An Underground Evaluation of BGI Steel Cyclone and Higgins-Dewell Cowl Type Gravimetric Samplers

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ABSTRACT

After initial studies by the CSIR indicating that a discrepancy exists in the dust concentration results between gravimetric dust samplers, alternative instruments or methods were sought. In the study that followed, it was recommended by the HSL in the UK that a cowl arrangement, together with a sampling rate equivalent to the CEN/ISO standard, be used to minimize over sampling. As such the CEN/ISO recommended sampling rate of 2.2 L/min was used for the first time in South African mines. A BGI-stainless steel cyclone sampler and a Higgins-Dewell type South African cyclone sampler with a round-steel-cowl arrangement were used in the study. Although extensive work has been carried out on the use of cyclones, most of the previous studies were carried out in the laboratory, which have an advantage over the extremely difficult evaluation conditions in underground coalmines. This paper describes the field results from the two gravimetric samplers tested in an underground bord and pillar CM section.

A BGI-stainless steel sampler, and a Higgins-Dewell type sampler with a round-steel-cowl arrangement were used in the study. Although the samplers differ according to their design, cost, and ease of use, hypothesis test results demonstrated no significant difference (95 % level) in the relative measured mean concentration values. A comparison of the individual regression lines derived from various sampling locations (intake, operator and return) show that, on average, the cowl sampler under-samples by approximately seven percent. This under-sampling appears to occur for samplers located at the operator's position and in the section return. Therefore, it could be concluded from these regression lines that adding the cowl to the sampler biases the measurement by about seven percent.

KEYWORDS

HIGGINS-DEWELL, CYCLONES, COAL MINE, DUST CONCENTRATION, SAMPLING, MEASUREMENT.

INTRODUCTION

Studies in the USA and Europe resulted in a new particle size-selective criteria for the measurement of dusts in the workplace. These criteria have been agreed upon by both the International Standards Organization (ISO, 1991) and the Comite European de Normalization (CEN, 1991). Several studies evaluating the performance of the samplers were carried out in the laboratories.

Due to the dynamic nature of mining and its ambient conditions, the behavior of particles and their generation are not clearly understood. It is not known yet whether the size distribution of particles is uniform throughout the mining operation. From the sampling point of view, it is well-observed phenomenon that some of the respirable dust particles deposit on the inner walls of samplers. This phenomenon is unavoidable and persisted during most of the sample measurements underground. Therefore, it can be speculated that the sample concentration results obtained are an underestimation of the mass concentration a worker is exposed to dust while underground.

Field experience of dust measurement in South African coal mines have suggested that when they are used in very high dust concentrations, samplers for respirable dust such as cyclones can become overloaded. A study was carried out at HSL in UK to modify the South African cyclones to reduce the concentrations of large particles entering the cyclone and hence to eliminate the potential for overloading. To provide a practicable means to avoid this problem, a round-steel cowl was fitted over the entire cyclone. Measurement of the size selection characteristics of the South African cyclones tested in UK has confirmed that they are similar to the Higgins-Dewell designs commonly used in UK and elsewhere in Europe (Kenny et al., 1998).

In South Africa, fears were expressed that the additional steel shield surrounding the cyclone would inevitably result in lower dust concentrations. Further studies were done in the USA to evaluate the use of cowls on personal samplers to help reduce bias when sampling in high velocity air streams and due to sampler inlet orientation (Cecela, 1983). Informal opinions from world experts in the area have suggested that the use of a cowl should not influence cyclone performance at high dust concentration levels (Oberholzer et al., 1998).

Most of the cyclone tests are carried out during laboratory tests in steady state air conditions, unlike the turbulent air conditions underground. Establishing the presence of non-respirable particles carried over onto the filter requires the ability to count and analyze the collected sample, which is a cumbersome and expensive process. Therefore, an evaluation of two identified samplers based entirely on their mass concentrations of respirable sample dust is presented in this paper. The drawback of determining sample performance by this method is that it does not provide an estimation of cyclone or penetration efficiencies.

