SAFETY IN MINES RESEARCH ADVISORY COMMITTEE

Final Report

Engineering Gravimetric Monitoring Methods to Cope With Excessively High Dust Levels - 2

B K Belle and J J L du Plessis

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Executive Summary

In the first-phase of the project, Oberholzer et al., (1998) developed the rationale for adapting an addition of a cowl (shield) to the existing South African cyclone for measuring dust at high concentrations. In this report, background to the reasons for sampling, rationale for adapting the sampling head, the evidence of various problems with discrepancies between instruments, the same instruments of different manufacturers, and the difficulties in evaluating these samplers are discussed.

This report, a second-phase of COL 515 project titled "Engineering Gravimetric Sampling Methods for Monitoring the Conditions of Excessively High Dust Levels-2." The objective of the second phase of the work was to assess the results of the field trials on modified cyclones for dust measurements.

Field experience of dust measurement in South African coal mines has suggested that in very high dust concentrations, cyclones for sampling respirable dust can become overloaded (Oberholzer, 1998). In the light of studies conducted by Kenny, Baldwin and Maynand (1998) in UK, the use of a cowl (shield) attachment was favoured. The study reported to have shown that there was no significant difference in the concentration level measured between the cyclone with and without the shield. The general view of the several international opinions is that the use of the cowl will help to increase the accuracy of dust concentration measurements without increasing the bias of samples. It is further recommended that the CEN/ISO respirable curve with a d_{50} of 4 µm should be introduced as the standard.

In overall, following conclusions were made from the current study:

- The work carried out in the field demonstrates equivalent dust concentration results from the two sampler types in different positions within the mine. The extent of the agreement between the two sets of results seems to be excellent and much better than that for results obtained in the laboratory results or in non-mining workplaces.
- From the statistical analysis (*t*-test and F-test), the mean dust concentration measured by pairs of cyclones is not significantly affected at 95 percent level of confidence. In other words, there is no difference between the measured mean dust concentration levels between various sampler pairs.

- From the general size distribution plots from the sample dust, we notice that the mine-face respirable dust has two relative maximums, called modes and can be referred to as a bi-modal distribution.
- From the size analysis on dust samples (with and without cowl samples) of the measured dust concentrations in the range 2,37 mg/m^3 to 10,59 mg/m^3, it is seen that the sampled respirable dust contained particles greater than 10 µm, except for the BGI sampler dust (3,89 mg/m^3 concentration).
- At very high measured dust concentrations, the cowl sampler lowered the loading of large particles. From the size distribution analysis data, we can conclude that the cowl samplers are the preferred samplers for taking engineering samples at high dust concentrations.
- However, the results showed that at very high dust concentrations, there is a huge variation in both the measured dust concentration and the size distribution for a paired sample. For a pair of cowl and without-cowl samplers, for the same dust concentration levels, the evidence showed the presence of wide size distributions.
- It is thus evident that, although the dust mass collection of the samplers conforms to the requirements, the size distribution of the dust is not concomitantly accurate.
- The field study failed to conclusively determine whether the modifications made to the South African cyclone either improve or degrade its performance for the conditions tested, based on the results of the size analyses.
- From the field observations, it can be stated that the cowl sampler can be used for engineering sampling to avoid the dependence of the cyclone inlet on orientation in the collection of particles.
- The data analysis and field experience have shown that in comparison with other samplers, BGI samplers greatly reduce the amount of oversized particles deposited onto the filter from the inversion of cyclones. Also, due to the design of its cyclone inlet, the BGI sampler is not affected by orientation dependence.
- The field observations did indicate that when collecting samples closer to the face, where high concentrations of dust are present, sample handling is extremely difficult. At high dust concentrations, the probability of non-respirable particles depositing onto the filter from the grit pot is very high when the pump is switched off. However, the BGI sampler, due to its design, alleviates this problem to some extent.
- In both the laboratory and field tests, a sufficient mass of sample dust was required for analysis with the Fritsch analyser to determine the presence of non-respirable particles. This led to the conclusion that there may have been non-respirable particles in the concentrations below 5 mg/m^3 (as found from this study).

- The size analysis of the collected dust mass for sample concentrations greater than 5 mg/m^3 did not follow the D_{50} of either BMRC or ISO/ACGIH/CEN respirable curves.
- The cowl sampler could not be recommended for personal sampling because the results of the size analysis are inconclusive and wide-ranging.
- Finally, question of cowl under-sampling (under-estimation of dust concentration) or over-sampling (over-estimation of dust concentration) could not be resolved with confidence from size distribution data at concentrations below 5 mg/m^3 despite the insignificant differences obtained from comparison of mass concentrations alone.

From the conclusions drawn, the following recommendations for future research are proposed, although it is suggested that there should be a paradigm shift in the existing sampling procedure and instruments in the future project:

- The results were inconclusive with regard to the recommendations on the usage of adding a cowl to the cyclone in the personal sampling method. However, the use of a cowl for taking engineering samples can be recommended on the grounds that it lowers sample-handling errors, the probable reason being that in practice it reduces factors such as the wind and orientation-dependence of the cyclone inlet. At high dust concentrations, it was difficult to determine which sampler measured the "true concentration." Therefore, future field tests should incorporate the aspect of "impactor sampling" from which both the mass concentration and the size distribution of ambient particles can be accurately determined.
- Despite some of the cyclones being accepted for sampling in the industry, concerns were expressed about the cyclone performance with respect to the BMRC and ISO/ACGIH/CEN respirable curves. Fears were also expressed about whether the cyclones do follow the BMRC respirable curve under concentrations below 5 mg/m^3. In addition to the investigation, further work on recommendations for the use of the cowl sampler for personal sampling could be considered.
- Similar studies should be carried out to compare these samplers with CIP10 samplers and to investigate their variances and size distribution. The different makes of samplers should also be investigated to determine the relationship between them, not only with regard to the mass of dust collected but also in terms of the size characteristics of the dust.
- Tests should be carried out to determine the size characteristics of personal dust samples and engineering dust samples to compare with the existing DME requirements for engineering sampling.

- Immediate attention needs to be given to analysing both the compliance and non-compliance samples from the mines, which have difficulty in maintaining the 1997 DME directive. On the basis of this outcome, there needs to be clarification on the matter of performance evaluation of all the cyclones currently used in the mines.
- An extensive facility, including a chamber and a particle size analyser for analysing sample mass on compliance samples of less than 5 mg/m^3, needs to be established for this serious issue of sampling. A programme needs to be established for dust sampling, measurement and data analysis for exposure assessment.

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Glossary of Abbreviations and Symbols

Abbreviations

ACGIH	American Congress of Governmental Industrial Hygienists
BMRC	British Medical Research Council
CEN	European Standards Organization
CM	Continuous Miner
DME	Department of Minerals and Energy, South Africa
HSL	Health and Safety Laboratories, UK
ISO	International Standards Organization
MRE	Medical Research Establishment, UK
NIOSH	National Institute for Occupational Safety and Health, USA
SC	Sample Concentration
SIMRAC	Safety in Mines Research Advisory Committee
TWA-CONC	Time-Weighted Average Dust Concentration
USBM	United States Bureau of Mines

Symbols

mg/m^3	milligrams per cubic metre
m^3/s	cubic metres per second
L/min	litres per minute
µm	micron
mm	millimetre
m	metre

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1 Introduction

In the first phase of the project, Oberholzer *et al*., (1998) developed the rationale for adding a cowl (shield) to the existing South African cyclone for measuring at high dust concentrations. In the report on the first phase, they discussed the background to the reasons for sampling, the rationale for adapting the sampling head, the evidence of various problems leading to discrepancies between instruments, the same instruments made by different manufacturers and the difficulties in evaluating these samplers.

The present report deals with the second phase of project COL 515, entitled "Engineering gravimetric monitoring methods to cope with excessively high dust levels-2." The objective of the second phase of the work was to assess the results of the field trials on modified samplers (cyclones) for dust measurements.

2 Background

Studies in the USA and Europe resulted in a new particle size selection criterion, namely the Soderholm respirable dust curve in which $D_{50} = 4\ \mu m$, for the measurement of dusts in the workplace (ACGIH, 1991; 1992). This criterion was agreed upon by both the International Standards Organization (ISO) and the Comité European de Normalisation (CEN) (ISO, 1991; CEN 1991).

Several laboratory evaluation studies were carried out on the performance of the various cyclones by determining the size characteristics of the sample dust collected by the cyclone. Determining the size distribution of the actual face dust underground is, however, a cumbersome and time-consuming process. Nevertheless, the size distribution of the sampled dust is one of the major parameters in determining sampler performance efficiencies.

Most of the cyclone tests are carried out in the laboratory under steady state air conditions, quite unlike the turbulent air conditions underground. Establishing the presence of non-respirable particles carried over onto the filter requires the ability to count and analyse the particles in the collected sample. Due to the dynamic nature of mining and the harsh environmental conditions underground, the behaviour of particles in this situation is not very clearly understood. It is not yet known whether the size distribution of the particles generated will be uniform throughout a particular mining operation. From the sampling point of view, it is a well-observed phenomenon that some of the respirable dust particles deposit on the inner walls of cyclones. This observed behaviour is unavoidable and persisted during most of the sampling done underground. It can therefore be speculated that the sample concentration results obtained are an underestimation of the sample mass concentration to which workers are exposed underground.

Growing concern about dust-related diseases and the concomitant emphasis on dust exposure levels make the precise and accurate assessment of exposure to harmful coal dust of the utmost importance. Currently, South African coal mines are assessing workers' dust exposure using various gravimetric dust samplers (cyclones), viz. Casella 10 mm cyclones, Gilian cyclones and MSA cyclones. These samplers are designed for monitoring coal dust and are approved by the South African Department of Minerals and Energy (DME) for use at an airflow rate of 1,9 L/min, in agreement with the BMRC respirable convention (BMRC, 1952). The CIP 10 sampler is also approved at an airflow rate of 10 L/min.

The mines are also obliged to submit "engineering samples" to the DME, consisting of samples collected at the operator's position on the continuous miner (CM) (irrespective of whether the machine is remotely operated or not). In addition, the DME separately collects two monthly "personal samples" from each section of each South African coal mine for assessing personal dust exposure levels.

Field experience of dust measurement in South African coal mines has suggested that in very high dust concentrations, cyclones for sampling respirable dust can become overloaded (Oberholzer, 1997, 1998). This study further indicated that there was a need to test an additional fitting (cowl) to the cyclones most commonly used in South African collieries, aimed at reducing the potential for large particle carryover. These tests were undertaken at the Health and Safety Laboratories (HSL) in the UK.

In the light of the findings by Kenny *et al*. (1998) at the HSL, the use of a cowl (shield) attachment was favoured. The HSL study reported that there was no significant difference in the dust concentration levels measured between the cyclone with and without the cowl. Several international expert opinions about the use of a cowl head were canvassed. The general view was that the cowl would help to increase the accuracy of dust concentration measurements, without increasing the bias of samples. It was further recommended that the CEN/ISO respirable dust curve in which D_{50} = 4 μm should be introduced as the standard.

In South Africa, fears were expressed that the additional cowl (shield) surrounding the cyclone would inevitably result in lower respirable dust concentration measurements. Studies had previously been carried out in the USA by Cecala *et al*. (1983) to evaluate the use of cowls on personal samplers to help reduce bias when sampling in high-velocity air streams and to reduce bias caused by sampler inlet orientation. The study indicated that the shield placed around the cyclone diminished the effects of wind velocity and sampler orientation on sampler performance. However, the study was not structured to produce definitive results, but rather to discern likely trends.

3 Test Samplers (Cyclones)

In this study the cyclones were operated at the proposed airflow rate of 2,2 L/min in accordance with the new ISO/CEN/ACGIH respirable dust curve. It was hoped that the new flow rate would confer an immediate advantage in sensitivity since existing South African cyclones sample 16 percent less air per minute. The cyclones used in this study are described below.

3.1 BGI Stainless Steel Cyclone

The BGI stainless steel cyclone used in the tests is of all-metal construction (Figure 3). 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 4 μm, 50 percent cut-off, respirable curve (ACGIH, 1991) and is not sensitive to charge effects (Bartley *et al*., 1994). The cyclone is also available with a plastic body and has been the subject of a careful study by the HSL (UK) (Maynard, and Kenny, 1995).

3.2 GME-G05 Cyclone

This locally manufactured and DME-approved cyclone (GME–G05, 10 mm cyclones), which was used in the tests and is hereafter referred to as "cyclone without cowl or C_{wcowl}", is shown in Figure 3. The cyclone body is fabricated from plastic. The dust cup (grit pot) is also fabricated from plastic and is fitted to the cyclone body. Filtration is accomplished with a 37-mm disposable cassette, which is pressed on over an “O” ring seal. Measurement of the size-selection characteristics of this cyclone, as tested in the UK, confirmed that they are similar to those of the Higgins-Dewell designs commonly used in the UK and elsewhere in Europe.

3.3 GME-05 Cyclone with Cowl

This locally manufactured and DME-approved cyclone (GME–G05, 10 mm cyclones) was fitted with an additional round steel shield, which is attached to surround the cyclone. It is hereafter referred to as "cyclone with cowl or C_{cowl}" (Figure 3) and was also used in the tests. The cowl surrounds the entire unit and is the same length as the cyclone. It operates as a vertical elutriator, preventing larger particles from entering the cyclone as a result of sedimentation within the cowl. It 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.

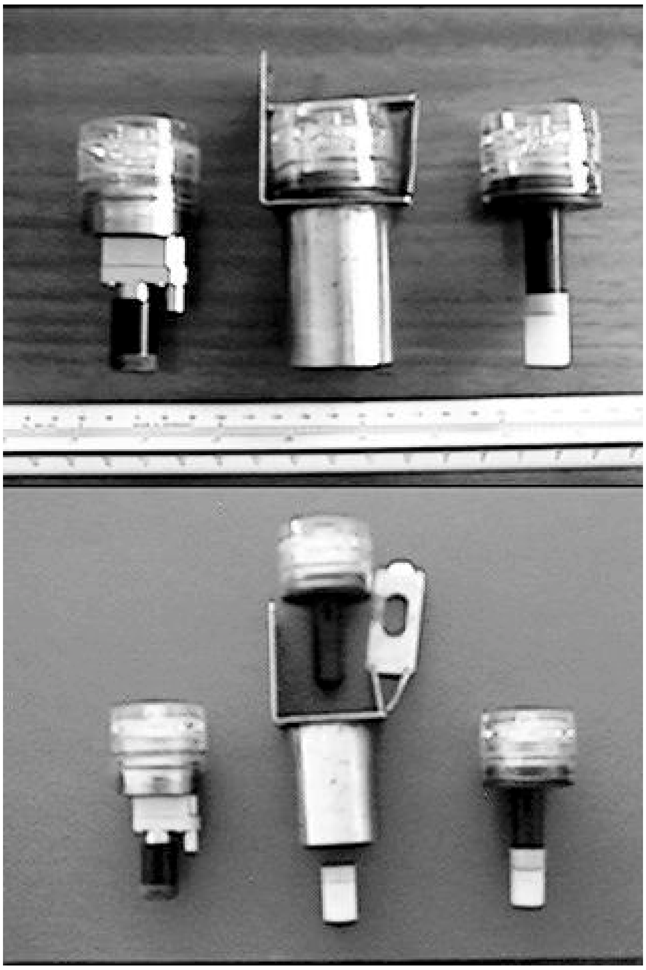

Figure 3: Pictorial view of the BGI stainless steel sampler (left), the cowl sampler (centre) and the without-cowl sampler (right)

Each sampling train consists of an air pump which draws air through the cyclone, and the cyclone itself which in turn selectively collects the fraction of airborne respirable dust less than 7 μm particles on a pre-weighed filter disc. Filters from the samplers were weighed on an analytical electronic balance calibrated in readable units of 0,0001 mg. The procedure for determining the particulate mass as given in the DME guidelines (DME, 1997) was followed. Well-maintained pumps were used to avoid the effect of pump pulsations and fluctuations in the flow rate, as reported by Berry (1990).

4 Sampler Positions

All the field measurements were carried out in a bord-and-pillar CM production section. Figure 4 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, with the following combinations of cyclone pairs:

- BGI sampler (C_{BGI}) and BGI sampler (C_{BGI})
- Cowl sampler (C_{COWL}) and cowl sampler (C_{COWL})
- Without-cowl sampler (C_{WCOWL}) and without-cowl sampler (C_{WCOWL})
- BGI sampler (C_{BGI}) and cowl sampler (C_{COWL})
- BGI sampler (C_{BGI}) and without-cowl sampler (C_{WCOWL})
- Cowl sampler (C_{COWL}) and without-cowl sampler (C_{WCOWL}).

Samplers were kept together (approximately 12 inches apart) at the same position to avoid the possibility of greater spatial variations in the aerosol concentrations.

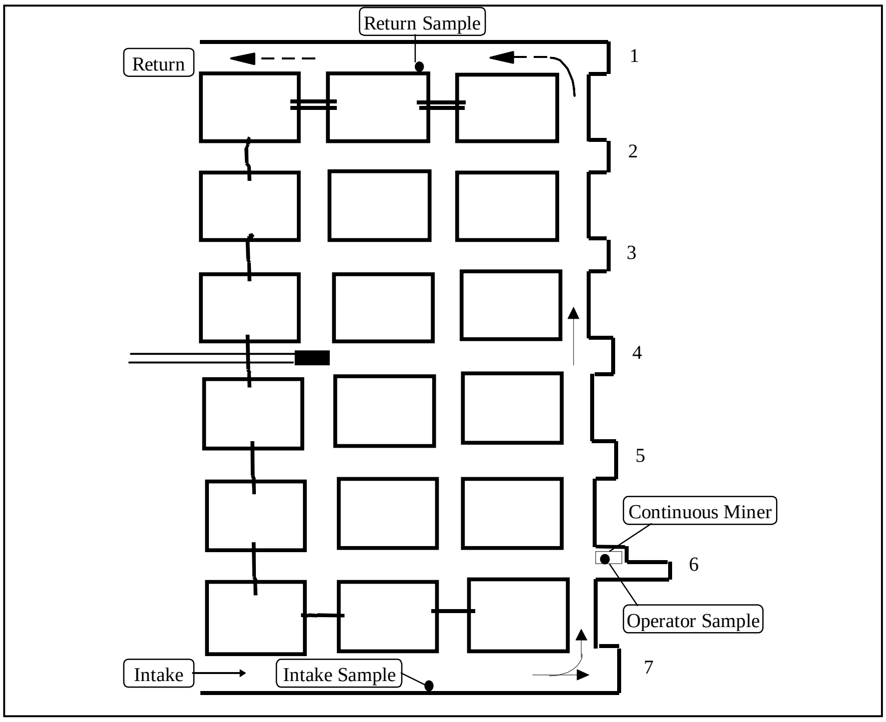

Figure 4: Layout of the test section

5 Data analysis

Typically, the inaccuracy maps and penetration curves for the cyclones used in the samplers are available from the instrument manufacturer or at laboratories for performance evaluation. However, for the calculation of inaccuracies, one needs to have information on the aerosol size distribution and this is not generally known at the time of sampling. Also, most cyclone tests are carried out in the laboratory under steady state air conditions, unlike the turbulent air conditions that prevail underground during tests. Carrying out successful sampler efficiency tests requires the ability to count and analyse both the collected sample and the ambient aerosol. Collecting a representative ambient air sample underground is difficult in itself, and determining the size distribution of the ambient air as well would be expecting too much. Therefore, in phase two of this project, a comparative evaluation of the various samplers was carried out. The comparison was based on the mass concentrations of the respirable dust sampled and on the results of the size distribution analyses of selected samples which contained enough dust mass to enable size analysis to be carried out.

