the PDR monitor overestimates the measured respirable dust concentration by approximately 15% at concentration levels below 0,5 mg/m³. Again, at concentration levels between 0,5 mg/m³ and 2,0 mg/m³, the two dust monitors show good linearity and, on average, the PDR monitor overestimates the measured respirable dust concentration by approximately 3,0%.

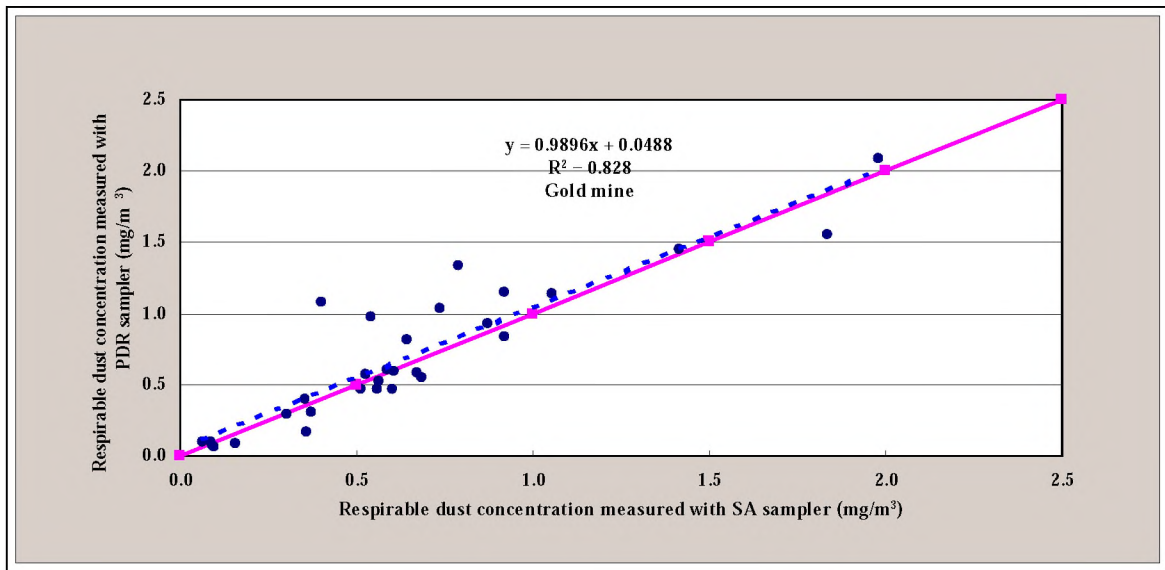


Figure 4.3.4b: Combined plot of the relationship between side-by-side PDR and SA samplers in gold mines

Similarly, the relationship between the concentration values obtained from the side-by-side PDR and SA samplers during the field trials in a platinum mine is shown in Figure 4.3.4c. The correlation coefficient (r) between the two monitors in the platinum mine is 0,605. The two monitors show comparatively poor linearity, with wide scatter for all the measured concentration ranges in the platinum mine. Also, we note that the measured respirable dust concentration levels in the platinum mine were between 0,2 mg/m³ and 4,0 mg/m³. From the regression equation it is estimated that, on average, the PDR monitor overestimates the measured respirable coal dust concentration by approximately 90% and 40% at the 0,5 mg/m³ and 2,0 mg/m³ concentration levels respectively.

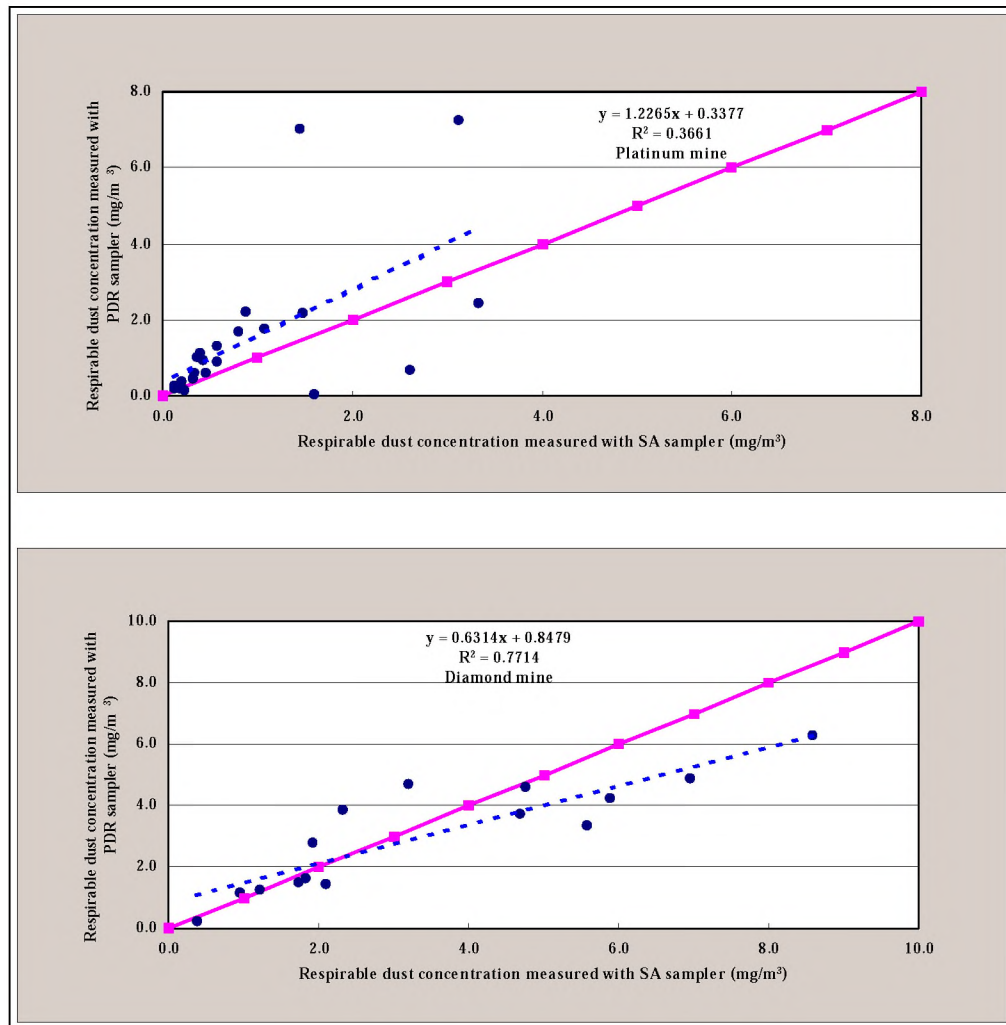


Figure 4.3.4c: Relationship between side-by-side PDR and SA samplers in platinum (top) and diamond mines (bottom)

Similarly, the relationship between the concentration values obtained from the side-by-side PDR and SA samplers during the field trials in a diamond mine is shown in Figure 4.3.4c. The correlation coefficient (r) between the two monitors in the diamond mine is 0,878. The plot (Figure 4.3.4c) indicates that there was a wide range of measured dust levels. At a compliance level of 2 mg/m^3 , the PDR sampler measures approximately the same as the SA sampler and follows the solid 1:1 linear relationship line. However, at higher concentration levels ($> 4,0 \text{ mg/m}^3$), this relationship no longer holds true and the underestimation of measurement by the PDR sampler decreases.

In order to determine the relationship between the concentration values obtained from the side-by-side personal PDR and SA samplers during the field trials in hard rock mines (gold, platinum and diamond), the data were plotted as shown in Figure 4.3.4d. The

correlation coefficient (r) between the two monitors in all hard rock mines is 0,781, demonstrating an average linear relationship between the samplers.

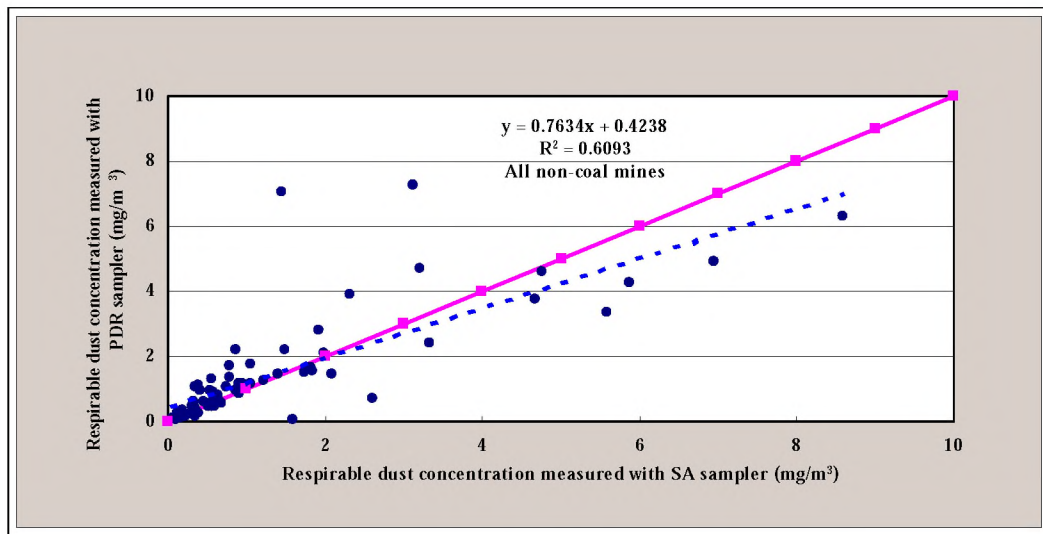


Figure 4.3.4d: Relationship between side-by-side personal PDR and SA samplers in all non-coal mines (gold, platinum, diamond)

The relationship between the concentration values obtained from the side-by-side PDR and SA samplers during the field trials in coal mines is shown in Figure 4.3.4e. The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two samplers in coal mine GP and coal mine B are 0,707 and 0,886 respectively.

