2012

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Publication Details

B. Belle, Experiences of the institute of occupational medicine foam respirable sampler use in mines, 12th Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2012, 202-211.

EXPERIENCES OF THE INSTITUTE OF OCCUPATIONAL MEDICINE FOAM RESPIRABLE SAMPLER USE IN MINES

Bharath Belle

ABSTRACT: The mining industry worldwide spends a significant amount of human and financial resources in sampling of safety and health hazards for ensuring adequate control measures. Most mining countries carry out personal exposure monitoring for respirable dust. Unlike Australia, very few countries spend their resources in sampling of inhalable dust in mining industry. Over the years, size-selective sampling curve and instruments which replicate human inhalation have also changed. In addition, since its inception in 1920s, the recommended occupational exposure limits of a substance have varied significantly between mining countries worldwide. This paper discusses the experiences of introducing newly available monitoring instruments through laboratory and field evaluation. The institute of occupational medicine respirable foam sampler was evaluated in coal, diamond, gold and platinum mines. For comparison purposes, Higgins-Dewell type cyclone that conforms to the new size-selective curve with a D50 of four microns was used as a "true" reference sampler. For the laboratory study, the two samplers were exposed to two types of dust, viz. coal and sandstone briquette dust with a quartz content of 50.6%.

Based on the results of the laboratory study, the correlation coefficient (r) between the foam and reference sampler was found to be 0.79 and 40% underestimation in measured values by the foam foam sampler (p-value of 0.000). Field evaluations of side-by-side foam and reference samplers in coal, gold, platinum and diamond mines, showed a poor non-linear relationship (r = 0.67) for a wide range of dust levels. From the non-linear regression equation, on average, the foam respirable sampler underestimated the dust levels by approximately 48% for a compliance level of 2 mg/m^3. For increased dust levels, the underestimation of the measured dust levels by the foam sampler also increased, which led to the sampler being unsuitable for use during engineering control purposes. In overall, the foam sampler failed to meet the NIOSH accuracy criteria and was not pursued further for use in South African mines. Study suggests sufficient and prior due-diligence of any new instruments or methodologies to industry wide applications. Any modifications to sampling methodology or introduction of new instruments must ensure that the collected exposure data is relevant for continued development of long term dose-response curves and understand potential level of risks.

INTRODUCTION

Monitoring of dust in mines is an important task and requires reliable instruments. There are various means of measuring dust, viz., personal sampling, area sampling and engineering sampling. Knowledge of routine dust exposure levels can help workers' and industry focus on protection of workers respiratory health. Against this background, the search for an improved or alternative instrument or sampling methodology that will measure occupational exposure more accurately and more reliably is continuing. This paper shares experience of introducing a new instrument for the exposure monitoring that is relevant to similar industries worldwide.

Past studies have suggested that the personal sampling method is the most suitable method for assessing, and most representative of, the worker's dust exposure (Leidel, *et al*., 1977; Kissell and Sacks, 2002). A decade ago, an effort was made to evaluate the newly available instruments for personal exposure assessment in the typically harsh conditions of South African underground mines.

Dust sampling is pursued in mines to understand the level of risk associated with exposure to hazards. Figure 1 provides a typical fraction of dust data in a British colliery taken up by exposed humans during breathing (Gibson, *et al*., 1987).

It was noted that the inspirable dust mass of 38.4 mg contained 6.6 mg of respirable dust, 3.7 mg of tracheobronchial dust, 13.5 mg of thoracic dust.

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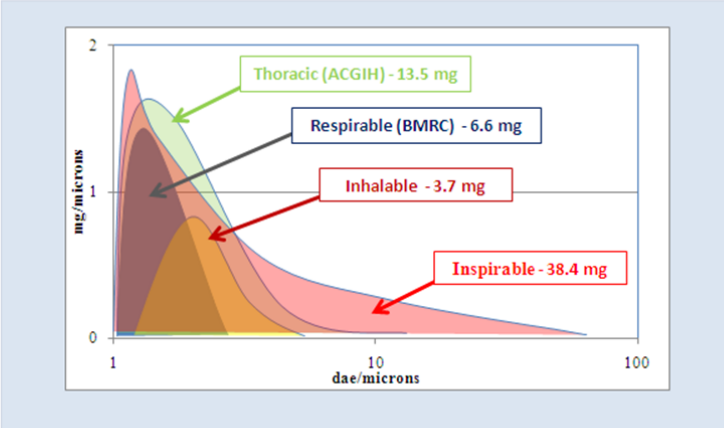