The dust concentrations presented throughout this report reflect gravimetric dust measurements taken over a specific sampling period with the sampler pair. The gravimetric concentration was calculated using the mass of the dust collected over the sampling period and the 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 = corrected initial filter mass in mg (correction factor is for moisture content change)

C_f = corrected final filter mass in mg (correction factor is for moisture content change)

Fl = sample flow rate in m^3/min

T = sampling time in min.

Since the "true value" of the concentration measured at the predetermined position is not known, measurement bias for a pair of samplers was defined as follows:

$$MB_{AB} = \frac{(C_A - C_B) \times 100}{C_A}$$

where:

MB_{AB} = measured mean concentration bias between the sampler pair type-AB

C_A = measured mean concentration by a sampler A (first sample in the pair)

C_B = measured mean concentration by a sampler B (second sample in the pair)

The sampler pair data at various positions were combined for analysis procedure, due to the small number of sampler pairs collected at the intake, operator and return. However, individual sampler pair data at various locations were plotted and shown in Appendix A.

6 Results and Analysis

The relationship between the concentration values obtained at the section intake, the CM operator's position and the section return from the various pairs of samplers used in the underground tests is shown in Appendix A (Figures A1 to A18). The measured concentration levels in the section (intake, operator and return) were combined in order to make a statistical comparison of six pairs of samplers and are shown in Figures 6a to 6f. The correlation coefficient (r) and the linear regression line between the various sampler pairs at the section intake, operator and return are summarised in Tables A1 to A4 in Appendix A. Summary statistics of the dust concentration values obtained with the various samplers at the different sampling positions are shown in Tables 6a and 6b.

In Table 6a, the comparison of similar sampler types is shown. In Table 6b, the dust concentration data for various combinations of samplers are shown.

Table 6a: Summary statistics of the concentration levels from the various sampler pairs

Statistics	Sampler Pair		Sampler Pair		Sampler Pair	
	C_{BGI}	C_{BGI}	C_{COWL}	C_{COWL}	C_{WCOWL}	C_{WCOWL}
Mean	2,69	2,54	2,63	2,74	3,27	3,12
Variance	5,32	3,94	4,76	5,86	4,34	4,14
Median	2,10	1,97	1,80	1,87	2,88	2,55
Minimum	0,79	0,84	0,45	0,43	1,04	0,93
Maximum	10,48	8,35	7,96	10,06	9,63	8,52
Count	23	23	40	40	22	22

Table 6b: Summary statistics of the concentration levels from the various sampler pairs

Statistics	Sampler Pair		Sampler Pair		Sampler Pair	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{WCOWL}	C_{COWL}	C_{WCOWL}
Mean	1,86	1,73	1,25	1,45	2,80	2,85
Variance	4,57	4,06	0,75	1,00	9,95	10,29
Median	1,15	1,17	1,10	1,62	1,07	1,43
Minimum	0,10	0,11	0,27	0,25	0,37	0,39
Maximum	13,62	15,87	2,81	2,95	11,38	11,79
Count	123	123	15	15	26	26

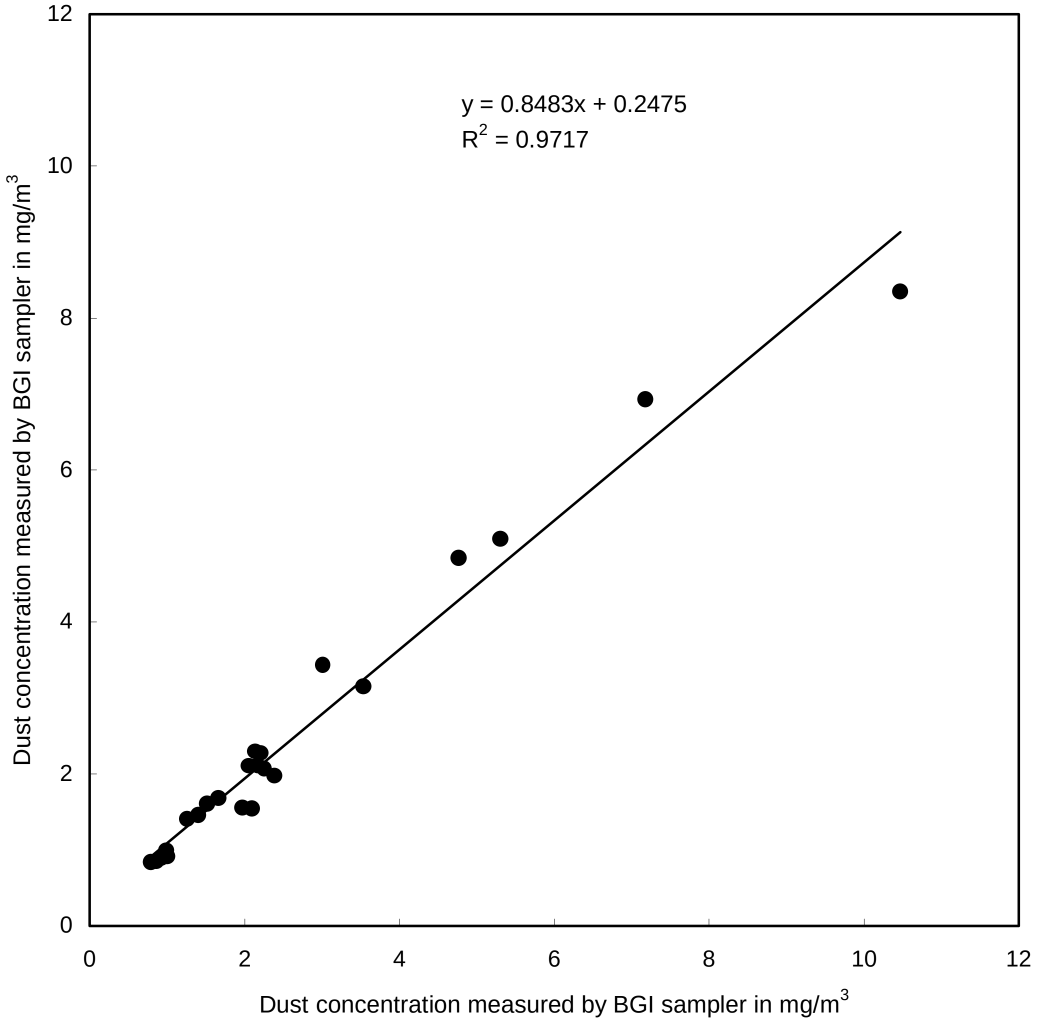

Figure 6a: Plot of combined dust concentrations obtained from two BGI samplers

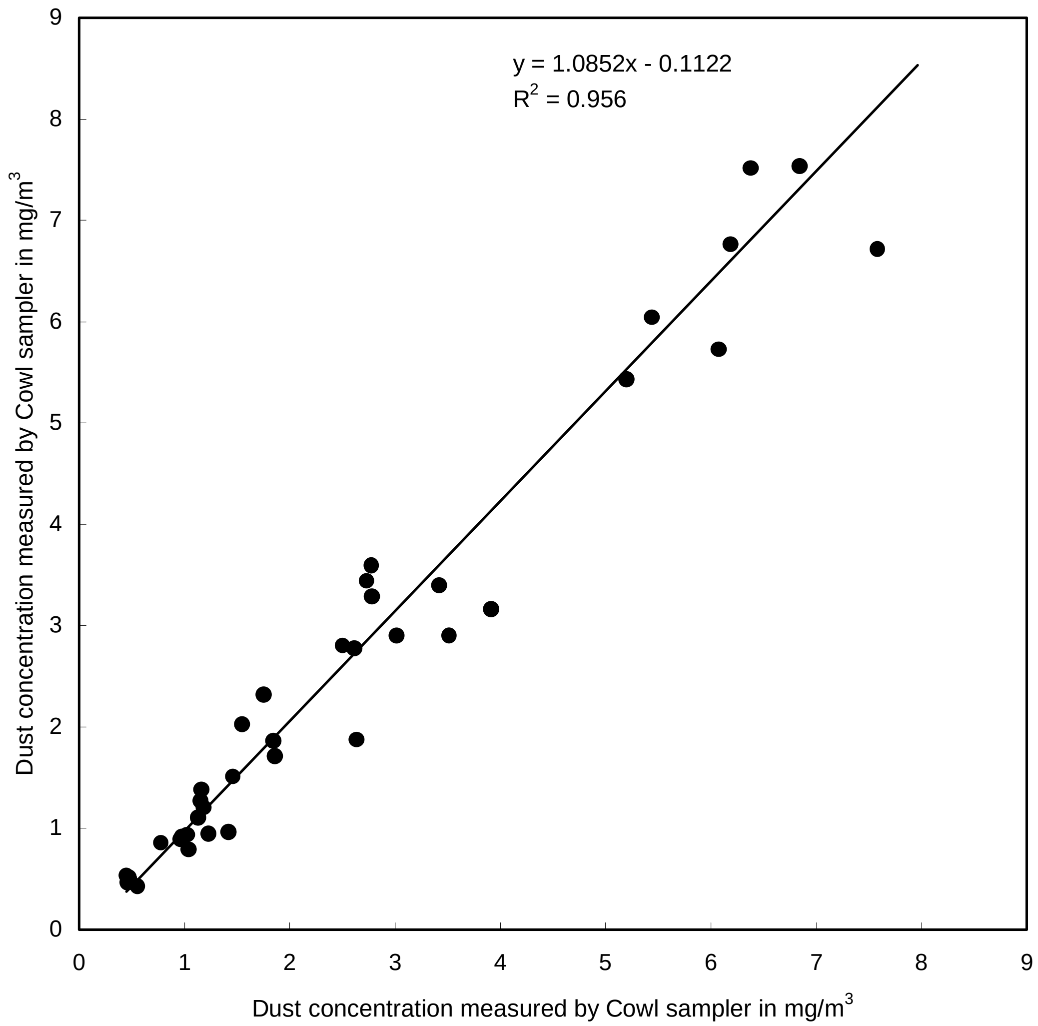

Figure 6b: Plot of combined dust concentrations obtained from two cowl samplers

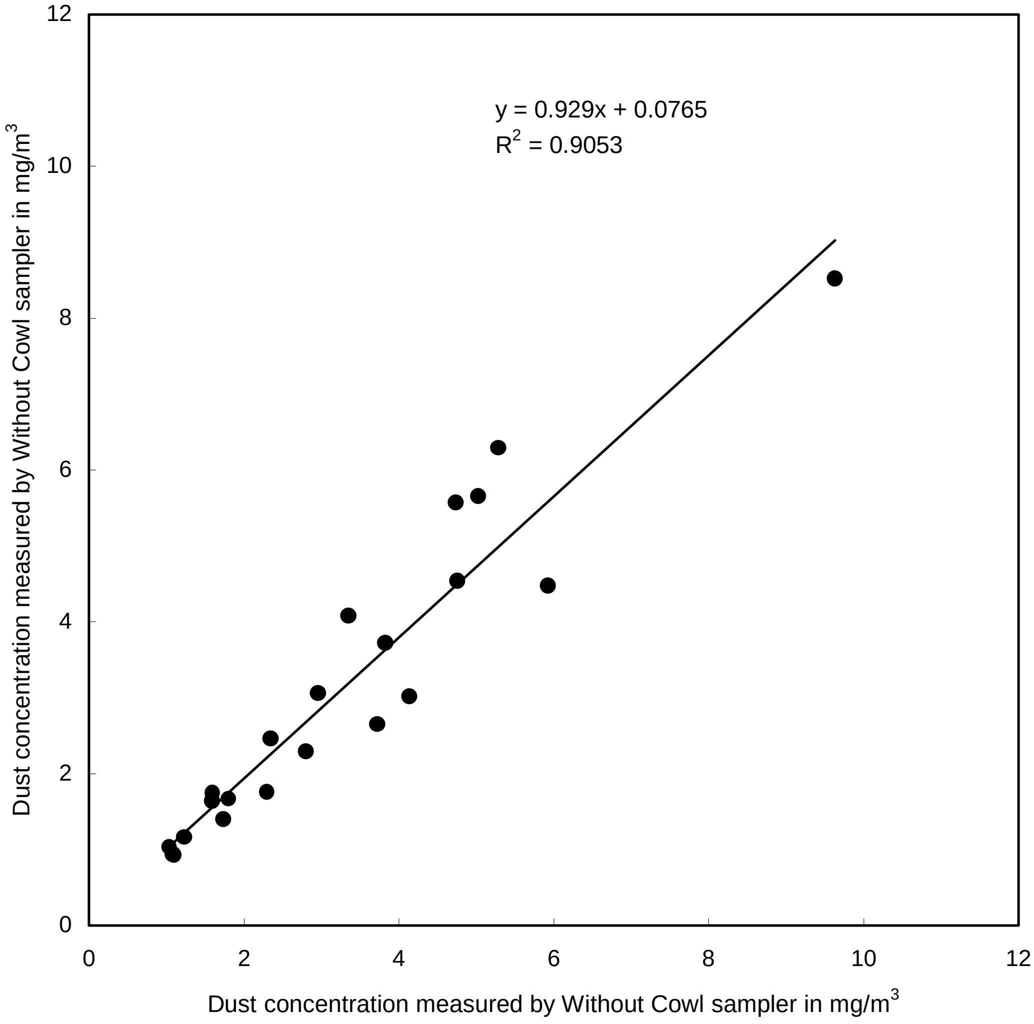

Figure 6c: Plot of combined dust concentrations obtained from two without-cowl samplers

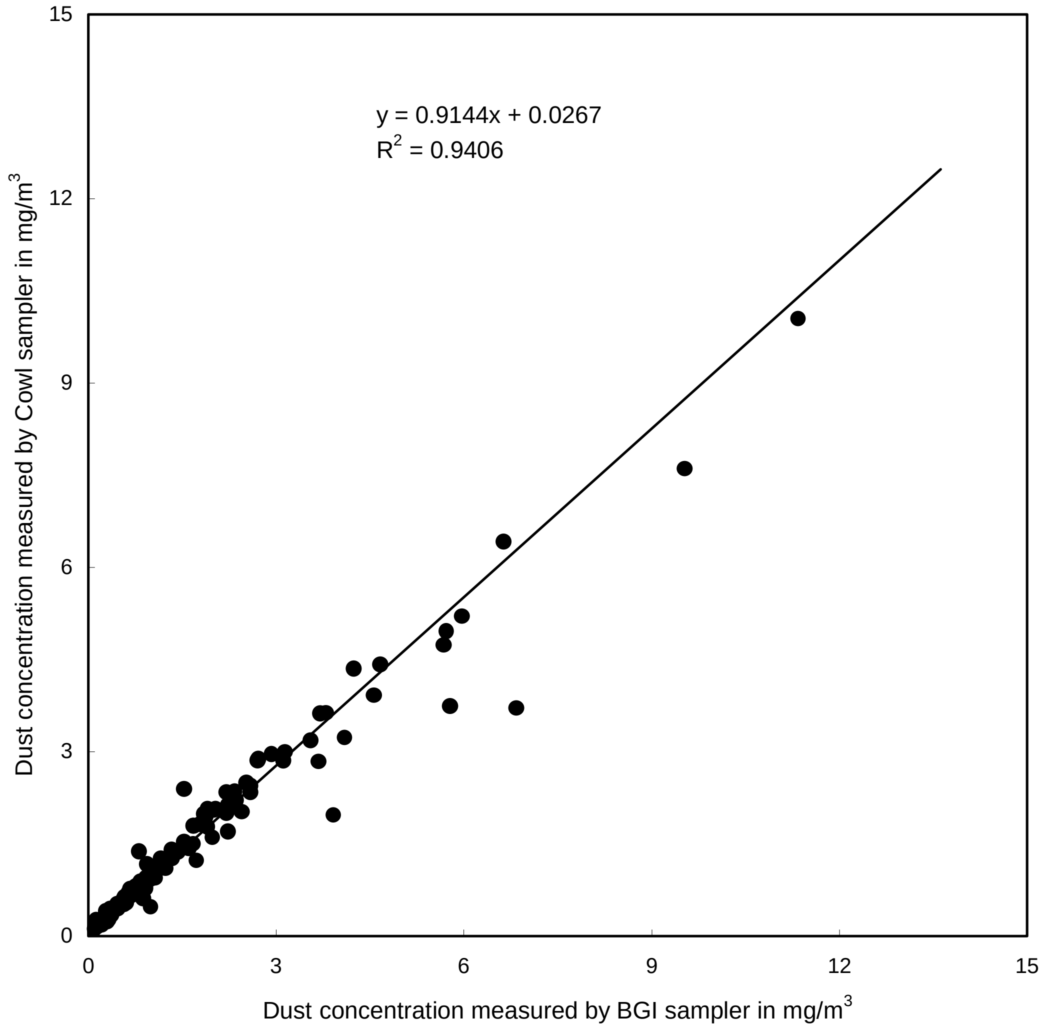

Figure 6d: Plot of combined dust concentrations obtained from BGI and cowl samplers

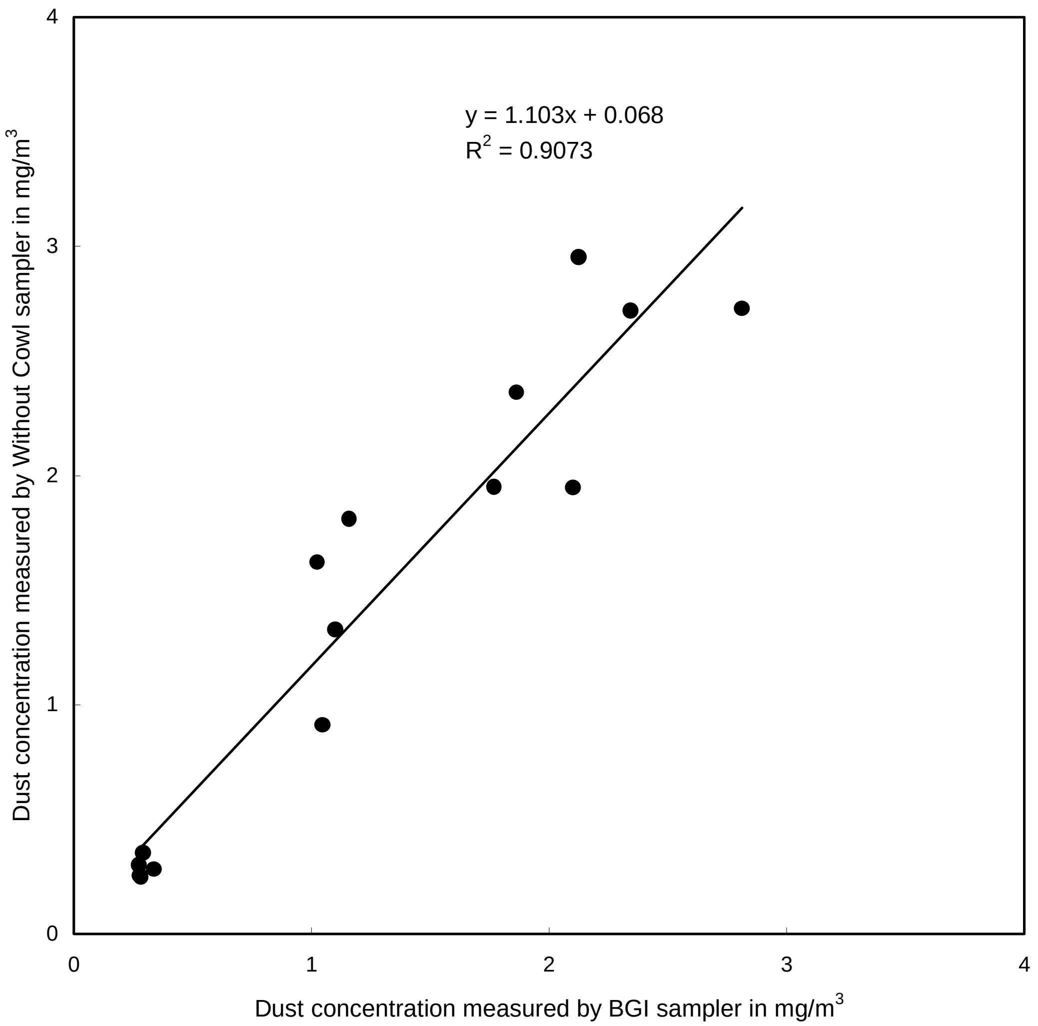

Figure 6e: Plot of combined dust concentrations obtained from BGI and without-cowl samplers

Figure 6f: Plot of combined dust concentrations obtained from cowl and without cowl samplers

The “bias” between samplers is calculated according to the formula discussed in Section 5. Sampler biases during the measurement by various sampler types at the section intake, operator and section return are shown in Table 6c.