A combined plot of the two coal mine data sets ($r = 0,892$) is shown in Figure 4.3.4f. The samplers show reasonable linearity when deployed in coal mines, but the ratio of PDR sampler concentration to SA sampler concentration was less than one for coal mines and the measured dust concentration levels were comparatively higher than in gold and platinum mines. One of the possible reasons for this could be the high air velocities (approximately 2,0 m/s) and the resulting spatial variations in the sampled dust cloud. The plot (Figure 4.3.4f) indicates that, on average, the PDR sampler underestimates the measured respirable coal dust concentration by approximately 25% for compliance dust levels.

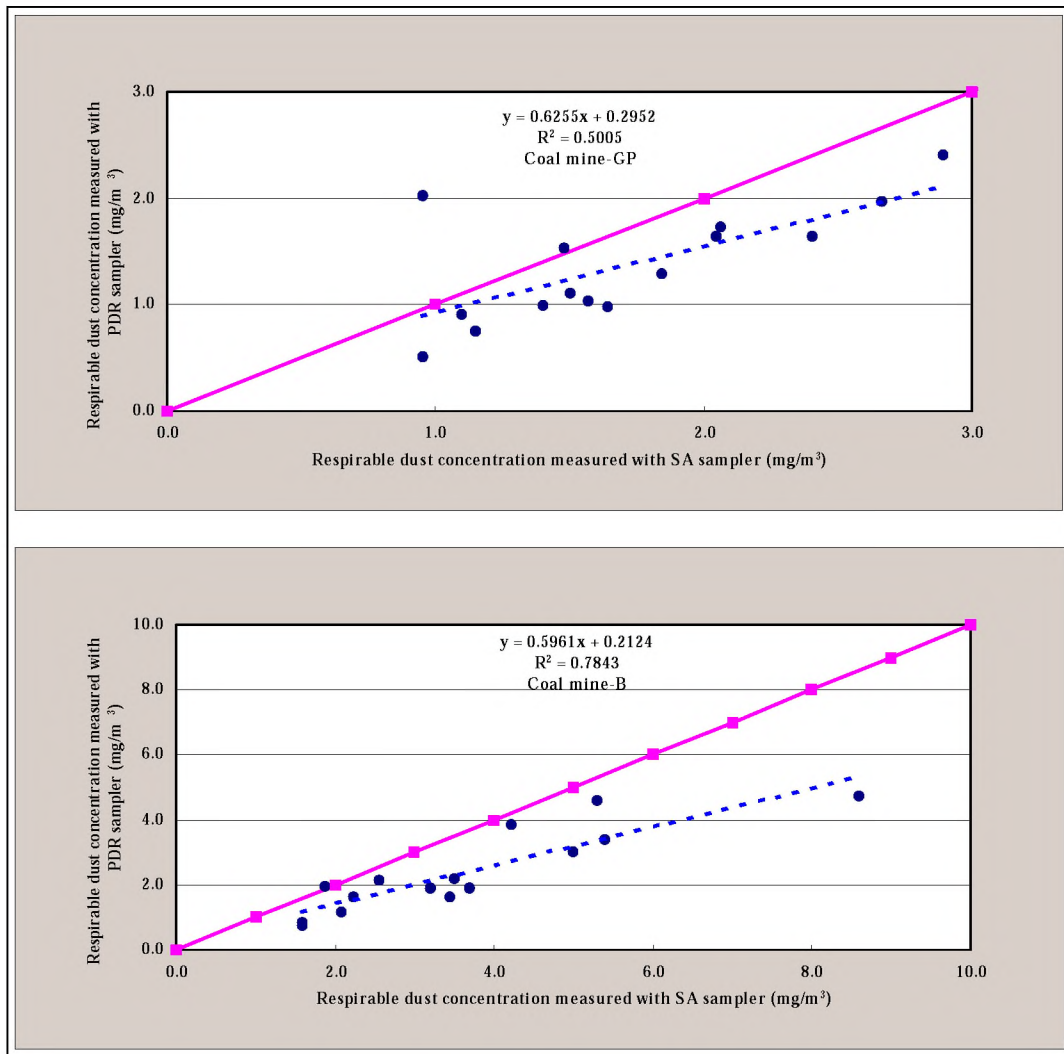


Figure 4.3.4e: Relationship between side-by-side personal PDR and SA samplers in coal mines (Top: mine GP; bottom: mine B)

The combined scatter plot of all mine data (Figure 4.3.4g) shows an average linear relationship ($r = 0,783$) between the PDR and SA sampler measurements in various types of mine with a wide range of dust levels. Overall, from the linear regression equation it is estimated that, on average, the PDR sampler underestimates the measured respirable dust concentration by approximately 12% for a compliance level of 2 mg/m^3 . As the measured dust levels increase, the PDR's underestimation of these levels also increases, and at twice the compliance levels, the amount by which it underestimates also doubles. However, at low concentrations ($0,1 \text{ mg/m}^3$), the PDR overestimates the reading by approximately five times the measured SA sampler levels. From a compliance and occupational hygiene perspective, these estimates (over- and under-) assist in achieving better control and greater precision of measurement.

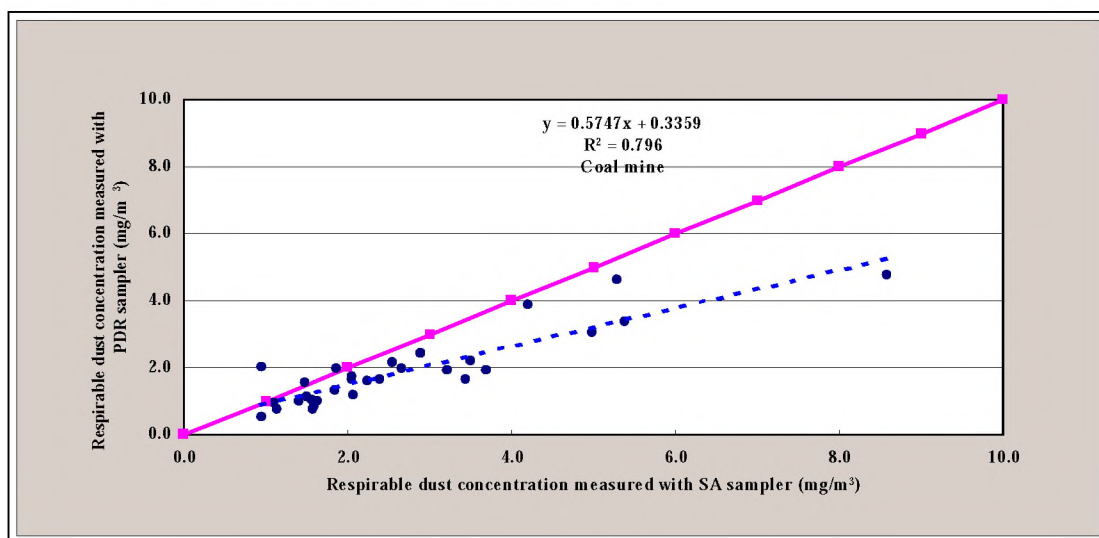


Figure 4.3.4f: Combined coal mine data of side-by-side PDR and SA personal samplers

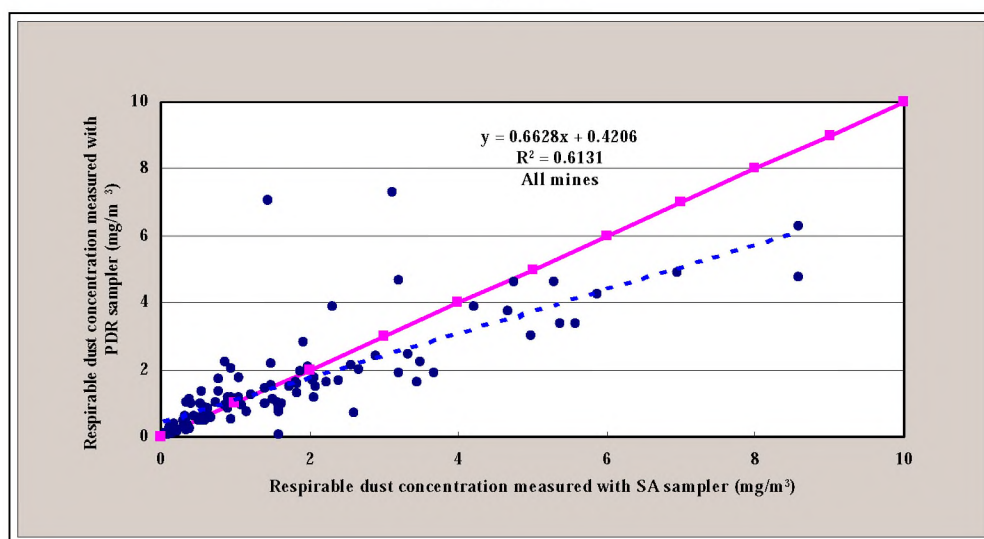


Figure 4.3.4g: Combined data of side-by-side PDR and SA samplers from all mines

As with any available near-real-time monitor, the use of the PDR sampler on a stand-alone basis for compliance purposes is not recommended, and the instrument will seriously overestimate at lower concentrations and underestimate at higher dust levels. However, greater benefits can be derived if the existing unit is modified as recommended in Chapter 5. From the underground experience, it was found that the PDR monitor is portable and has all the desired features, such as one-touch sampling time, 8-h TWA, maximum dust levels and STEL levels, which would be of benefit to the ventilation officers, the occupational hygienist and the mine inspectors.