TEST SAMPLERS

For all test purposes BGI stainless steel cyclone (BGI Inc., USA) and South African Department of Minerals and Energy (DME) approved cyclones (Higgins-Dewell type) were used. The BGI stainless steel cyclone used in the tests is of all metal construction (Figure 1). The BGI cyclone is a Higgins-Deweell type as designated in NIOSH method 0600, 4th edition. The cyclone body is fabricated from stainless steel. The dust cup (grit pot) is fabricated from aluminum and is threaded to the cyclone body with an "O" ring seal. Filtration is accomplished with a 37 mm disposable cassette, which is pressed on over an "O" ring seal. This instrument has a recommended flow rate of 2.2 L/min to match the new respirable curve with a 50 per cent cut-off point of 4 µm and is not sensitive to charge effects (Bartley et al., 1994).

Figure 1. Pictorial view of Cowl sampler (left), BGI sampler (right) and Real-Time Dust Monitor (centre)

The locally manufactured and DME approved cyclone (GME–G05, 10 mm cyclone), was fitted with an additional round steel shield, which attaches itself surrounding the cyclone and hereafter referred to as "cowl sampler or C_{COWL}" and is shown in Figure 1. The steel cowl surrounds the entire unit, and is the same length as the cyclone. The cowl operates as a vertical elutriator, preventing larger particles from entering the cyclone as a result of sedimentation within the cowl. The cowl has the additional benefit of protecting the cyclone inlet slit from strong external winds, which are known to affect the sampling characteristics of an open slit entry.

In South African underground mines, dust samplers are currently being operated at 1.9 L/min, in agreement with the BMRC respirable convention (BMRC, 1952). However, Maynand and Kenny (1995) have suggested that sampling at 2.2 L/min will lead to better agreement with the new ISO/CEN/ACGIH respirable dust curve. Therefore, for the first time in South Africa, the BGI stainless steel sampler and cowl samplers were tested at the proposed flow rate of 2.2 L/min.

DESCRIPTION OF EXPERIMENTS

Tests were conducted in a bord-and-pillar continuous miner (CM) production section. Figure 2 shows the typical deployment of the dust-monitoring instruments in the test section. The samplers were positioned in the section intake, in the operator's cabin and in the section return airway.

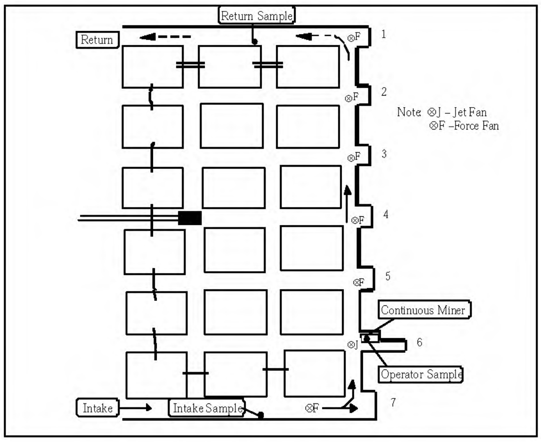

Figure 2. Layout of the test section

The dust-monitoring set-up contained two gravimetric samplers, viz., a BGI sampler and a cowl sampler. The gravimetric samplers consist of an air pump, which draws 2.2 L/min of air through a mini-cyclone, which in turn selectively collects the fraction of airborne respirable dust less than 10 µm particles on a pre-weighed filter disc. Filters from the samplers were weighed on an analytical electronic balance with readable 0.0001 mg. The procedure for determining the particulate mass was followed as per the DME guidelines (DME, 1997). The dust samplers were kept together in the same position to minimize the possibility of spatial variations in the aerosol concentrations. Well-maintained pumps were used to avoid the effect of pump pulsations and fluctuations in the flow rate, as shown by Berry (1990).