Table 6c: Results of the sampler biases at the intake, operator and return

	Intake (% bias)			**Operator (% bias)**			**Return (% bias)**		
	C_{BGI}	**C_{COWL}**	**C_{WCOWL}**	**C_{BGI}**	**C_{COWL}**	**C_{WCOWL}**	**C_{BGI}**	**C_{COWL}**	**C_{WCOWL}**
C_{BGI}	5,8	-1,96	1,37	8,6	10,25	-12,21	2,3	1,1	-28,63
C_{COWL}		-3,97	2,71		-8,33	2,21		8,08	-19,31
C_{WCOWL}			4,34			5,62			3,44

From a comparison of the results of the mean dust concentrations measured at the ***intake*** with the various sampler pairs, the following conclusions were drawn (Appendix A - Figures A1 to A6, and Table 6c):

- On average, with the same sampler types, there was a bias of 4,7 percent in the concentration measurement (i.e., 5,78 percent for C_{BGI}-C_{BGI}; 3,97 percent for C_{COWL}-$C_{COWL;}$ and 4,34 percent for C_{WCOWL}-C_{WCOWL}).
- A comparison of the mean concentration levels from C_{BGI} and C_{COWL} data shows that the cowl sampler oversamples by approximately 1,96 percent when compared with the BGI sampler.
- A comparison of the mean concentration levels from C_{BGI} and C_{WCOWL} data shows that, on average, the sampler without cowl undersamples by approximately 1,37 percent when compared with the BGI sampler.
- However, a comparison of the mean concentration levels from C_{COWL} and C_{WCOWL} data shows that, on average, the without-cowl sampler undersamples by 2,71 percent when compared with the sampler with cowl.

From a comparison of the results of the mean dust concentrations measured at the ***operator*** with the various sampler pairs, the following conclusions were drawn (Appendix A - Figures A7 to A12, and Table 6c):

- On average, with the same sampler types, there was a bias of 7,5 percent in the concentration measurement (i.e. 8,6 percent for C_{BGI}-C_{BGI}; 8,33 percent for C_{COWL}-C_{COWL}; and 5,68 percent for C_{WCOWL}-C_{WCOWL}).

- A comparison of the mean concentration levels from C_{BGI} and C_{COWL} data shows that the cowl sampler undersamples by approximately 10,25 percent when compared with the BGI sampler.
- A comparison of the mean concentration levels from C_{BGI} and C_{WCOWL} data shows that, on average, the without-cowl sampler, i.e. a normal 10 mm cyclone without a shield, oversamples by approximately 12,21 percent when compared with the BGI sampler.
- However, a comparison of the mean concentration levels from C_{COWL} and C_{WCOWL} data shows that, on average, the sampler without-cowl under-samples by 2,21 percent when compared with the cowl sampler.

From a comparison of the results of the mean dust concentrations measured at the ***return*** with the various sampler pairs, the following conclusions were drawn (Appendix A - Figures A13 to A18, and Table 6c):

- On average, with the same sampler types, there was a bias of 4,6 percent in the concentration measurement (i.e. 2,30 percent for C_{BGI}-C_{BGI}; 8,08 percent for C_{COWL}-C_{COWL}; and 3,44 percent for C_{WCOWL}-C_{WCOWL}).
- A comparison of the mean concentration levels from C_{BGI} and C_{COWL} data shows that the cowl sampler undersamples by approximately 1,1 percent when compared with the BGI sampler.
- A comparison of the individual mean concentration levels derived from C_{BGI} and C_{WCOWL} data shows that, on average, the without-cowl sampler, i.e. a normal 10 mm cyclone without a shield, oversamples by approximately 28,63 percent when compared with the BGI sampler.
- However, a comparison of the mean concentration levels derived from C_{COWL} and C_{WCOWL} data shows that, on average, the sampler without cowl over-samples by 19,31 percent when compared with the cowl sampler.

Sampler biases on the combined data (intake, operator and return) using measured concentrations by various sampler types are shown in Table 6d.

Table 6d: Overall results of the sampler biases

	Overall (% bias)		
	C_{BGI}	C_{COWL}	C_{WCOWL}
C_{BGI}	6,04	7,10 (C_{COWL} under-samples)	-15,71 (C_{WCOWL} over-samples)
C_{COWL}		-4,20	-1,60 (C_{WCOWL} over-samples)
C_{WCOWL}			4,76

By combining and comparing the results of the mean dust concentrations measured at the intake, operator and return, the following conclusions were drawn (Appendix A - Figures 6a to 6f, and Table 6d):

- On average, with the same sampler types, there was a bias of 5 percent in the concentration measurement (i.e. 6 percent for C_{BGI}-C_{BGI}; 4,2 percent for C_{COWL}-C_{COWL}; and 4,76 percent for C_{WCOWL}-C_{WCOWL}).
- A comparison of the mean concentration levels derived from C_{BGI} and C_{COWL} data from the different respective positions shows that the cowl sampler undersamples by approximately 7,1 percent when compared with the BGI sampler.
- A comparison of the individual mean concentration levels derived from C_{BGI} and C_{WCOWL} data from the different respective positions shows that, on average, the sampler without-cowl, i.e. a normal 10 mm cyclone without a shield, oversamples by approximately 15,1 percent when compared with the BGI sampler. It is interesting to note that the highest concentration measured in this pair was 2,95 mg/m^3, which is low in comparison with the other pairs (see Table 6b).
- However, a comparison of the mean concentration levels derived from C_{COWL} and C_{WCOWL} data from the different respective positions shows that, on average, the without-cowl sampler, i.e. a normal 10 mm cyclone without a shield, oversamples by a mere 1,6 percent when compared with the cowl sampler.

In order to conclusively determine the significant differences in measured concentration levels (variance and mean), using various sampler pairs, further statistical analyses were carried out between the sampler pairs at 95 percent level of significance.

6.1 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 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 on the hypothesis that the measurements were $\log_e$ normally distributed. The improved fit of the normal distribution to the $\log_e$ transform of the concentration data was obvious.

6.1.1 F–Test Hypothesis

First, F-test statistics were calculated to determine whether 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 the measured concentration levels between sampler pairs. The test of hypothesis was developed to compare the sample variance measured with two sampling instruments (σ_A and σ_B). The null and alternative hypotheses for the tests for the various sampler pairs were:

- Hypothesis (a)

H_0: $\sigma_{BGI} = \sigma_{BGI}$, and any observed variability is due to chance
H_1: $\sigma_{BGI} \neq \sigma_{BGI}$, and there is some variability between the samplers.

- Hypothesis (b)

H_0: $\sigma_{COWL} = \sigma_{COWL}$, and any observed variability is due to chance
H_1: $\sigma_{COWL} \neq \sigma_{COWL}$, and there is some variability between the samplers.

- Hypothesis (c)

H_0: $\sigma_{WCOWL} = \sigma_{WCOWL}$, and any observed variability is due to chance
H_1: $\sigma_{WCOWL} \neq \sigma_{WCOWL}$, and there is some variability between the samplers.

- Hypothesis (d)

H_0: $\sigma_{BGI} = \sigma_{COWL}$, and any observed variability is due to chance
H_1: $\sigma_{BGI} \neq \sigma_{COWL}$, and there is some variability between the samplers.

- Hypothesis (e)

H_0: $\sigma_{BGI} = \sigma_{WCOWL}$, and any observed variability is due to chance
H_1: $\sigma_{BGI} \neq \sigma_{WCOWL}$, and there is some variability between the samplers.

- Hypothesis (f)

H_0: $\sigma_{COWL} = \sigma_{WCOWL}$, and any observed variability is due to chance
H_1: $\sigma_{COWL} \neq \sigma_{WCOWL}$, and there is some variability between the samplers.

In the above F-test, hypothesis H_0 states that the sample variances from both samples (σ_A and σ_B) are equal. On the other hand, the alternative hypothesis states that there is some difference in sample variances between two samplers. The hypotheses stated were $\sigma_{A =} \sigma_B$ and $\sigma_A \neq \sigma_B$. All analyses were two-tailed (95 percent confidence level) to account for both conditions $\sigma_A < \sigma_B$ and $\sigma_A > \sigma_B$. Hypothesis tests were carried out for sampler pairs, and the results of the F-test statistical analyses are given in Tables 6.1.1a and 6.1.1b.

The tables show that all hypothesis test pairs, H_0, were accepted. In other words, the level of confidence that the dust measurement readings from the two samplers are not affected is 95 percent. For example, for the test hypothesis (d), the number of degrees of freedom associated with the numerator γ_{Cowl} = 124 – 1 = 123; for the denominator γ_{BGI} = 124 - 1 = 123. At the 0,95 confidence level for 123 (123 degrees of freedom, two-tailed test), we would accept that H_0 as the F-value (1,127) was within the critical F-value range (0,74<F<1,348).

From the F-test analysis, following conclusions were made:

- F-test results indicate that the sample variances from measured dust concentrations using various sampler pairs are equal. In other words, dust readings measured by the two samplers are not affected at 95 percent level of confidence on the basis of differences in dust concentration variances.

Table 6.1.1a: Results of the F-test hypothesis (on transformed values)

	Hypothesis (a)		Hypothesis (b)		Hypothesis (c)	
	C_{BGI}	C_{BGI}	C_{COWL}	C_{COWL}	C_{WOWL}	C_{WCOWL}
Mean	0,744	0,704	0,620	0,629	1,001	0,935
Variance (S^2)	0,462	0,432	0,752	0,814	0,394	0,433
Size	23	23	40	40	22	22
F-statistic	1.069		0.924		0.911	
Critical F-value	0,488<F<2,048		0,586<F<1,704		0,479<F<2,084	
Hypothesis	Accept H_0		Accept H_0		Accept H_0	

Table 6.1.1b: Results of the F-test hypothesis (on transformed values)

	Hypothesis (d)		Hypothesis (e)		Hypothesis (f)	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{WCOWL}	C_{COWL}	C_{WCOWL}
Mean	0,123	0,094	-0,085	0,018	0,470	0,521
Variance (S^2)	1,059	0,939	0,799	0,958	1,156	1,088
Size	123	123	15	15	26	26
F-statistic	1,127		0,832		1,062	
Critical F-value	0,741<F<1,348		0,403<F<2,484		0,512<F<1,955	
Hypothesis	Accept H_0		Accept H_0		Accept H_0	

6.1.2 *t*–Test Hypothesis

F-test of hypothesis results showed that there is no significant difference between the sample variances. Therefore an additional statistical test was performed to identify if there is any significant difference between sample mean concentrations. A paired t-test was performed on the set of all the sampler-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 caused by differences between the pairs. The null and alternative hypotheses for the tested sampler pairs were:

- Hypothesis (a)

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

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

- Hypothesis (b)

  H_0: $\mu_{COWL} = \mu_{COWL}$

  H_1: $\mu_{COWL} \neq \mu_{COWL}$

- Hypothesis (c)

  H_0: $\mu_{WCOWL} = \mu_{WCOWL}$

  H_1: $\mu_{WCOWL} \neq \mu_{WCOWL}$

- Hypothesis (d)

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

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

- Hypothesis (e)

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

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

- Hypothesis (f)

  H_0: $\mu_{COWL} = \mu_{WCOWL}$

  H_1: $\mu_{COWL} \neq \mu_{WCOWL}$

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 concentration levels. It is therefore necessary to use hypothesis testing to accept or reject H_0.

For this work, a standard 95 percent 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 $t_{0,05}$. The results of the t-test statistical analyses are given in Tables 6.1.2a and 6.1.2b.

P-values are often used in hypothesis tests in which one either rejects or fails to reject a null hypothesis. The p-value represents the probability of making a Type 1 error, that 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 percent confidence level). From the analysis tables, we observe that with various degrees of freedom, the large p-value is >0,05, suggesting that the measured mean concentration levels are consistent with the null hypothesis, $H_0 = \mu_A = \mu_B$, i.e. the dust concentration measured by pairs of cyclones is not affected at the 95 percent level of confidence. Further, the confidence interval for the difference between the pairs of cyclones includes zero, which suggests that there is no difference between the measured concentration levels between the various sampler pairs.

Table 6.1.2a: Results of the paired t-test hypothesis (on transformed values)

Statistics	**Hypothesis (a)**		**Hypothesis (b)**		**Hypothesis (c)**	
	C_{BGI}	C_{BGI}	C_{COWL}	C_{COWL}	C_{WCOWL}	C_{WCOWL}
Mean	0,744	0,704	0,620	0,629	1,001	0,935
Variance	0,462	0,432	0,752	0,814	0,394	0,433
Size	23	23	40	40	22	22
t-statistic	1,70		-0,32		1,89	
Critical t-value	-2,01 < t < 2,01		-1,99< t < 1,99		-2,02 < t < 2,02	
P–value	0,103		0,750		0,072	
95 % CI	(-0,009, 0,089)		(-0,063, 0,046)		(-0,007, 0,138)	
Hypothesis	Accept H_0		Accept H_0		Accept H_0	

From Table 6.1.2b, we observe that the t-statistic C_{BGI}-C_{COWL} was 1,78. This indicates that the mean dust concentration level from the BGI sampler (C_{BGI}) was generally higher than the mean dust concentration level from the cowl sampler (C_{COWL}) at all positions. Similarly, the t-statistic C_{BGI}-C_{WCOWL} was –1,91 and the t-statistic C_{COWL}-C_{WCOWL} was -1,09. This indicates that the mean dust concentration level from the BGI sampler (C_{BGI}) was generally less than the mean dust concentration level from the without-cowl sampler (C_{WCOWL}) at all positions. Similarly, the mean dust concentration level from the cowl sampler (C_{COWL}) was generally lower than the mean dust concentration level from the without-cowl sampler (C_{WCOWL}) at all positions.

From the *t*-test analysis, following conclusions were made:

- The mean dust concentration measured by pairs of cyclones is not significantly affected at 95 percent level of confidence. In other words, there is no difference between the measured mean dust concentration levels between various sampler pairs.
- It is also important to note that, *t*-statistic, indicates that mean dust concentration level from the BGI sampler (C_{BGI}) was greater than the mean dust concentration level from the Cowl sampler (C_{COWL}) at all locations.
- Similarly, *t*-statistic, indicates that mean dust concentration level from the BGI sampler (C_{BGI}) was less than the mean dust concentration level from the without Cowl sampler (C_{WCOWL}) at all locations.

Table 6.1.2b: Results of the paired t-test hypothesis (on transformed values)

Statistics	Hypothesis (d)		Hypothesis (e)		Hypothesis (f)	
	C_{BGI}	C_{COWL}	C_{BGI}	C_{WCOWL}	C_{COWL}	C_{WCOWL}
Mean	0,123	0,094	-0,085	0,018	0,470	0,521
Variance	1,059	0,939	0,799	0,958	1,156	1,088
Size	123	123	15	15	26	26
t- statistic	1,78		-1,91		-1,09	
Critical t-value	-1,97 < t < 1,97		-2,05 < t < 2,05		-2,01 < t < 2,01	
P-value	0,078		0,076		0,284	
95 % CI	(-0,003, 0,062)		(-0,219, 0,013)		(-0,147, 0,045)	
Hypothesis	Accept H_0		Accept H_0		Accept H_0	

6.2 Particle Size Distribution

Table 6.2a summarises the respirable fractions and the dust concentrations measured in the UK using the South African cyclone with cowl and without cowl. The respirable fractions were determined as the ratio of the cyclone concentration to the concentration measured using a reference probe. It can be seen that the average measured dust concentrations (from six tests) were 34,63 mg/m^3 and 42,09 mg/m^3 respectively. From the measured concentration alone, we can conclude that the addition of cowl results in a "measured concentration bias" of approximately 18 percent. However, the study could not conclusively report if the addition of cowl results in under-estimation or over-estimation of dust concentration.

Table 6.2a: Measured respirable dust fraction and mass concentrations using the cowl and without-cowl samplers (Kenny* et al.*, 1998)

Test No.	Test Concentration (mg/m^3)	Respirable Fraction (%)		Mass Concentration in (mg/m^3)	
		Without Cowl	Cowl	Without Cowl	With Cowl
1	35	40	22	14,00	7,70
2	68	39	36	26,52	24,48
3	140	42	34	58,80	47,60
4	122	27	26	32,94	31,72
5	106	59	41	62,54	43,46
6	165	35	32	57,75	52,80
Av.	106	40,33	31,83	42,09	34,63

Table 6.2b shows the average size distribution of the sample dust measured from six laboratory tests in the UK using the South African cyclones with cowl and without cowl (Figure 6.2). One observes from the plot that the cumulative percentage of particles finer than 10 μm measured using the cyclones with and without cowl were 84 percent and 90 percent respectively. Similarly, the cumulative percentage of particles finer than 10 μm measured using the reference test probe was 66 percent.

Generally, more than 90 percent of the sampled mass is contained particles with volume diameters less than 10 μm. Using cyclones; the actual numbers of particles counted having diameters exceeding 10 μm were in all cases very small and given the level of coincidence counts, not significant (Kenny *et al*., 1998). The CEN respirable convention requires 1,3 percent of particles having an aerodynamic diameter of 10 μm to be sampled; however, no particles with aerodynamic diameters greater than 16 μm should be sampled.

Table 6.2b: Measured particle size distributions (by volume) using the cowl and without-cowl samplers (Kenny* et al.*, 1998)

Test No.	Reference Probe			Without Cowl			Cowl		
	% mass finer			% mass finer			% mass finer		
	5 µm	10 µm	38 µm	5 µm	10 µm	38 µm	5 µm	10 µm	38 µm
1	52	85	100	66	78	100	60	91	100
2	55	83	99	83	97	100	57	68	100
3	57	84	98	68	88	100	80	91	100
4	43	74	98	73	90	100	58	75	100
5	35	70	100	69	94	100	66	87	100
6	45	79	100	71	92	100	76	91	100

Finally, the laboratory tests carried out in the UK (at the HSL) deduced the following (Kenny *et al*, 1998):

- The modifications made to the South African cyclones did not either improve or degrade their performance in the laboratory experiment.
- However, consideration should be given to adding the cowl to the South African design because this provides a simple means of reducing the wind and orientation dependence of the cyclone inlet in practical use.
- The laboratory study concluded that the inadequate field performance of South African cyclones was attributable to the particular conditions of use in mines, and may be related to the sample-handling procedures.