4.3.4.1 Accuracy criteria

Table 4.3.4.1 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the PDR and SA samplers as measured in the coal, gold, platinum and diamond mines by three different units.

Table 4.3.4.1: Summary of the correction factors for the PDR and SA samplers in all mines

Mine type	PDR	Mean SA conc. mg/m ³	Mean ratio of PDR/SA conc.	No. of readings	SD	RSD or CV (%)
Coal mine GP	P1	2,005	0,731	5	0,045	6,15
	P3	1,697	1,131	5	0,561	49,60
	P2	1,431	0,628	5	0,063	10,03
	Total	1,711	0,829	15	0,377	45,48
Coal mine B	P1	3,516	0,576	5	0,095	16,49
	P3	4,836	0,759	5	0,160	21,08
	P2	2,504	0,640	5	0,230	35,93
	Total	3,618	0,658	15	0,177	26,89
Overall	Total	2,665	0,744	30	0,302	40,59
Gold mine K	P1	0,533	0,862	5	0,252	29,23
	P3	0,483	0,859	5	0,188	21,89
	P2	0,491	0,929	5	0,283	30,46
	Total	0,502	0,884	15	0,228	25,79
Gold mine GN	P1	0,774	1,210	7	0,681	56,28
	P3	0,889	1,290	7	0,341	26,43
	P2	0,381	0,951	2	0,132	13,88
	Total	0,775	1,213	16	0,495	40,80
Overall	Total	0,643	1,053	31	0,418	39,69
Platinum mines	P1	0,731	1,683	14	0,558	33,16
	P3	0,840	1,809	14	1,116	61,69
	P2	2,09	0,144	2	0,173	120,0
	Total	0,872	1,639	30	0,931	56,80
Diamond mine C	P1	4,480	0,964	5	0,425	44,09
	P3	3,733	1,095	5	0,342	31,23
	P2	2,212	0,813	5	0,246	30,25
	Total	3,475	0,957	15	0,342	35,74
All non coal mines	Total	1,293	1,266	76	0,721	56,95
All mines	Total	1,681	1,118	106	0,673	60,19

From the summary statistics table (Table 4.3.4.1) we observe that there is no clear relationship between accuracy and the measured concentration levels. Overall, the CV of

the ratio between the sampler dust concentrations was below the NIOSH and CEN accuracy criteria (except in 3 cases out of a total of 18). Overall, the PDR near-real-time dust monitor failed to meet the NIOSH and CEN accuracy criteria and its correction factor for the test mines ranged between 0,527 and 1,736. This could be because of the dust particles sampled, which were polydisperse and not homogeneously mixed in the mine atmosphere or in the micro environment where the PDR was located, or it could be due to variations in the particle sizes of the sampled dust.

4.3.5 Comparison of measured concentration levels using the real-time Split-2 and SA gravimetric samplers

During the underground trials, the Split-2 near-real-time dust-monitoring instrument was evaluated as a passive real-time personal dust monitor in gold, platinum, diamond and coal mines. During the trials, the Split-2 and SA samplers were positioned side by side on the right and left lapels of the wearer respectively in the breathing zone.

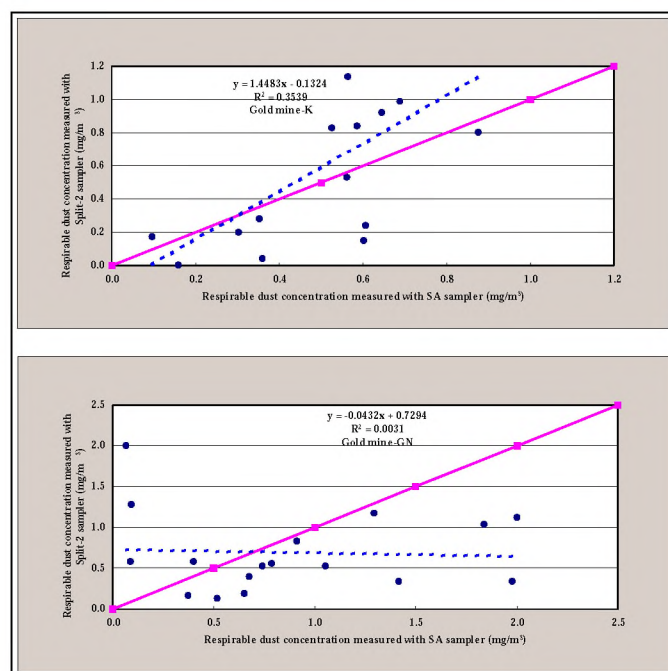


Figure 4.3.5a: Scatter plot of Split-2 and SA sampler concentration levels in gold mines

The average measured dust concentration level recorded by the Split-2 and the dust concentration level measured by the SA sampler from individual wearers were compared one to one. The scatter plots and regression analysis of the one-to-one relationship

between the Split-2 and SA samplers during the field trials in the gold mines are shown in Figure 4.3.5a.

The solid black line represents a 1:1 relationship. The correlation coefficients (r) between the two samplers in gold mine K and gold mine GN are 0,595 and 0,056 respectively. The linear relationship between the two monitors was average in mine K but there was no relationship (linear or otherwise) between the two monitors in mine GN at both extremes of the measured dust levels. A combined plot of the two gold mine data sets ($r = 0,11$) set is shown in Figure 4.3.5b. The dust monitors showed poor linearity when measured in gold mines, with wide scatter for the measured dust levels. The correction factor for the Split-2 varied from 0,2 to 1,43 in the gold mines.

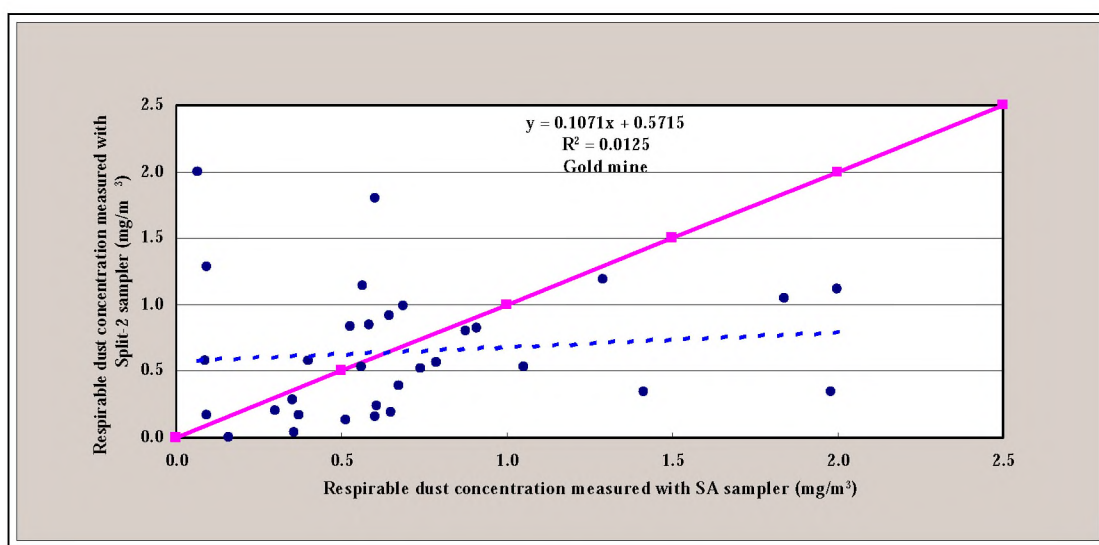


Figure 4.3.5b: Combined plot of the relationship between side-by-side Split-2 and SA samplers in gold mines

The regression line from the plot (Figure 4.3.5b) indicates that, on average, the Split-2 monitor overestimates the measured respirable dust concentration by an order of magnitude at low concentrations. At concentrations between 1,0 mg/m³ and 2,0 mg/m³, the Split-2 underestimates the measured concentration by up to 60%.

Similarly, the relationship between the concentration values obtained from the side-by-side Split-2 and SA samplers during the field trials in a platinum mine is shown in Figure 4.3.5c. The correlation coefficient (r) between the two monitors in the platinum mine is 0,497. The two monitors show poor linearity, with wide scatter for all the

measured concentration ranges in the platinum mine. Also, we note that majority of the measured respirable dust concentration levels in the platinum mine were below 1,0 mg/m³. Overall, the Split-2 sampler overestimates the measured respirable dust concentration as most of the data points were above the ideal solid line.