DATA ANALYSIS

The dust concentrations presented throughout this paper reflect gravimetric dust measurements taken over a specific sampling period for both the samplers. The gravimetric concentration was calculated using the mass of the dust collected over the duration and flow rate. Using the mass of dust collected on the filters, the sample dust concentration (SC) in mg/m^3 is obtained as follows:

$$SC = \frac{(C_f - C_i)}{(Fl \times T)} \qquad (1)$$

where:

C_i = initial filter mass in mg
C_f = final filter mass in mg
Fl = sample flow rate in m^3/min
T = sampling time in min

RESULTS AND DISCUSSIONS

Sampling Results

Table 1 shows a summary statistic of respirable dust concentration levels obtained by the BGI sampler and cowl sampler at different positions. The relationship between the concentration values obtained at the section intake, CM operator's position and section return, from the BGI and cowl sampler, during the underground tests, is shown in Figure 3. The correlation coefficient (r) between the BGI sampler and the cowl sampler is 0.975. The relationship between the concentration values obtained from the two samplers at section intake, CM operator and section return positions are shown in Figures 4, 5, and 6 respectively. The correlation coefficient (r) at the intake, operator and return position is 0.987, 0.952, and 0.993, respectively.

Table 1. Summary statistic of dust concentrations

	Section Intake		CM Operator		Section Return		Overall	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}
Mean	0.505	0.514	3.882	3.494	1.502	1.492	1.955	1.826
Variance	0.127	0.125	7.026	6.996	3.510	3.128	5.509	4.901
Median	0.414	0.440	3.026	2.852	1.152	1.169	1.157	1.197
Minimum	0.101	0.113	1.001	0.932	0.377	0.365	0.101	0.113
Maximum	1.679	1.788	13.62	15.88	12.75	12.07	13.62	15.88
Size	43	43	42	42	41	41	126	126

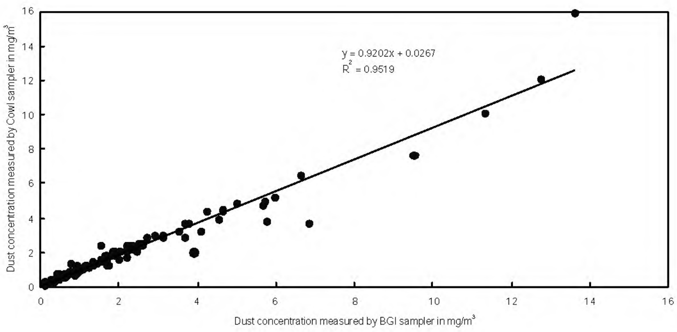

Figure 3. Plot of the dust concentrations obtained from BGI and Cowl sampler

Statistical Analysis

An analysis of frequency distribution of the concentration values obtained by the samplers yielded in 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 lead to the conclusion on the hypothesis that the measurements were log$_e$-normally distributed. The improved fit of the normal distribution to the log$_e$-transformation of the concentration data was obvious.

A paired t-test was performed on the set of all the sample pair data to determine if 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 level measured with two sampling instruments (μ_{BGI} and μ_{COWL}). A paired t-test analysis procedure would probably have a smaller error term than the corresponding unpaired procedure because it removes variability that is due to differences between the pairs.

The null and alternative hypothesis for the tested sample pairs were: H_0: $\mu_{BGI} = \mu_{Cowl}$ and H_1: $\mu_{BGI} \neq \mu_{Cowl}$