In this work, laboratory study of Kenny, Baldwin and Maynand (198) was re-visited to clarify the evaluation structure on its definitive results. The following critical comments were made on the laboratory evaluation of cowl samplers that was carried out in UK:

- The laboratory test aerosol for sampler evaluation contained too few large particles compared with the bulk of the coal dust supplied by the CSIR Miningtek, Kloppersbos. The dust supplied was specifically sized to ensure that although there were sufficient of the smaller-size particles available, it also contained a significant amount of larger dust particles (more than 50 percent of the bulk coal contained particle sizes (volume diameter) greater than 13 µm). Due to the losses of larger particles within the aerosol generation and dispersal system in the laboratory, the conclusive inference on the influence of a large amount of non-respirable particles on individual cyclone collection performance is questioned. The tests may have failed to ensure that the cyclone has the ability to separate the larger dust particles from the respirable range.

- Although there was a 17 percent difference in the mean measured dust concentration between the samplers with cowl and without cowl, at very high test-dust concentration levels (35 mg/m^3 to 165 mg/m^3), the conclusion was reached that the modifications made to the South African cyclones did not either improve or degrade their performance in the laboratory experiment.

In this second phase of the project, particle size analysis on the sample dust collected from the field experiments was carried out using a Fritsch size analyser at the CSIR Miningtek laboratory. The volume diameter of the particle data was converted to aerodynamic diameter by a factor of 1.183 using the density of the particle. Table 6.2c summarises the particle size distributions from the BGI, cowl and without-cowl sampler dust.

Table 6.2c: Measured particle size distributions from the BGI, cowl and without-cowl samplers (using a Fritsch size analyzer)

Sampler Pair[o]	**Particulate % Finer, μm**		
	< 16 %	< 50 %	< 84 %
C_{WCOWL} (2,37 mg/m³)	0,75	2,20	6,50
C_{BGI} (3,89 mg/m³)	0,70	2,00	3,50
C_{WCOWL} (5,21 mg/m³)	0,85	3,00	24,0
C_{WCOWL} (6,13 mg/m³)	1,30	4,50	27,0
C_{COWL} (5,62 mg/m³)	1,50	4,50	27,0
C_{WCOWL} (5,56 mg/m³)	1,30	3,10	27,0
C_{WCOWL} (10,59 mg/m³)	1,30	3,50	17,0
C_{WCOWL} (9, 37 mg/m³)	0,95	2,40	7,00
C_{COWL} (39,92 mg/m³)	1,30	3,50	23,0
C_{WCOWL} (36,60 mg/m³)	1,30	4,00	26,0
C_{WCOWL} (53,26 mg/m³)	1,30	4,30	25,0
C_{WCOWL} (38,17 mg/m³)	1,40	4,30	26,0
C_{BGI} (17,11 mg/m³)	1,30	3,50	22,0
C_{WCOWL} (1261,72 mg/m³)	2,90	17,0	31,0
C_{COWL} (91,81 mg/m³)	1,50	6,00	24,0
C_{WCOWL} (2991 mg/m³)	5,00	20,0	35,0
C_{COWL} (1156 mg/m³)	2,00	10,0	27,0
C_{WCOWL} (42,89 mg/m³)	1,30	4,20	24,0
C_{BGI} (1201 mg/m³)	1,40	4,00	26,0
C_{WCOWL} (2471 mg/m³)	2,00	12,0	29,0

Dust sample pairs with enough weight for size analysis (greater than 2 mg) were collected for analysis. However, only a few samples with low concentrations were analyzed due to the sample mass limitations of FSA for size characterization. Therefore, in order to obtain a higher mass of dust on the filter, samples collected at a distance of greater than 2,5 m from the operator's position[1], whose concentration for the sampling period was in the range of 36 mg/m³ to 2 991 mg/m³ were analysed.

[o] Numbers in parentheses are the respective measured dust concentrations for the sampling period.
[1] This concentration should not be interpreted as the operator position concentration.

The plots of the size analysis of the sampled dust are shown in Appendix A (Figures A19 to A29) using the BGI, cowl and without-cowl samplers. From the results, the following conclusions were drawn:

- From the size distribution plots (Figures A19, A20 to A29), we notice that the mine-face atmospheric dust has two relative maximums, called modes (term adopted from statistics). Thus, the size distribution depicted can be referred to as a bi-modal distribution of mine-face atmospheric dust. The two identified modes are in the respirable (< 10 μm) and non-respirable (> 10 μm) size range of the dust size distribution.
- From the size analysis data of all the measured dust concentrations in the range 2,37 mg/m^3 to 10,59 mg/m^3, it is seen that the sampled respirable dust contained particles greater than 10 μm, except for the BGI sampler dust (3,89 mg/m^3 concentration).
- At very high measured dust concentrations, the cowl sampler lowered the loading of large particles (Figures A26). From the size distribution analysis data, we can conclude that the cowl samplers are the preferred samplers for taking engineering samples at high dust concentrations.
- However, the results showed that at very high dust concentrations, there is a huge variation in both the measured dust concentration and the size distribution for a paired sample (Figures A25 to A29).
- For a pair of cowl and without-cowl samplers, at a concentration of 5,6 mg/m^3, the D_{50} for the cowl and without-cowl samplers was 4,5 μm and 3,1 μm respectively (Figure A9). At a concentration of 38 mg/m^3, the D_{50} for cowl and without-cowl samplers was 3,5 μm and 4,0 μm respectively (Figures A24).
- At concentrations ranging from 5 mg/m^3 to 1 200 mg/m^3, the BGI performed well on the criteria of D_{50} and the presence of non-respirable particles.
- The analysis of the various samplers indicated the presence of wide size distributions for the same mass concentration of dust.
- Efforts were made to carry out a size analysis of dust mass concentrations of less than 5 mg/m^3. The analysis on the dust sample concentrations in the range of 5 to 6 mg/m^3 for an approximate sampling period of 300 minutes did indicate the presence of non-respirable particles (both with cowl and without cowl samplers).
- The D_{50} value of 4,0 μm with the use of a sample flow rate of 2,2 L/min, regardless of sampler type, could not be obtained for the dust samples analysed.
- The size analysis on the BGI sampler did indicate that the amount of non-respirable particles present is lower than that with the cowl and without-cowl samplers.

- It is thus evident that, although the dust mass collection of the samplers conforms to the requirements, the size distribution of the dust is not concomitantly accurate.

7 Discussions

Extensive work has been done to identify the factors associated with the variability of measured dust concentrations overseas. In connection with the current research work, the following studies reflect the extent of and the possible reasons identified for the variability in the measured sample concentrations:

- A Government Accounting Office (1975) report to the US Congress indicated that, under certain conditions, the error associated with respirable mine dust samples could be as great as 50 percent.
- A US National Bureau of Standards (1975) study focused specifically on gravimetric sampling and analysis, examining each step of the sampling process such as dust weighing and pump flow variation. It was concluded that under tightly controlled conditions, with a “well-trained” technician, the average standard deviation associated with the process was $\pm$ 0,39 mg/m^3, or 19 percent (at the 2 mg/m^3 standard dust concentration).
- NIOSH (1976) found that in high-risk mine sections, which failed to comply with the 2 mg/m^3 standard, the coefficient of variation in dust measurements was 91,6 percent.
- The National Resource Council in the USA (1980) concluded that the uncertainties associated with spatial and temporal variation in dust estimates from machine-mounted samplers precluded this method for estimating personal exposures.
- A study by Page and Jankowski (1984) comparing the dust measurements from paired RAM gravimetric samplers in a longwall mining operation gave results, expressed as dust ratios, of 0,41 to 1,63. The authors attributed this variation to differences in the aerosol cloud being sampled, to airflow velocity at the face and to cyclone orientation.
- Comparative studies of personal and fixed-point (area) samplers by Breslin *et al*. (1983) reported that the coefficient of variation of measured mine dust concentrations was typically less than 20 percent.
- In 1986, a study by Kissell *et al*. reviewed several factors contributing to the variability in measured dust concentration. They concluded that sampler position, geological variation in the composition of the coal (for variability in measured free silica), production factors such as deep or continuous cutting and failure to control known

sources such as shuttle-car loading, play an crucial role in dust concentration sample results.

- Sampling of and laboratory variability in respirable mine dust was studied by Hall *et al.* (1997) using 23 and 20 pairs of dust samples from coal and non-coal mines. In coal mines, mine dust ratios (larger to smaller values) exceeded 1,5 in half of the paired samples and 2,5 in 10 percent of the pairs. The variability of mine dust was somewhat lower in non-coal mines, with 50 percent of the samples having ratios greater than 1,13. Ten per cent of the samples demonstrated ratios of 6,19. Discussions indicated that in coal mines, the position of the sampler was an important contributor to the variability. Machine-mounted samplers showed a 40 percent improvement in variability for all measured parameters compared with personal samplers.

In spite of the problems facing the mining industry with regard to the accuracy of dust measurements, the industry's goal should be to find a standard measurement procedure using well-accepted sampling instruments. In an underground environment, the ideal sampler would collect a sample that represents the mine-ambient aerosol. In this study, the cyclone efficiencies of samplers were not evaluated, as a particle size analyser is needed to determine the size fraction characteristics of both the ambient and sample dust. Until now, it is not known whether the ambient coal dust size characteristics remain in a closely defined size range during the underground production period. Had data been available on such size characteristics, it would have been possible to determine the collection efficiency of samplers and the penetration contours to arrive at a conclusive judgment.

In an underground face, there is no clear air direction in terms of upwards or sideways as one finds in a test tunnel. Due to the harsh conditions that prevail underground, the effect of wind (speed and direction) on sampler performance at the operator could not be determined. However, the use of correlation coefficients and regression lines at individual positions does allow one to speculate as to the probable reasons.

Although the two sampling instruments differ with regard to their design, cost and ease of use, the statistical analysis showed that there were no significant differences between the mean dust concentrations measured by the various sampler pairs tested in the underground section. From all the measured sampling positions, the coefficient of correlation (r) determined was better than 0,95 for various regression lines (combinations of C_{BGI}, C_{COWL}, and C_{WCOWL}). Unlike in the laboratory experiments, the reference concentration could not be measured underground.

Overall, the following ***inferences*** can be drawn from the analysis of the concentration data from field tests:

- On average, for the same sampler types (C_{BGI}-C_{BGI}, C_{COWL}-C_{COWL} and C_{WCOWL}-C_{WCOWL}), there was a bias of 5,0 percent in the mean concentration measurement at the intake, operator and return positions.
- A comparison of the mean concentration data for C_{BGI} and C_{COWL} from the different positions shows that, on average, the cowl sampler under-samples by approximately 7,1 percent compared with the BGI sampler.
- A comparison of the combined mean concentration data from C_{BGI} and C_{WCOWL} from the different respective positions shows that, on average, the sampler without cowl over-samples by approximately 15,1 percent compared with the BGI sampler. However, it can be stated with confidence that this relation will hold for concentrations above 5,0 mg/m^3.
- A comparison of the combined C_{COWL} and C_{WCOWL} data from the different positions shows that, on average, the sampler without cowl over-samples by a mere 1,6 percent compared with the cowl sampler.
- From the statistical analysis (*t*-test and F-test), the mean dust concentration measured by pairs of cyclones is not significantly affected at 95 percent level of confidence. In other words, there is no difference between the measured mean dust concentration levels between various sampler pairs.

Overall, the following ***inferences*** can be drawn from the size analysis of the sample dust from various cyclones from field tests:

- From the size distribution plots, we notice that the mine-face atmospheric dust has two relative maximums, called modes. Thus, the size distribution depicted can be referred to as a bi-modal distribution of mine-face atmospheric dust. The two identified modes are in the respirable (< 10 μm) and non-respirable (> 10 μm) size range of the dust size distribution.
- From the size analysis data of all the measured dust concentrations in the range 2,37 mg/m^3 to 10,59 mg/m^3, it is seen that the sampled respirable dust contained particles greater than 10 μm, except for the BGI sampler dust (3,89 mg/m^3 concentration).

- At very high measured dust concentrations, the cowl sampler lowered the loading of large particles. From the size distribution analysis data, we can conclude that the cowl samplers are the preferred samplers for taking engineering samples at high dust concentrations.
- However, the results showed that at very high dust concentrations, there is a huge variation in both the measured dust concentration and the size distribution for a paired sample.
- For a pair of cowl and without-cowl samplers, for the same dust concentration levels, the D_{50} of both samples were different. The analysis of the various samplers indicated the presence of wide size distributions for the same mass concentration of dust.
- At concentrations ranging from 5 mg/m^3 to 1 200 mg/m^3, the BGI performed well on the criteria of D_{50} and the presence of non-respirable particles.
- The analysis on the dust sample concentrations in the range of 5 to 6 mg/m^3 for an approximate sampling period of 300 minutes did indicate the presence of non-respirable particles (both with cowl and without cowl samplers).
- The D_{50} value of 4,0 µm with the use of a sample flow rate of 2,2 L/min, regardless of sampler type, could not be obtained for the dust samples analysed.
- The size analysis on the BGI sampler did indicate that the amount of non-respirable particles present is lower than that with the cowl and without-cowl samplers.
- It is thus evident that, although the dust mass collection of the samplers conforms to the requirements, the size distribution of the dust is not concomitantly accurate.

8 Conclusions

In summary, following conclusions were made from the current study:

- The work carried out in the field demonstrates equivalent dust concentration results from the two sampler types in different positions within the mine. The extent of the agreement between the two sets of results seems to be excellent and much better than that for results obtained in the laboratory results or in non-mining workplaces.
- The field study failed to conclusively determine whether the modifications made to the South African cyclone either improve or degrade its performance for the conditions tested, based on the results of the size analyses.
- From the field observations, it can be stated that the cowl sampler can be used for engineering sampling to avoid the dependence of the cyclone inlet on orientation in the collection of particles.

- The data analysis and field experience have shown that in comparison with other samplers, BGI samplers greatly reduce the amount of oversized particles deposited onto the filter from the inversion of cyclones. Also, due to the design of its cyclone inlet, the BGI sampler is not affected by orientation dependence.
- The field observations did indicate that when collecting samples closer to the face, where high concentrations of dust are present, sample handling is extremely difficult. At high dust concentrations, the probability of non-respirable particles depositing onto the filter from the grit pot is very high when the sampling pump is switched off. However, the BGI sampler, due to its design, alleviates this problem to some extent.
- In both the laboratory and field tests, a sufficient mass of sample dust was required for analysis with the Fritsch analyser to determine the presence of non-respirable particles. This led to the conclusion that there may have been non-respirable particles in the concentrations below 5 mg/m^3 (as found from this study).
- The size analysis of the collected dust mass for sample concentrations greater than 5 mg/m^3 did not follow either BMRC or ISO/ACGIH/CEN respirable curves. The evaluation of the same samplers in the UK laboratory produced conflicting results.
- The cowl sampler could not be recommended for personal sampling because the results of the size analysis are inconclusive and wide-ranging.
- Finally, question of cowl under-sampling or over-sampling could not be resolved confidently from size distribution data at concentrations below 5 mg/m^3 despite the insignificant differences obtained from comparison of mass concentrations alone.

9 Recommendations

From the conclusions drawn, the following recommendations for future research are proposed, although it is suggested that there should be a paradigm shift in the existing sampling procedure and instruments in the future project:

- The results were inconclusive with regard to the recommendations on the usage of adding a cowl to the cyclone in the personal sampling method. However, the use of a cowl for taking engineering samples can be recommended on the grounds that it lowers sample-handling errors, the probable reason being that in practice it reduces factors such as the wind and orientation-dependence of the cyclone inlet. Further work on proving the use of the cowl sampler for personal sampling could be considered.

- At high dust concentrations, it was difficult to determine which sampler measured the "true concentration." Therefore, future field tests should incorporate the aspect of "impactor sampling" from which both the mass concentration and the size distribution of ambient particles can be accurately determined.
- Despite some of the cyclones being accepted for sampling in the industry, concerns were expressed about the cyclone performance with respect to the BMRC and ISO/ACGIH/CEN respirable curves. Fears were also expressed about whether the cyclones do follow the BMRC respirable curve under concentrations below 5 mg/m^3. Further work for recommendations on the use of cowl sampler for personal sampling could be considered.
- Similar studies should be carried out to compare these samplers with CIP10 samplers and to investigate their variances and size distribution. The different makes of samplers should also be investigated to determine the relationship between them, not only with regard to the amount of dust collected but also in terms of the size characteristics of the dust.
- Immediate attention needs to be given to analysing both the compliance and non-compliance samples from the mines which have difficulty in maintaining the 1997 DME directive. On the basis of this outcome, there needs to be clarification on the matter of evaluating all the cyclones currently being used in the mines.
- An extensive facility, including a chamber and a particle size analyser for analysing sample mass on compliance samples of less than 5 mg/m^3, needs to be established for this serious issue of sampling. A respirable dust programme needs to be established covering the area of dust sampling, measurement and data analysis that will enable the mines to resolve the technical aspects of exposure assessment.

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APPENDIX A

Table A1: Linear regression details between pairs of samplers at the intake

Sample Pair @ Intake	Regression Line	Correlation Coefficient (r)
C_{BGI} - C_{BGI}	y = 0,6202x + 0,3839	0,881
C_{COWL} - C_{COWL}	y = 1,1587x – 0,1134	0,975
C_{WCOWL} - C_{WCOWL}	y = 0,7505 x + 0,3279	0,687
C_{BGI} - C_{COWL}	y = 0,9783x + 0,0211	0,987
C_{BGI} - C_{WCOWL}	y = 0,151x + 0,2437	0,090
C_{COWL} - C_{WCOWL}	y = 0,8345x + 0,0715	0,850

Table A2: Linear regression details between pairs of samplers at the operator

Sample Pair @ Operator	Regression Line	Correlation Coefficient (r)
C_{BGI} - C_{BGI}	y = 0,8201x + 0,4258	0,978
C_{COWL} - C_{COWL}	y = 1,0746x + 0,0384	0,967
C_{WCOWL} - C_{WCOWL}	y = 0,928x + 0,0751	0,912
C_{BGI} – C_{COWL}	y = 0,9492x - 0,1984	0,952
C_{BGI} – C_{WCOWL}	y = 0,6017x + 1,0441	0,823
C_{COWL} – C_{WCOWL}	y = 1,1193x - 0,883	0,975

Table A3: Linear regression details between pairs of samplers at the return

Sample Pair @ Return	Regression Line	Correlation Coefficient (r)
C_{BGI} - C_{BGI}	y = 1,0251x - 0,0041	0,989
C_{COWL} - C_{COWL}	y = 0,9032x + 0,0373	0,859
C_{WCOWL} - C_{WCOWL}	y = 0,9288x + 0,1008	0,942
C_{BGI} - C_{COWL}	y = 0,9409x + 0,0589	0,910
C_{BGI} - C_{WCOWL}	y = 1,5487x - 0,3487	0,938
C_{COWL} - C_{WCOWL}	y = 0,8734x + 0,4167	0,927

Table A4: Combined linear regression details between pairs of samplers

Sample Pair (all positions)	Regression Line	Correlation Coefficient (r)
C_{BGI} - C_{BGI}	y = 0,848x + 0,247	0,986
C_{COWL} - C_{COWL}	y = 1,085x – 0,1122	0,978
C_{WCOWL} - C_{WCOWL}	y = 0,929x + 0,076	0,951
C_{BGI} - C_{COWL}	y = 0,914x + 0,0267	0,969
C_{BGI} - C_{WCOWL}	y = 1,103x + 0,068	0,953
C_{COWL} - C_{WCOWL}	y = 1,002x + 0,0396	0,985