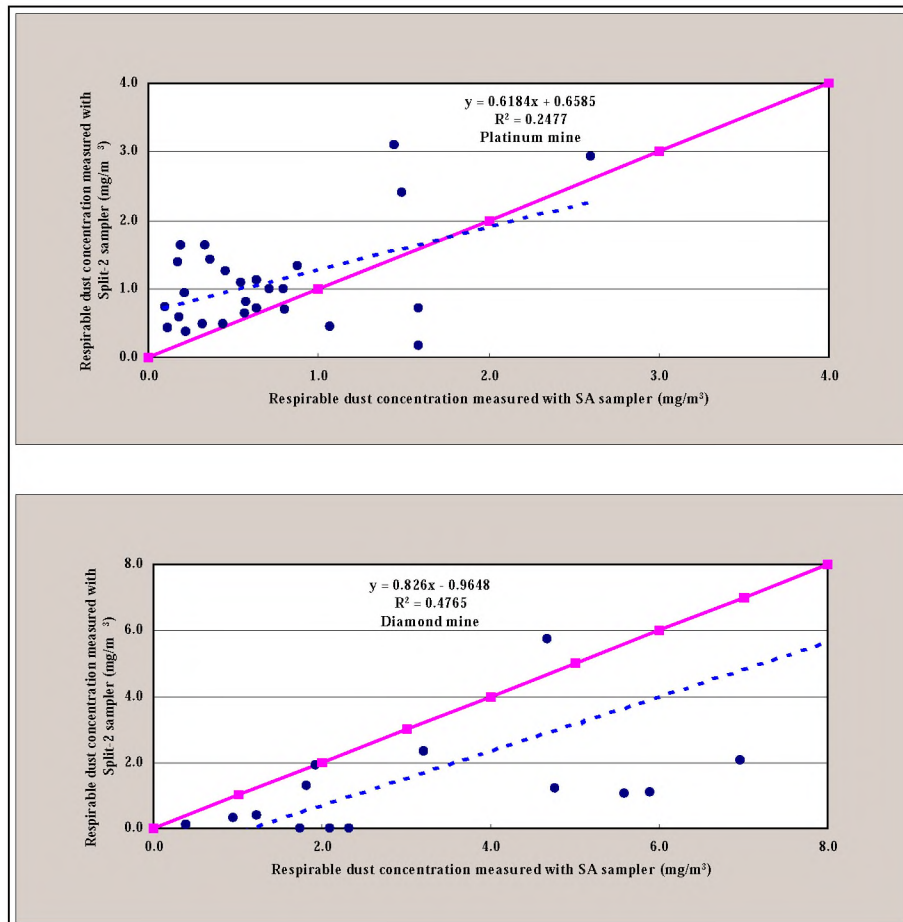


Figure 4.3.5c: Relationship between side-by-side Split-2 and SA samplers in platinum (top) and diamond mines (bottom)

Similarly, the relationship between the concentration values obtained from the side-by-side Split-2 monitor and SA sampler during the field trials in a diamond mine is shown above (Figure 4.3.5c). The correlation coefficient (r) between the two monitors in the diamond mine is 0,690. The plot (Figure 4.3.5c) indicates that the measured dust levels were comparatively higher than in the gold and platinum mines and all the data points except one were below the ideal solid line of the 1:1 relationship. This indicates that the Split-2 monitor underestimated the measured respirable dust in the diamond mine.

In order to determine the overall relationship between the concentration values obtained from the side-by-side Split-2 and SA personal samplers during the field trials in hard rock mines (gold, platinum and diamond), this was plotted as shown in Figure 4.3.5d. The correlation coefficient (r) between the two monitors in all hard rock mines is 0,634, demonstrating an average linear relationship between the samplers. With regard to compliance levels, the Split-2 sampler underestimated the measured level by approximately 25%.

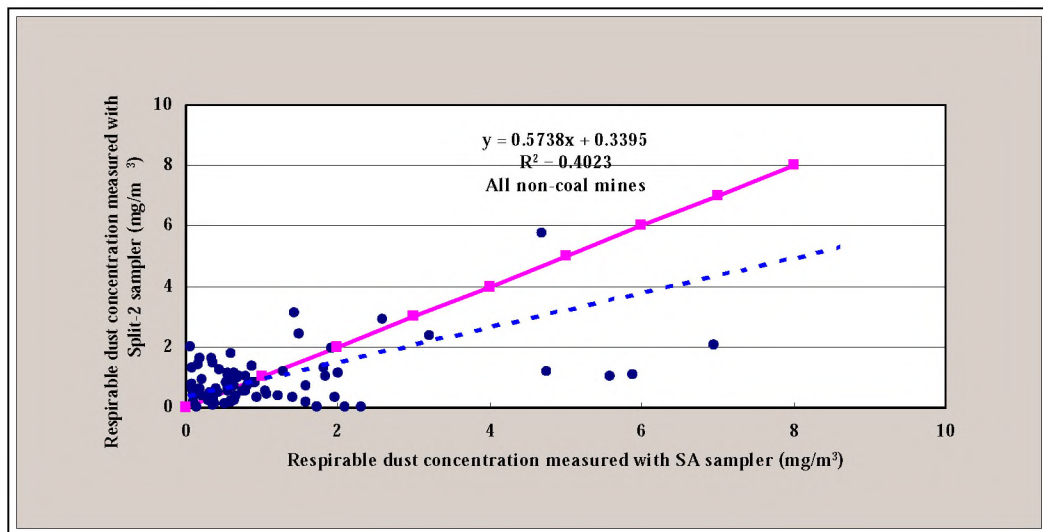


Figure 4.3.5d: Relationship between side-by-side Split-2 and SA samplers in all non-coal mines (gold, platinum, diamond)

The relationship between the concentration values obtained from the side-by-side Split-2 and SA samplers during the field trials in the coal mines is shown in Figure 4.3.5e. It was found that there was no conclusive relationship between the two monitors in the two mines.

A combined plot of the two coal mine data sets ($r = 0,157$) is shown in Figure 4.3.5f. The monitors showed poor linearity when measured in the coal mines, but the ratio of Split-2 concentration to SA sampler concentration was greater than one for coal mines (though not in the diamond mine) and the measured concentration levels were comparatively higher than in the gold and platinum mines. The plot (Figure 4.3.5f) indicates that, on average, the Split-2 sampler overestimates the measured respirable coal dust concentration by approximately 50% for compliance dust levels.

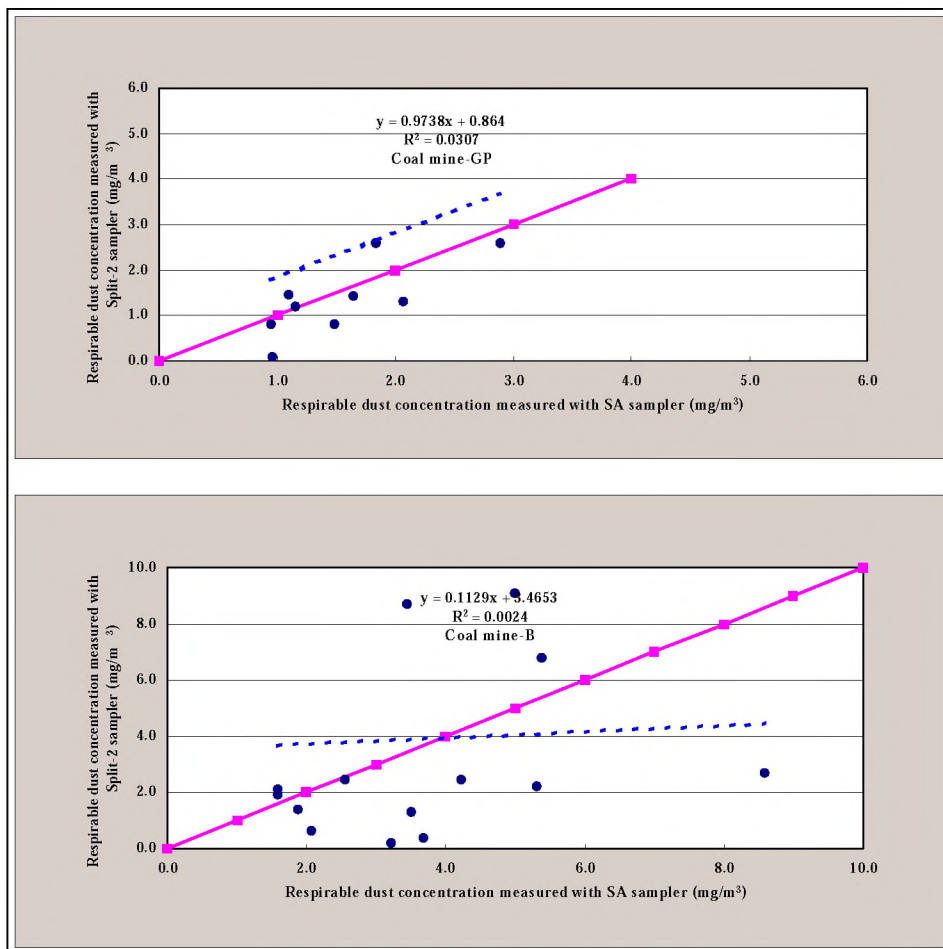


Figure 4.3.5e: Relationship between side-by-side Split-2 and SA personal samplers in coal mines (Top: mine GP; bottom: mine-B)