Figure 1 - Illustration of typical respirable fraction of coal dust breathed

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

- Some of the "new" gravimetric-type instruments, such as the Institute of Occupational Medicine (IOM) sampler, do not yield any additional information on respirable dust or help the mining industry as the existing gravimetric samplers are capable of collecting the necessary personal exposure data;
- The errors associated with personal sampling are usually the result of the worker's body movements, instrument portability and other sampler-handling mistakes. Therefore, ultimately, an accurate sampling instrument that would be able to cope with the worker's usual production demands is required for the harsh environment of the mining industry.

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

- They must be intrinsically safe for use in underground mines;
- They must sample according to the accepted size-selective criteria at specified flow rates;
- They must meet the ± 25 % NIOSH accuracy criterion;
- They should preferably use a different quick analysis procedure to the weighting method that is currently used;
- They must be robust enough to withstand the harsh conditions prevailing in mines;
- They must be compact and portable for personal sampling;
- They must offer the possibility of collecting dust samples for further quartz analysis.

INSTITUTE OF OCCUPATIONAL MEDICINE FOAM SAMPLER

The IOM foam sampler, as shown in Figure 2, was designed by Mark and Vincent (1986) and collects dust samples by the gravimetric method. It has a 15 mm diameter inlet orifice. Aerosol is aspirated into the IOM sampler at a flow rate of 2.0 L/min. Particles aspirated into the inlet are either collected by a 25 mm filter or deposited on the inside surfaces of an internal two-piece cassette. The original IOM foam sampler that was modified by Health and Safety Laboratory is already in widespread use above ground for sampling inhalable dust (MDHS 14/2, 1997). The cassette of the sampler has been modified to incorporate two size-selective foams in front of the usual filter; this means that the sampled inhalable dust is further subdivided into thoracic and respirable dust fractions, i.e. all three fractions are sampled simultaneously. The three dust fractions can be quantified by analysing the foams and filter separately. The respirable dust collected on the filter can be further analysed for quartz content.

The IOM sampling head weighs only 20 g and as in the case of the cyclone, an intrinsically safe pump is required. Historically, as no study had been carried out in South Africa, the respirable foam sampler was considered for evaluation as a personal sampler in South African mines. Unlike Australia, very few countries spend their resources in sampling of inhalable dust in the mining industry.

Figure 2 - IOM foam sampler

Area sampling performance of six inhalable aerosol samplers was studied using monodisperse, solid particles by Li *et al.* (2000). The study reported that the area sampling performance of the foam sampler is highly dependent on wind orientation, wind speed and particle size. When the measured sampling efficiency was compared with the inhalable convention, the IOM sampler over sampled the large particles (>20 µm).

Laboratory evaluations

The laboratory Polley dust duct of the National Institution of Occupational Health (NIOH) in Johannesburg is shown in Figure 3. The experimental design, the laboratory tests and the data analysis procedures are given elsewhere (Belle, 2002). For all laboratory comparison purposes, the Government Mining Engineer (GME) approved South African Higgins-Dewell type cyclone (GME#GE05) was used as a 'true' reference sampler. Figure 4 shows a typical side-by-side positioning of samplers in the laboratory test chamber. Tests were carried out with instrument pairs exposed to coal and sandstone briquette dust.

During both the laboratory and field trials, the foam respirable sampler operated at 2.0 L/min and the HD type cyclone operated at 2.2 L/min. They were positioned side by side inside the dust chamber and exposed to the coal and sandstone briquette dust.

Figure 3 - Photo of the laboratory Polley dust duct

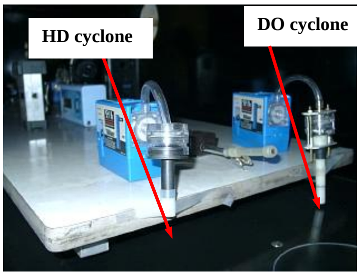

Figure 4 - Laboratory test table for samplers

Field evaluations - test mines and instrumentation

The foam sampler was compared with HD type South African cyclones. It was assumed that the cyclone samplers gave negligible errors and a "true" measurement of personal dust concentration. In order to carry out the personal sampling in mines, a sampling harness was prepared and the dust monitors were worn in a specific position consistently in all the test mines (Figure 5).