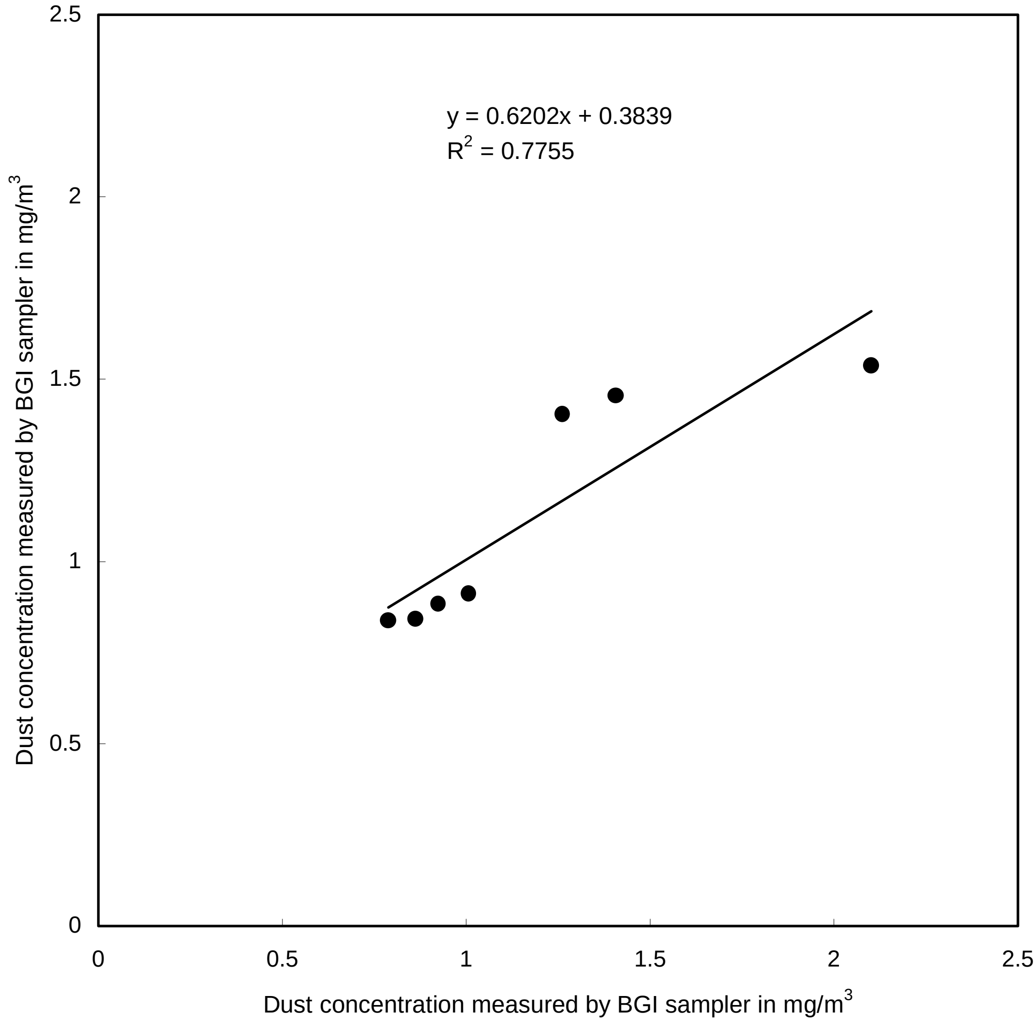

Figure A1: Plot of combined dust concentrations obtained from two BGI samplers at the section intake

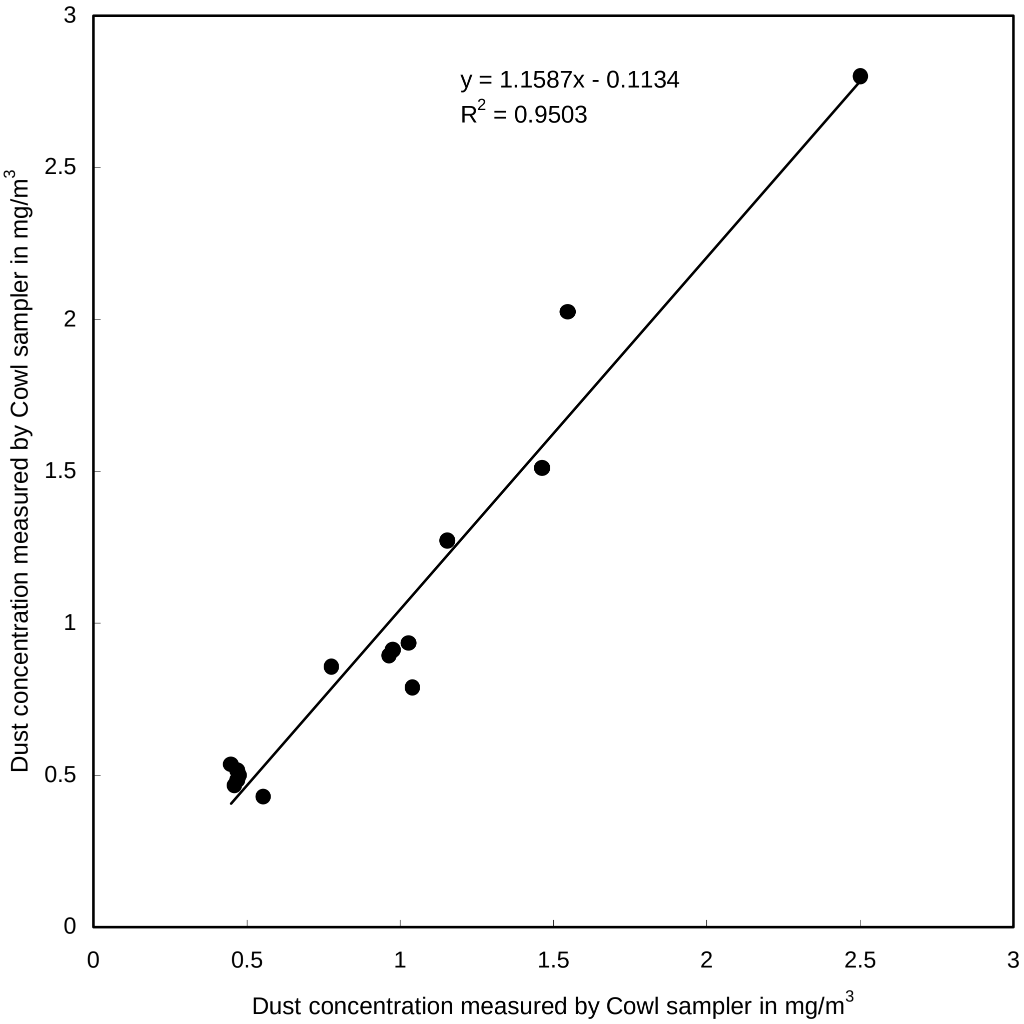

Figure A2: Plot of combined dust concentrations obtained from two cowl samplers at the section intake

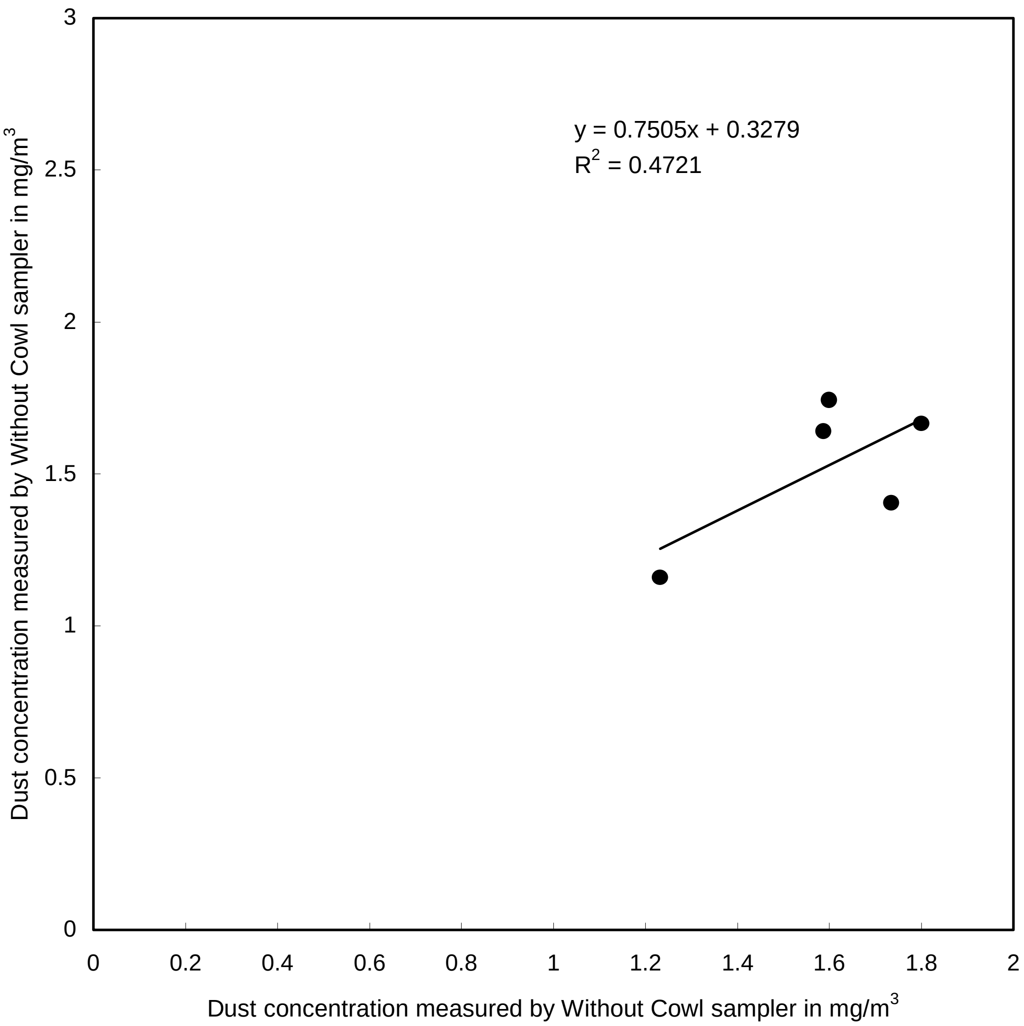

Figure A3: Plot of combined dust concentrations obtained from two without-cowl samplers at the section intake

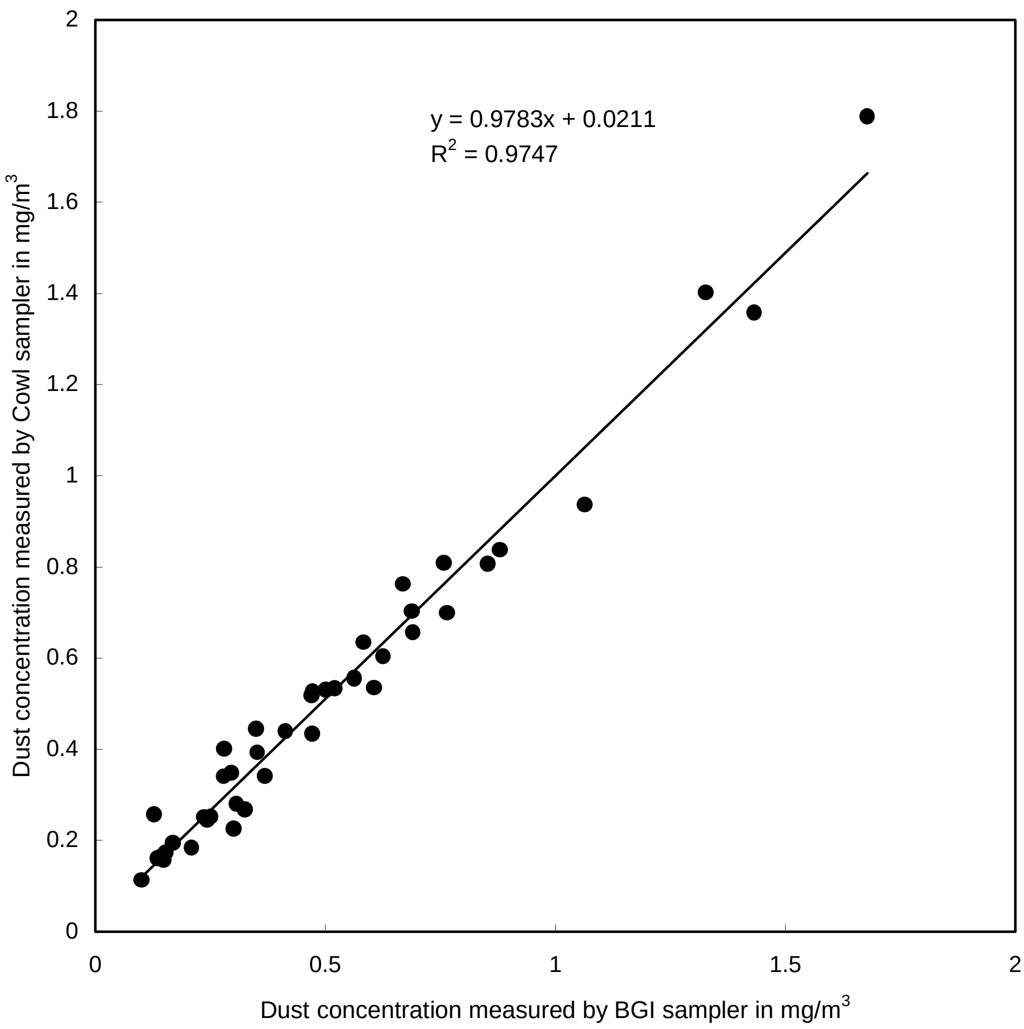

Figure A4: Plot of combined dust concentrations obtained from BGI and cowl samplers at the section intake

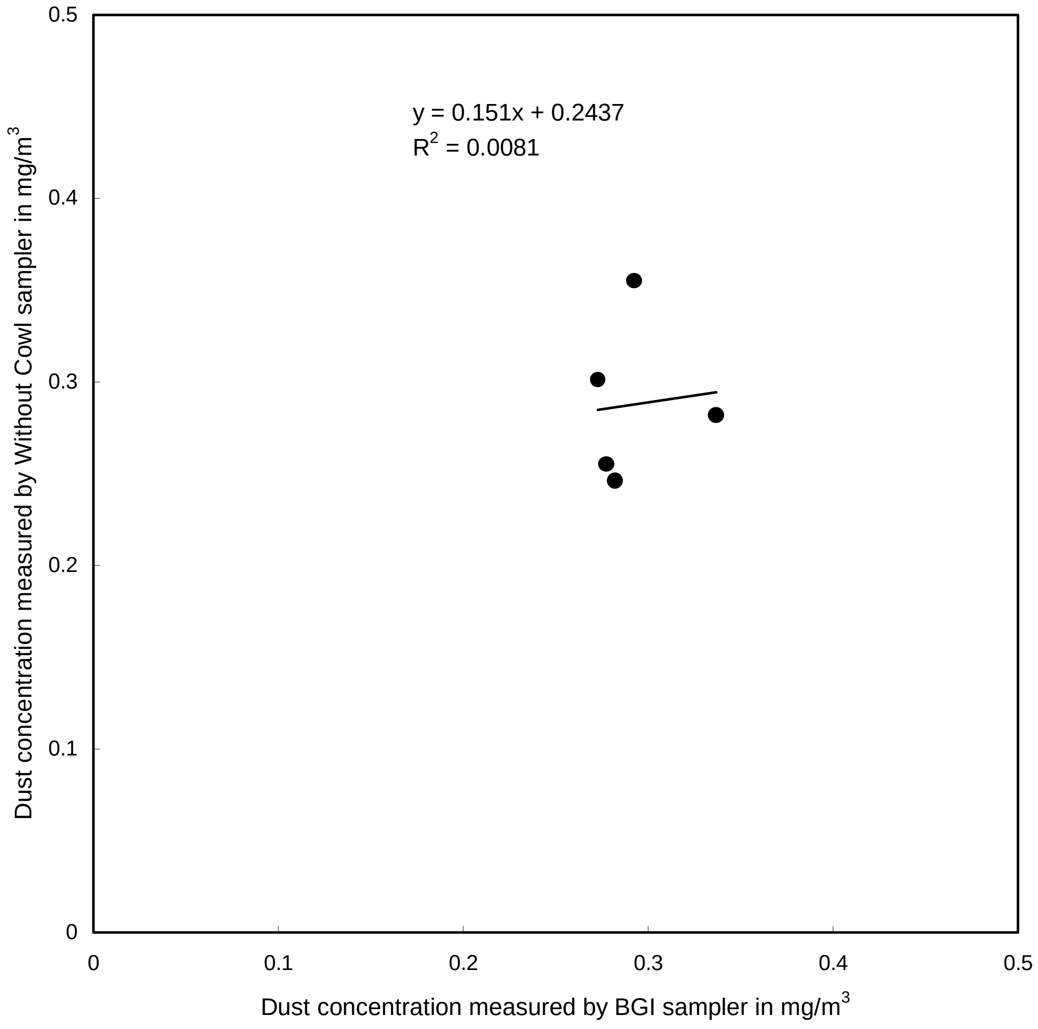

Figure A5: Plot of combined dust concentrations obtained from BGI and without-cowl samplers at the section intake

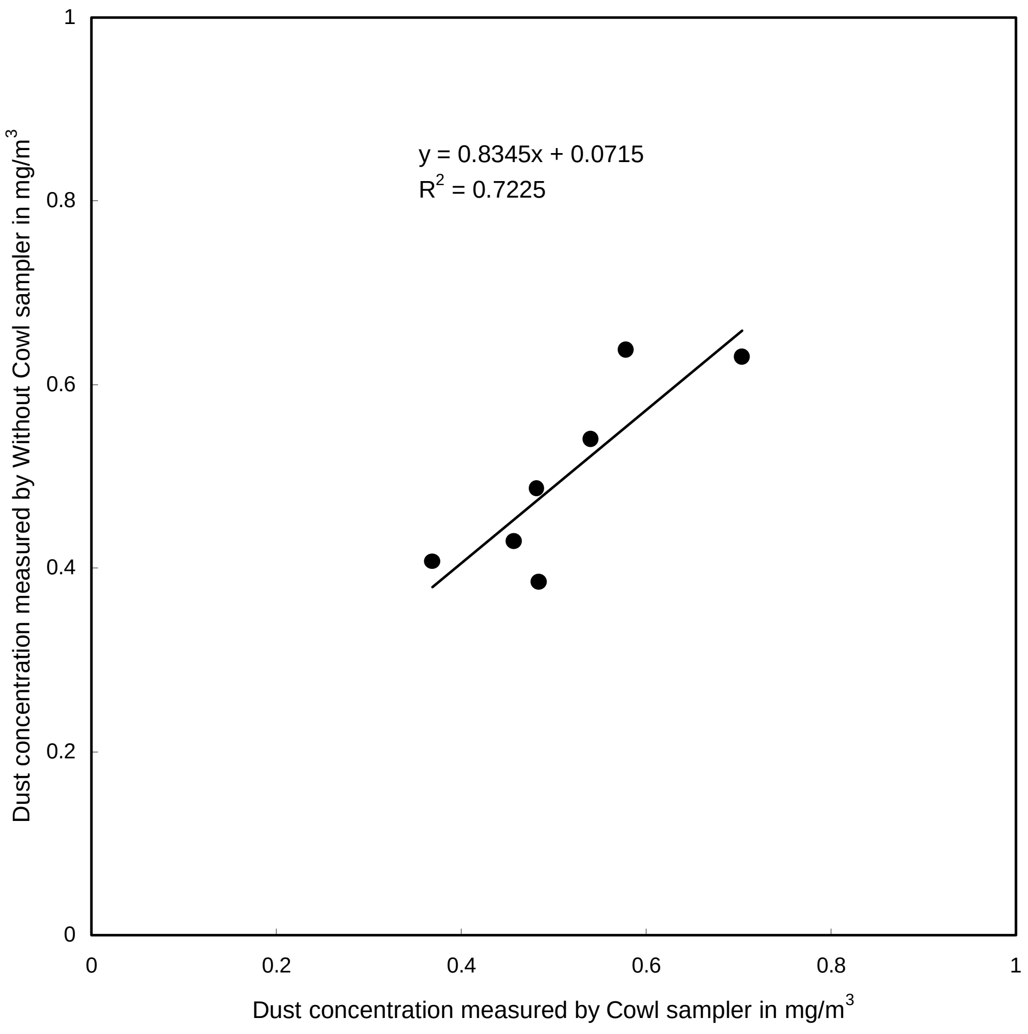

Figure A6: Plot of combined dust concentrations obtained from cowl and without-cowl samplers at the section intake