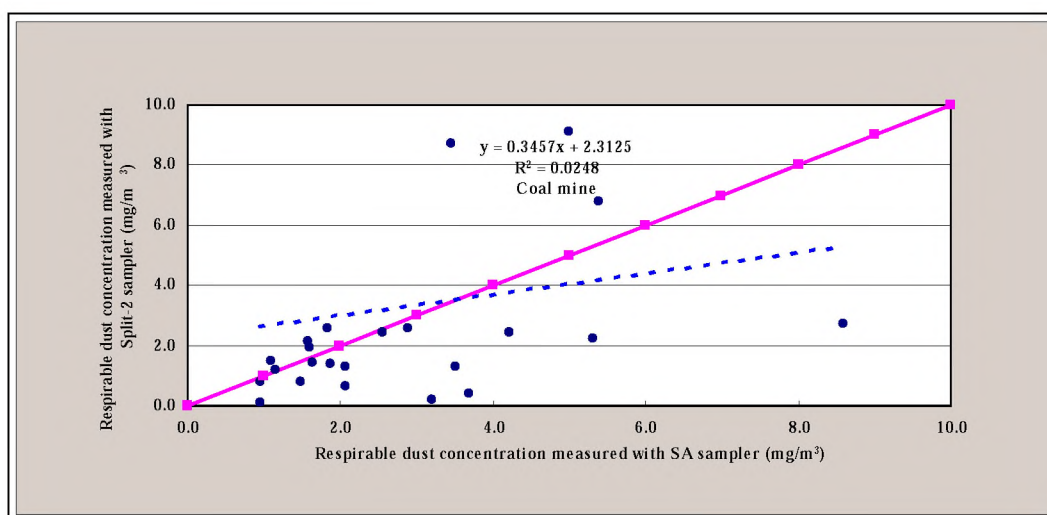


Figure 4.3.5f: Combined coal mine data for side-by-side Split-2 and SA samplers

The combined scatter plot of all mine data (Figure 4.3.5g) shows an average linear relationship ($r = 0,449$) between the Split-2 and SA samplers measured in various mine types with a wide range of measured dust levels.

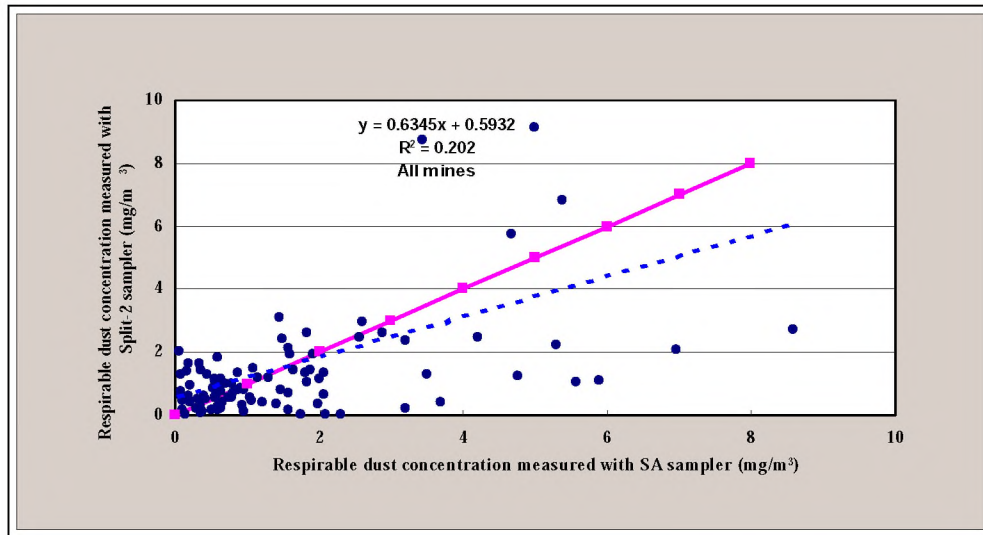


Figure 4.3.5g: Combined data of side-by-side Split-2 and SA samplers from all mines

Overall, from the linear regression equation it is estimated that, on average, the Split-2 monitor overestimated the measured respirable dust concentration for a compliance level of 2 mg/m^3 . As the measured dust levels increase, the Split-2's underestimation of the levels also increases, and at twice the compliance levels the underestimation is approximately 22%. However, at low concentrations ($0,1 \text{ mg/m}^3$), the Split-2 overestimates the reading by approximately six times the measured SA sampler levels.

In the field trials it was noted that most of the time, the Split-2 monitor was reading "zero" despite visibly high dust levels and required constant "zeroing". As with any of the other available near-real-time monitors, the use of the Split-2 monitor on a stand-alone basis for compliance purposes is not recommended and the instrument will seriously overestimate at lower concentrations and underestimate at higher dust levels. By comparison with the PDR dust monitor, the Split-2 requires greater modifications in terms of size, portability, IS approval, a user-friendly touch pad and sampling information. The discrepancies in the measurement values can also be attributed to those discussed for the PDR monitor.

4.3.5.1 Accuracy criteria

Table 4.3.5.1 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the Split-2 and SA samplers in coal, gold, platinum and diamond mines by three different units.

Table 4.3.5.1: Summary of the correction factors for the Split-2 and SA samplers in all mines

Mine type	SPLIT-2	Mean SA conc. mg/m ³	Mean ratio of Split-2/SA conc.	No. of readings	SD	RSD or CV (%)
Coal mine GP	S1	2,005	failed	0	-	-
	S3	1,697	0,849	5	0,310	36,56
	S2	1,431	2,163	5	2,974	137,5
	Total	1,564	1,506	10	2,110	140
Coal mine B	S1	3,516	2,310	5	2,852	123,46
	S3	4,836	0,526	5	0,256	48,66
	S2	2,504	0,970	5	0,441	45,46
	Total	3,618	1,268	15	1,736	136,90
Overall	Total	2,797	1,363	25	1,856	136,17
Gold mine K	S1	0,533	0,701	5	0,584	83,31
	S3	0,483	1,824	5	0,756	41,45
	S2	0,491	0,810	5	0,632	78,02
	Total	0,502	1,112	15	0,805	72,39
Gold mine GN	S1	0,749	2,870	6	5,257	183
	S3	0,902	5,385	6	12,377	230
	S2	0,994	1,879	5	2,588	138
	Total	0,775	3,466	17	7,775	224
Overall	Total	0,701	2,363	32	5,737	243
Platinum mines	S1	0,550	2,333	7	1,551	66,48
	S3	0,613	3,343	10	2,810	84,05
	S2	0,902	1,993	10	2,160	108
	Total	0,704	2,582	27	2,297	88,96
Diamond mine C	S1	4,480	0,603	5	0,609	101
	S3	3,733	0,598	5	0,315	52,67
	S2	2,212	0,162	5	0,156	96,29
	Total	3,475	0,454	15	0,432	95,15
All non-coal mines	Total	1,264	2,056	74	4,07	198
All mines	Total	1,651	1,881	99	3,643	193,7

From the summary table (Table 4.3.5.1) we observe that there is no clear relationship between accuracy and the measured respirable concentration levels. Overall CV of the ratio between the sampler dust concentrations was below the NIOSH and CEN accuracy criterion. In overall the Split-2 near-real-time dust monitor failed to meet the NIOSH and CEN accuracy criterion. In overall, the Split-2 correction factor for the test mines ranged between 0,185 and 2,202. Some of the reasons can be attributed due to particles, which were poly-disperse and not homogeneously mixed in the mine atmosphere or orientation of micro compartment of the Split-2, variations in the particle sizes of sampled air.

4.3.6 Discussion

The results of the study showed that the respirable dust mass measurements obtained with the two real-time instruments, the PDR and the Split-2, employing the principles of light scattering, were linearly related to the measurements obtained with the gravimetric SA sampler. The response of the real-time instruments can be adjusted so that the mass concentration determined by the light-scattering system is equivalent to that of gravimetric sampler. However, the range of correction factors is wide and, therefore, the likelihood of being able to use a real-time monitoring instrument as a "stand-alone" unit is extremely remote and not advisable for the purposes of determining compliance. However, the instruments can be used for engineering dust control purposes by environmental supervisors, ventilation engineers and occupational hygienists.

In general, the correction factors of the real-time direct-monitoring instruments can be explained by the size-dependent light-scattering characteristics of the instruments with respect to any of the respirable size-selective sampling conventions. According to the ISO/CEN/ACGIH convention, an "ideal sampler" cuts off the particles larger than 10 µm. However, the near-real-time monitoring instruments may measure or detect particles larger than 10 µm.

Studies have shown the relationship between the size of airborne particles and the type of production (Belle, 2001). In the case of coal mines, the correction factors are independent of the measured dust levels. We observe that in coal mine GP, a CM was producing the coal and in coal mine B, a road header was producing the coal. Therefore, the differences in correction factors of 0,829 and 0,658 could also be attributed to the characteristics of airborne particles. For this reason, it is possible to determine the real-time correction factor for CM-specific coal mines, which will be consistent throughout South Africa. This also explains why, depending on the size of the airborne particles, the light-scattering

instruments may overestimate or underestimate the "true" respirable dust concentration measured by the gravimetric-type samplers. From the field trials, it was found that this was true in the case of the gold and platinum mines.

Dust-monitoring instruments also depend on air movement to move the air into the sensing zone of the monitor. The orientation of the SA sampler (and that of the wearer) may also give "biased" results, depending on the particle size. In the field trials, unlike the Split-2, the PDR performed without significant "zero" calibration problems. All samplers were exposed to similar temporal and spatial environmental conditions. Therefore any differences in their responses were due to the sampling characteristics of the dust monitors alone. Time had no significant influence on the sensors or lenses, or on the correction factor of the near-real-time monitors. In the case of the real-time monitoring instruments, the localised air movement was solely responsible for introducing dust particles, respirable or otherwise, into the sensing chamber (i.e. passive sampling) unlike the active sampling gravimetric-type instruments. However, the instruments did also have the capacity for active sampling – one of the objectives of the study is to "replace" the gravimetric type of sampling.

