Comparison of Three Side-By-Side Real-Time Dust Monitors in a Duct Using Average and Peak Display Dust Levels As Parameters of Performance Evaluation

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ABSTRACT: In South Africa, the monitoring of dust in the mines is a requirement in terms of Section 12.2 and 12.3 of the Mine Health and Safety Act (MHSA) of 1996. In order to ascertain the magnitude and range of dust levels and to react when an unhealthy dust exposure occurs, a real-time personal monitoring instrument for mineworkers is undoubtedly required. This paper discusses a comparative study of the three real-time (PDR units) monitors in a duct using coal and sandstone dust. The Higgins-Dewell (HD) and Dorr-Oliver (DO) type cyclone operated in accordance with the international size-selective curve were used as 'true samplers.' The average and peak display levels recorded by the three PDR units positioned randomly side by side, in the duct were analyzed using statistical techniques. The results of the study have showed that the dust levels measured with the three PDR units were not significantly different to the HD sampler data. Interestingly, the results showed significant differences in measured dust levels between HD and DO cyclones positioned side-by-side. The implication of this finding is that the majority of real-time monitors (e.g., Tapered Element Oscillating Microbalance (TEOM)) use these as a 'reference sampler'. This means that, based on measured differences found between the two cyclones, the introduction of TEOM for legal monitoring purposes may create ambiguity in its current state, i.e., agreement on the use of 'true cyclone.' The study demonstrated that, if the DO cyclone were used in the TEOM, it would measure significantly lower dust levels than the HD cyclone. Therefore, consensus on a "true sampler for use in real-time monitors" must be established in the mining industry.

Pair-wise t-test analyses were performed to compare the three PDR units using the average and peak recorded level. The study indicated that when peak value is used to evaluate the performance between instruments, it resulted in different inferences on the recorded levels when compared with the average value. The implication of this is that in practice, the random selection and use of a real-time monitor for engineering dust control application may be in favor of or against the seriousness of the dust problem. Although the recorded levels show the differences in dust levels, ANOVA results showed the contrary: dust type, monitoring units or position were not the sources of variation in the measured average and peak dust levels between the three PDR units. Light scattering monitors depend solely on air movement to move the dust particles into the sensing zone. It is not known if the particle charges have any specific effect in terms of their movement towards the sensing chamber that could have contributed to the recorded differences. It is proposed that, for real-time monitor evaluation, the use of 'peak display' level may ascertain the probable sources of variations. The intention of this paper is not to suggest that the peak levels should be used in place of average levels for exposure monitoring, rather as an evaluation parameter in understanding the variations experienced by researchers.

Key Words: Peak dust levels, real-time monitor, coal dust, silica dust, evaluation, mining

1 INTRODUCTION

In South Africa, the monitoring of dust in the mines is a requirement in terms of Section 12.2 and 12.3 of the Mine Health and Safety Act (MHSA) of 1996. In order to ascertain the magnitude and range of dust levels and to react when an unhealthy dust exposure occurs, a real-time dust monitor for mineworkers is undoubtedly required. Mainly in the USA, the need for the development of a real-time continuous respirable dust monitor has resulted in a new product based on the Tapered Element Oscillating Microbalance (TEOM) principle. In South Africa, the quest for real-time monitoring has resulted in a number of research projects that have focused on the issues pertaining to the assessment of dust hazards in mining operations (Unsted, 1997; Biffi et al., 2000). The research work has shown that the use of direct-reading light-scattering instruments is not reliable due to their inherent sensitivity to particulate matter other than dust. Against this background, the search for an improved or an alternative instrument capable of measuring dust more accurately and reliably is continuing. Therefore, any new information on the real-time dust monitoring techniques or their performance evaluation would be beneficial to the mining industry worldwide.

2 REAL TIME MONITORS

Direct-reading instruments or real-time monitors based on light scattering are available to estimate exposure to dust in underground mines. Real-time direct-reading instruments for mine dust have been used worldwide for routine engineering control and risk assessment purposes over two decades due to their added benefits when compared with the gravimetric samplers. All the available real-time monitors are calibrated using "mono-disperse" particles (Arizona road dust). However, each monitor to be used underground requires a user-determined "correction factor" obtained from a side-by-side gravimetric size-selective sampler, evaluated with "poly-disperse" mine specific dust. There is no "absolute correction factor" available for an individual real-time monitor. The "correction factor" changes with the history of the sampling data obtained in side-by-side comparisons of the real-time monitor and the type of gravimetric size-selective sampler used.