The left lapel of the harness contained the reference sampler and the foam sampler. A summary of the sampled mines and individual sampling locations is given in Table 1. The sampled gold, platinum, coal and diamond mines are unique with regard to their extremely challenging environmental conditions. Some of the mines used diesel-operated equipment and machinery. The test procedure is described in the underground test protocol and was discussed by Belle (2002).

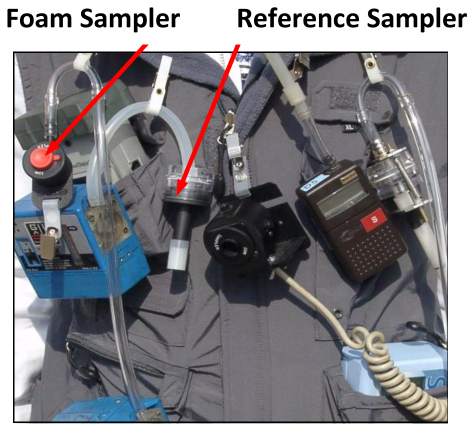

Figure 5 - Sampling harness with Foam and HD sampler

Table 1 - Summary of mines and operations sampled

Mine Type	Operations Sampled
Gold, Platinum	Reef and waste tips; shaft levels Ore tips along the haulage Development and stopes
Coal	Coal face Out-bye face Feeder-breaker Intake airways Transfer points Shaft Intake
Diamond	Ore pass Haulage way Development Heading Crusher and transfer points

Establishing an accuracy criterion

For all comparison purposes, the dust level measured by the HD type cyclone sampler was considered the "true" concentration. Therefore, the concentration ratio of the "evaluation instrument" to the reference instrument (in this study, the HD sampler) was calculated. If the variability in the concentration ratio is small, then one can consider accepting the "evaluation instrument" for further use. The concentration ratio is analogous to the bias as described by Kennedy *et al.* (1995). The relative standard deviation (RSD) was calculated from the standard deviation and the mean concentration ratio.

Accuracy criteria of ± 25% analogous to the NIOSH instrumentation accuracy criterion (Kennedy, *et al.*, 1995) were used. For normally distributed data, 95% of the measurements fall within the range ± 1.96s, where s is the standard deviation. For example, assuming that the mean is 100, for the criterion of ± 25%, then 1.96s = 25 or s = 12.7. Because the mean is 100, the standard deviation divided by the mean (called RSD or CV) is 0.127. Thus, the ± 25% accuracy criterion (NIOSH) is met at RSD = 0.127 or less.

RESULTS OF PAIR-WISE COMPARISON OF FOAM SAMPLER AND HIGGINS-DEWELL CYCLONES

Laboratory results

This section of the paper discusses the results of the laboratory evaluation of the foam sampler. The relationship between the measured values obtained from the side-by-side foam and HD reference samplers during the laboratory evaluation for both types of dust is shown in Figure 6

The correlation coefficient (r) between the two samplers is 0.79. The plot shows a nominal linear relationship and there is a significant difference between the IOM and reference samplers and clearly indicates the underestimation by the foam sampler for various measured dust levels. For coal dust, the average measured levels using the reference and foam samplers are 7.23 mg/m^3 and 3.09 mg/m^3 respectively for the test conditions. Similarly, for sandstone dust, the average measured levels using the reference and foam samplers are 11.29 mg/m^3 and 5.41 mg/m^3 respectively. From the regression line it can be inferred that the foam sampler underestimates the respirable dust levels by about 36% at a compliance level of 2 mg/m^3, but at greater dust levels the underestimation of measured dust levels is much higher.