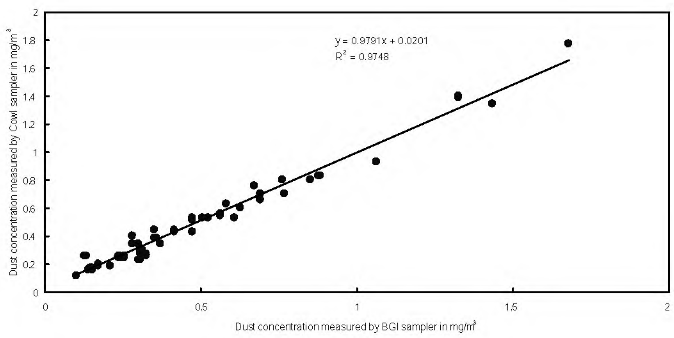

Figure 4. Relationship between BGI and Cowl results at the section intake

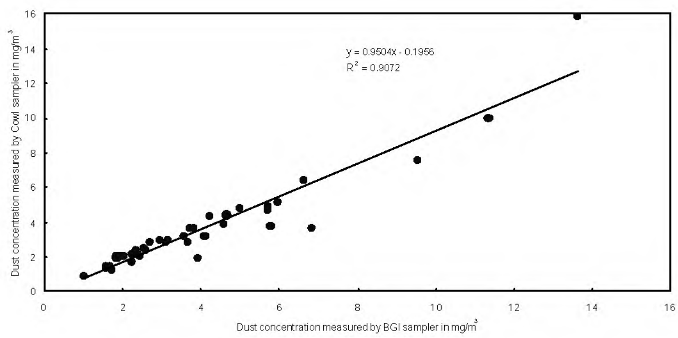

Figure 5. Relationship between BGI and cowl results at the operator

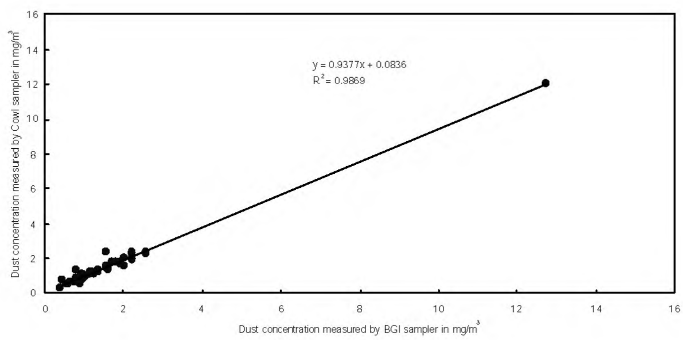

Figure 6. Relationship between BGI and Cowl results at the section return

In the paired *t*-test, hypothesis H_0 states that the mean dust concentration levels from both samples (μ_{BGI} and μ_{COWL}) are equal. On the other hand, 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 hypothesis stated were $\mu_{BGI} = \mu_{Cowl}$ and $\mu_{BGI} \neq \mu_{COWL}$, all analyses were two tailed to account for both conditions $\mu_{BGI} < \mu_{COWL}$ and $\mu_{BGI} > \mu_{COWL}$. Therefore, the critical *t*-values were determined by $t_{0.025}$ rather than $t_{0.05}$. Hypothesis tests were carried out at each of the locations as the sampling environment varies in terms of air velocity, dust concentration and fixed-point (intake position and return position) or moving (operator cabin) samplers. Results of the paired *t*-test statistical analyses are given in Table 2.

Table 2. Results of paired *t*-test hypothesis (on transformed values)

Statistics	Section Intake		CM Operator		Section Return	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}
Mean	-0.907	-0.865	1.178	1.070	0.167	0.173
Variance	0.469	0.411	0.342	0.329	0.337	0.323
Size	42	42	41	41	40	40
***t*- statistic**	-1.717		4.125		-0.268	
Critical – *t*	$-2.018 < t < 2.018$		$-2.019 < t < 2.019$		$-2.02 < t < 2.02$	
P – value	0.093		0.0001		0.789	
Hypothesis	Accept H_0		Reject H_0		Accept H_0	

P (probability) - values are often used in hypothesis tests, where one either rejects or fail to reject a null hypothesis. The p -value represents the probability of making a Type 1 error, which is rejecting the null hypothesis when it is true. The smaller the p-value, the smaller is the probability that one would be making a mistake by rejecting the null hypothesis. In this study a cut-off p-value of 0.05 was used (95 % confidence level). From the analysis table, we observe that 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 cyclones are not affected at 95 % level of confidence. Further, the confidence interval for the difference between the pairs of cyclones include zero, which suggests that there is no difference between the measured mean concentration levels between various sampler pairs.

From Table 2, we observe that, at the operator position, *t*-statistic C_{BGI}-C_{COWL} was 4.125. This indicates that mean dust concentration level from the BGI sampler (C_{BGI}) was generally greater than the mean dust concentration level from the cowl sampler (C_{COWL}) and the null hypothesis is rejected (small p-value). This does not hold true for the intake and return sample position, where the concentration value obtained by the BGI sampler was less than by the cowl sampler.