From the results, one observes that there is a significant variation in the real-time dust concentration levels between instruments of the same type tested under the same dust cloud. Further statistical analyses will be carried out on the above data, which will identify the most important factor in instrument selection. The study indicates that "secondary" acceptance parameters may be necessary in order to accept the manufacturers' claims for the instruments for use in the mining industry.

4.3.7 Statistical analyses

All the dust concentration data for each sample set were tested for Anderson-Darling normality and it is evident that the data do not follow a normal distribution. Preliminary data analysis indicated that $\log_e$ -transformed data gave an improved fit of the normal distribution. Therefore, for the statistical analysis, $\log_e(H_a)$ and $\log_e(H_b)$ were compared (paired t -test). The subscripts, H_a (SA sampler) and H_b (test sampler), are the dust concentration values measured using the identified personal sampling instruments in the sample pair (random) at various test mines. Hypothesis tests were carried out at each of the mines to test the sampling environment (gold, diamond, platinum and coal). The null and alternative hypotheses for the tested sample pairs were:

$$H_0: \mu_{\text{diff}} = 0$$

$$H_a: \mu_{\text{diff}} \neq 0$$

In the paired t -test, hypothesis H_0 states that the mean difference in concentration values (transformed values) between side-by-side personal instrument pairs is equal to zero. On the other hand, the alternative hypothesis states that the two personal dust-monitoring instruments positioned side by side in fact measured different mean concentration levels or the difference was not equal to zero. For this research work, a standard 95% confidence level was chosen. The results of the paired t -test statistical analyses are given in Table 4.3.7a.

Table 4.3.7a. Results of paired t-test (on transformed values)

Statistic	Mine type	Difference in monitoring concentration between sample pairs			
		H _{SA-DO}	H _{SA-IOM}	H _{SA-PDR}	H _{SA-SKC}
95% LCL	Gold	0,0354	-0,643	-0,1179	-0,345
	Platinum	-0,139	-0,7941	-0,606	-0,951
	Diamond	0,2714	0,736	-0,0864	0,623
	Coal	0,4501	0,6427	0,2351	-0,185
95% UCL	Gold	0,4146	-0,175	0,1367	0,532
	Platinum	0,387	-0,4908	0,096	-0,192
	Diamond	0,5856	1,326	0,2820	2,512
	Coal	0,6071	0,9942	0,4593	0,765
t-statistic	Gold	2,41	-3,58	0,15	0,44
	Platinum	1,01	-8,84	-1,48	-3,10
	Diamond	5,85	7,49	1,14	3,56
	Coal	13,77	9,53	6,33	1,26
P-value	Gold	0,021	0,001	0,881	0,667
	Platinum	0,330	0,000	0,149	0,005
	Diamond	0,000	0,000	0,274	0,003
	Coal	0,000	0,000	0,000	0,220
Hypothesis (accept or reject)	Gold	Reject	Reject	Accept	Accept
	Platinum	Accept	Reject	Accept	Reject
	Diamond	Reject	Reject	Accept	Reject
	Coal	Reject	Reject	Reject	Accept
Sample size	Gold	34	30	31	32
	Platinum	15	21	30	27
	Diamond	15	15	15	15
	Coal	30	30	30	25
Overall statistics	All mines	H _{SA-DO}	H _{SA-IOM}	H _{SA-PDR}	H _{SA-SKC}
95% LCL		0,2490	-0,0275	-0,0746	-0,071
95% UCL		0,4274	0,3244	0,1601	0,481
t-statistic		7,53	1,67	0,72	1,48
p-value		0,000	0,097	0,472	0,143
Sample size		94	96	106	99
Hypothesis (accept or reject)		Reject	Reject	Accept	Accept

From Table 4.3.7a we observe that, for all test mines, there was a significant difference in measured dust concentration levels between the South African, Dorr-Oliver (USA) and IOM samplers. Similarly, the measured mean personal dust concentration levels from each pair of SA and PDR real-time dust monitors did not differ significantly and the null hypothesis is accepted, except in the coal mines. Comparison of the Split-2 and SA sampler concentration levels indicates that there was a significant difference in the measured levels in the platinum and diamond mines, but no significant difference was observed when they were tested in coal and gold mines.

A paired *t*-test was performed on the combined data of all four dust monitors to determine whether there was a statistical difference in the results obtained from the SA sampler and

the other monitors tested. The result of the paired *t*-test was a test statistic with 105 degrees of freedom, $p = 0,472$, indicating no significant difference between the measured mean concentration levels using the SA sampler and the near-real-time PDR dust monitor side by side. A similar observation was made for the Split-2 real-time dust monitor and SA sampler pair, with 98 degrees of freedom, $p = 0,143$, indicating a less-significant difference between the two samplers. However, both gravimetric dust monitors, i.e. the DO sampler and the IOM sampler, showed rejection of the hypothesis. In other words, the dust readings measured by the two samplers side by side are significantly affected at the 95% level of confidence. Finally, from the above analysis we conclude that the PDR is the instrument with the most potential for use in the mines ($p = 0,472$), based on intensive field evaluations in all types of mines in South Africa.

Analysis of variance (ANOVA)

The measured dust concentration ratios between the data from the test samplers (Dorr-Oliver, IOM, PDR and Split-2) and the reference sampler (SA sampler) were used to perform an analysis of variance (ANOVA). A discussion of the ANOVA models and their underlying assumptions can be found in any of the standard books on statistics. In order to quantify statistically the influence of mine (dust) type (gold, coal, diamond and platinum), individual sampler and dust monitor type on the ratio of measured dust concentration levels between the instruments, a factorial analysis was carried out. Essentially the measured dust concentration ratio data that were used for analysis were in the form of C_{ijkl} (mg/m^3). The subscripts have the following definitions:

i = mine type (MT), $i = 0$ is a coal mine, $i = 1$ is a diamond mine, $i = 2$ is a gold mine and $i = 3$ is a platinum mine

j = mine level (ML), $j = 0$ is a sub-mine type A, $j = 1$ is a sub-mine type B

k = dust monitor type (DM), $k = 0, 1, 2$ and 3 indicate the Dorr-Oliver sampler, IOM sampler, PDR real-time monitor and Split-2 real-time monitor respectively

l = instrument wearer (IW), $l = 0, 1$ and 2 respectively indicate the sampling individuals B, L and J respectively.

The results of the analyses of variance (ANOVA) on the data are summarised in Table 4.3.7b. The main factors of the statistical analysis were: mine or dust type; sub-mine type, dust monitor type and sampling individual. The ANOVA table gives, for each term in the model, the degrees of freedom, the sums of squares (SS), the adjusted means squares (MS), the F-statistic from the adjusted means squares, and its p-value.

In the ANOVA table, some p-values are less than 0,05, indicating that these factors are significant. Individual two-factor, three-factor or multi-factor interactions were not calculated due to the imbalance in the data structure.

Table 4.3.7b: Results of analysis of variance (ANOVA)

Sources of variation	Df	SS	MS	F-value	Pr > F
Mine (dust) type	3	84,15	28,05	7,80	0,000
Sub-mine type	1	5,84	5,84	1,62	0,204
Dust monitor type	3	52,36	17,45	4,85	0,003
Individual sampler	2	8,15	4,08	1,13	0,323
Error	385	1384,99	3,59		
Total	394	1535,49			

From the results of the ANOVA, the following conclusions can be deduced:

- The effect of mine (dust) type on the dust concentration ratio between the two side-by-side monitors positioned in the breathing zone of the workers is highly significant, with a mean square (MS) value of 28,05. Apart from the dust type encountered in the individual test mines, the environmental conditions (such as humidity and temperature) and conditions such as continuous sweating and discomfort may have contributed to significant variations in the measured personal dust levels.
- There is also strong evidence (p-value of 0,003) of the effect of the type of monitoring instrument on measured personal dust levels in the breathing zone of the worker for all mine types (the MS value for the cutting distance is 17,45).
- The dust-monitoring instrument's performance is not significantly affected by the sampling individual nor is there a significant difference between units of the same instrument (p=0,323) as all of them were exposed to the same mine environmental conditions. Similarly, when the instruments were tested under similar dust clouds or in similar mine types, no pronounced effects were observed (0,204).
- Based on the magnitude of each test parameter, the dust or mine type, dust instrument type, sub-mine type and sampling individuals can be arranged in descending order of importance. As we note from the table, the mine type and instrument type have a pronounced effect on the measured dust levels (p-value of 0,00 and high MS values).

- It is also possible that the interactions between these factors may have had a significant effect on the personal dust concentration levels measured in the mines.
- Finally, the main factors, viz. dust-monitoring instrument type and dust type or mine, that influence the measured dust levels for estimating personal exposure levels have been well demonstrated.

5 Conclusions

An extensive laboratory and field evaluation of six near-real-time and gravimetric-type dust monitors positioned side by side was carried out. Laboratory evaluation of the instruments as area samplers was carried out in the Polley dust duct. Field evaluation of the instruments as personal dust-monitoring instruments, side by side in the breathing zone, was carried out in gold, platinum, coal and diamond mines.