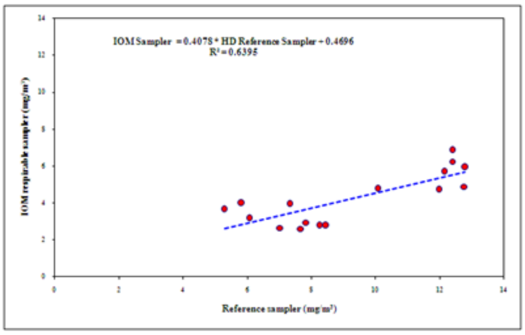

Figure 6 - Laboratory relationship between side-by-side foam and HD reference samplers

Statistical analyses: Laboratory data

Table 2 shows summary statistics of respirable dust values obtained from the side-by-side comparison of foam and reference samplers when exposed to coal and sandstone briquette dust. From the summary statistics table (Table 2) it can be seen that there is no clear relationship between the accuracy of an instrument and its measured concentration levels. Overall, the CV of the ratio between the sampler dust levels failed to meet the NIOSH accuracy criteria.

Table 2 - Summary of the IOM correction factors

Dust	SP	MRSC	MRC	NT	SD	RSD or CV (%)
C, S	HD-HD	10.80	1.035	15	0.074	7.15
C	IOM-HD	7.232	0.442	8	0.133	30.09
S	IOM-HD	11.293	0.493	8	0.098	19.87
Overall	IOM-HD	9.263	0.468	16	0.116	24.78

C: Coal; S: Sandstone; SP: Sample Pair; MR: Mean Reference Sampler Concentration; MRC: Mean Ratio of Concentrations; NT: No. of Tests

A paired t-test (Table 3) was performed on the set of sample pair data to determine whether there was a statistical difference in the loge-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 (µA and µB). The null and alternative hypotheses for the sample pairs tested were:

H0: µA = µB
H1: µA ≠ µB

In the paired t-test, hypothesis H0 states that the mean dust concentration levels from both samples (µA and µB) are equal. On the other hand, the alternative hypothesis states that the two samplers in fact measure different mean concentration levels. Hypothesis tests were carried out for the data set.

In this study, a cut-off p-value of 0.05 was used (95% confidence level). From the analysis table it was observed, with various degrees of freedom, the large p-value (>0.05) suggesting that the measured mean concentration levels are consistent with the null hypothesis, H0: µA =µB, that is, the dust concentration measured by foam sampler and reference sampler is not affected at the 95% level of confidence.

From Table 3, for both dust types, there was a significant difference in the measured dust levels between the reference HD sampler and the foam sampler.

Table 3 - Results of paired t - test (on transformed values)

Dust	SP	NT	95 % LCL	95 % UCL	p-value
C	IOM-HD	8	0.618	1.08	0.000
S	IOM-HD	8	0.566	0.880	0.000
Total	IOM-HD	16	0.660	0.915	0.000

C: Coal; S: Sandstone; SP: Sampler Pair; LCL: Lower Confidence Level; UCL: Upper Confidence Level; NT: No. of Tests

Underground results

The relationship between the measured values obtained from the side-by-side foam and reference samplers in coal mines is shown in Figure 7. The correlation coefficients (r) between the two samplers in coal mine A and coal mine B are 0.77 and 0.47 respectively. A combined plot of the two coal mine data sets (r = 0.52) and samplers show poor linearity when measured in coal mines, despite there being less scatter. The plot indicates that, on average, the foam sampler underestimates the respirable coal dust levels by more than 50%.

The relationship between the dust values obtained from the side-by-side foam and the reference sampler in two gold mines is shown in Figure 8. The correlation coefficients (r) between the two cyclones in gold mine A and gold mine B are 0.86 and 0.95 respectively. A combined plot of the two gold mine data sets (r = 0.76) and the two samplers show comparatively reasonable linearity when measured, with wide scatter. The plot indicates that, on average, the foam sampler underestimates the measured respirable dust level by approximately 35%.