Direct reading instrument evaluation is not new to the mining industry. Various studies (Williams and Timko, 1984; Page and Jankowski, 1984; Gero and Tomb, 1988; Tsai et al., 1996, Baldwin et al., 1997; Tarkington et al., 1997; Thorpe and Walsh 2002) have evaluated different types of real-time monitors for their usage as personal or area monitors. The conclusions from these studies are similar in terms of their recommendations on the usage of the real-time monitors, but with varying degree of certainty. It is well known that the use of a real-time monitor as a stand-alone unit is not recommended for personal exposure assessment purposes but rather it is more suited to the identification of dust trends during a working shift. Currently, there is no consensus standard on the selection of a suitable real-time instrument for use to the industry. Field trials using real-time dust monitors used in conjunction with the visualization system revealed that its response could vary significantly from one day to the next (Thorpe and Walsh, 2002). The sources of variability of the real-time monitors can be attributed to dust levels, dust type, dust size, air velocity, monitor orientation and contamination of optics, etc. This paper investigates the results of three real-time monitors positioned side-by-side in a duct and evaluates the instruments based on the average and peak measured dust levels as parameters of evaluation.

3 LABORATORY STUDY

This section of the paper discusses the laboratory evaluation of three real–time monitors (PDR) positioned side by side along with gravimetric samplers in a laboratory known as the Polley duct (Figure 1).

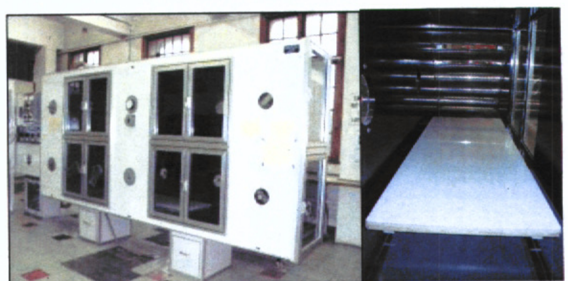

Figure 1: Pictorial view of the Polley duct with a rectangular rolling sampling table (right)

3.1 *Polley Duct*

The Polley duct consists of a closed-circuit duct and two dust generators (Figure 2). The closed-circuit duct consists of two sections: a horizontal section and a vertical section. The horizontal section is the main section and measures 7.0 m long by 2.0 m high by 0.7 m wide.

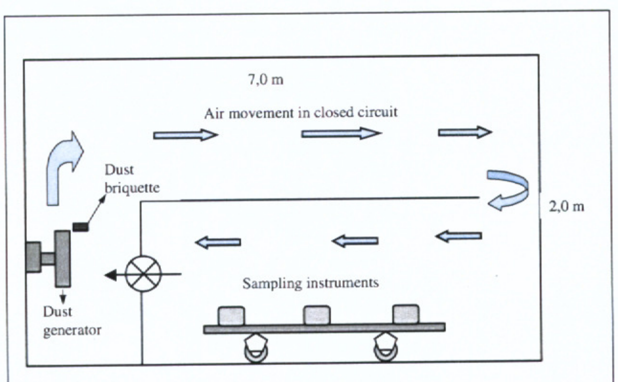

Figure 2: Line diagram of the Polley dust duct operation

The air flows along the horizontal channel into and along the top half of the large horizontal section. It returns along the bottom half of the large horizontal section through a flow-straightening section and flows along the lower, small horizontal channel into, and upwards in the vertical section to close the circuit. The duct also has other auxiliary parts such as time relays, two fans to circulate the air and a third to exhaust the dust-laden air through a filter to atmosphere, and a dust briquette press.

3.2 *Test Instruments and Methodology*

The three real-time monitors that were used for evaluation purposes were commonly known as PDR or MIE DataRam (USA). The units operate on a forward light-scattering particle detection principle, which relies on ambient air movement to introduce particles into the sensing chamber. The PDR real-time monitor displays dust level in mg/m^3 in addition to TWA, Max, Min, STEL and sampling time on the display readout. The instrument has a preliminary Intrinsically Safe (IS) certificate obtained from the South African Bureau of Standards (Grupping, 2001).

