2018

Evaluation of Gravimetric Samplers and Proposal for the Use of a Harmonised Performance Based Dust Sampler for Exposure Assessment

Bharath Belle
Anglo American Coal, Australia

EVALUATION OF GRAVIMETRIC SAMPLERS AND PROPOSAL FOR THE USE OF A HARMONISED PERFORMANCE BASED DUST SAMPLER FOR EXPOSURE ASSESSMENT

Bharath Belle[1]

ABSTRACT: The period of the last three years brought about alarming news of re-identification of Coal Worker's Pneumoconiosis (CWP) or 'black lung" in Australia after reports nearly being absent for over five decades. In South Africa, the CWP statistics are unverifiable, but certainly they have not been eliminated. These events have re-kindled the need for better understanding of dust monitoring, performance of sampling devices and compliance determination. Over the last half century, gravimetric sampling has been the fundamental means for dust exposure monitoring using recognised respirable size-selective standards. In both South Africa and Australia, gravimetric sampling technique in coal mines has been followed since 1988 and 1983 respectively using samplers of original Higgins-Dewell (HD) type designs.

With an aspirational mine dust exposure limit of 1.5 mg/m^3 after the revision of US dust standard, it is equally important to understand the sampling tools used for exposure monitoring. This paper provides the evaluation results of currently used South African and Australian gravimetric samplers compared against the original UK SIMPEDS 'true reference' sampler. The results consistently suggested that the South African and Australian cyclones do not conform to the required BMRC or ISO 1995 curve. The results show that the currently used SA and Australian instruments showed a D_{50} sampling bias as high as 59% and 47% respectively against the size-selective curve. Similarly, when tested under the controlled laboratory coal dust test conditions, the measured levels by South African, Australian and UK standard SIMPEDS sampler were 8.4 mg/m^3, 9.8 m/m^3 and 6.7 mg/m^3 respectively, aligned with the sampling bias. The differences can in part be attributed to the 'un-auditable' inherent design and manufacturing quality, or unverifiable data on the size-selective sampling curve. This finding has significant implications towards exposure data collected over the last 25 years and their subsequent use in the arrival of the dose-response curves. Therefore, it is strongly recommended that the harmonised use of 'true reference' SIMPEDS cyclone that meets the ISO (1995) criteria uniformly across the industry would benefit the exposure assessment and compliance determination as practiced in the USA.

INTRODUCTION

Respirable dust sampling is pivotal in estimating the 'dose' of individual worker exposure to dust and in deriving quantitative respiratory disease risks in epidemiological studies. Based on the past epidemiological knowledge (Orenstein, 1960), it has been established that the respirable dust particle size distribution is critical due to its potential health effects and the need to quantify the risks. Respirable dust refers to particles that settle deep within the lungs and that are not ejected by exhaling, coughing, or expulsion by mucus. Since these particles are not collected with 100% efficiency by the lungs, respirable dust is defined in terms of size-selective sampling efficiency curves. This had led to internationally recognised respirable size-selective sampling (Orenstein, 1960) widely known as the British Medical Research Council (BMRC) definition of the respirable dust fraction or Johannesburg curve with a median aerodynamic diameter of 5 µm collected with a 50 % efficiency (D_{50}). In reality these size-selective curves represent lung penetration of dust particles that dust sampling instruments attempt to replicate. The International Standards Organization (ISO) in 1995 recommended that the definition of respirable dust follow the theoretical convention described

[1] *Bharath Belle, Anglo American Coal, Australia. Email: bharath.belle@angloamerican.com Tel: XXXXXXXXX*

by Soderholm (1989, 1991) with a D_{50} of 4 μm. An international collaboration (ACGIH, 1985, ACGIH 1999, ISO 1995, CEN, 1993) for sampling harmonisation has led to the agreement on the definitions of health-related aerosol fractions in the workplace, defined as the inhalable, thoracic and respirable curve. Figure 1 summarises the BMRC and ISO size-selective curves for dust sampling in mines (NIOSH, 1995; ISO1995). The new respirable size-selective curve is different from previous definitions used in the United States, South Africa, Australia and Europe and truly represents an international harmonization of the definition of respirable dust.

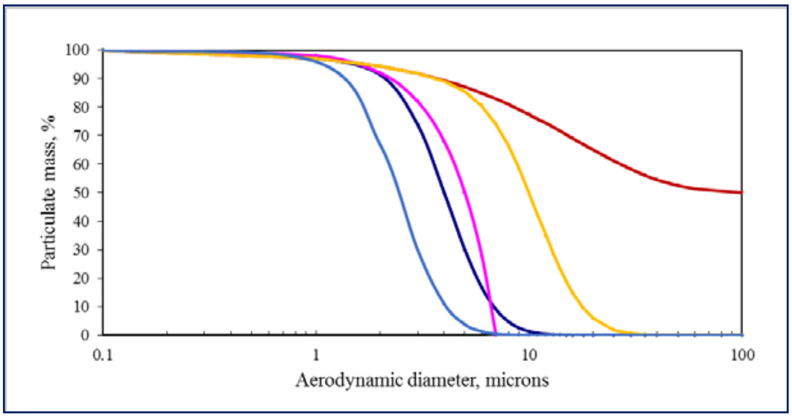

Figure 1: Respirable dust size-selective sampling curves.

Therefore, for any personal exposure monitoring, the chosen respirable dust sampling device should achieve the theoretical sampling definition criterion as closely as possible to minimize bias using the D_{50} performance criteria at the recommended flow rates. Due to the complex nature of sampler performance evaluations and their differences, regulatory bodies have dealt with this aspect by decreeing one specific sampling device, (i.e., MRE, Dorr-Oliver, HD), as the reference sampler of choice. What is important herein is whatever sampler is used for exposure measurement; they are to be referenced to epidemiological health effects data to derive any meaningful benefits.

Formerly, sampling conventions corresponded more to some device than to health related issues. E.g., BMRC respirable aerosol convention adopted in 1959 at the Johannesburg Pneumoconiosis Conference (Orenstein, 1960) fitted the efficiency of the MRE 113A horizontal elutriator. In addition, a dust sample collected by some sampler used in a country was declared to be “respirable aerosol fraction” and thus many “reference samplers” found in the literatures. With the ISO (1995) harmonisation curve resulted in the standardisation of health-related aerosol fractions independently from the samplers used but the standardised “size-selective specification” to be conformed by any compliance sampler. As a result, there were modifications and operation of the samplers required samplers to be tested in ideal conditions to yield their sampling efficiency curve and their performance expressed by bias maps. While there may be differing views on the choice of sampler to be used in the industry, the use of D_{50} as selection criteria is the only widely used and accepted criteria for dust sampler selection, in conjunction with the comparative laboratory concentration tests under controlled calm air conditions.