The instruments evaluated during the laboratory and underground trials were (1) the SA sampler, (2) the Dorr-Oliver (DO) 10 mm sampler, (3) the RDD tube, (4) the IOM sampler, (5) the PDR and (6) the Split-2 dust monitor. All the instruments were operated according to the new CEN/ISO/ACGIH size-selective curve. The locally manufactured South African sampler, operated at 2,2 L/min in accordance with the new ACGIH/ISO/CEN size-selective curve, was used as a reference sampler.

The main objective of the laboratory and underground evaluations was to compare the performance of the identified instruments in terms of accuracy, intrinsic safety and practical implications, such as portability, ease of use and wearability underground. Overall, ten weeks were spent underground in gold, platinum, coal and diamond mines.

Main findings

The following overall conclusions were drawn from this study:

- From both laboratory and field studies, it was noted that when two samplers (the SA sampler and the DO sampler) were operated according to the ACGIH/ISO/CEN size-selective curve, there was a significant difference in the measured respirable dust concentrations. From this it can be inferred that either the SA sampler overestimates or the DO sampler underestimates the "true" concentration. In the USA, the DO sampler is considered to give a "true" measured concentration and in South Africa, the locally manufactured Higgins-Dewell-type SA sampler is considered to give a "true" measured concentration.

Surprisingly, when the SA sampler and the BGI sampler were compared in the coal mines as area samplers according to the ACGIH/ISO/CEN curve, it was found that there was an insignificant difference in measured dust levels (Belle *et al.*, 2001).

- The portable near-real-time dust monitor (PDR) proved to have the highest potential as a personal dust monitor for exposure assessment. Nevertheless, all the near-real-time instruments can be used for engineering control or for quick estimation of dust levels, but using the near-real-time monitoring instrument as a stand-alone unit for compliance is not recommended. However, modifying the current PDR unit (by adding a micro-size-selective device and improving the battery life and intrinsic safety) is likely to turn the monitor into a unique near-real-time compliance instrument for personal monitoring specially suited to South African mining conditions.
- From the laboratory and field trials, it was found that the responses of most of the newly developed dust monitors were linear compared with the SA sampler over a wide range of concentrations and aerosol distributions of various dust types. These variations in the dust monitors' performance are not surprising given the wide correction factors that have to be applied since the performance of a monitor is dependent on the size characteristics of the environmental aerosol, the level of environmental dust, the wind factor, the orientation of the sampler (sensing chambers in the case of real-time monitors) and the micro environment of the workers' breathing zone.
- The RDD near-real-time dust monitor was easy to use and wear as a personal sampler under extremely harsh environment conditions such as in hard rock mines. However, in view of the poor relationship between pressure drop and dust mass of dust collected on the filter, the RDD needs further fine-tuning. Further, the RDD is not recommended for use in an environment where diesel particulate matter (DPM) is present. Also, there is no confirmed procedure for evaluating the quartz content of the RDD foam dust sample.
- From the field experience, it was noted that personal sampling in the harsh conditions of underground hard rock mines is extremely difficult. Drawing rational conclusions as to the reasons for the variations in the measured dust levels is notoriously complex. It is therefore suggested that in future personal sampling evaluations and comparisons of the performance of personal dust samplers in the workplace be carried out on a rotating 'mannequin'.

- The study has gathered a large amount of data on personal dust-monitoring instruments and built up considerable expertise on the subject. The identified instruments were successfully evaluated and new research directions that should be pursued for developing a near-real-time monitoring instrument have been determined. The project has led to technical knowledge and to know-how on the feasibility and practicality of providing information on the use of personal samplers in some of the harsh conditions underground.
- Finally, this study has generated a wealth of "unique" information and experience related to the evaluation of newly available dust-monitoring instruments for personal sampling purposes and to the difficulties encountered in some of the deepest and hottest mines in the world.

(DO I NEED TO PUT THIS??) DISCUSS WITH DME!

Based on the laboratory and field evaluations and the criteria set for an instrument's potential use in South African underground mines, the instruments tested were ranked as shown in Table 5 **(Need input and discuss with Doug Rowe)**. It is not the intention of this study to exclude or recommend any particular type of dust instrument, but rather to show their comparative performance when evaluated under the same broad conditions as personal samplers in the field and area samplers in the laboratory.

Table 5: Rankings of the potential instruments for use in underground mines

Criterion	Sampler type					
	SA	DO	IOM	RDD	PDR	Split-2
Intrinsically safe	1,0	1,0	1,0	1,0	2,0	3,0
Respirable curve	1,0	1,0	1,0	1,0	1,0	1,0
Accuracy	1,0	3,0	4,0	3,0	2,0	5,0
Quartz analysis	1,0	1,0	1,0	2,0	2,0	2,0
Real-time values	3,0	3,0	3,0	2,0	1,0	1,0
TWA	3,0	3,0	3,0	2,0	1,0	1,0
Sampling time	1,0	1,0	1,0	1,0	1,0	1,0
Robustness	1,0	1,0	2,0	1,0	1,0	3,0
Portability	3,0	3,0	3,0	1,0	2,0	4,0
Cost	1,0	1,0	1,0	2,0	3,0	3,0
Analytical work	2,0	2,0	3,0	1,0	1,0	1,0

TOTAL	18,0	20,0	23,0	17,0	17,0	25,0
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6 Recommendations

Following recommendations are made based on the extensive laboratory and field study:

- The ACGIH, CEN and ISO have called for a harmonised approach worldwide to dust sampling in accordance with the same international size-selective sampling conventions. This study has shown that when the two size-selective samplers were operated according to the new ISO/CEN/ACGIH curve, the result was a significant difference in the respirable dust concentration levels measured. It is against this background that the South African mining and allied industries must should resolve to carry out basic and pragmatic research into defining the detailed penetration characteristics (aspiration efficiency) of the SA sampler for the size fractions of respirable dust. Side-by-side comparison of the BGI cyclone and the Dorr-Oliver cyclone according to the new respirable curve may lead to an understanding of why the SA sampler's measurements vary from the "true" concentration.
- In the past decades, researchers used the MRE 113a, which followed the Johannesburg (BMRC) curve as a benchmark "true sampler" because it was based on health studies. Ideally, samplers with penetration characteristics that "exactly" follow the respective size-selective curves should provide "true" concentrations (Vincent, 2002). However, there is no single physical sampler that precisely duplicates the theoretical size-selective curve. Owing to the differences observed, the study identifies the need for consensus on a "true SA sampler" which will operate according to the proposed new size-selective curve for international sampling harmonisation.
- In South Africa, no study has yet been carried out to determine how closely non-ideal SA samplers conform to either the BMRC or the ISO/CEN/ACGIH size-selective curves when used in the field. Furthermore, the DME does not provide any guidelines as to which of the samplers conform to the specified collection efficiencies for either the BMRC or the ISO/CEN/ACGIH curve. Also, a draft guideline should be developed for the South African mining industry based on the results of recommended research and investigations into acceptance

criteria for overseas instruments and, if necessary, "secondary acceptance parameters" for specific samplers should be pursued.

- The study highlights the lack of infrastructure for applied aerosol research for the mining industry. What is lacking in this field at present is a well-established state-of-the-art centre for aerosol sampler testing to cater for the needs of the local mining and allied industries. This need is emphasized by the considerable current research outputs in the field of aerosol sampling research from various universities, laboratories and research institutes in European, North American and some South East Asian countries. In view of the needs required of the local mining industry, southern Africa needs to take a quantum leap in this area. Such a centre would acquire various sampling instruments, which could be used for comparing the test results from a wide range of manufactured dust-monitoring instruments and would facilitate the calibration of these instruments. Informal exchanges between dust experts have demonstrated that the "need for worldwide interaction" still exists. Therefore, the establishment of this centre would lift South Africa's and the region's capacity in dust research and should be regarded as a national priority. This should be the strategic aim of the Advisory Committee for the future of dust measurement and control research.
- Use of area sampling as an alternate to personal sampling in extremely harsh conditions such as deep gold mines be reviewed, based on the practicality and quality of the exposure data obtained.
- Further work is needed to develop suitable test facilities and methods in consultation with overseas research agencies (Vincent, J., NIOSH, MSHA). Some of the shortcomings identified in this study should be regarded as pointing a way forward for better understanding of personal sampling in mines.

7 REFERENCES

ACGIH (American Conference of Governmental Industrial Hygienists), 1985, Particle size-selective sampling in the workplace. Cincinnati, OH.

Baldwin, P.E.J., Maynard, A.D. and Northage, C., 1997,. An investigation of short-term gravimetric sampling in pig farms and bakeries. *Appl. Occup. Environ. Hyg.*, 12(10): 662-669.

Bartley, D.L; Chen, C-C, Song, R. *et al.*, 1994, Respirable aerosol sampler performance testing. *AIHA J*, 55(11): 1036.

Belle, B.K. *et al.*, 1999,

Belle, B.K., 2001,

Belle, B.K. and Ramani, R.V., 1997,. Evaluation of two-phase spray system in a longwall gallery. Final Report, Vols I and II, submitted to NIOSH, USA.

Biffi, M., Belle, B.K. and Unsted, D., 2000,. Proposed rational criteria for routine dust sampling of respirable dust in South African mines. Project HEALTH 604b, SIMRAC Research Report, South Africa, 110 p.