Table 3. Results of F-test hypothesis (on transformed values)

Statistics	Section Intake		CM Operator		Section Return	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}
Mean	-0.907	-0.865	1.178	1.070	0.167	0.173
Variance (S^2)	0.469	0.411	0.342	0.329	0.337	0.323
Size	42	42	41	41	40	40
***F*- statistic**	1.142		1.038		1.044	
Critical *F* value	$0.592<F<1.685$		$0.592<F<1.687$		$0.591<F<1.690$	
P - value	0.333		0.452		0.446	
Hypothesis	Accept H_0		Accept H_0		Accept H_0	

A paired t-test was performed on all the data to determine if there was a statistical difference in the results obtained between two samplers at all locations. The result of the paired t-test was a test statistic with 125 degrees of freedom, p = 0.216 indicating no difference between measured mean concentration levels using BGI and cowl samplers.

Having known from test of hypothesis that there is no difference between means, we would be interested to know if there is any significant difference between sampler variances. Therefore, F-test statistics was calculated to determine if there was a statistical difference in the variance obtained between two samplers. A test of hypotheses was carried out to determine the difference in the variances of measured concentration levels between sampler pairs.

Test of hypothesis was developed to compare the sample variance measured with two sampling instruments (σ_{BGI} and σ_{COWL}). The null and alternative hypothesis for the tests for the various sampler pairs were:

H_0: $\sigma_{BGI} = \sigma_{COWL}$, any observed variability due to chance
H_1: $\sigma_{BGI} \neq \sigma_{COWL}$, there are some variability

In the above F-test, hypothesis H_0 states that the sample variances from both samples (σ_{BGI} and σ_{COWL}) are equal. On the other hand, alternative hypothesis states that there is some difference in sample variances between two samplers. Hypothesis stated were $\sigma_{BGI} = \sigma_{COWL}$ and $\sigma_{BGI} \neq \sigma_{COWL}$, all analyses were two tailed (95 % confidence level) to account for both conditions $\sigma_{BGI} < \sigma_{COWL}$ and $\sigma_{BGI} > \sigma_{COWL}$. Hypothesis tests were carried out for sampler pairs, and the results of the *F*-test statistical analyses are given in Table 3.

From the Table 3, we observe that all hypothesis test pairs, H_0 were accepted. At the operator position, the number of degrees of freedom associated with the numerator $\gamma_{Cowl} = 41$; and for the denominator $\gamma_{BGI} = 41$. At the 0.05 level for the 41 degrees of freedom, two-tailed test, it would be accepted that H_0 as the F-value (1.038) was within the critical F-value range ($0.592 < F < 1.687$). Therefore, hypothesis H_0 was accepted. In other words, dust readings measured by the two samplers are not affected at the 95 % level of confidence.

CONCLUSIONS

One of the South African mining industry's goals is to establish a standard measurement procedure using sampling instruments with minimal resources without compromising the health of mine workers. In an underground environment, the ideal sampler would collect the sample that represents the mine-ambient aerosol. In this study, the cyclone efficiencies of BGI and cowl samplers were not evaluated, as a particle size analyzer is needed to determine the size fraction characteristics of both the ambient and the sample dust. Due to the harsh conditions existing underground, the effect of sampler performance at the operator's position due to wind effects (wind speed and wind direction) was not determined.

Although the two evaluated dust samplers differ according to their design, cost, and ease of use, the hypothesis tests results of section data demonstrate no significant difference (95 % level) in the relative mean concentration values measured in the section. However, at the operator position, mean dust concentration level from the BGI sampler (C_{BGI}) was generally greater than the mean dust concentration level from the cowl sampler (C_{COWL}). This does not hold true for the intake and return sample positions, where the concentration value obtained by the BGI sampler was less than by the cowl sampler.

A comparison of the individual regression lines derived from data from the different respective location shows that, on average, the cowl sampler under-samples by approximately seven percent. This under-sampling appears to occur for samplers located at the operator's position and in the section return. Therefore, it could be concluded from these regression lines that adding the cowl to the sampler biases the measurement by just about seven percent.

This paper recommends detailed studies on the size consist of the samples collected by the BGI stainless steel sampler and cowl samplers. The study further suggests use of very compact cascade impactors to simultaneously calculate respirable dust concentrations as well as to measure size distribution of ambient air underground. It is hoped that future underground studies comparing the various pairs of Higgins-Dewell cyclones sampled with or without a shield placing side by side underground may clarify questions arising from this study.

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