BASICS OF PERSONAL DUST SAMPLERS

The primary purpose of personal respirable dust sampling is to characterize (with regard to mass and size) the quality of the ambient air to evaluate a miner’s dust exposure. The mass of respirable dust inhaled can be determined by sampling. The measurement of dust in mines is usually carried out using various gravimetric sampling instruments. For personal coal mine dust sampling, the dust sampler or cyclone is normally mounted on the upper chest, close to the collarbone within the breathing zone (HSE, 2000). The breathing zone is the space around the worker's face from where the breath is taken, and is generally accepted to extend no more than 30 cm from the mouth. Gravimetric dust monitoring involves sampling a known volume of ambient air through a filter. The filter is weighed before and after exposure to determine the mass of particles. The collected dust sample is expressed as mass of dust (mg) per cubic meter (m^3) of air.

With acceptance of defined gravimetric based size-selective sampling, various types of dust samplers called 'cyclones' were developed and used in mines worldwide since the 1960s (NIOSH, 1995). Cyclones are named for the rotation of air within its chamber that separates and selects dust particles of interest from ambient airborne dust. The cyclone functions on the basis of a centrifugal force principle, i.e., the rapid circulation of sampled air separate particles according to their equivalent aerodynamic diameter.

In a cyclone, non-respirable particles are forced to the periphery of the airstream and collected in a grit pot, while the specified particles remain in the centre of the air stream and are deposited onto a pre-weighted filter medium. The size fractions sampled are very sensitive to the type of cyclone used and variations in flow rate. Various commercially available cyclones can approximate specified size-selective curves when operated at certain flow rate. Any minor deviation from the recommended flow rate would lead to differences in measured dust results. For example, a mere change in flow rate of HD type cyclone from 1.9 Lpm to 2.2 Lpm can result in differences of up to 20% in measured dust values (Kenny, Bristow and Ogden, 1996, Belle, 2004). Both South Africa and Australia have adopted the new size-selective curves with a change in sampler flow rates from 1.9 Lpm to 2.2 Lpm. Therefore, there is a need for amendment to the exposure limits to incorporate the measurement differences due to the change in sampling flow rates.

With the advent of the internationally accepted respirable size-selective curves, research studies have compared various dust samplers available for use in mines. What is obvious from the various studies (Liden and Kenny, 1991, Kenny and Gussman, 1997, Gudmundsson and Liden, 1998, Görner, *et al*., 2001) is that there are significant differences in measured dust levels from different samplers measuring the same aerosol. The reasons affecting the performance of these different dust samplers can be attributed to inherent cyclone design, air velocity, and direction of airflow, humidity, sampler inlet size, geometry, orientation, aerosol particle size, aerosol density differences, electrical charge, particle bounce properties, and conductive properties of cyclones. Globally, over the last 6 decades, various size-selective conventions have been used, as well as various types of personal gravimetric samplers being used by mines. Until recently (Feb 2016, in the USA, the Dorr-Oliver 10 mm nylon cyclone (Jacobsen and Lamonica, 1969, Lippman and Harris, 1962, Caplan. *et al.,* 1977) was the widely used sampler operated at 2.0 Lpm across the *entire* U.S. coal mining industry. On the other hand, most of the European countries (including UK) use the HD type cyclone (Higgins and Dewell, 1967; Harris and Maguire, 1968; Maguire et al., 1973; Gwatkin and Ogden, 1979; Ogden, *et al.,* 1983; Blackford et al., 1985, Gudmundsson and Liden, 1998). The latest real-time Continuous Personal Dust Monitor (CPDM), PDM3700 uses a HD cyclone operated at 2.2 Lpm and manufactured by MESA Laboratories (USA).

In a review of respirable dust samplers used in mines globally, it is noted that the UK HD plastic cyclone or also called as UK SIMPEDS (Safety in Mines Personal Equipment for Dust Sampling) is used as a reference sampler operating at a flow rate of 2.2 Lpm which has been characterized previously by Maynard and Kenny (1995). The SIMPEDS or Casella cyclone sampler of the generic HD type is recommended for use in the UK for optimal agreement with the respirable convention. Currently, these HD cyclones are referred to by commercial names such as Casella, SKC, BGI, MESA. For all cyclone performance evaluation purposes, HSE uses Casella SIMPEDS plastic sampler as a 'true reference' sampler. Some of these HD type cyclones are metal as well as plastic type. It is possible that different laboratories recommend different flow rates for the same cyclone.

Gudmundsson and Liden (1998) investigated various cyclone models in laboratory studies at a flow rate of 2.1 Lpm and observed that D_{50}, increased with increasing inner diameter of the vortex tube or surface properties of cyclone material. For example, what this would mean is that Supplier D HD cyclone vortex tube with an inner diameter of 3.12 mm would result in higher D_{50} of 5.32 microns than the Supplier A HD plastic cyclone vortex tube with an inner diameter of 3.02 mm D50 of 4.54 microns, a difference in D_{50} of 0.7 microns. The laboratory results and a study by Liden (1993) provide the explanation on the differences (of up to twice as large) increased measured dust concentrations by supplier D cyclones when compared with the Supplier A metal cyclones. It is certain that manufacturer modifications such as blacking, tapering of the vortex tube inlet, and gasket type do influence the cyclone penetration curves.

History of South African gravimetric samplers

The original Department of Mineral and Energy Affairs (DME) document (DME, 1988) titled "Guidelines for the Gravimetric Sampling of Respirable Airborne Dust Concentrations in Coal Mines" for risk assessment in terms of the occupational diseases in mines and works Act (1973) do not refer to specific dust sampler for use in South African mines. However, a note on the instrument acceptable as gravimetric samplers (Grabe, 1988) documents a few samplers and were required to meet the following criteria:

- The particle size distribution of the dust on the filter in the test instrument must comply with the 'Johannesburg Curve' for respirable dust, i.e., particle aerodynamic diameter of less than 7 microns.
- The coefficient of correlation must be 0.9 for the linear regression line against MRE 113A gravimetric dust sampler.
- The standard error of estimate must not exceed 10% of the mean sample mass.
- A calibration curve is required for deviations of approximately greater than 10 % from the reference curve.