For the evaluation purposes of real-time monitors, Higgins-Dewell (HD) and Dorr-Oliver Cyclones were used, as these are the commonly used size-selective devices used worldwide. It is assumed that HD cyclone and DO cyclone or sampler gave zero or negligible errors and is a representative sample of 'true' measured dust level in the chamber. The HD cyclone was operated at 2.2 L/min and the DO cyclone was operated at 1.7 L/min in terms of new international harmonization (ISO/ACGIH/CEN) size-selection curve. For each test, the samplers were positioned side by side inside the lower chamber of the duct (Figure 3). Each of the three real-time monitors was randomly positioned on locations D, E or F, while HD and DO cyclones were positioned at location A or C.

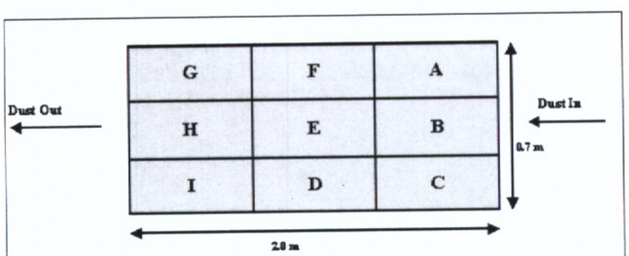

Figure 3: Instrument positions on the sampling table

A low air velocity (~0.8 m/s) in the chamber was maintained consistently for all the tests. For the study, the instruments were exposed to two types of dust, viz. coal and sandstone briquette dust. The quartz content of the sandstone briquette dust was 50.63 %. The real-time monitors were calibrated (zeroing) using an airtight polythene bag supplied by the manufacturer after each test. The test chamber did not have any instruments to measure the size distribution of the airborne dust in real-time. The detailed experimental procedures are discussed elsewhere (Belle, 2002). The cyclone inlets faced the direction of the airflow in order to avoid the effect of nozzle inlet orientation on sampler performance. New Gillian constant volume flow pumps were used and were calibrated to the nearest ml per minute flow rate, using a digital Gillibrator. The gravimetric sampler dust levels were determined in accordance with the established Department of Minerals and Energy procedures (DME, 1997). A photographic view of the real-time monitors and their positions during tests in the chamber is shown in Figure 4.

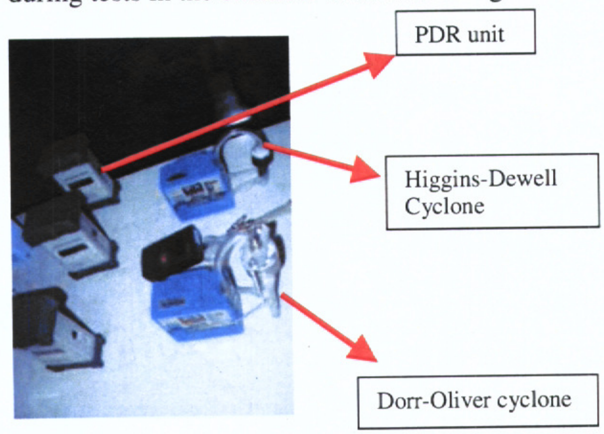

Figure 4: Pictorial view of test real-time monitors (left) and gravimetric samplers (right)

4 LABORATORY RESULTS

Initially tests were carried out to confirm that the dust levels across the Polley duct were uniform. Both DO and HD cyclones were positioned side-by-side in the dust chamber and tests were conducted for both coal and sandstone dust. Preliminary results indicated that there is no significant difference in the measured dust levels across the chamber. For example, the measured coal dust levels at positions B and H were 4.94 mg/m^3 and 4.91 mg/m^3, respectively. Similarly, the measured sandstone dust levels at positions B and H were 33.35 mg/m^3 and 31.90 mg/m^3 respectively. Figure 5 shows the respirable dust levels obtained in the side-by-side comparisons of similar types of cyclones. The correlation coefficient (r) between the two side-by-side DO cyclones was 0.993. Similarly, the correlation coefficient (r) between the two side-by-side HD cyclones was 0.998. A combined plot of the two data (r = 0.998) indicates a strong linear relationship between the two side-by-side cyclones. The two data sets of dust values showed that concentration across the chamber was uniform during the test conditions.

Figure 6 show the relationship between the measured dust levels using the DO cyclone and the HD cyclone positioned randomly, side by side in the test chamber. From the plot and the regression equations it is noted that the DO cyclone measured approximately 16% less respirable dust than the HD cyclone for a personal coal dust compliance limit of 2 mg/m^3.