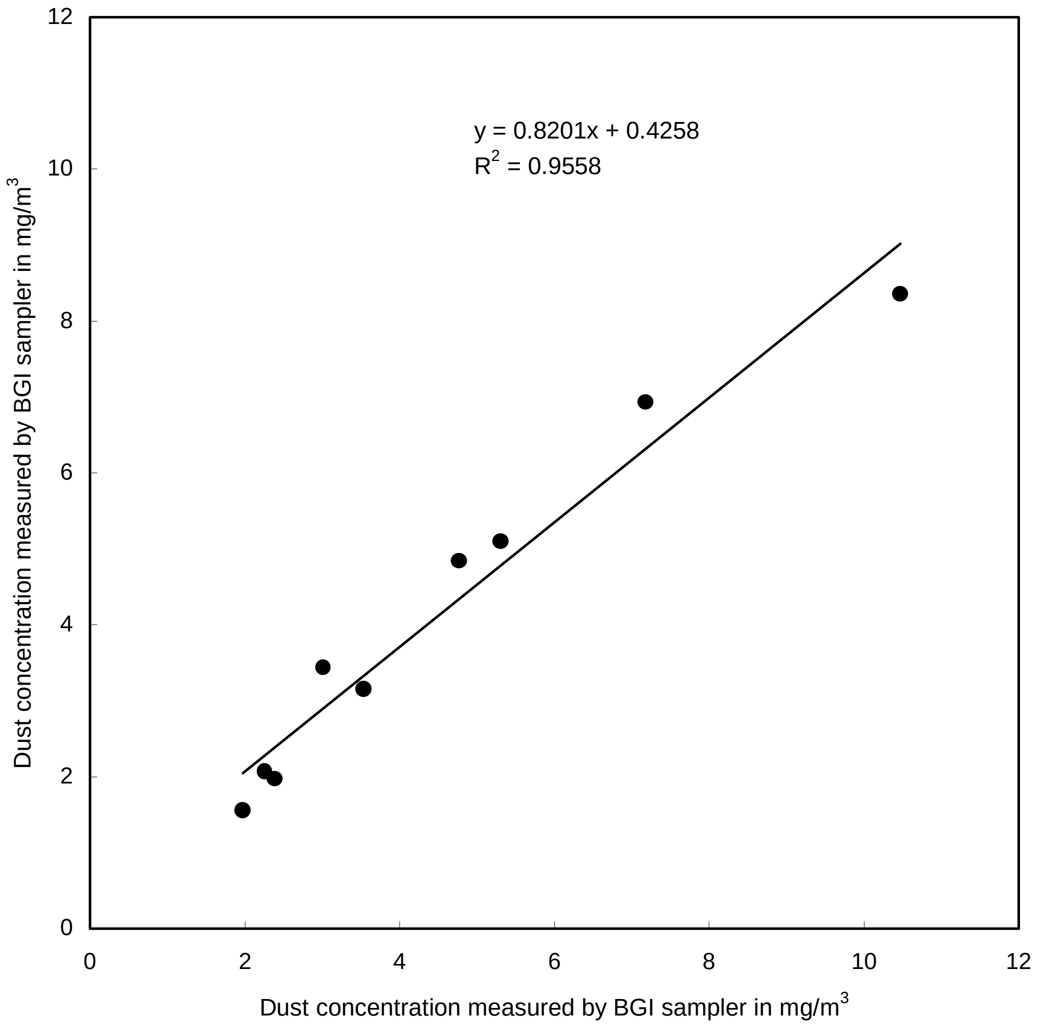

Figure A7: Plot of combined dust concentrations obtained from two BGI samplers at the operator

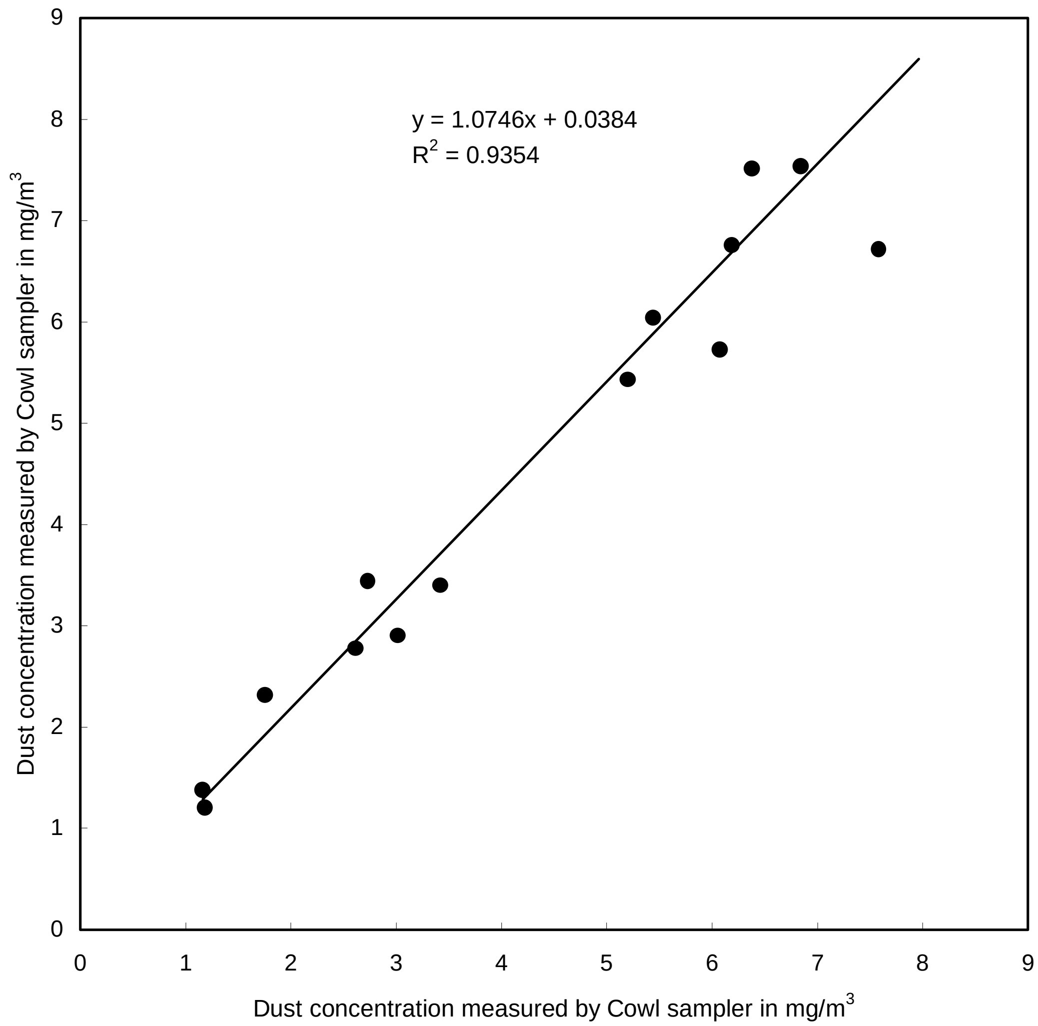

Figure A8: Plot of combined dust concentrations obtained from two cowl samplers at the operator

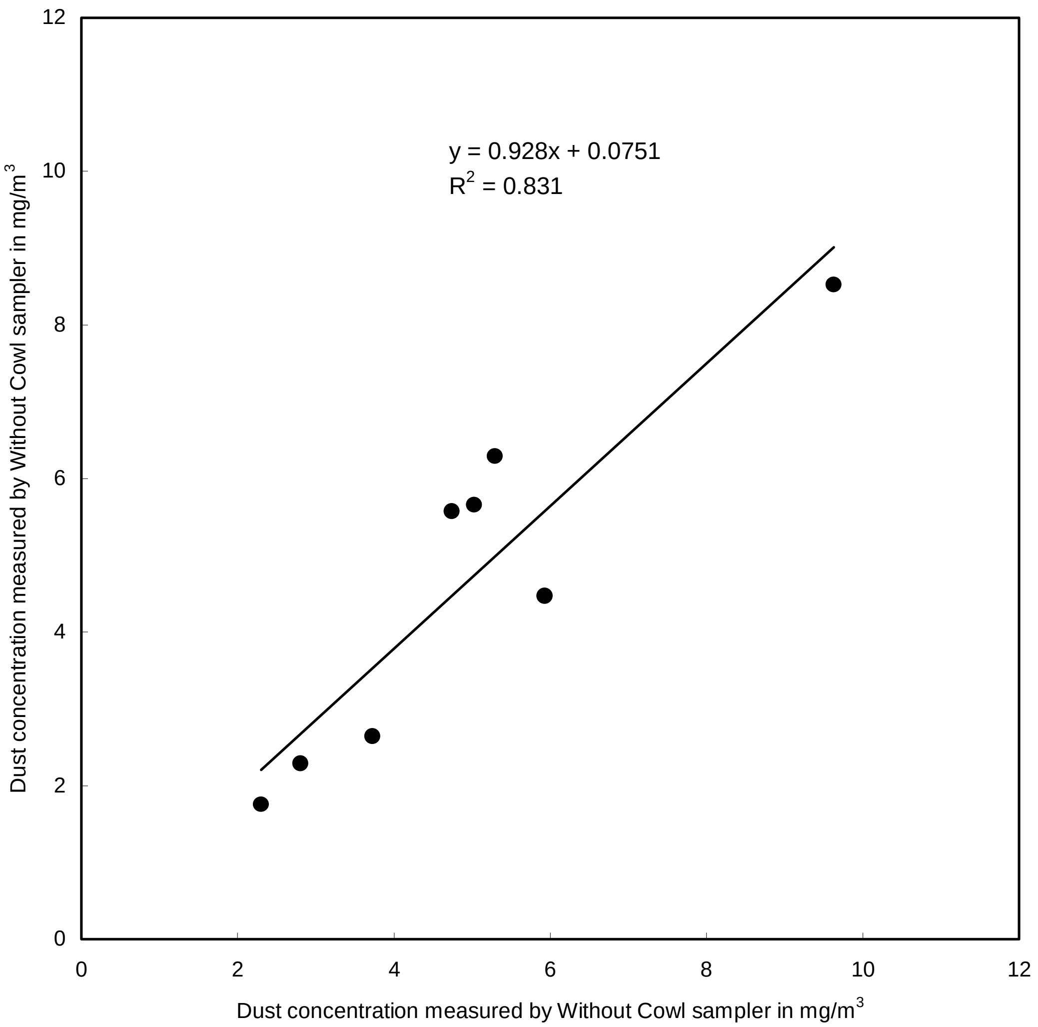

Figure A9: Plot of combined dust concentrations obtained from two without-cowl samplers at the operator

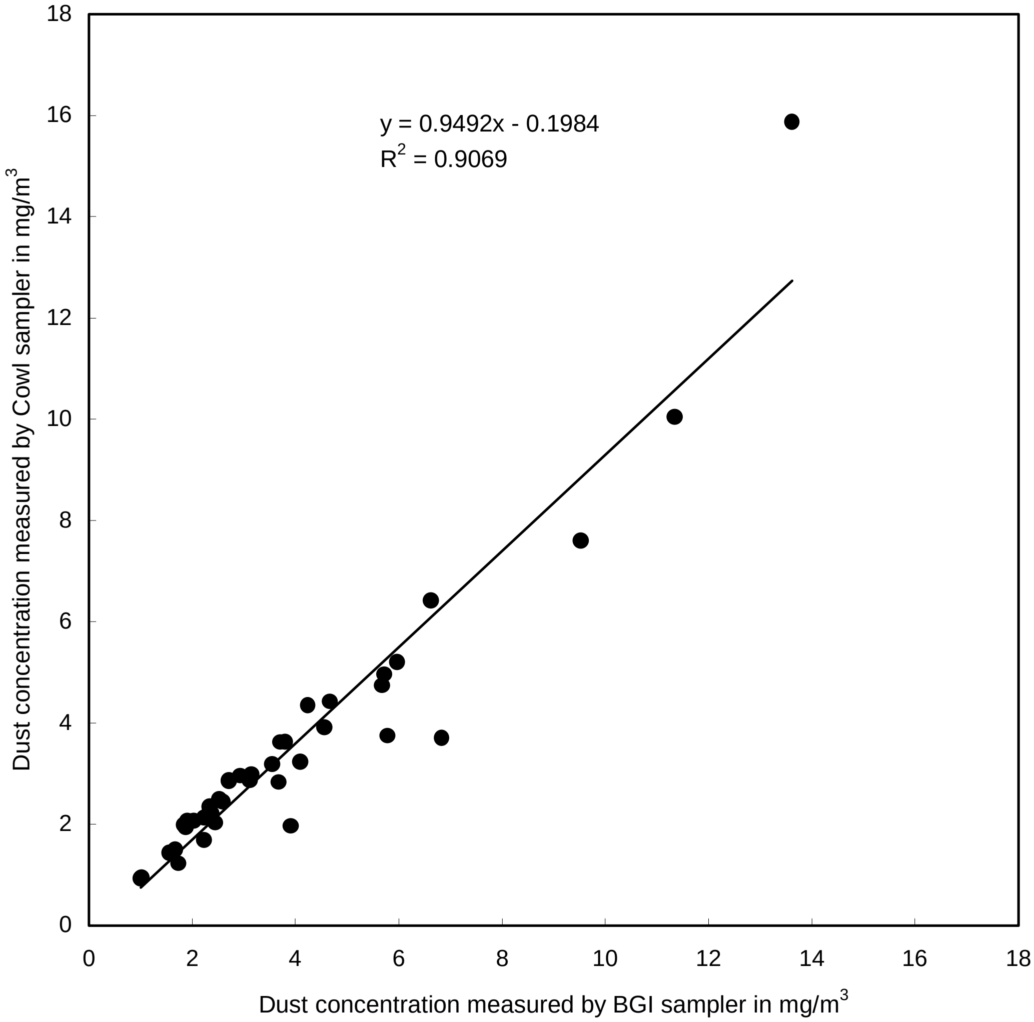

Figure A10: Plot of combined dust concentrations obtained from BGI and cowl samplers at the operator

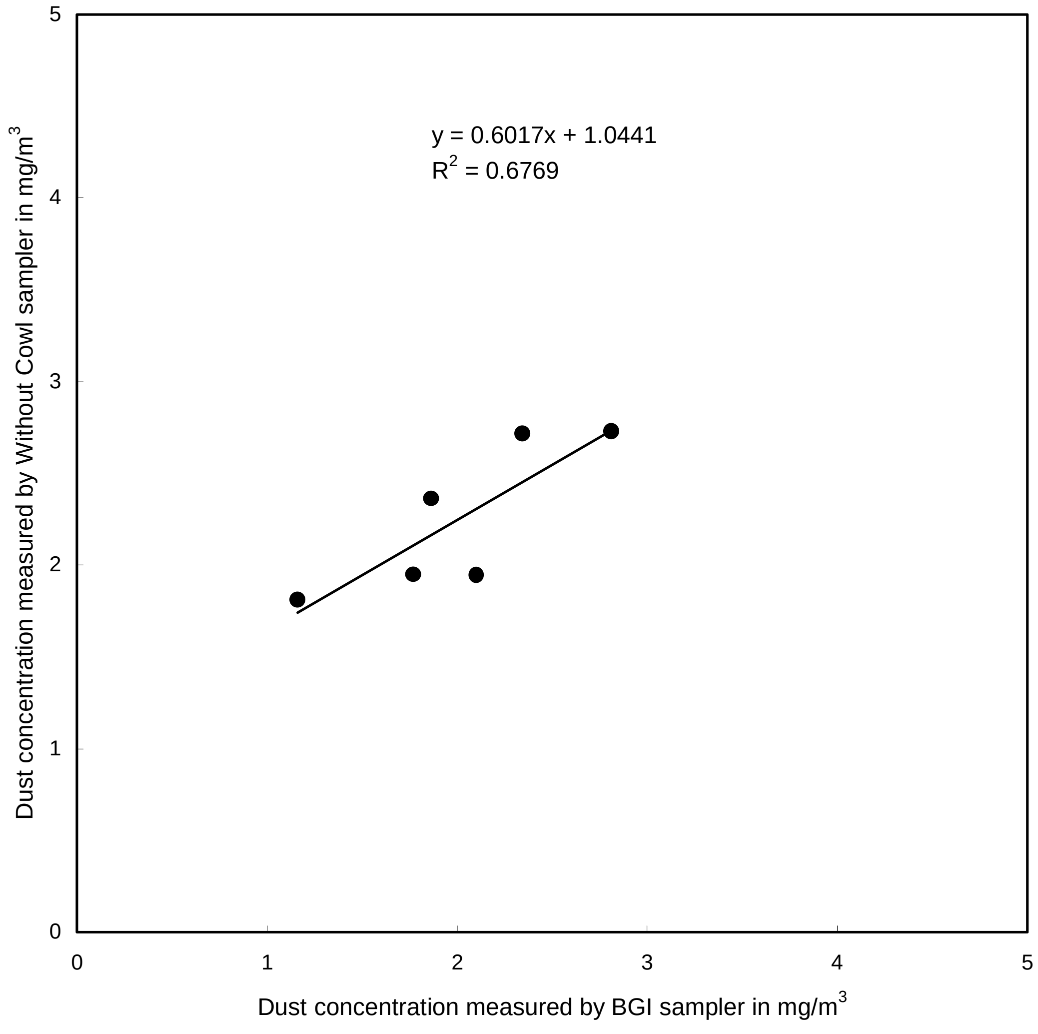

Figure A11: Plot of combined dust concentrations obtained from BGI and without-cowl samplers at the operator

