
A Field Evaluation of the BGI and Cowl Type Gravimetric Samplers

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Summary

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 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 sampler with a cowl arrangement were used in the study. Implementation of the recommended changes to samplers and the flow rate will interrupt the continuity of monitoring data built up over the years, but they will raise South African dust measurements to international standards. 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 conditions in underground coal mines. This paper describes the field results from the two gravimetric samplers tested underground.

Introduction

Studies in the U.S.A. and Europe resulted in 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) and the Comité European de Normalization (CEN)[1,2]. Several studies evaluating the performance of the samplers were carried out in the laboratory to determine the size characteristics of the sample dust collected by the cyclone, as determining the ambient size distribution of the face-dust underground is a cumbersome and time-consuming process. Size distribution of the sampled dust is one of the major parameters in determining sampler performance efficiencies.

Due to the dynamic nature of mining and its ambient conditions, the behaviour 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 to which a worker is exposed 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 over-loaded. A study was carried out at GSL in the 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 large 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[3].

In South Africa, fears were expressed that the additional shield surrounding the cyclone would inevitably result in lower dust concentrations. In a study conducted by Kenny[3] at the HSE laboratory (UK), it was shown that cowl samplers performed similarly to the Higgins-Dewell type samplers. 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 resulting from sampler inlet orientation[4]. Informal opinions from world experts in the area have suggested that the use of a cowl should not influence cyclone performance at high dust concentrations[5].

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 carry over onto the filter requires the ability to count and analyze the collected sample, which is a cumbersome process. Therefore, in this paper, an evaluation of two samplers based entirely on their mass concentrations of respirable sample dust, is presented. The drawback of determining sample performance by this method is that it does not provide an estimation of cyclone or penetration efficienceis.

Test Samplers

For all test purposes BGI stainless steel cyclone and South African Department of Minerals and Energy (DME) approved cyclones were used. The BGI stainless steel cyclone used in the tests is of all metal construction (Figure 1). The cyclone body is fabricated from stainless steel. The dust cup (grit pot) is fabricated from aluminium and is threaded to the cyclone body with an "O" ring seal. Filtration is accomplished with a 37mm 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 4 μm, 50 % cut -off, and is not sensitive to charge effects.[6]

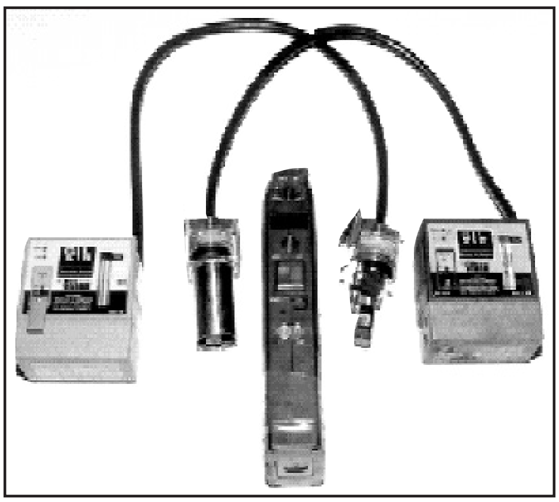

Figure 1. *Pictorial view of Cowl sampler (left), BGI sampler (right) and Real-Time Dust Monitor (Centre)*

The locally manufactured and DME approved cyclone (GME-G05, 10 mm cyclones), was fitted with an additional round steel shield, which attaches itself surrounding the cyclone and hereafter referred to a "cowl sampler or C cowl" and is shown in Figure 1. The 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.[7] However, Maynard and Kenny[8] have suggested that sampling at 2.2 ℓ/min will lead to better agreement with the new ISO/CEN/ACGIH respirable dust curve, with a 50% cut off point (d_{50}) of 4 μm. 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 as a part of an underground mechanical miner environmental control study[9]. 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.