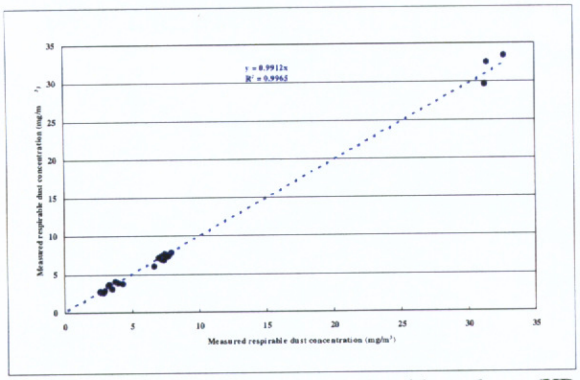

Figure 5: Combined data of two side-by-side cyclones (HD and DO).

The implications of this finding is that the majority of the real-time monitors use cyclones as a 'reference sampler' operated in accordance with the accepted size-selective curve. The newly developed Tapered Element Oscillating Microbalance (TEOM) real-time monitor uses the HD cyclone for its operation. This means that, based on measured differences found between the two cyclones for the US or SA industry, the introduction of TEOM for legal monitoring purposes may create ambiguity at its current state, i.e., agreement on the use of the 'true cyclone' in real-time monitors. This study did not evaluate any imprecision of either HD or DO cyclones. Also, from South African experience, by switching over to the new size-selective curve, the measured coal dust levels were 11% lower than before at 2.0 mg/m^3 personal exposure limit (Belle, 2005). Currently there are no changes to the personal exposure limit due to the change over to the new size-selective curve. For this paper the HD sampler was used as a reference sampler.

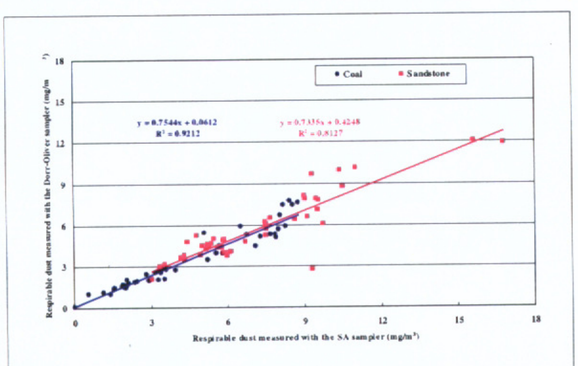

Figure 6: Relationship between measured dust levels using side-by-side DO and HD cyclones n the test chamber.

4.1 *PDR RESULTS*

The results of the variation between the dust levels measured by three PDR dust monitors positioned side-by-side in conjunction with the gravimetric samplers are discussed below. Figure 7 show the relationship between gravimetric and real-time monitors for two different dust types. The solid line represents a 1:1 relationship between gravimetric and real-time monitors. The coefficient of variation (CV) of the mean correction factors is in an increasing order for PDR instruments, P1 (8%), P2 (14%) and P3 (17%). The lower the CV of the mean correction factor, the more linear the response of the monitor.

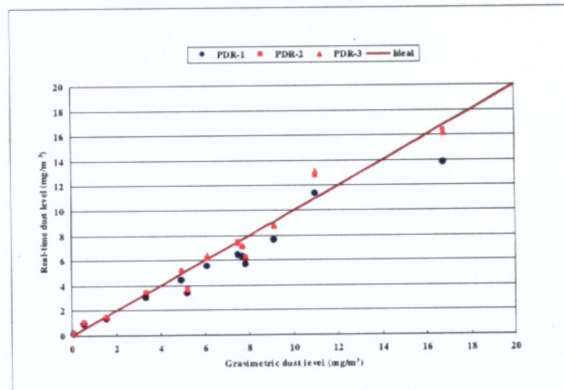

Figure 7: Relationship between measured gravimetric and recorded real-time monitor dust levels.

Figures 8 and 9 show the average and peak (maximum) dust levels recorded by the PDR instruments positioned side by side, randomly, in the test chamber for two dust types, respectively. Tables 1 and 2 show the summary statistics of the average and peak respirable dust values obtained from the side-by-side comparison of the PDR monitors using coal and sandstone dust respectively.