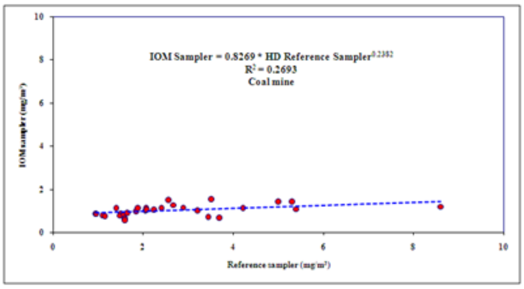

Figure 7 - Combined plot of side-by-side foam and HD Reference Sampler in coal mines

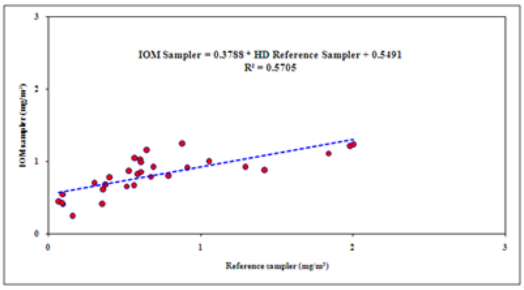

Figure 8 - Combined plot of side-by-side personal foam and HD Reference sampler in gold mines

Similarly, the relationship between the concentration values obtained from the side-by-side foam and reference samplers during the field trials in a platinum mine is shown in Figure 9. The correlation coefficient (r) between the two cyclones in the platinum mine is 0.58. The two samplers show poor linearity, with wide scatter. On average, the plot indicates that the foam sampler underestimates the measured respirable coal dust concentration by approximately 13% at low concentration levels.

The relationship between the concentration values obtained from the side-by-side foam sampler and reference samplers during the field trials in a diamond mine is shown in Figure 10. The correlation coefficient (r) between the two cyclones in the diamond mine is 0.83. The measured dust levels had a wide range and at compliance levels the foam sampler underestimates the measured respirable coal dust concentration by more than 60%. From the plot we observe that at higher dust concentrations, the foam sampler underestimates to a larger extent.

In order to determine the relationship between the dust values obtained from the side-by-side personal foam and reference samplers during the field trials in hard rock mines (gold, platinum and diamond), the relationship was plotted as shown in Figure 11. The correlation coefficient (r) between the two cyclones in all hard rock mines is 0.67, showing a poor non-linear relationship between the samplers. The combined scatter plot of all mine data (Figure 12) again shows a poor non-linear relationship (r=0.67) between the foam and SA samplers measured in various mine types with a wide range of measured dust levels.

From the non-linear regression equation we can deduce that, on average, the foam sampler underestimates the measured respirable dust levels by approximately 48% for a compliance level of

2 mg/m^3. As the dust levels increase, the underestimation of the measured dust levels by the foam sampler also increases, which makes the sampler unsuitable for use even for engineering control purposes. Also at low concentrations, the foam sampler measures higher than the reference sampler. From the plot we can observe that all underground measurement values included both compliance and non-compliance levels for the sampling period and that the scatter was wide for both low and high dust concentrations.

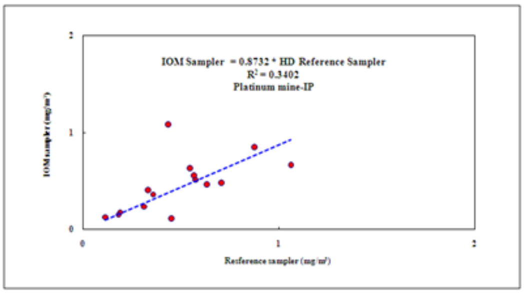

Figure 9 - Relationship between side-by-side personal foam and HD Reference sampler in a platinum mine

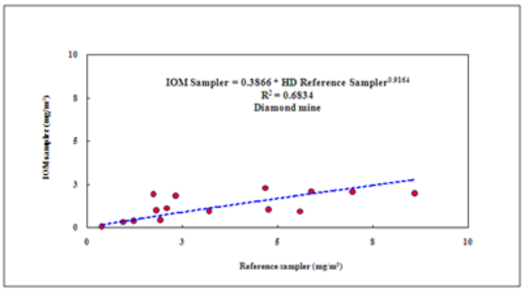

Figure 10 - Relationship between side-by-side personal foam and HD Reference sampler in a diamond mine

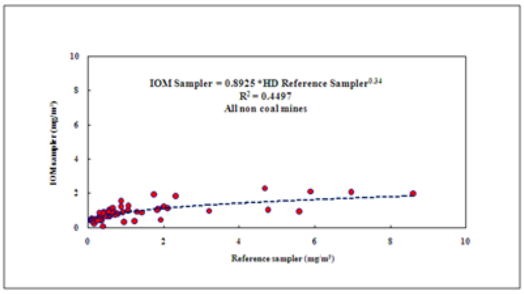

Figure 11 - Relationship between side-by-side personal foam and HD Reference sampler in non-coal mines (gold, platinum, diamond)