Brown, R.C., Hemingway, M.A., Wake, D. and Thompson, J., 1995,. Field trials of an electret based passive dust sampler in metal-processing industries. *Ann. Occup. Hyg.*, 39(5): 603.

Cantrell, B.K., Williams, K.L., Stein, S.W., Hassel, D. and Patashnick, H., 1997,. Continuous respirable dust monitor development. Proceedings of the 6th International Mine Ventilation Congress, Society of Mining Engineers, Littleton, USA.

CEN (Comité European de Normalisation), 1993, Workplace atmospheres: Size fraction definitions for measurement of airborne particles in the workplace. CEN Standard EN 481. CEN, Brussels.

DME (SA Department of Minerals and Energy), 1997, Measurement guidelines. Pretoria, South Africa.

Du Toit, R.S.J., Murray, N.M. and Owen, T.B., 1973, A steady concentration dust duct. *Journal of Mine Ventilation Society of South Africa*.

Fabries, J-F., 1990, Simulation of particle size-selective samplers placed in a polydisperse aerosol. *Aerosol Sci. Tech*, 12:673-685.

Gautam, M. and Sreenath, A., 1997, Performance of a multi-inlet cyclone sampler. *J Aerosol Sci*, 28(7): 1265-1282.

Gorner, P. and Fabries, J.F., 1997, Industrial aerosol measurement according to the new sampling conventions. *Occupational Hygiene*, 3:361.

Grabe, J., Personal communication, South Africa.

Gruppig, T., 2001, Personal communications, AMS Haden, SA.

Gudmundsson, A. and Liden, G., 1998, Determination of cyclone model variability using a time-of-flight instrument," *Aerosol Sci. Tech.*, 28(3): 197-214.

Hemingway, M.A., 1996, Field trials of a passive dust sampler in coal mines. HSL Report No. IR/L/Q/WQ/96/04.

Hemingway, M.A., Brown, R.C. and Arthur, J., 1997, Field trials of an Electret-based passive dust sampler in coal mines. Paper presented at the 27th International Conference on Safety in Mines Research Institutes.

International Standards Organisation (ISO), 1995, Air quality - Particle size fraction definitions for health-related sampling. ISO Standard 7708. ISO, Geneva.

Kennedy, E.R., Fishbach, T.J., Song, R., Eller, P.M. and Shulman, S.A., 1995, Guidelines for air sampling and analytical method development and evaluation. DHHS (NIOSH) Publication No. 95-117.

Kenny L.C., Aitken, R., Chalmers, C., Fabries, J-F., Gonzalez-Fernandez, E., Kromhout, H., Liden, G., Mark D., Riediger, G. and Prodi, V., 1997, Outcome of a collaborative European study of personal inhalable sampler performance. *Ann. Occup. Hyg.*, 41(2): 135-154.

Kenny, L., 2002, Improved dust sampling methods for mines: Final report. Health and Safety Laboratory Report, HSL/2000/06, UK.

Kenny, L., Baldwin, P.E.J. and Maynard, A.D., 1998, Respirable dust sampling at very high concentrations, HSL Confidential Report, IR/L/A/98/01.

Kenny, L.C., 2001, Improved dust sampling methods for mines. HSE Report, IR/A/98/05, UK.

Kissell, F.N. and Thimmons, E.D., 2001, Test report on the machine-mounted continuous respirable dust monitor. Proceedings of the 7th International Mine Ventilation Congress, Krakow, Poland, pp 253-260.

Kissell, F.N. and Sacks, H.K., 2002, Inaccuracy of area sampling for measuring the dust exposure of mining machine operations in coal mines. SME, USA.

Kissell, F.N., Ruggieri, S. and Jankowski, R.A., 1986, How to improve the accuracy of coal mine dust sampling. *American Industrial Hygiene Association Journal*, 47:602 - 606.

Koch, W., Dunkhorst, W. and Lodding, H., 1997, Respicon TM-3F: A new personal measuring system for size segregated dust measurements at workplaces. *Gefahrstoffe Reinhaltung der Luft*, 57: 177.

Koch, W., 1999.

Kogut, J., Tomb, T.F., Parobeck, A., Gero, J. and Suppers, K.L., 1997, Measurement precision with the coal mine dust personal sampler. *Applied Occupational Environmental Hygiene*, 12(12): 999–1006.

Kohler, J., 2002, Personal communications, NIOSH, USA.

Leidel, N.A., Busch, K.A. and Lynch, J.R., 1977, The inadequacy of general air (area) monitoring for measuring employee exposures. Technical Appendix C in: Occupational Exposure Sampling Strategy Manual, NIOSH Publication No. 77-173, pp 75-77.

Li, Lungdren and Rixx, 2000.

Liden, G. and Kenny, L.C., 1993, Optimization of the performance of existing respirable dust samplers. *Appl. Occup. Environ. Hyg.*, 8(4): 386-391.

Liden, G., 1993, Evaluation of the SKC personal respirable dust sampler cyclone. *Appl. Occup. Environ. Hyg.*, 8(3): 178-190.

Liden, G. and Gudmundsson, A. 1996, Optimisation of a cyclone to the 1993 International Sampling Convention for Respirable Dust. *Appl. Occup. Environ. Hyg.*, 11(12): 1398-1408.

Mark D. and Vincent, J.H., 1986, A new sampler for airborne total dust in workplaces. *Ann. Occup. Hyg.*, 30 (1):89-102.

Marple, V.A. and Rubow, K.L., 1984, Upgrading and evaluation of test chamber: Respirable dust measurement. BU Mines OFR No. 98-95, NTIS No. PB85-245843, pp 15-25.

MDHS 14/2, 1997, General Methods for Sampling and Gravimetric Analysis of Respirable and Total Inhalable Dust, HSE Books.

MSHA, 1992, Review of program to control respirable coal mine dust in the United States, US Department of Labor, Washington, DC, 60 pp.

MSHA, 1996, Report of the Secretary of Labor's Advising Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers. US Department of Labor, Washington, DC, 156 pp.

NIOSH, 1995, Criteria for a Recommended Standard Occupational Exposure to Respirable Coal Mine Dust. DHHS (NIOSH) Publication No. 95-106 CDC, US Department

of Health and Human Services (Education and Information Division), Cincinnati, OH, 336 pp.

NIOSH, 2001, Current research projects. Pittsburgh Research Laboratory, USA.

Page, S.J., Volkwein J.C., Baron P.A. and Deye G.J., 2000, Particulate penetration of porous foam as a low flow rate respirable dust size classifier. *Appl. Occup. & Environ. Hyg.*, 15(7): 561-568.

Patashnick, H. and Rupprecht, E.G., 1991, Continuous PM-10 measurements using the tapered element oscillating microbalance", *Journal of the Air and Waste Management Association*, 41(8).

Ramani R.V., Mutmansky, J.M., He, H., Volkwein J.C., Marple, V.A., Olson, B. and Luna, P., 2001, A comparative evaluation of the differential pressure-based dust detector with the personal gravimetric respirable dust sampler in underground coal mines. Paper presented at the 7th International Ventilation Symposium, Krakow, Poland, June.

Ramani, R.V., 1998, Independent laboratory evaluation of a pressure differential based respirable dust detector. Proposal submitted in response to RFP No.2000-98-8003(p) to Centers for Disease Control and Prevention, PRL-NIOSH, Pittsburgh, PA.

Ramani *et al.*, 2001,

Rowe, D., 2001, Personal Communications, DME, South Africa.

Rubow, K.L., Cantrell, B.K. and Marple, V.A., 1990, Measurement of coal dust and diesel exhaust aerosols. Proceedings of the VIIIth International Pneumoconiosis Conference, Pittsburgh, PA, pp 645-650.

Soderholm, 1991,

Tarkington, S.B., Rimmer, T.W., Keller, R.J. and Fowler, C.F., 1997, A comparison of two direct reading aerosol instruments to each other and various gravimetric samplers in several different aerosol environments. AIHA Abstract, USA.

Thompson, E.M, Treafis, H.N., Tomb, T.F, Beckert, A.J. and Gero, A.J., 19??, Laboratory evaluation of instantaneous reading dust monitors.

Unsted, D., 1996, Personal gravimetric dust sampling and risk assessment. Project GAP 046, SIMRAC Research Report, South Africa, 221 p.

Unsted, D., 1997a, Gravimetric dust sampling for control purposes and occupational dust sampling. Project GAP 326, SIMRAC Research Report, South Africa, 293 p.

Unsted, D., 1997b, Dust sampling for engineering control purposes. Project GEN 417, SIMRAC Research Report, South Africa, 47 p.

Unsted, D., 1997c, Respiratory hazard risk assessment methods. Project GEN 408, SIMRAC Research Report, South Africa, 293 p.

Volkwein, J.C., Schoeneman, A.L. and Page, S.J., 2000, Laboratory evaluation of pressure differential based respirable dust detector tube. *Appl. Occup. & Environ. Hyg.*, 15(1): 158-164.

Volkwein, J.C., Page, S.J., Baron, P.A. and Deye, G.J., 1997, Particulate penetration of porous foam as a low flow rate dust size classifier. Poster presentation at the 16th Annual Conference of AAAR, Denver, CO.

Volkwein, J.C., 2002, Personal Communications, PRL, NIOSH, USA.

Volkwein, J.C., Tuchman, D.P. and Vinson, R.P., 2002, Performance of a prototype personal dust monitor for coal mine use. Proceedings of 9th US Mine Ventilation Symposium, Canada, pp 632-639.