However, the approved sampling cyclones suggested during the 1980s were SKC cyclone, Casella cyclone with relevant filters and sampling pumps to be operated at 1.9 Lpm. There has also been a reference to a Dorr-Oliver cyclone used in conjunction with Chamber of Mines South Africa (COMSA) inhalable dust sampler used in gold mines that were initially operated at 1.0 Lpm and then changed to be operated at 1.85 Lpm (Schroder, 1982) or rounded off to 1.9 Lpm to align with the UK SIMPEDS sampler. Another technical note (Lamprecht and Rowe, 1991), documents the use of Gilian GX-37 cyclone, GX-35 cyclone and the Gilian GX-R25 mm cyclone operated at 1.9 Lpm for use in South African mines. However, the evaluations were done merely on mass concentration comparison basis (< 5 % measured difference) and no information on size-selective curves was available.

Although, original gravimetric sampler lists included various traditional cyclone manufacturer trade name/s such as Casella and SKC, their use at mines disappeared from the exposure monitoring regime completely. Currently, in South Africa it is noted that almost all of the sampling is carried out using locally manufacturer "plastic type HD (Envirocon model GX1)" cyclone without any published knowledge of its size-selective performance as required by the original criteria (Grabe, 1988). The reason for the use of this particular cyclone head or the operating specifications such as flow rate of 1.9 or 2.2 Lpm could not be established. Interestingly, South Africa was the first country in the world to switch over to the new size-selective curve (Belle, 2004) and no amendments to the OEL to coal dust or silica dust has been made.

A French study (Gorner et al., 2001) of fifteen respirable aerosol samplers had studied the South African 25 mm cyclone had noted that the cyclones when operated at 1.9 lpm and 2.5 lpm flow rate, they conform to BMRC and ISO (1995) respirable curve with a D_{50} of 5.81 microns and 4.21 microns respectively. Despite the above there appears to no regulatory guidance on operating these South African manufactured cyclones used for exposure monitoring.

A HSE size selection characteristic study (Kenny, Baldwin and Maynand, 1998) noted that the locally manufactured South African cyclones were very similar in performance to the HD type cyclone. The HSE tests were carried out at 1.8 Lpm, 2.0 Lpm and 2.3 Lpm with a resulting D50 of 5.9 microns, 5 microns and 4.6 microns. There were no size-selective data for the SA cyclone that were readily available from the HSE (Kenny, 2016) to calculate the bias maps. However having without being tests carried out, HSE had recommended to operate the SA cyclone at flow rate of 2.2 Lpm and cyclones were being operated since 1997 (Belle and Du Plessis, 1998) to emulate ISO (1995) curve.

History of Australian gravimetric samplers

Since the adoption of gravimetric sampling in Australia in 1983, the plastic and aluminium HD cyclones have been used and operated at 1.9 Lpm. As per AS2985 (1987), Australian dust sampling followed the BMRC (Orenstein, 1960) with zero efficiency for particles of 7 microns. The AS2985 recommended dust sampling devices included the British Cast Iron Research Association (BCIRA), HD cyclones and SIMPED cyclones. However, AS2985 (2004, 2009) made amendments to the definition of the respirable dust aligned with the ISO (1995) definition and cyclones were recommended to be operated at 2.2 Lpm flow rate. Currently, further investigations have indicated that almost all of the sampling in some mining regions is carried out using a specific manufacturer, “plastic type HD” cyclone without any reference knowledge of its size-selective performance. The reason for the selection of this particular supplier of cyclones could not be established other than ease of its availability. In addition test evaluation reports about, conformity of the currently available SKC cyclone or Casella cyclone that are used in Australia are not readily available. Amendments to the OEL by switching over to the new size-selective curve have been made in NSW dust standards but not in QLD dust limits. The absence of publicly available original field evaluation data on switchover to the newly adopted curve has resulted in confusions over the validity of dust limits between the two states.

As a general observation, other than slight design modifications, currently available various cyclone particle elutriators are of the same design as that described by Higgins and Dewell (1966) used in the cyclone originally manufactured by the British Cast Iron Research Association. The South African, Australian and the UK SIMPEDS sampler are shown in Figure 2. The air inlet configuration of the SA cyclone sampler is different to the BGI, Casella and SKC cyclone samplers. It comprises a tangential slot entry rather than the tubular entry found on the other cyclones. The SA cyclone sampler is a sealed unit so the vortex finder is permanently attached to the cyclone elutriator.

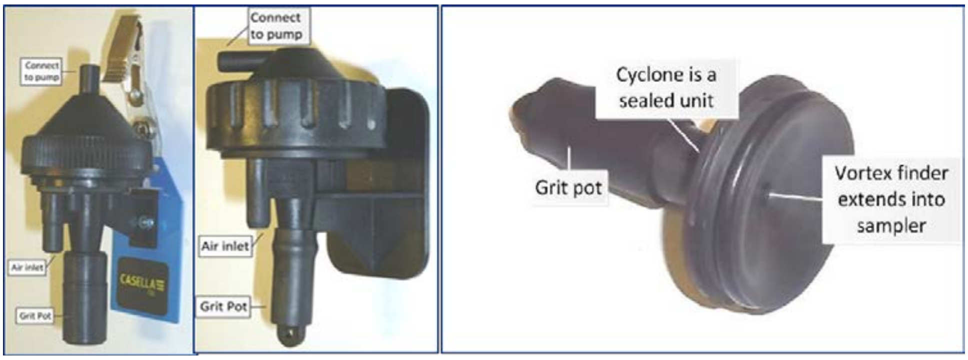

Figure 2: HD test samplers: SIMPEDS cyclone (Left); Australian cyclone (AS) (Middle) and South African cyclone (SA) (Right).

In the absence of the original HSE (2016) data on South African cyclone tests (1998), it was decided to contact and obtain the raw test results carried out on SA samplers in 1996-97 from the French laboratory (Gorner, 2017) that recommended the sampler to be operated at 2.5 Lpm. Figure 3 shows the penetration efficiency of the cyclones for different flow rates using the French cyclone size characterisation tests. From the fractional penetration efficiency and Bias map at 2.5 Lpm for the HD type sampler (25 mm), it is noted that at 1.9 Lpm the cyclone largely oversamples both the BMRC and and ISO1995 respirable aerosol fraction. The French study recommended that the SA cyclone be operated at 2.5 Lpm to satisfy the requirement of D50=4 µm. The French study data noted that the SA cyclone didn’t perform to Johannesburg curve at 1.9 Lpm nor the new ISO curve when operated at 2.2 Lpm. These conflicting French and UK studies necessitated the need for the review of penetration efficiency tests of South African cyclones for operations. In addition, the service providers or research laboratories both in Australia and South Africa could not demonstrate the exposure monitoring indeed meets the required ISO (1995) respirable dust sampling specifications.