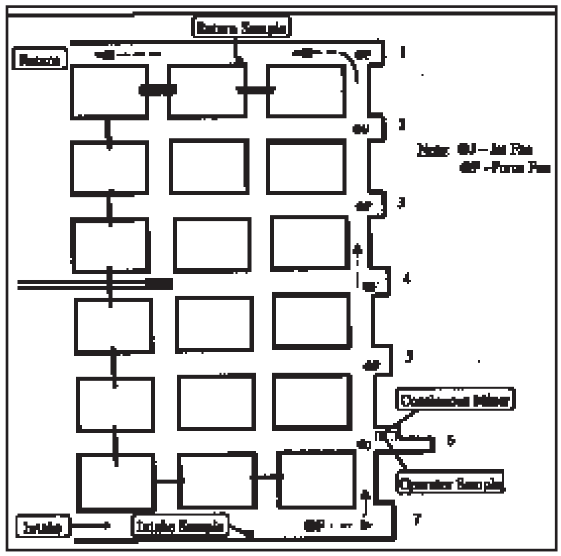

Figure 2. *Layout of the test section*

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 7 μm particles on a pre-weighted filter disc. Filters from the samplers were weighed on an analytical electronic balance readable to 0.0001 mg. The procedure for determining the particulate mass was followed as per DME guidelines[10]. 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.[11]

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 (DC) in mg/m^3 is obtained as follows:

$$SC = \frac{(C_f - C_i)}{(F1 \times T)} \qquad (1)$$

where :

C_i = initial filter mass in mg
C_f = final filter mass in mg
$F1$ = sample flow rate in m^3/min
T = sampling time in min

Results

The relationship between the concentration values obtained at the section intake, CM operator's position and section return, from the BG1 and cowl sampler, during the underground tests, is shown in Figure 3. The correlation co-efficient (r) between the BGI sampler and cowl sampler is 0.975. Table 1 shows a summary statistic of respirable dust concentration values obtained by the BGI sampler and cowl sampler at different positions. The relationship between the concentration values obtained from the two samplers is shown in Figures 4, 5, and 6. The correlation co-efficient (r) at the intake, operator and return position is 0.987, and 0.993, respectively.

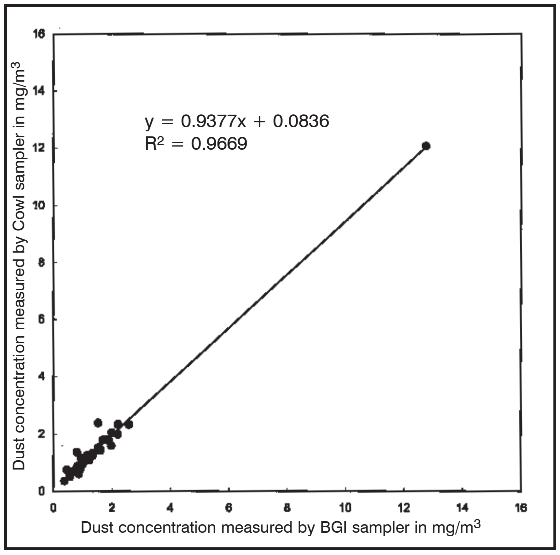

Figure 4. *Relationships between BGI and Cowl sampling results at the section intake*