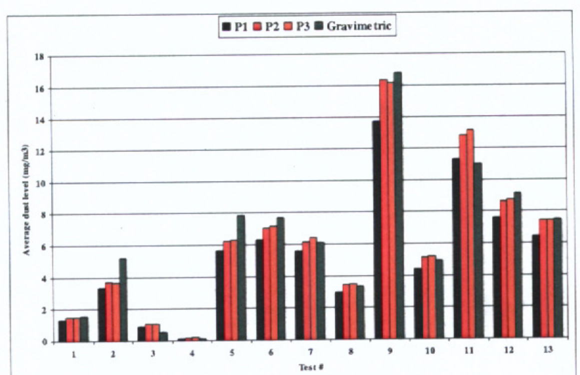

Figure 8: Relationship between average dust levels recorded by PDR units and gravimetric sampler.

From the data it is noted that the average measured levels by the units P1, P2, P3 and gravimetric sampler were 2.94 mg/m^3, 3.29 mg/m^3, 3.32 mg/m^3, and 3.83 mg/m^3, respectively for coal dust. From the sandstone dust, it is noted that the average measured dust levels by the units P1, P2, P3 and gravimetric sampler were 7.44 mg/m^3, 8.57 mg/m^3, 8.67 mg/m^3, and 8.40 mg/m^3, respectively. Using the combined data, the average measured levels by the units P1, P2, P3 and gravimetric samplers were 5.36 mg/m^3, 6.13 mg/m^3, 6.19 mg/m^3, and 6.29 mg/m^3, respectively.

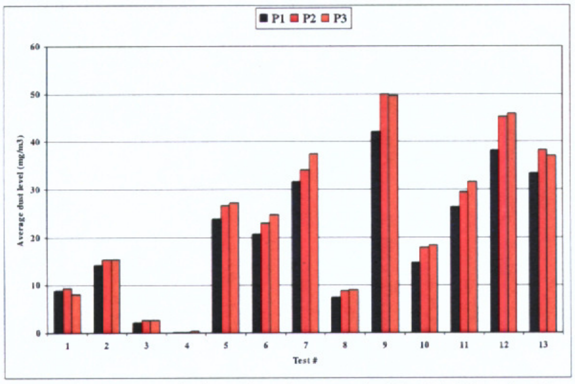

Figure 9: Peak real-time levels recorded by PDR units for coal and sandstone dust

Similarly, peak dust levels recorded by the three real-time units were compared. From the data it is noted that the average of peak recorded dust levels recorded by the units P1, P2, and P3 were 11.64 mg/m^3, 12.86 mg/m^3, and 13.05 mg/m^3, respectively for coal dust. From the sandstone dust data, it is noted that the average of peak dust levels recorded by the units P1, P2, and P3 were 27.63 mg/m^3, 31.95 mg/m^3, and 32.69 respectively. Using the combined data, the average of peak levels recorded by the units P1, P2, and P3 were 20.25 mg/m^3, 23.14 mg/m^3, and 23.65 respectively.

Table 1: Average and Peak dust levels using Coal Dust

Test #	Average dust levels, mg/m3			
	P1	P2	P3	HD*
40	1.30	1.50	1.48	1.56
41	3.34	3.70	3.67	5.22
42	0.91	1.05	1.07	0.55
43	0.13	0.17	0.19	0.09
44	5.63	6.25	6.30	7.86
53	6.32	7.04	7.19	7.69

Test #	Peak dust levels, mg/m3			
	P1	P2	P3	HD*
40	8.80	9.29	8.09	1.56
41	14.2	15.33	15.32	5.22
42	2.18	2.72	2.63	0.55
43	0.23	0.26	0.33	0.09
44	23.84	26.62	27.18	7.86
53	20.57	22.96	24.77	7.69

* Higgins-Dewell gravimetric value

Table 2: Average and Peak dust levels using Sandstone Dust

Test #	Average dust levels, mg/m3			
	P1	P2	P3	HD*
45	5.56	6.15	6.44	6.11
46	2.99	3.43	3.50	3.35
47	13.78	16.37	16.18	16.77
49	4.43	5.14	5.22	4.94
50	11.30	12.83	13.17	10.99
51	7.61	8.65	8.77	9.12
52	6.41	7.45	7.41	7.49

Test #	Peak dust levels, mg/m3			
	P1	P2	P3	HD*
45	31.51	34.02	6.44	6.11
46	7.33	8.78	8.95	3.35
47	41.99	49.95	49.61	16.77
49	14.69	17.87	18.27	4.94
50	26.36	29.54	31.59	10.99
51	38.20	45.15	45.91	9.12
52	33.33	38.35	36.99	7.49

* Higgins-Dewell gravimetric value

From the plots and tables it is observed that the average and peak display dust levels recorded by the three PDR units positioned side by side would differ when the instruments were exposed to the same dust cloud with inherently the same size characteristics (the dust source, dust generation and airborne mechanism). Comparison of the PDR and the HD sampler dust levels indicate that there is no statistically significant difference in measured levels for both dust types for all three units (high p-value). It appears that the difference between recorded levels by the real-time monitors is slightly pronounced when peak value is used as a performance indicator.