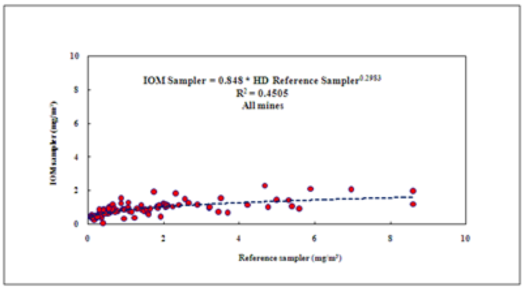

Figure 12 - Relationship between side-by-side personal foam and HD Reference sampler from all mines (gold, platinum, diamond and coal)

Statistical analyses - mine data

Table 4 shows summary statistics of the respirable dust concentration values obtained from the side-by-side comparison of the foam and reference samplers measured in coal, gold, platinum and diamond mines by three personnel. The CV is the ratio of standard deviation and mean value expressed as a percentage. From the summary table (Table 4) it is observed that there is no clear relationship between accuracy and the measured concentration levels. Overall, the foam sampler failed to meet the NIOSH accuracy criteria.

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

H0: $\mu diff = 0$
Ha: $\mu diff \neq 0$

In the paired t-test, hypothesis H0 states that the mean difference in concentration values (transformed values) between side-by-side personal instrument pairs is equal to zero. On the other hand, the alternative hypothesis states that the two personal dust-monitoring instruments positioned side by side in fact measured different mean concentration levels or the difference was not equal to zero. For this research work, a standard 95% confidence level was chosen. The results of the paired t-test statistical analyses are given in Table 5.

Table 4 - Summary of the correction factors for the foam and Reference samplers in all mines

Mine Type	Person	MRSC	Ratio of IOM/SA Conc	NT	SD	RSD or CV (%)
C1	B	2.005	0.577	5	0.146	25.30
	L	1.697	0.634	5	0.206	32.49
	J	1.431	0.641	5	0.160	24.96
	Total	1.711	0.617	15	0.162	26.26
C2	B	3.516	0.297	5	0.112	37.71
	L	4.836	0.345	5	0.175	50.72
	J	2.504	0.421	5	0.155	36.73
	Total	3.618	0.354	15	0.149	42.09
	Overall	2.665	0.486	30	0.203	41.77
G1	B	0.533	1.763	5	0.333	18.89
	L	0.483	2.072	5	1.248	60.23
	J	0.721	1.457	5	0.233	15.99
	Total	0.502	1.764	15	0.748	42.40
G2	B	0.752	2.219	5	2.057	92.69
	L	0.953	2.072	5	2.673	129.0
	J	0.994	1.642	5	1.724	104.9
	Total	0.899	1.978	15	2.041	103.2
	Overall	0.701	1.870	30	1.514	80.96
P	B	0.450	2.221	8	0.886	39.89
	L	0.399	1.877	6	0.489	26.05
	J	0.434	1.876	7	0.692	36.88
	Total	0.431	2.008	21	0.712	35.46
D	B	4.480	0.401	5	0.250	62.34
	L	3.733	0.324	5	0.137	42.28
	J	2.212	0.512	5	0.355	69.33
	Total	3.475	0.412	15	0.256	62.13
MM	Total	1.245	1.583	66	1.267	80.03
AM	Total	1.689	0.936	96	1.172	125.2

C: Coal; G: Gold; P: Platinum; D: Diamond; MM: Metal Mines; AM: All Mines; MRSC: Mean Reference Sampler Concentration; NT: No. of Tests

From Table 5 it is observed that, for all test mines, there was a significant difference in measured dust levels between the reference and foam samplers. A paired t-test was performed on the combined data of two dust monitors to determine whether there was a statistical difference in the results obtained from the reference sampler and the other monitors tested. The foam sampler showed rejection of the hypothesis that the dust readings measured by the two samplers side by side are significantly affected at the 95% level of confidence.