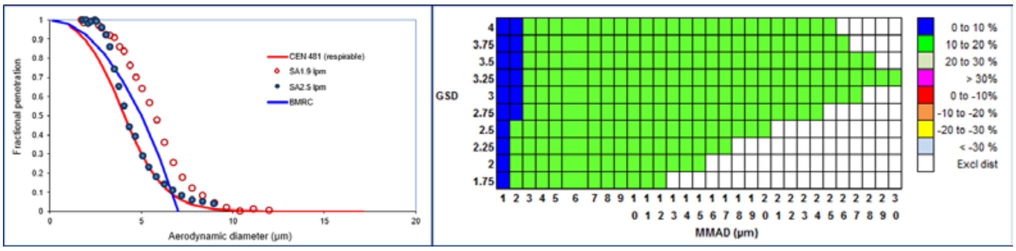

Figure 3: Fractional penetration of particles through South African gravimetric sampler and Bias map for 2.5Lpm flow rate (using 1996 French test data).

CYCLONE SAMPLING EFFICIENCY AND DUST CONCENTARTION TEST

The cyclone sampling efficiency and dust concentration tests are very complex and require sophisticated laboratory test chambers, which are scarce with a shortage of expertise on operational monitoring experience. Currently, there are very few such facilities available globally such as in UK, France, Sweden and USA. Therefore, in the absence of such quality facilities in Australia and South Africa, tests were carried out independently at the HSE (UK). Tests were carried out to determine the penetration characteristics of a total of nine plastic cyclone samplers, 3 South African cyclones, three used Australian cyclones from three different mines and three new Australian samplers and three UK SIMPEDS sampler (HSE, 2016). The HSE tests are standard cyclone sampling efficiency tests with a well-defined protocol that can be repetitive and reproducible for evaluation purposes. For all comparison purposes, the UK SIMPEDS Casella plastic cyclone is considered as a ‘true reference sampler’ by the HSE. This is based on the previously well-established research study by Maynard and Kenny (1995) and the evaluation standard set forth by the HSE -UK (2000)) to the mining industry. The design of the sampler test system is based on that described by Kenny and Liden (1991) used for the measurement of polydisperse aerosol penetration through cyclone samplers inside a calm air chamber and is not discussed here. The approach requires measurements of the aerodynamic size distribution of an aerosol penetrating through the cyclone sampler under test and that of the aerosol challenging it. The two size distributions are compared to obtain the penetration characteristics of the cyclone sampler. The experimental cyclone efficiency and dust concentration test set-up is shown in Figure 4. The laboratory confirmed that the cyclone flow rate before and after each test and was found to be within 2% of the target value of 2.2 Lpm.

Figure 4: Cyclone sampler testing (left) and dust concentration experimental test set up (Source, HSE, 2016).

DATA ANALYSIS AND CALCULATION OF SAMPLER BIAS FOR TEST AEROSOL

All the data associated with the evaluations in this study were obtained from the independently commissioned study at the HSE laboratories (UK). The reference SIMPEDS plastic cyclone and test cyclone sampler particle concentrations and particle size, and cyclone penetration was measured as a fraction of the reference aerosol. Using the measured size data, fractional penetration efficiency were plotted to determine the D_{50} from the fitted curves for each of the test and reference cyclones. The measured performance data for each cyclone sampler was assessed against the respirable target convention defined in BS EN 481(1993). For the evaluation purposes, the bias values were calculated for the respirable aerosol size distribution range of 1 µm to 30 µm Mass Median Aerodynamic Diameter (MMAD) with up to 30 µm with geometric standard deviation (GSD) range of 1.75 to 4.0 (step of 0.25) as specified using the bias map approach in BS EN 13205-2 (2014). Using the calculated bias values, a two- dimensional diagram (bias map) showing the GSD and MMAD on the axes, and points of equal bias joined to form contours are drawn. In this paper the average of all the repeat tests for each of the gravimetric samplers were calculated and bias maps are produced for the identical calm test chamber conditions for test cyclones. For any aerosol size distribution *A*, the bias in the sampled concentration is defined in Workplace exposure - Assessment of sampler performance for measurement of airborne particle concentrations (BS EN 13205-2:2014) as:

$$\Delta \boldsymbol{i} = \Delta \boldsymbol{i}\ (\boldsymbol{D_A}, \boldsymbol{\sigma_A}) = \frac{\boldsymbol{cC_i} - \boldsymbol{C_{std}}}{\boldsymbol{C_{std}}} \tag{1}$$

Where:

*C*std	is the concentration that would be sampled by a sampler that perfectly follows the sampling convention and is a function of the sampled aerosol size distribution, *A*;
c	is the correction factor stated either in the manufacturer's instructions for use or in the relevant measuring procedure; No other correction factor may be applied to the sampled concentrations. If no correction factor is stated, c is assigned a value of 1.00.
Ci	is the mean sampled relative concentration and is a function of the sampled aerosol size distribution, *A*;
*D*A	is the mass median aerodynamic diameter of the sampled aerosol, *A*;
Δi	is the bias or relative error in the aerosol concentration measured using the candidate sampler, for aerosol size distribution A, and
σA	is the Geometric Standard Deviation (GSD) of the sampled aerosol, *A*.

Similarly, for the sampler flow rate of 2.2 Lpm, the Fractional Mass Sampled (FMS) from an test aerosol with lognormal size distribution (aerodynamic mas median diameter, MMAD, and GSD, σg) will be a function of (Liden and Kenny, 1993) the size distribution parameters and the flow rate, Q, and is evaluated as an integral over all aerodynamic particle sizes, Dae,

$$\textbf{FMS}(\boldsymbol{MMAD}, \boldsymbol{\sigma_g}, \boldsymbol{Q}) = \boldsymbol{corr} \int_{\boldsymbol{0}}^{\infty} \boldsymbol{eff}(\boldsymbol{D_{ae}}, \boldsymbol{Q})\, \boldsymbol{f}(\boldsymbol{D_{ae}}, \boldsymbol{MMAD}, \boldsymbol{\sigma_g}) \boldsymbol{dD_{ae}} \tag{2}$$

Where:

eff (Dae, Q)	= the sampler efficiency curve, including measured or assumed aspiration losses.
f(Dae, $MMAD$,σg)	= the mass distribution density function of an aerosol with parameters MMAD and σg
corr	= a correction factor used to overcome sampler bias.