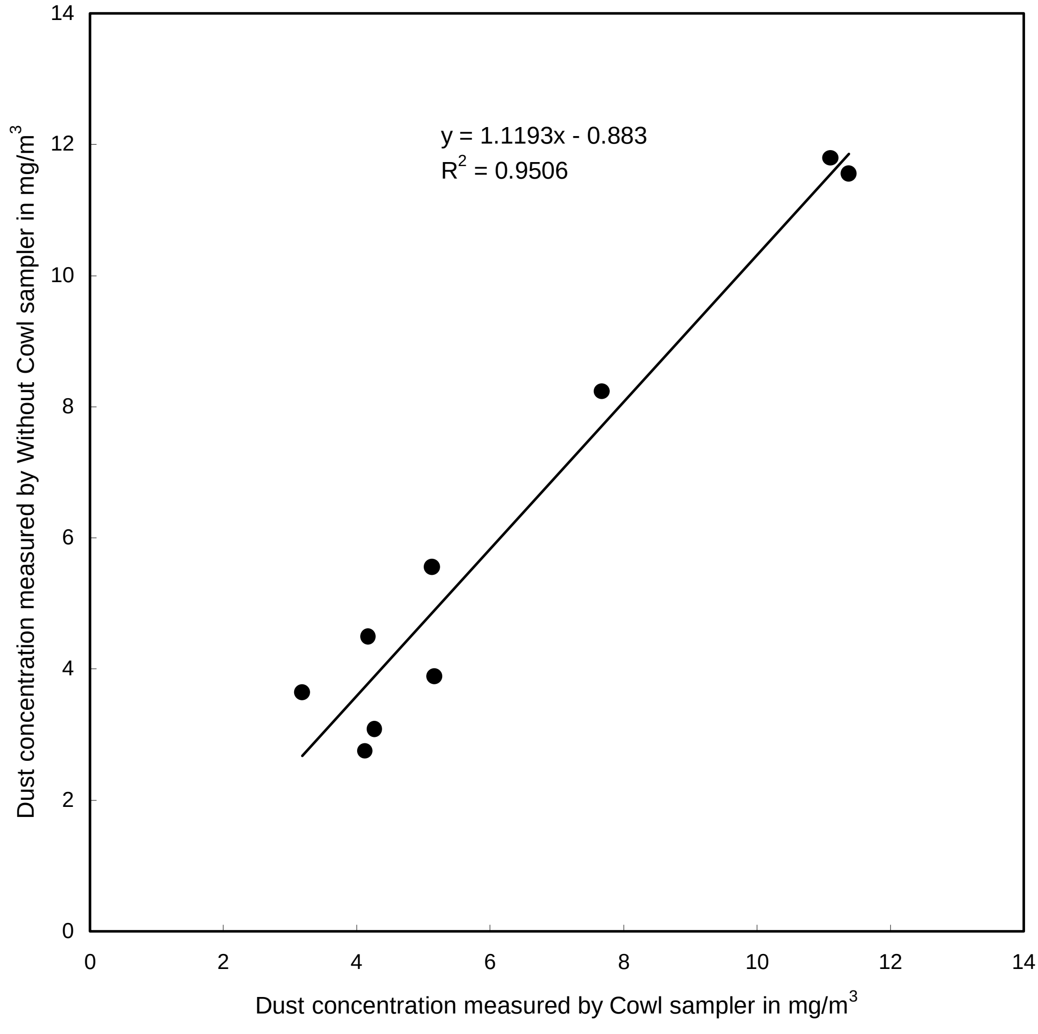

Figure A12: Plot of combined dust concentrations obtained from cowl and without-cowl samplers at the operator

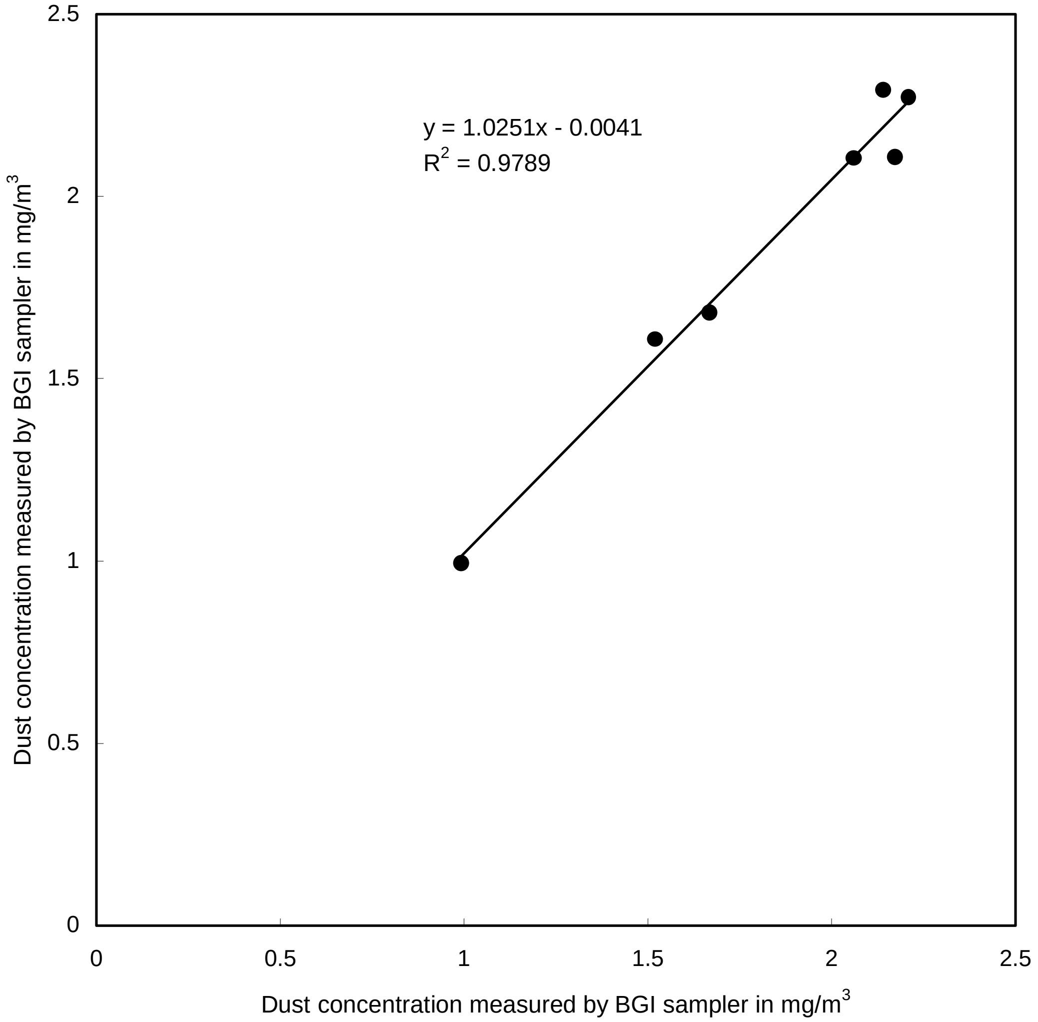

Figure A13: Plot of combined dust concentrations obtained from two BGI samplers at the section return

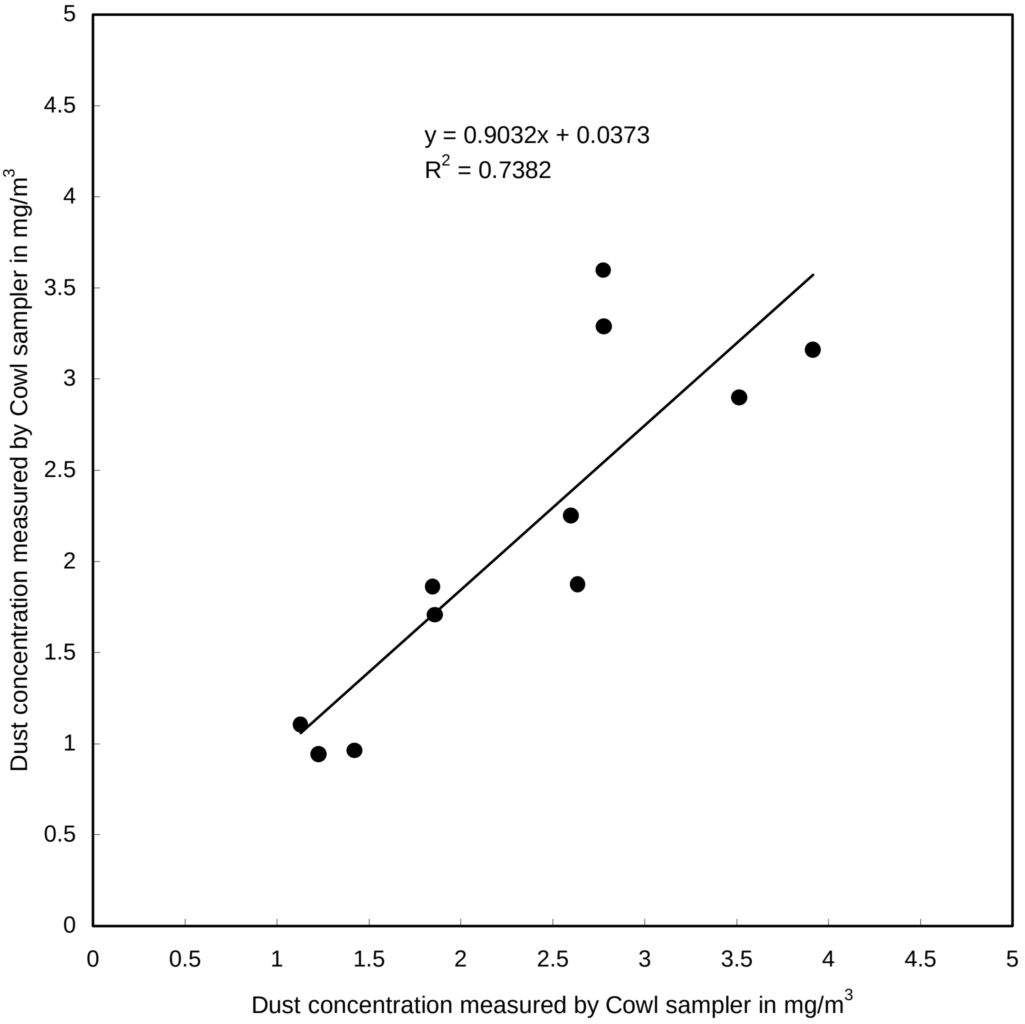

Figure A14: Plot of combined dust concentrations obtained from two cowl samplers at the section return

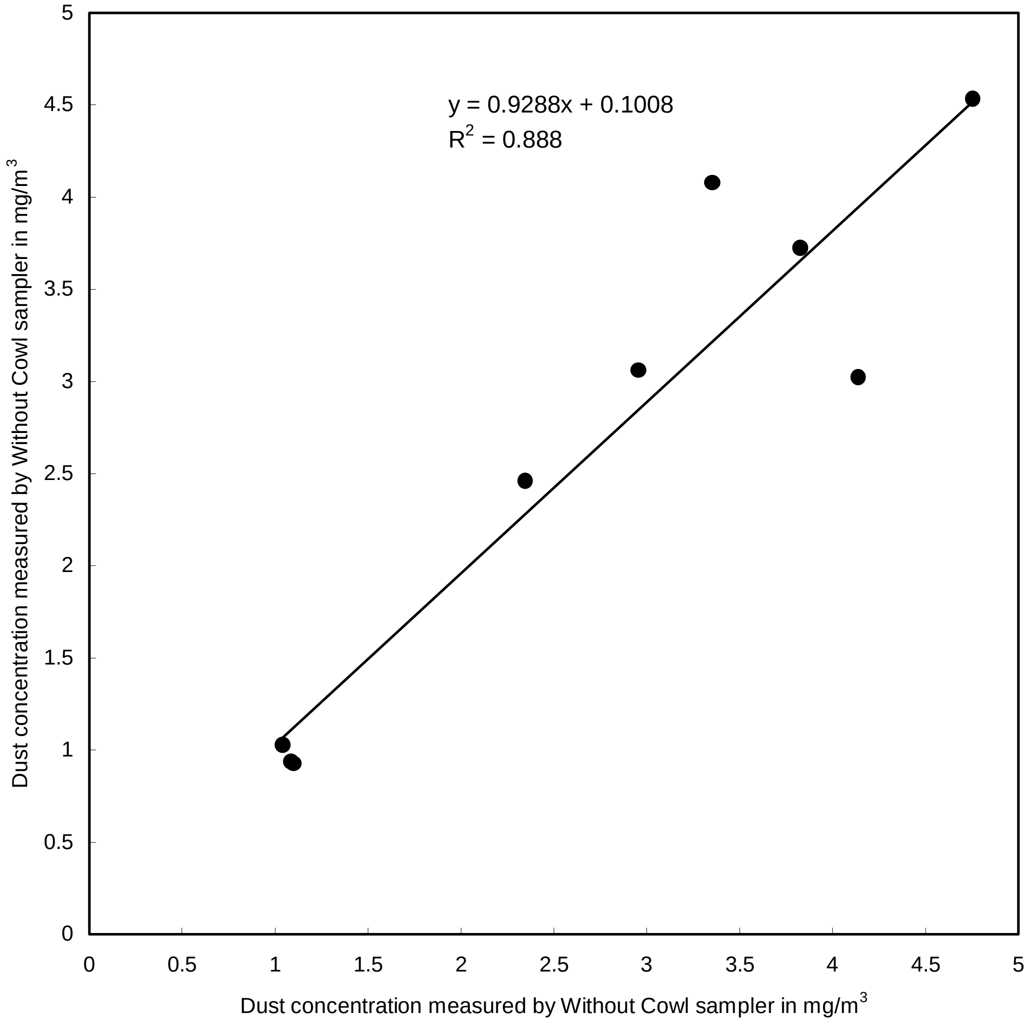

Figure A15: Plot of combined dust concentrations obtained from two without-cowl samplers at the section return

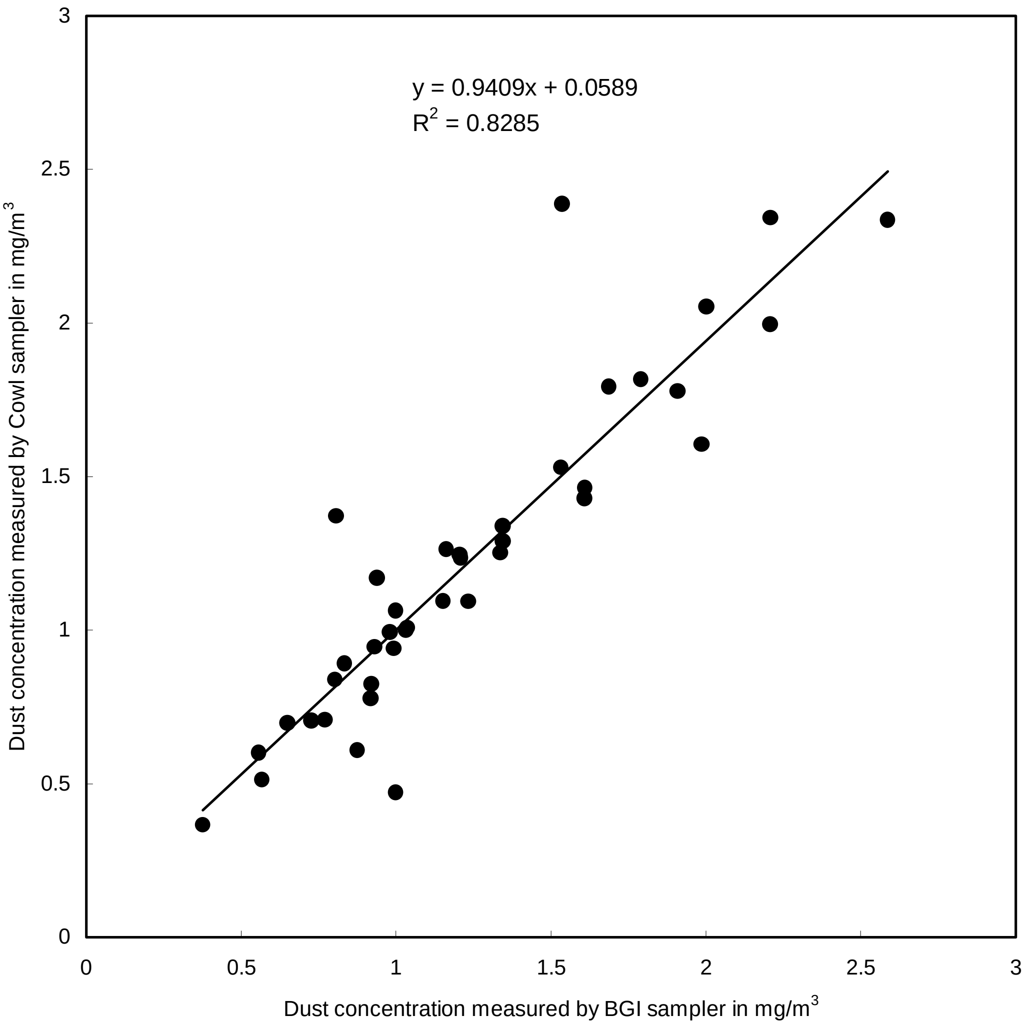

Figure A16: Plot of combined dust concentrations obtained from BGI and cowl samplers at the section return

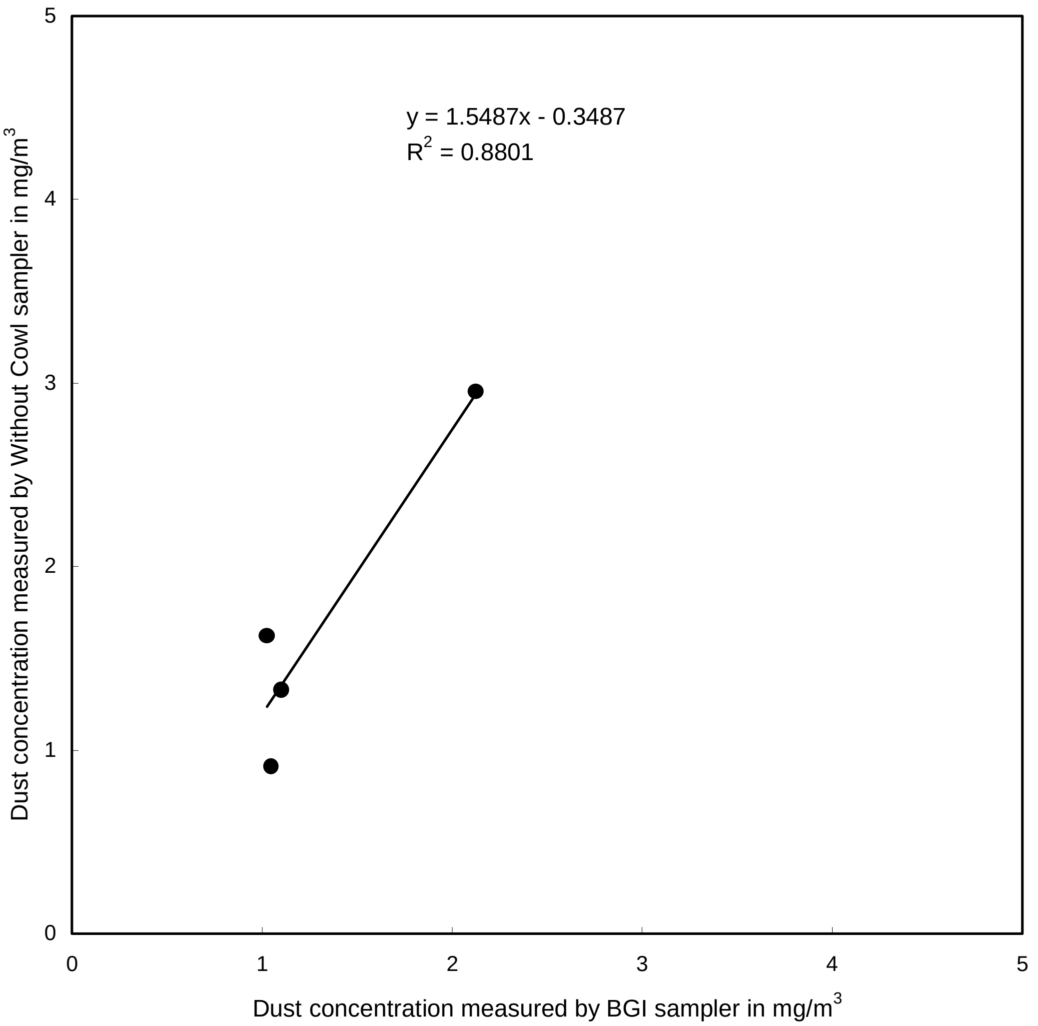

Figure A17: Plot of combined dust concentrations obtained from BGI and without-cowl samplers at the section return