The measured dust concentration ratios between the data from the test samplers (Reference Sampler and foam sampler) were used to perform an analysis of variance (ANOVA). A discussion of the ANOVA models and their underlying assumptions can be found in any of the standard books on statistics. From the results of the ANOVA, the following relevant conclusions for foam sampler can be deduced:

- The effect of mine (dust) type on the concentration ratio between the two side-by-side monitors positioned in the breathing zone of the workers is highly significant. Apart from the dust type encountered in the individual test mines, the environmental conditions (such as humidity and temperature and thus worker's orientation to wind directions) and conditions such as continuous sweating and discomfort may have contributed to variations in the measured dust levels.
- The foam sampler's performance is not significantly affected by the sampling individual ($p=0.323$) as all of them were exposed to the same mine environmental conditions.

Table 5 - Results of paired t-test (on transformed values)

Statistic	Mine Type	$H_{SA\text{-}IOM}$
95% LCL	Gold	-0.643
	Platinum	-0.794
	Diamond	0.736
	Coal	0.643
95% UCL	Gold	-0.175
	Platinum	-0.491
	Diamond	1.33
	Coal	0.994
t-statistic	Gold	-3.58
	Platinum	-8.84
	Diamond	7.49
	Coal	9.53
P–value	Gold	0.001
	Platinum	0.000
	Diamond	0.000
	Coal	0.000
Hypothesis (accept or reject)	Gold	Reject
	Platinum	Reject
	Diamond	Reject
	Coal	Reject
Sample size	Gold	30
	Platinum	21
	Diamond	15
	Coal	30
Overall statistics	**All mines**	$H_{SA\text{-}IOM}$
95% LCL		-0.028
95% UCL		0.324
t-statistic		1.67
p-value		0.097
Sample size		96
Hypothesis (accept or reject)		Reject

CONCLUSIONS

An extensive laboratory and field evaluation of respirable foam sampler positioned side by side of a HD reference sampler. The HD type sampler was used as a 'true' reference sampler operated according to the CEN/ISO/ACGIH size-selective curve. Field evaluation of the instruments as personal dust-monitors, side by side in the breathing zone, was carried out in gold, platinum, coal and diamond mines of South Africa. The results of the evaluation are relevant to Australian mines in the context of practices of personal dust exposure monitoring.

Based on the results of the laboratory study, the correlation coefficient (r) between the foam and reference sampler was found to be 0.79 and 40% underestimation in measured values by the foam sampler (p-value of 0.000). Field evaluations of side-by-side personal foam and reference samplers in coal, gold, platinum and diamond mines, showed a poor non-linear relationship (r = 0.67) for a wide range of dust levels. From the non-linear regression equation, on average, the foam respirable sampler underestimated the dust levels by approximately 48% for a compliance level of 2 mg/m^3. For increased dust levels, the underestimation of the measured dust levels by the foam sampler also increased, which led to the sampler being unsuitable for use during engineering control purposes. In overall, the foam sampler failed to meet the NIOSH accuracy criteria and was not pursued further for use in South African mines.

Mining industry worldwide spends significant amount of resources in sampling safety and health hazards for ensuring adequate control measures. Most mining countries sample for respirable dust, however sampling of inhalable dust in mining industry is carried out in very few countries like Australia. Over the years, size-selective sampling curve and instruments which replicate human inhalation have also changed. In addition, the recommended compliance limits of a substance have varied significantly between various mining countries worldwide.

This evaluation experience suggests sufficient and prior evaluation of any new instruments for industry wide applications. Any modifications to sampling methodology or introduction of new instruments must ensure that the exposure data collected is relevant for continued development of long term dose-response curves and to understand potential level of risks.

Over the years, exposure limits of substances have changed and exposure assessment or compliance determination is becoming more confusing and complex due to terminologies used (for example, Indicative OELVs), instrument used, exposure period, work status. Finally, what is quintessential is the consistent approach to sampling, instruments used, availability of measurement relationships between past and new instruments that will be readily available for correcting systematic biases in sampling which in the longer term assists in exposure determination and for continued formulation of dose-response relationships.

ACKNOWLEDGEMENTS

The author hopes that the knowledge sharing of relevant findings presented in this paper will enhance complex issues of dust monitoring, challenges of introducing a new dust monitoring instrument and need for data for continued development of dose-response relationships so as to improve safety and health of workers. Various inputs of all relevant parties are clearly acknowledged.

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