The sampler bias is then calculated (Liden and Kenny, 1993) for each aerosol size distribution selected, and each flow rate (in this study at 2.2 Lpm), by comparing the numerically modelled FMS values to what would have been obtained by an ideal sampler perfectly following a sampling convention,

$$\boldsymbol{bias}(\boldsymbol{MMAD}, \boldsymbol{\sigma_g}, \boldsymbol{Q}) = \boldsymbol{100}\, \frac{\boldsymbol{FMS_{SAMPLER}} - \boldsymbol{FMS_{IDEAL}}}{\boldsymbol{FMS_{IDEAL}}} \tag{3}$$

RESULTS AND DISCUSSION

Table 1 shows the measured particle size at which 50% of the particles penetrated for all test cyclones (D_{50}) for each test, along with the percentage deviation, Bias D_{50}, from the D_{50} given in EN 481/ISO 1995 (4µm). Figure 5 shows the average fractional penetration curve for the three South African, six Australian (3 used and 3 new) and three SIMPEDS gravimetric samplers operated at 2.2 Lpm flow rate. The plot also highlights the ISO (1995) respirable convention, defined in EN 481 (1993), for comparison.

Table 1: Summary statistics of measured D_{50} of SIMPEDS, Australian and South African samplers.

	Test-1		Test -2		Test-3		Average		SD	RSD
Gravimetric Sampler	D_{50}, µm	% Bias D_{50}	D_{50}, µm	% Bias D_{50}	D_{50}, µm	% Bias D_{50}	D_{50}, µm	% Bias D_{50}	µm	
SA1	5.51	37.75	5.36	34.00	5.33	33.25	5.40	35.00	0.096	1.79
SA2	5.87	46.75	5.68	42.00	5.82	45.50	5.79	44.75	0.098	1.70
SA3	4.62	15.50	4.68	17.00	4.61	15.25	4.64	15.92	0.038	0.82
AS1*	5.80	45.00	5.48	37.00	5.64	41.00	5.64	41.00	0.160	2.84
AS2*	6.13	53.25	6.36	59.00	6.10	52.50	6.20	54.92	0.142	2.30
AS3*	6.20	55.00	5.85	46.25	6.00	50.00	6.02	50.42	0.176	2.92
AS1**	5.70	42.50	5.42	35.50	5.42	35.50	5.51	37.83	0.162	2.93
AS2**	6.28	57.00	6.14	53.50	6.04	51.00	6.15	53.83	0.121	1.96
AS3**	5.67	41.75	5.65	41.25	5.71	42.75	5.68	41.92	0.031	0.54
SIMPEDS1	4.40	10.00	4.36	9.00	4.31	7.75	4.36	8.92	0.045	1.04
SIMPEDS2	4.39	9.75	4.33	8.25	4.28	7.00	4.33	8.33	0.055	1.27
SIMPEDS3	4.18	4.50	4.18	4.50	4.12	3.00	4.16	4.00	0.035	0.83

* Used Australian samplers from different mine sites; ** New Australian sampler

From Table 1, it is noted that the D_{50} value for South African, Australian and the SIMPEDS samplers were 5.28, 5.95 and 4.28 microns respectively. From the tabulated results, it can be clearly seen that cyclone samplers SA1 and SA2 exhibited a higher positive sampling bias (>35%) compared to the respirable convention (BS EN 481, 1993) for theoretical aerosols with mass median aerodynamic diameters 1– 30 µm and geometric standard deviations 1.75–4. They would therefore be expected to overestimate measurements of the respirable dust in the field. However, SA3 sampler exhibited unusually lower bias of <20%, but demonstrated significant variations between the other two in terms of sampling performance.

The reason for the higher D_{50} cut-point and high bias for SA1 and SA2 is not clear as the cyclone specifications are not readily available. Laboratory inspections concluded that there was an observed difference in the air inlet slot dimension for SA2, which appeared to be wider than SA1 and SA3 whose dimensions appeared similar. It was noticed that the SA1 sampler had been extensively used as there were signs of wear to the body. Whether these observations were the cause of the differences in sampling performance is speculative, but suggest a potential variation in manufacturing tolerance. On the other hand, the measured D50 of the Australian gravimetric sampler (both new and used) was up to 59% higher (AS2 in Test2) than the target value of 4 µm.

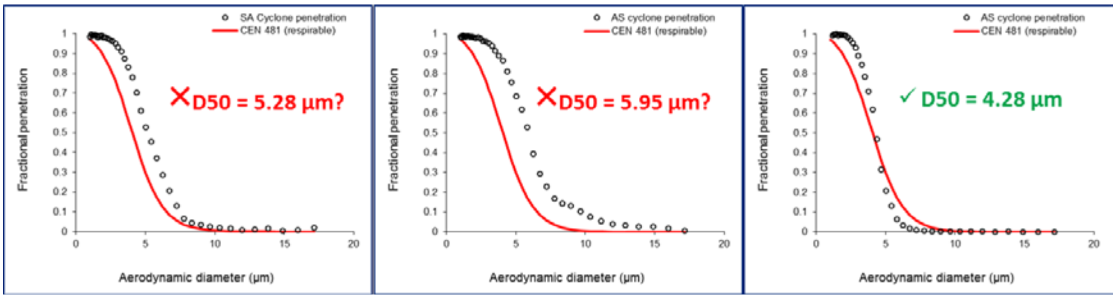

Figure 5: Fractional penetration average of particles through South African (left), Australian (middle) and UK SIMPEDS cyclone (Right) gravimetric samplers as a function of aerodynamic particle diameter (HSE, 2016).

From the Table 1 and Figure 5 it is noted that the measured D_{50} for the South African samplers was considerably higher than the target value of 4 µm (given in BE EN 481) i.e. between 33% and 47% higher, except for SA3 sampler with a D_{50} of 4.64 microns for 3 repeat tests. Similarly, measured D_{50} for the Australian (used and new) cyclones was considerably higher than the target value of 4 µm (given in EN 481), i.e. between 35% and 59% higher. In contrast, the measured D_{50} for the 'true reference' UK SIMPEDS plastic cyclone was much closer to the target value i.e. 3 – 10 % higher with an average D50 of 4.28 microns. It is also interesting to note that there are differences in individual Australian and South African cyclone samplers or larger scatter in terms of measured D_{50} values given by a higher coefficient of variation (RSD) in Table 1. Similarly, what is a critical finding from the penetration plots (Figure 5) is that both the South African and Australian sampler is that the tail of the penetration graphs also extends much further than the reference SIMPEDS UK 'true' cyclone samplers i.e. the penetration approaches zero at about 8 µm for the SIMPEDS and > 15 µm for the South African and Australian cyclones respectively.