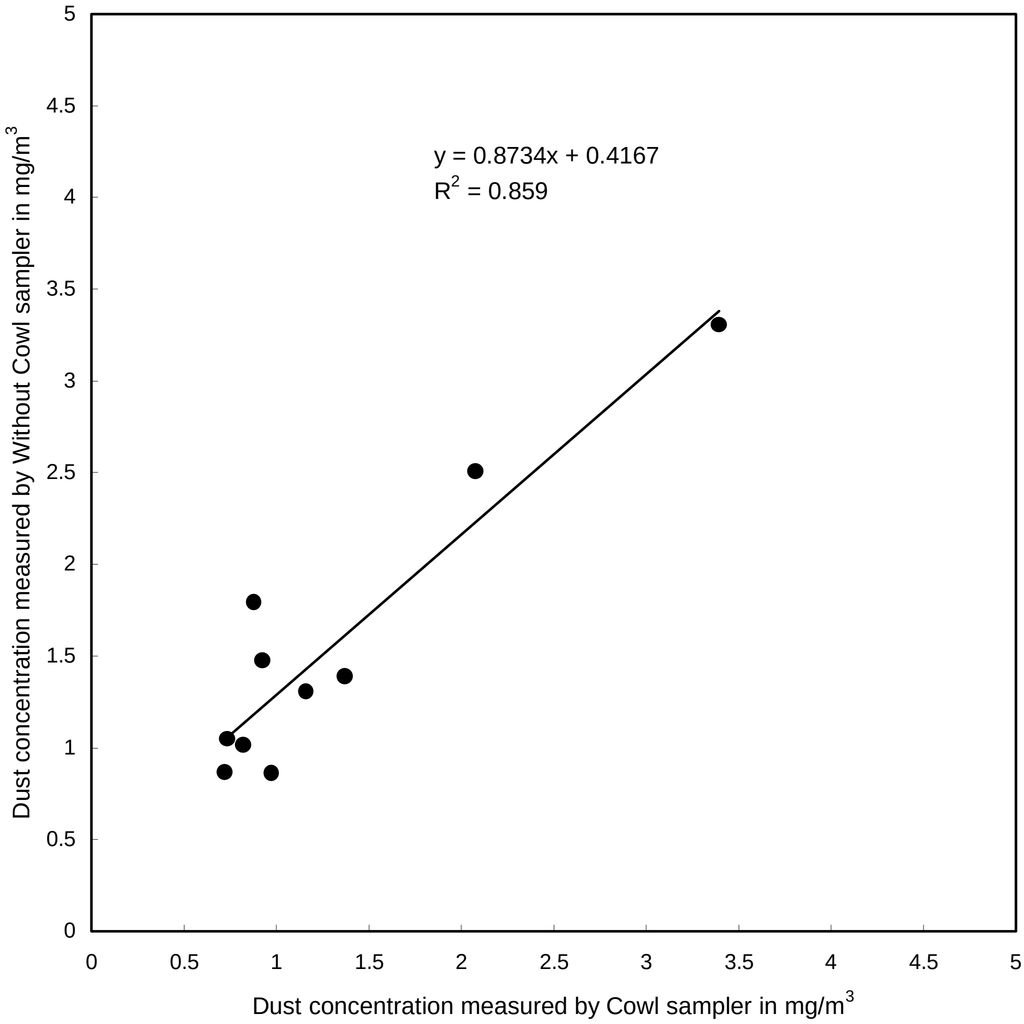

Figure A18: Plot of combined dust concentrations obtained from cowl and without-cowl samplers at the section return

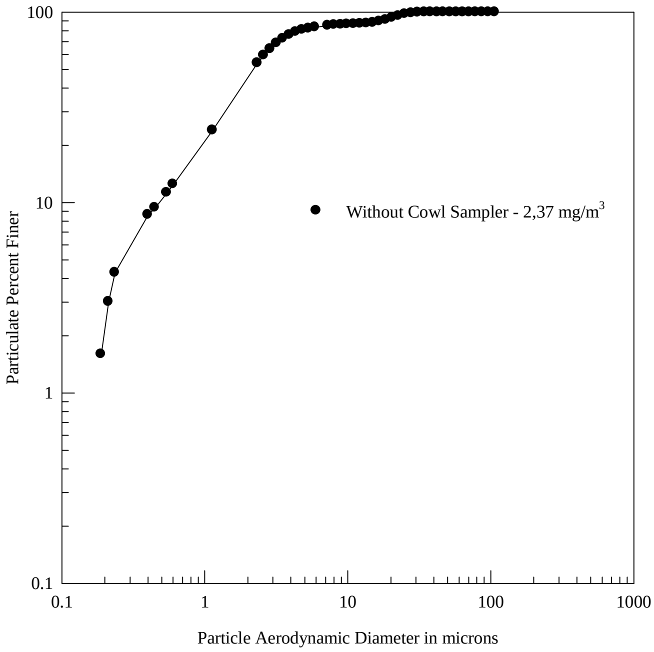

Figure A19: Particle size distribution of sampled dust from without cowl cyclone

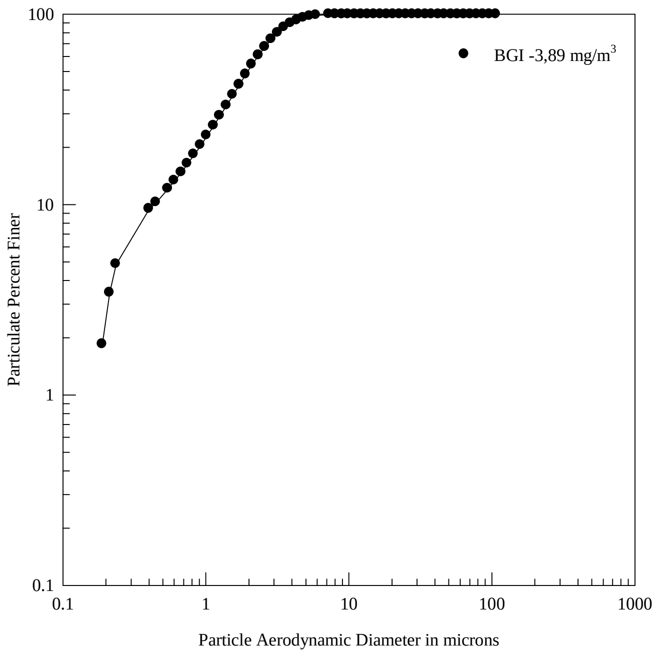

Figure A20: Particle size distribution of sampled dust from BGI cyclone

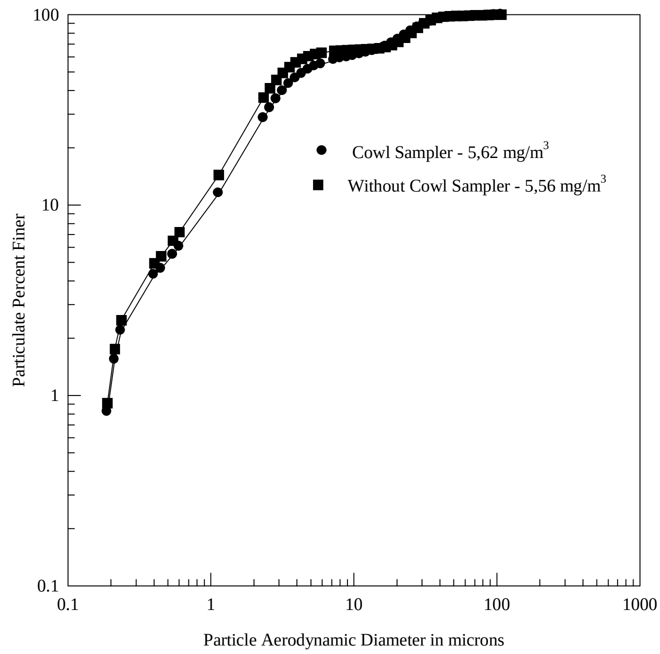

Figure A21: Particle size distribution of sampled dust from cowl and without cowl cyclone

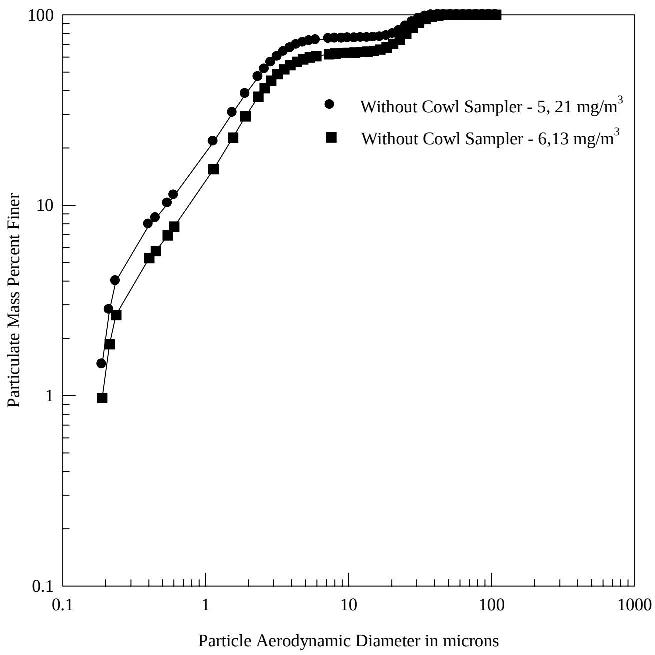

Figure A22: Particle size distribution of sampled dust from without cowl cyclone

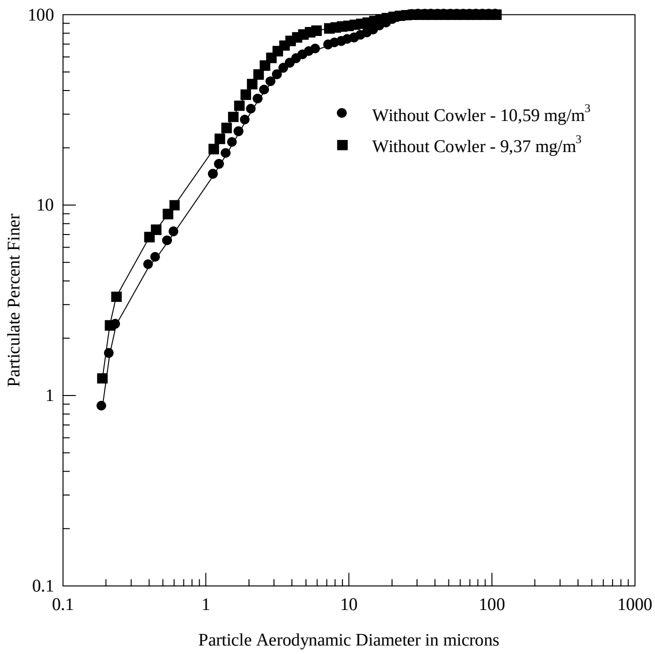

Figure A23: Particle size distribution of sampled dust from without cowl cyclone

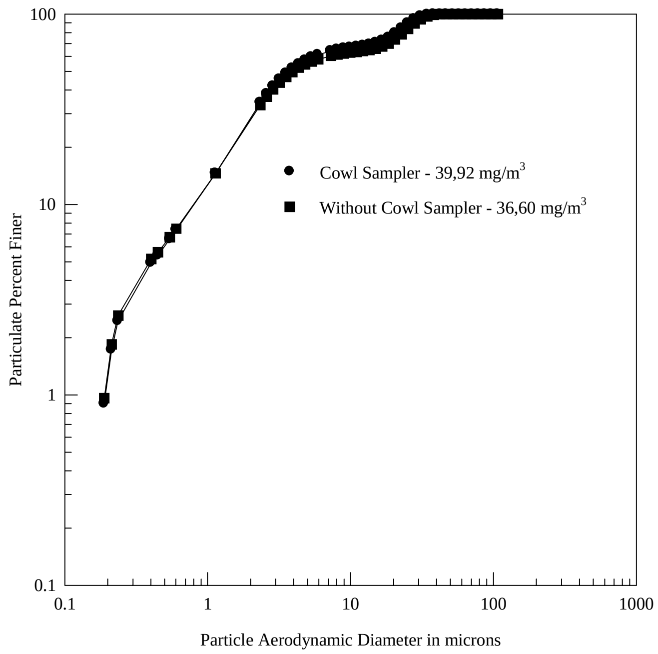

Figure A24: Particle size distribution of sampled dust using cowl and without cowl cyclone

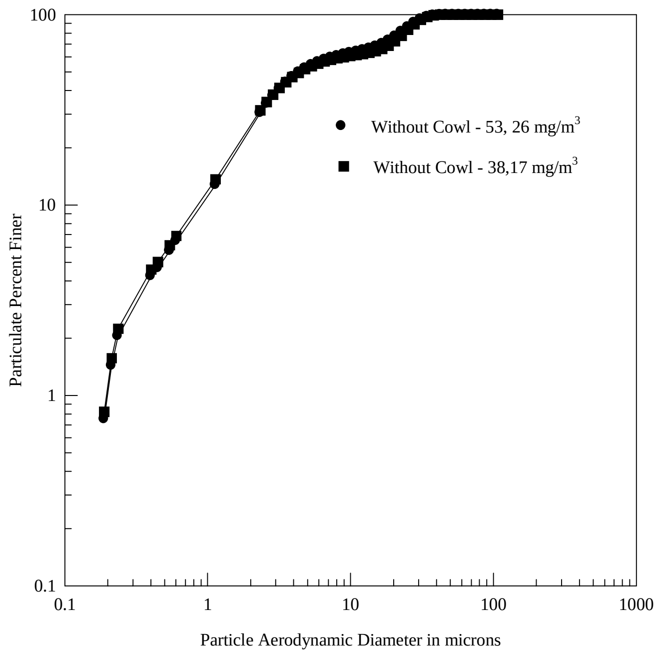

Figure A25: Particle size distribution of sampled dust from without cowl cyclone

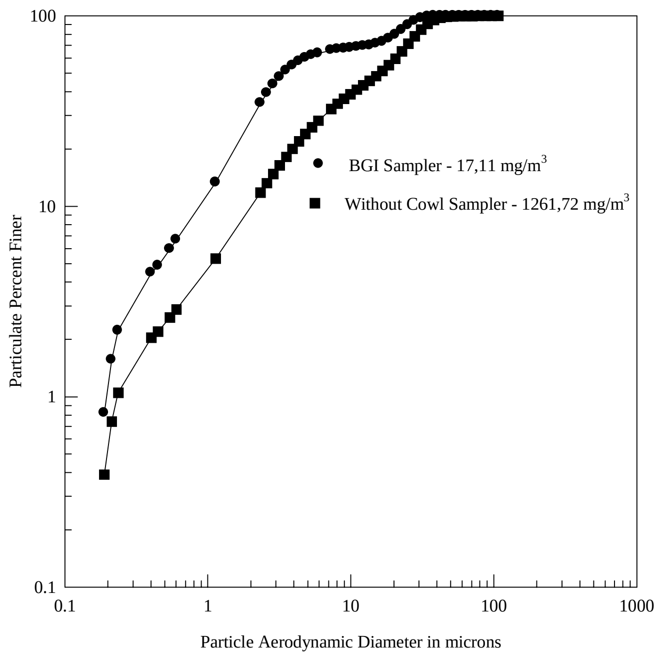

Figure A26: Particle size distribution of sampled dust from BGI and without cowl cyclone

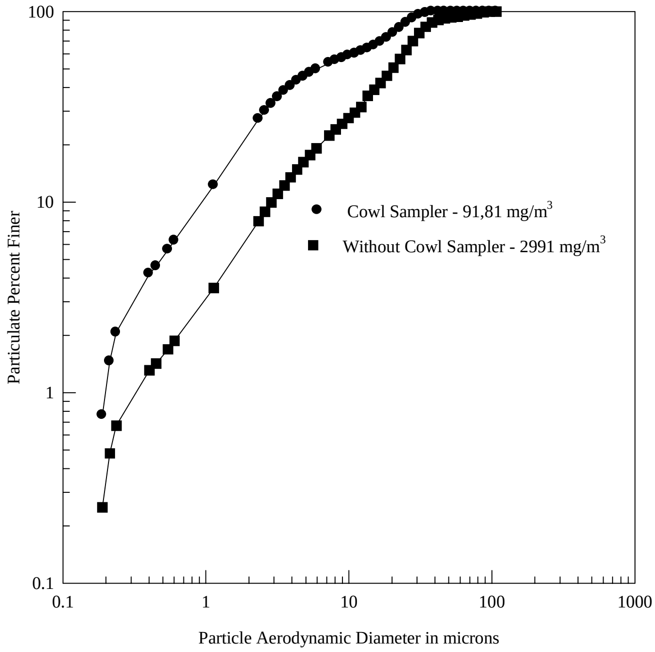

Figure A27: Particle size distribution of sampled dust from cowl and without cowl cyclone

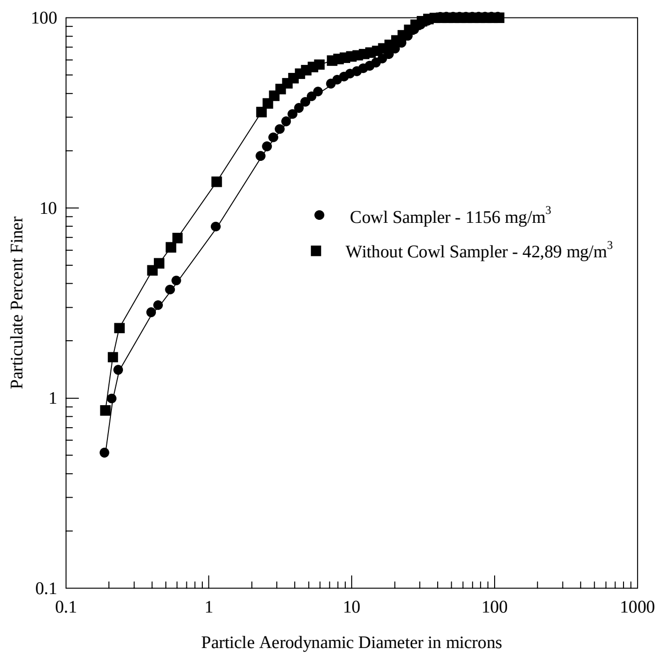

Figure A28: Particle size distribution of sampled dust from cowl and without cowl cyclone

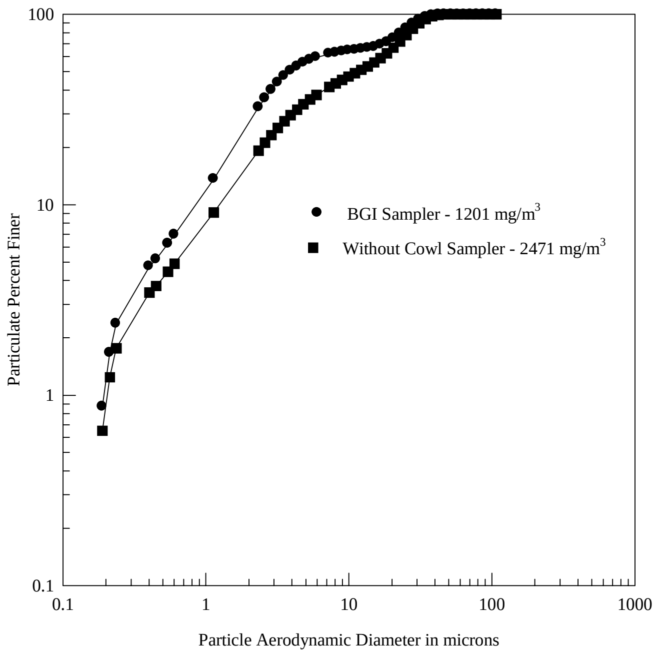

Figure A29: Particle size distribution of sampled dust from BGI and without cowl cyclone