5 STASTICAL ANALYSES

This section of the paper discusses the analyses of the data using appropriate statistical techniques. A paired t-test was performed on the set of real-time pair dust data to determine whether there was a statistical difference in the ratio of dust levels measured between real-time monitor and HD cyclone. A paired t-test of hypotheses was developed to compare the concentration level ratios (mean and peak) measured with three real-time monitors (P1, P2 and P3) and HD cyclone. The null and alternative hypotheses for the sample pairs tested were:

H_0: $CR_{P1} = CR_{P2}$
H_a: $CR_{P1} \neq CR_{P2}$

For example, in the paired t-test, hypothesis H_0 states that the average dust ratios between two real-time monitors (P1 and P2) are equal. On the other hand, the alternative hypothesis states that the two real-time monitors, in fact, measure different average dust levels. The results of the paired t-test statistical analyses (for average and peak data) are given in Tables 3 and 4. For the analyses, a cut-off p-value of 0.05 was used (95% confidence level).

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

Pair	Dust	#	T-value	p-value	Hypothesis

P1-P2	Coal	6	-4.46	0.007	Reject
P1-P3	Coal	6	-3.59	0.016	Reject
P2-P3	Coal	6	-1.24	0.270	Accept
P1-P2	Sandstone	7	-16.30	0.000	Reject
P1-P3	Sandstone	7	-48.01	0.000	Reject
P2-P3	Sandstone	7	-2.07	0.083	Accept
P1-P2	Combined	13	-9.18	0.000	Reject
P1-P3	Combined	13	-7.68	0.000	Reject
P2-P3	Combined	13	-2.22	0.046	Reject

Using the average recorded level as a performance evaluation parameter (Table 3), a large p-value (>0.05) is observed suggesting that the measured mean concentration ratios are consistent with the null hypothesis. That is, the dust levels recorded by P2 and P3 are not affected at the 95% level of confidence for coal and sandstone dust. For the combined data, there was a significant difference between the recorded dust (coal and sandstone) levels between all the three units, viz., P1 and P2; P1 and P3 (p-value of 0.000); and P2 and P3 (p-value <0.05).

Table 4: Results of paired t-test (peak transformed values)

Pair	Dust	#	T-value	p-value	Hypothesis
P1-P2	Coal	6	-4.71	0.005	Reject
P1-P3	Coal	6	-2.42	0.060	Accept
P2-P3	Coal	6	-0.54	0.613	Accept
P1-P2	Sandstone	7	-9.42	0.000	Reject
P1-P3	Sandstone	7	-12.98	0.000	Reject
P2-P3	Sandstone	7	-1.53	0.176	Accept
P1-P2	Combined	13	-9.20	0.000	Reject
P1-P3	Combined	13	-5.93	0.000	Reject
P2-P3	Combined	13	-1.09	0.295	Accept

Similarly, using the peak recorded level as a performance evaluation parameter (Table 4), a large p-value (>0.05) is observed suggesting that the measured peak and mean concentration ratios are consistent with the null hypothesis. That is, the dust levels recorded by P2 and P3 are not affected at the 95% level of confidence for both types of dusts. For the combined data, there was a significant difference between recorded dust (coal and sandstone) levels between the units, viz., P1 and P2; P1 and P3 (p-value of 0.000). The study indicates that, when peak value is used as a parameter to evaluate the performance between monitors, different inferences could be drawn on recorded dust levels by the three PDR units when compared with the average value.

5.1 *ANOVA*

Upon noting the differences between the recorded levels by the three real-time units, an analyses of variance (ANOVA) were performed. Typical sources for these variation are sampling type (active or passive), dust types, monitor orientation, size distributions of dust, air velocity, sensor contamination etc. The measured dust concentration ratio between the real-time dust monitors' data (average and peak) and the reference HD sampler data was used to perform an ANOVA using MINITAB 13.2 statistical software.