Figure 6 shows the bias maps of gravimetric samplers (South Africa-Top); Australian Sampler (Middle) and SIMPEDS sampler (Bottom). Both the South African and Australian gravimetric samplers exhibited a high sampling bias, giving a positive bias often greater than 30% higher than the respirable convention (EN 481, 1993). They would therefore be expected to overestimate measurements of the respirable concentration of airborne dust in the workplace.

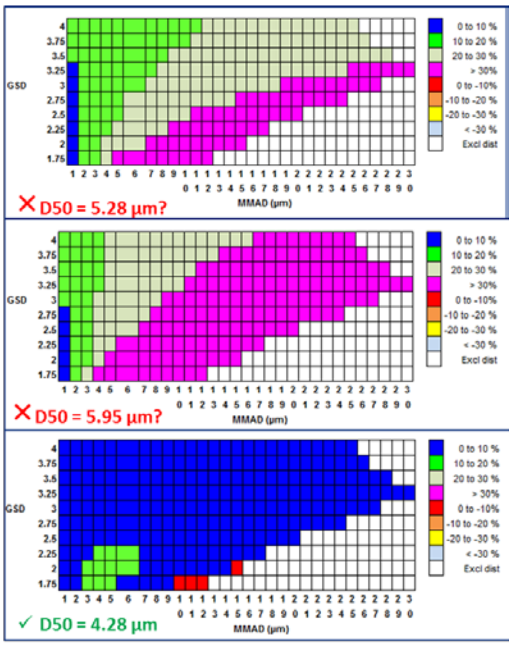

Figure 6: Bias map of gravimetric samplers (South Africa-Top); Australian Sampler (Middle) and SIMPEDS sampler (Bottom) for various dust

These independent laboratory results with higher D_{50} values and bias have reinforced the conclusions that the current South African and Australian gravimetric samplers significantly overestimated the measured respirable dust levels based on size analyses during field measurements (Belle, 2017). Regardless of the attributable reasons for the non-conformance to the ISO (1995) size-selective curve, both the current South African and Australian cyclones must be discontinued from use in their current design.

MEASURED CYCLONE DUST CONCENTRATIONS

Table 2 and Figure 7 show the dust levels measured by each gravimetric test sampler when exposed to an airborne coal dust cloud in the HSE laboratory test chamber. It can be seen that the samples of each SIMPEDS and Australian cyclone sampler gave consistent measurements of the dust concentration, given by a coefficient of variation (RSD) value of less than 5% between samplers for each repeat test. However, the SA cyclone showed a significant variation in performance between samplers illustrated by a RSD of 13.3%, 19.2% and 21.5% for each test. This supports the variation in D_{50} between the three SA cyclone samplers shown in Table 1. The ratio of SA cyclone sampler dust levels to average SIMPEDS cyclone sampler dust levels increased in the order SA3 (0.99), SA1 (1.13), SA2 (1.40). This is consistent with the increase in D_{50} values shown in Table 1 with only SA3 sampler closely matching the SIMPEDS sampler. The ratio of Australian cyclone dust measurement to SIMPEDS cyclone dust measurement is consistently around 1.41 - 1.53, i.e. the Australian cyclone sampler measured approximately 40 - 50% higher dust levels than the reference SIMPEDS cyclone sampler. This is consistent with the higher value of D_{50} measured previously for all three used and new Australian cyclones.

From the results it was noted that the measured dust levels of gravimetric samplers are significantly different when operated at the same sampler flow rates. The average measured dust levels for the SIMPEDS, South African and Australian samplers for the sampling period were 6.71 mg/m^3, 9.79 mg/m^3 and 7.87 mg/m^3 respectively. Using the linear regression of the data, it can be inferred that there is a positive ‘concentration measurement bias’ in respirable dust levels for Australian and South African samplers by 46% and 26 % respectively at the current coal dust compliance limit. The implication of this finding is significant where there exist an open-ended compliance determination process without specific and transparent guidance mechanisms for review.

Table 2: Summary of measured dust levels under controlled coal dust tests

Test#	**#1**				**#2**				**#3**			
Sampler	mg/m3	Avg	SD	RSD	mg/m3	Avg	SD	RSD	mg/m3	Avg	SD	RSD
SA1*	8.4				7.2				7.0			
SA2*	10.2	8.9	1.1	13.3	9.0	7.5	1.4	19.1	8.7	7.1	1.5	21.5
SA3*	8.03				6.2				5.7			
AS1**	10.7				9.0				9.0			
AS2**	11.5	10.9	0.5	4.6	9.7	9.2	0.4	4.6	9.6	9.2	0.39	4.25
AS3**	10.6				8.9				8.9			
RC1***	7.4				6.4				6.4			
RC2***	7.7	7.5	0.2	3.3	6.1	6.3	0.2	3.1	6.2	6.2	0.15	2.48
RC3***	7.3				6.5				6.1			

*South African HD sampler; ** Australian HD sampler

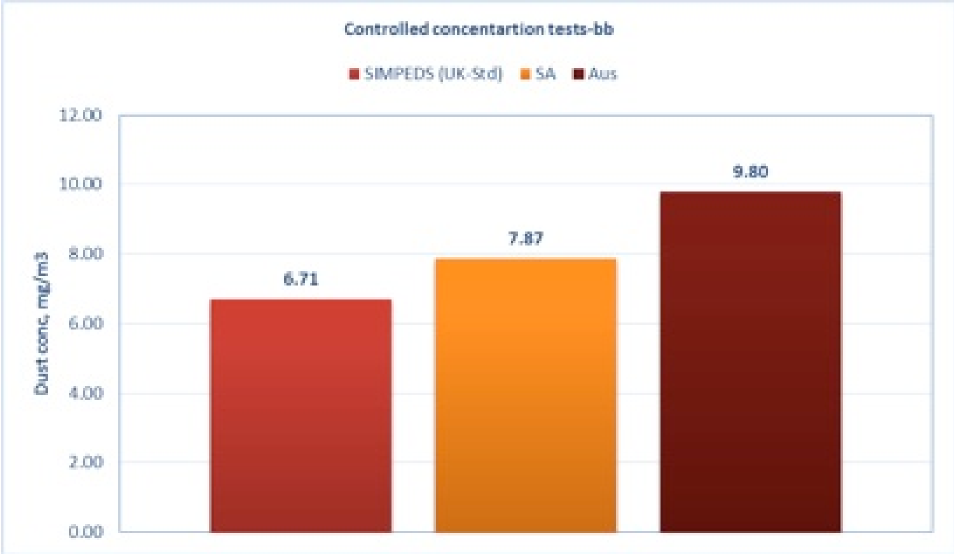

Figure 7: Measured average dust levels under controlled test conditions (HSE, 2016).