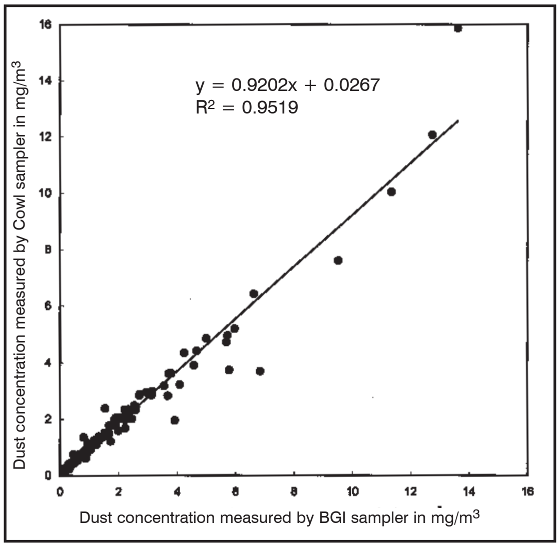

Figure 3. *Plot of the dust concentrations obtained from BGI and Cowl sampler*

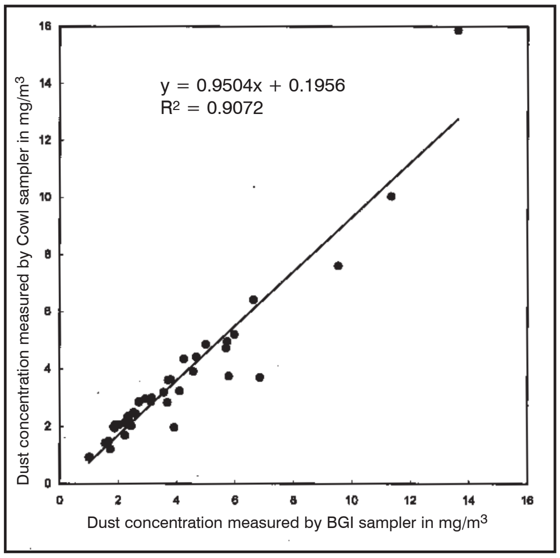

Figure 5. *Relationships between BGI and Cowl sampling results at the operator*

Table 1: *Summary statistics of dust concentrations*

	Section Intake		CM Operator		Section Return		Overall	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{BGI}	C_{COWL}	C_{CBGI}	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

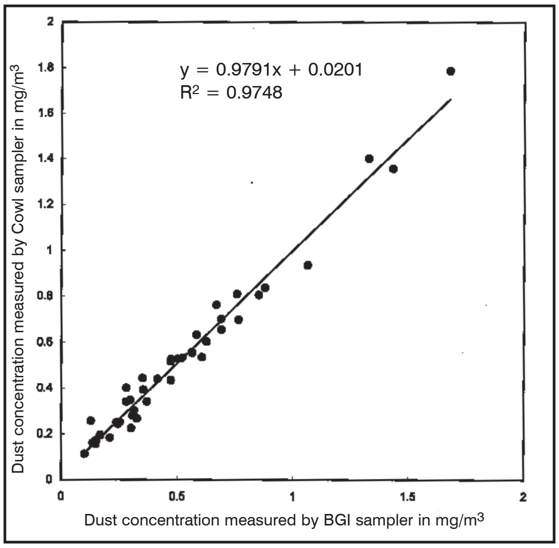

Figure 6. *Relationships between BGI and Cowl sampling results at the section return*

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 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 :

$$H_0 : \mu_{BGI} = \mu_{Cowl}$$

$$H_1 : \mu_{BGI} \neq \mu_{Cowl}$$

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 hypotheses 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 Table 2.

P (probability) - values are often used in hypotheses tests, where one rejects or fails to reject a null hypothesis. The p-value represents the probability of making a Type 1 error, which is rejecting the null hypotheses 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 the various degrees of freedom, the large p-value (>0.05) suggesting that the measured mean concentration levels are consistent with the null hypothesis, $H0 = \mu_A = \mu_B$ that is, the dust concentration measured by pairs of cyclones are not affected at 96 % level of confidence. Further, the confidence interval for the difference between the pairs of

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	-0.717		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	

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

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.

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: $\sigma_{BGI} = \sigma_{COWL}$,
and any observed variability is due to chance

H_1: $\sigma_{BGI} \neq \sigma_{COWL}$,
and there are some variability between the samplers.

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. Hypotheses stated were $\sigma_{BGI} = \sigma_{COWL}$ and $\sigma_{BGI} \neq \sigma_{COWL}$, all analysis 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 numberator Υ_{Cowl} = 42-1 = 41; and for the denominator Υ_{BGI} = 42-1 = 41. At the 0.05 level for the 41, 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 should be to determine 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. At a face underground, there is no clear air direction in terms of vertical or

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	

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

horizontal as would be found in a test tunnel.

Although the two instruments differ according to their design, cost, 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 position, 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 distribution of the samples collected by the BGI stainless steel sampler and cowl samplers. The study further suggests the 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 further study 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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