For this study, the sources of variation quantified were the influence of dust type (coal and sandstone), monitoring units (P1, P2 and P3) and the position of the dust-monitoring units in the dust chamber. Essentially, the measured dust concentration ratio data that were used for the analysis were in the form of CA_{ijk} (mg/m^3) and CP_{ijk} (mg/m^3) with the following definitions:

CA = Ratio between real-time dust monitor and average dust level measured using HD cyclone

CP = Ratio between real-time peak value and average HD cyclone

i = dust type (DT), i = 0 is a coal dust, i = 1 is a sandstone dust

j = monitoring unit (MU), j = 0 is unit-P1, j = 1 is unit-P2, and j = 2 is unit-P3

k = unit position (UP), k = 0, 1, and 2 indicate the sampling positions (randomly selected) across the dust chamber respectively.

The results of the analysis of variance (ANOVA) on the average and peak concentration ratio data are summarized in Tables 5 and 6.

Table 5: Results of ANOVA for average values

Sources of variation	Df	SS	MS	F-value	Pr>F
Monitoring Unit (MU)	3	0.39	0.13	1.07	0.359
Dust Type (DT)	1	0.35	0.82	6.59	0.017
Unit Position (UP)	2	0.27	0.32	2.57	0.096
MU*DT	2	0.03	0.11	0.89	0.425
MU*UP	4	0.57	0.18	1.44	0.251
DT*UP	2	0.62	0.31	2.51	0.102
High order Interactions	25	3.11	0.12		
Total	38	5.31			

The ANOVA tables give for each term in the model, the degrees of freedom, the sums of squares (SS), the adjusted mean squares (MS), the F-statistic from the adjusted mean squares and its p-value.

Table 6: Results of ANOVA for peak values

Sources of variation	Df	SS	MS	F-value	Pr>F
Monitoring Unit (MU)	3	2.26	0.26	0.21	0.816
Dust Type (DT)	1	0.06	0.45	0.35	0.560
Unit Position (UP)	2	2.68	0.41	0.32	0.727
MU*DT	2	0.16	1.11	0.88	0.429
MU*UP	4	7.52	2.77	2.17	0.102
DT*UP	2	5.70	2.85	2.23	0.128
High order Interactions	25	31.9	1.28		
Total	38	50.33			

In the ANOVA table some p values were less than 0.05, indicating that these factors are significant in influencing the concentration values. From the ANOVA results using average and peak level data, the conclusions are summarized hereafter. The effect of dust type on the dust concentration ratio between the real-time monitors positioned side by side is significant (p-value of 0.017). There is slight evidence (p–value of 0.096) of the effect of unit position on the measured dust levels when the units are exposed to the same dust cloud using average value as the reference parameter of evaluation. However, the dust-monitor's performance is not significantly affected by the position of the monitoring unit within the chamber or dust type for peak dust data (p-value >0.50). As we note from the table, the interactions between the main factors do not have any significance on the measured dust levels for both average and peak data. Overall, the ANOVA conclusively indicated that the factors such as dust type, monitoring unit or its position are not the sources of variation in the measured average and peak dust levels between the three PDR units.

6 DISCUSSIONS

The following paragraphs discusses the results of the study in light of the use of appropriate 'true reference sampler' for real-time monitor and probable unknown sources of variation in measured levels between three PDR units.

6.1 *Use of Appropriate Reference Sampler*

Using cyclones as 'true reference' samplers for real-time monitor evaluation is not new to the mining industry (Kissell et al., 2002). The conclusions from the historic real-time studies are similar in terms of their recommendations on its usage. In past decades, researchers used the MRE 113a, which followed the Johannesburg curve, as a benchmark "true sampler." In general, the correction factors of the real-time monitors could be explained by the size-dependent light-scattering characteristics of the sensors with respect to any of the respirable size-selective sampling conventions and reference samplers.