CONCLUSIONS

This paper summarises comparative cyclone penetration efficiency and dust concentration results evaluated under controlled conditions between the South African, Australian and the 'reference true' SIMPEDS UK reference sampler operated in accordance with the ISO (1995) size-selective curve at a flow rate of 2.2 Lpm. The following conclusions can be drawn from the sampler evaluations:

- An independent particle penetration efficiency results showed that the measured D50 for the 'true reference' UK SIMPEDS standard plastic cyclone was much closer to the target value i.e. 3 – 10 % higher with an average D50 of 4.28 microns.
- In contrast, particle penetration efficiency results showed that the D50 value for South African and the Australian samplers were 5.28, and 5.95 microns respectively. It can be clearly shown that the South African samplers exhibited a higher positive sampling bias, than the target value of 4 µm (given in BE EN 481, 1993) i.e. between 33% and 47% higher, except for SA3 sampler with a D50 of 4.64 microns for 3 tests. Similarly, measured D50 for the Australian (used and new) cyclone samplers was considerably higher than the target value of 4 µm, i.e. between 35% and 59% higher.
- Based on the particle size penetration plots, it is noted that in both the South African and Australian samplers is that the tail of the penetration graphs also extends much further than the reference SIMPEDS 'true' cyclone samplers i.e. the penetration approaches zero at about 8 µm for the SIMPEDS and > 15 µm for the South African and Australian cyclones respectively.
- Calculated average bias maps were prepared using the sampling efficiency data, it is noted that both the South African and Australian gravimetric samplers exhibited a high sampling bias, giving a positive bias often greater than 30% higher than the respirable convention. They would therefore be expected to overestimate measurements of the respirable dust levels in the workplace.
- An independent concentration measurement of dust aerosol showed that the average measured dust levels for the SIMPEDS, South African and Australian samplers for the sampling period were 6.71 mg/m3, 9.79 mg/m3 and 7.87 mg/m3 respectively. Using the linear regression of the data, it can be inferred that there is a 'concentration measurement bias' in respirable dust levels for Australian and South African samplers by 46% and 26 % respectively at the current coal dust compliance limit. The implications of this finding are significant where there exist an open-ended compliance determination process without specific and transparent guidance mechanisms for review.

In summary, independent laboratory data and their analyses with higher D_{50} values and bias have reinforced the conclusions that the current South African and Australian gravimetric sampler results significantly overestimated the measured respirable dust levels. It is acknowledged that the manufacturing challenges of sampler design variations, inlet geometry variations of samplers, sampler material type, and some discrepancies in evaluation methodology difficulties in particle-size dependent efficiency measurement are well understood by the aerosol professionals. However, they should not be the reason in over or underestimation of the personal exposure results and also cause significant non-compliance and loss of confidence in the exposure data that ultimately gets used in deriving dose-response relationships. This situation can be avoided by following the path of single SIMPEDS sampler in the South African and Australian industry as practiced in USA. The benefits of harmonised use of a single true standard sampler would enable greater understanding of exposure data derived worldwide or within the mining industry. Regardless of the attributable reasons for the non-conformance to the ISO (1995) size-selective curve, both the current South African and Australian cyclones must be discontinued for use in their current design. The study has demonstrated that it is critical to ensure the samplers used at the operations by the third party service providers or research laboratories for exposure monitoring indeed demonstrate and meet the ISO (1995) performance criteria and quality.

ACKNOWLEDGEMENTS

The author would like to thank all the reviewers for their constructive comments and encouraging remarks. Also, appreciates Mr. A. Thorpe, L Kenny of HSE who carried out the experimental work and the opportunities to witness the cyclone evaluations and technical exchanges on laboratory work. Hopefully the findings in this paper will assist in ensuring the selection and use of the samplers and more importantly, result in the implementation of the harmonised use of prescribed dust sampler for use in the global mining industry. This paper and the work contained herein is an effort to improve the exposure monitoring and improve engineering controls in workplaces.

REFERENCES

Australian Standard (AS 2985) 1987, *Workplace atmospheres-method for sampling and gravimyetric determination of respirable dust*, September 1987.

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

American Conference of Governmental Industrial Hygienists (ACGIH), 1994, *Threshold limit values for chemical substances and physical agents and biological exposure indices*, Cincinnati, OH, USA.

American Conference of Governmental Industrial Hygienists (ACGIH, 1999), *Particle size-selective sampling for particulate air contaminants*, 1999, J.H. Vincent, Ed. ACGIH, Cincinnati, OH, USA.

BMRC, 1952, British Medical Research Council Report, UK.

BS EN 481 (1993). *Workplace atmospheres: Size fraction definitions for measurement of airborne particles in the workplace*. Comité Européen de Normalisation (CEN) standard EN 481.

BS EN 13205-2 (2014). *Workplace exposure - Assessment of sampler performance for measurement of airborne particle concentrations*. Part 2: Laboratory performance test based on determination of sampling efficiency.

Bartley, D L, Chen, C C, Song, R and Fishbach, T J, 1994. *Respirable aerosols sampler performance testing*, Am. Ind. Hyg. Assoc. J. 55(11):1047-1050.

Blackford, D B, Harris, G W and Revell, G, 1985. *The reduction of dust losses within the cassette of the SIMPEDS personal dust sampler*, Ann. Occup. Hyg. 29(2):169-180.

Belle, B, 2004. *International harmonisation sampling curve (ISO/CEN/ACGIH): Background and its influence on dust measurement and exposure assessment in South African mining industry*, Journal of the Mine Ventilation Society of South Africa, April/June 2004, pp56-58.

Belle, B and Du Plessis, J J L, 1998. *Summary report on underground mechanical miner environmental control*, CSIR-Miningtek, SIMRAC, ESH 98-0249, South Africa.

Belle, B, 2017. *Pairwise evaluation of PDM3700 and traditional gravimetric sampler for personal dust exposure assessment*, Mine Ventilation Conference, Brisbane, 28-30 Aug 2017, Australia, AusIMM Publication Series No 4/2017,ISBN 978-1-925100-61-7.

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, CO.

Caplan, K J, Doemeny, L J and Sorensen, S D. 1977. *Performance characteristics of the 10 mm cyclone respirable mass sampler*, Am. Ind. Hyg. Assoc. J. 38(2):83-95.

Comite´ Europe´en de Normalisation (CEN), 1993, *Workplace atmospheres: size fraction definitions for measurement of airborne particles in the workplace,* European Standard EN 481:1993E, CEN, European Committee for Standardization, rue de Stassart 36, B-1050, Brussels, Belgium, 1993.

CSIRO, 2016, *Short semi-quantitative report on the composition of respirable coal dust*, Particle Analysis Service by Laurie Glossop, Australia, pp5.

DME, 1988. Department of Mineral and Energy Affairs (DME) document (1988) titled *"Guidelines for the Gravimteric Sampling of Respirable Airborne Dust Concentrations in Coal Mines"*, First Edition, GME 16/3/2/3/2, South Africa, pp16.

Grabe, F H, 1988. *Instruments acceptable as gravimeteric samplers*, AQS 96, AQS 2/17, COM Air Quality Research, South Africa, pp3.

Gwatkin, G and Ogden, T L. 1979. The SIMPEDS respirable dust sampler-side-by-side comparison with the 113A, Colliery Guardian, June.

Gorner, P, Wrobel, R, Micka, V, Skoda, V, Denis, J and Fabries, J, 2001. *Study of fifteen respirable aerosol samplers used in occupational hygiene,* Ann. occup. Hyg. Vol. 45, No. 1, pp. 43–54.

Gorner, P, 2017. Personal Communications, France.

Gudmundsson, A and Lidén, G, 1998. *Determination of cyclone model variability using a time-of-flight instrument,* Aerosol Science and Technology, 28:3, 197-214.

HSE (2000). MDHS 14/3 General methods for sampling and gravimetric analysis of respirable and inhalable dust, Methods for the determination of hazard substances. HSE Books, London.

Kenny L C, Liden G, 1991. *A technique for assessing size selective dust samplers using the APS and polydisperse test aerosols.* Journal of Aerosol Science. 22, 91-100.

Maynard A D and Kenny L C, 1995. *Performance assessment of three personal cyclone models, using an Aerodynamic Particle Sizer*. J. Aerosol Sci, Vol 26, No 4, pp 671-684.

HSE, 2016, Testing the performance of personal cyclone samplers, CBRU/2016/093, Internal Confidential Report (Thorpe, A), UK. pp 29.

Harris, G W and Maguire, B A, 1968. *A gravimetric dust sampling instrument (SIMPEDS): Preliminary results,* Ann. Occup. Hyg.11:195-201.

Higgins R J, Dewell P 'A gravimetric size selecting personal dust sampler' The British Cast Iron Research Association Inhaled particles II 1967 575–586 ed C N Davies CN.

Higgins, R I and Dewell, P, 1967. A Gravimteric Size-Selecting Personal Sampler, In: Inhaled Particles and Vapours II, Ed. C.N. Davies, Pergamon Press. p575.

International Standards Organization (ISO), 1995. Air quality: particle size fraction definitions for health-related sampling. Geneva, Switzerland: International Organization for Standardization. ISO 7708:1995, Geneva.

Jacobsen M., Lamonica, J A, 1969. *Personal respirable dust sampler*, Washington, D.C, U.S Department of the Interior, Bureau of Mines, IC8458.

Kenny, L, Bristow, S, Ogden, T, 1996. *Strategy and timetable for the adoption of the CEN/ISO sampling conventions in the UK*, AIHCE.

Kenny, L, Baldwin, P E J and Maynard, A D. 1998. Respirable dust sampling at very high concentrations, UK.

Kenny L C, Gussman R A, 1997. *Characterization and modelling of a family of cyclone aerosol pre-separators*. Journal of Aerosol Science; 28: 677-688.

Kenny L C, Liden G, 1991. *A technique for assessing size selective dust samplers using the APS and polydisperse test aerosols.* Journal of Aerosol Science. 22, 91-100.

Kenny, L, 2016, Personal Communications, UK.

Lidén G, Kenny L C, 1991. *Comparison of measured respirable dust sampler penetration curves with sampling conventions*. Annals of Occupational Hygiene; 35: 485-504.

Lippmann, M, Harris, W B, 1962. *Size-selective sampler for estimating respirable dust concentrations*, Health Physics, Vol.8, pp155-163.

Lamprecht, A and Rowe, D. 1991. Note on the evaluation and approval of gravimetric sampling instruments: Gilian GX-37 cyclone, Gilian GX-25 cyclone and the Gilian GX-R25

mm cyclone versus the GME Reference instrument MRE 113A, GME 16/3/2/8, South Africa, pp15.
Maguire, B A, Barker, D and Wake, D, 1973. Size-selection characteristic of the cyclone used in the SIMPEDS 70 MK2 Gravimetric Dust Sampler, Staub 33(3):95-98.
Maguire, B A, Barker, D and Badel, D A, 1971. *SIMPEDS 70: An improved version of the SIMPEDS personal gravimetric sampling instrument*, Inhaled Particles III, Ed. W.H. Walton, Unwin. Old Woking, 1053-1056.
Mace, G, Goodwin, G and Shepherd, M, 2005. Coal Services Health and Safety Trust Project No. 20083 Final Report, Australia.
Maynard A D and Kenny L C, 1995. *Performance assessment of three personal cyclone models, using an Aerodynamic Particle Sizer*. J. Aerosol Sci, Vol 26, No 4, pp671-684.
NIOSH 1995, Criteria for a Recommended Standard: Occupational Exposure to Respirable Coal Mine Dust, DHHS (NIOSH) Publication Number 95-106.
Orenstein, A J, 1960. Proceedings of the 1959 Pneumoconiosis Conference, Johannesburg. Churchill, London, UK.
Ogden, T L, Barker, D and Clayton, M P 1983. Flow-dependence of the Casella Respirable-Dust Cyclone, Ann. Occup. Hyg. 27: 261-271.
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, Vol. 41, No.8.
Schroder, H H E, 1982. A note on dust measurements in coal mines, South Africa, pp8.
Soderholm, S C, 1989. Proposed International Conventions for Particle Size -Selective Sampling, Ann. Occupational Hygiene, Vol. 33, No. 3, pp301-320.
Soderholm, S C, 1991. *Why change ACGIH's definition of respirable dust*, Appl. Occup. Environ. Hyg. 6 (4), pp248-250.