The implications of the findings on the differences in measured levels between HD and DO cyclones considered to be "true samplers" is that the majority of real-time monitors use them as a 'reference sampler.' The newly developed Tapered Element Oscillating Microbalance (TEOM) real-time monitor uses the HD cyclone for its operation as a real-time monitor. This means that, based on measured differences found between the two cyclones, the introduction of TEOM for legal monitoring purposes may create ambiguity in its current state, i.e., agreement on the use of 'true cyclone.' The study has demonstrated that, if the DO cyclone were used in the TEOM, it would measure significantly lower dust levels than the HD cyclone (although the HD cyclone is beneficial in terms of its sensitivity to higher flow rates). Therefore, owing to the differences observed in this study, the need for a consensus on a "true sampler for usage in real-time monitors" which operates according to the proposed new international size-selective curve exist in the mining industry. Furthermore, from the South African experience, by switching over to the new size-selective curve from Johannesburg curve using the HD cyclone, the measured coal dust levels were 11% lower than before at 2.0 mg/m^3 (Belle, 2004). Currently there are no changes proposed to the personal coal dust exposure limit due to the change over to the new size-selective curve.

6.2 *Sources of Variation between PDR units*

The results of the study have showed that the dust levels measured with the three PDR units were not significantly different to the HD sampler data. Historically, sources of variations in measured dust levels in real-time monitors have been evaluated for parameters such as dust types, dust levels, monitor orientation, particle size, air velocity, and sensor contamination. In this study, sources of variations evaluated in recorded levels between three PDR units were dust type, monitoring unit and monitor position. Although the recorded levels show the differences in dust levels, dust type or monitoring units or position were not the sources of variation. Therefore, probable other sources, which are not known or understood, may provide answers to differences in measured levels between three PDR units. Parameters such as air velocity, monitor orientation, particle size were not the sources of variation, as they remained constant for all the tests.

It is often noted in studies that one of the major sources of variations in measured dust levels by the dust monitors could be the size distribution of the parent dust (Soderholm, 1989, Volkwein, 2002; Ramani, 2004). However, in these tests, the size distribution of the parent dust source, dust generation and airborne mechanism has been consistent for all the tests. All units were exposed to similar temporal and spatial environmental conditions. Therefore any differences in their responses were due to the sampling characteristics of the dust monitors alone. The monitor differences can be attributed to the differences in sensor detection range of units, which is "in-built" to the calibration factors of the PDR units as these units does not have any manual calibration feature. Usually if the optics of the sensor is contaminated, the calibration of the monitor gives 'high background' readings. Interestingly, during the tests, none of the three PDR units gave any "high background" or "calibration problem" conditions despite exposure to high dust levels. Also, time had no significant influence on the sensors or lenses, or on the correction factor of the real-time monitors as all the three units had the equal exposure period.

A study by Thorpe and Walsh (2002) showed that effects of three separate PDR orientations to the airflow (upright, on its back on its side) and its influence on measured concentration showing the variation in correction factor of 0.69 to 0.92. In this study, for the same orientation of three PDR units had the correction factors of 0.95, 1.10, and 1.13. Therefore, the PDR orientation to the airflow may not be the source of variation. Lastly, light scattering real-time dust monitors depend solely on air movement to move the dust particles into the sensing zone of the monitor. It is not known if the particle charges of airborne respirable dust have any specific effect in terms of their movement towards the sensing chamber that could have contributed to the recorded differences in dust levels by the three PDR units.

7 CONCLUSIONS

The following conclusions can be drawn from the laboratory evaluation of real-time monitors evaluated using average and peak recorded dust levels. From the statistical analysis of side-by-side comparison of three PDR units and HD cyclone indicate that there is no significant difference in measured dust levels. The use of peak-recorded levels indicates that the differences in recorded dust levels between monitors exist. The evidence from the study suggested that, while the 'average' dust level is a commonly used parameter for evaluating monitor performance, the use of the 'peak display' parameter may lead to different conclusion on the variations between measured dust levels. The implication of this is that, in practice, the random selection and use of a real-time monitor for engineering related dust control application may be in favor or against the seriousness of the dust problem and could impact the decision making process on the appropriate allocation of financial and administrative resources. It is proposed that for any new real-time monitors the use of peak display level as a parameter of evaluation may ascertain the probable sources of variations in recorded levels. These additional data analyses steps may facilitate the adjudging of the sources of variations in measured dust levels in real-time monitors. The intention of this paper is not to suggest that the peak levels be should used in place of average levels for exposure monitoring, rather an evaluation parameter in the understanding of variations experienced by researchers worldwide should be applied. It is recognized that Tapered Element Oscillating Microbalance instrument developed by Rupprecht and Patashnick (USA) may be a step closer to minimizing errors in dust measurement than the light scattering instruments.

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