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HOW RELEVANT ARE ENGINEERING SAMPLES IN THE MANAGEMENT OF PERSONAL DUST EXPOSURE?

Bharath Belle¹

ABSTRACT: A directive, legislated by the South African Department of Minerals and Energy (DME) in 1997, was introduced to reduce the respirable dust exposure of Mechanical Miner (MM) operators to below 5 mg/m³, when measured at the operator's cab position. This was to be achieved by ensuring that ventilation and dust control systems are effective in minimising the worker dust exposure. The focus of this paper is to review the effectiveness of this rule for almost two decades by using engineering sampling data to compare cost of monitoring versus success in dust control, to discuss perceptions arising from the application of this rule and to suggest improvement opportunities in the management of this hazard within the South African industry. The results of this study have demonstrated that the fixed-location Continuous Miner (CM) engineering sample results cannot predict the shift dust exposure of an MM operator. Therefore, it is recommended that the CM engineering sampling, as currently practiced, should be reviewed with the potential objective to discontinue it and replace it by personal exposure monitoring using the new MSHA-approved real-time monitoring device (NIOSH PDM3700). This instrument is able to collect relevant engineering dust control data for effective exposure management. The conclusions of this paper are based on extensive data analyses and should enable each mine and the regulator to make step-changes in current daily engineering sampling requirements and provide the flexibility required to approach the management of personal exposure more effectively by reducing human errors in sampling and optimising the use of available resources for the benefit of the South African Mining Industry.

INTRODUCTION

Major hazards in an underground coal mine include methane and coal dust explosions and personal exposure to dust. Based on the first ever recorded coal mine explosion in Southern Africa in Natal in 1891 (Landman, 1992), it can be inferred that underground coal mines have been operational for over 125 years. Considering where the global coal mining industry is positioned today and the arduous efforts that have resulted in improved public perceptions of the coal industry, Figure 1 demonstrates the success of various initiatives in reducing fatalities resulting from underground gas and dust explosions.

The statistics shown in Figure 1 include events from early 1900s to 2015 from USA, South African and Australian coal mines. Coal mining in South Africa has matured over the decades in both safety and health management with a unified approach towards management of risks. The reduction in explosions is factual evidence of the coal mining industry taking responsibility and being proactive in preventing such major incidents with innovative technologies, technical leadership and being eternally vigilant in dealing with multiple hazards in the workplace.

Understanding the risk of exposure to respirable dust was pioneered in South Africa in the early part of the 20th century with initial dust sampling techniques employing the konimeter, the use of the real-time Hund Tyndallometer, and later the introduction of gravimetric sampling in the mid-1990s, despite the USA and the rest of the world adopting it in the early 1970s. Similarly, the management of exposure to coal dust has also improved over the last two decades with major industry initiatives and regulatory interventions. One of the milestones in dust management in coal mines was a directive,

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effectively termed as “the 12 m rule”, introduced by the South African Department of Minerals and Energy (DME) in 1997. In addition, during this period, South Africa became the first country in the world to adopt the new ISO/CEN/ACGIH size-selective respirable dust curve for monitoring dust as opposed to the original Johannesburg size-selective curve of the 1960s (Orenstein, 1960; Belle, 2004).

Increasing concern about coal dust related lung diseases, together with the Leon Commission Report (1995), caused the South African DME to review the legislation aimed at protecting the health and safety of mine employees. Directive B7, titled “A Guideline for the Ventilating of Mechanical Miner Sections” was issued by the DME to the South African coal mining industry. This directive stipulated that one daily dust sample, termed “a CM engineering sample” was to be taken at every Mechanical Miner with an acceptable limit of 5 mg/m^3 . The sampling pumps were to be positioned on the CM at the operator’s position or at a position where the CM operator would be seated if on board the machine. Analysis of the results (Belle and Phillips, 2003) indicated that mere application of 12 m rule on its own does not solve the dust problems, but rather that this is achieved by the meticulous application of available state-of-the-art dust control technologies, leading work practices, and the regular maintenance of installed systems to ensure that they work at all times. In combination these measures would ensure a reduction in worker exposure to coal dust.

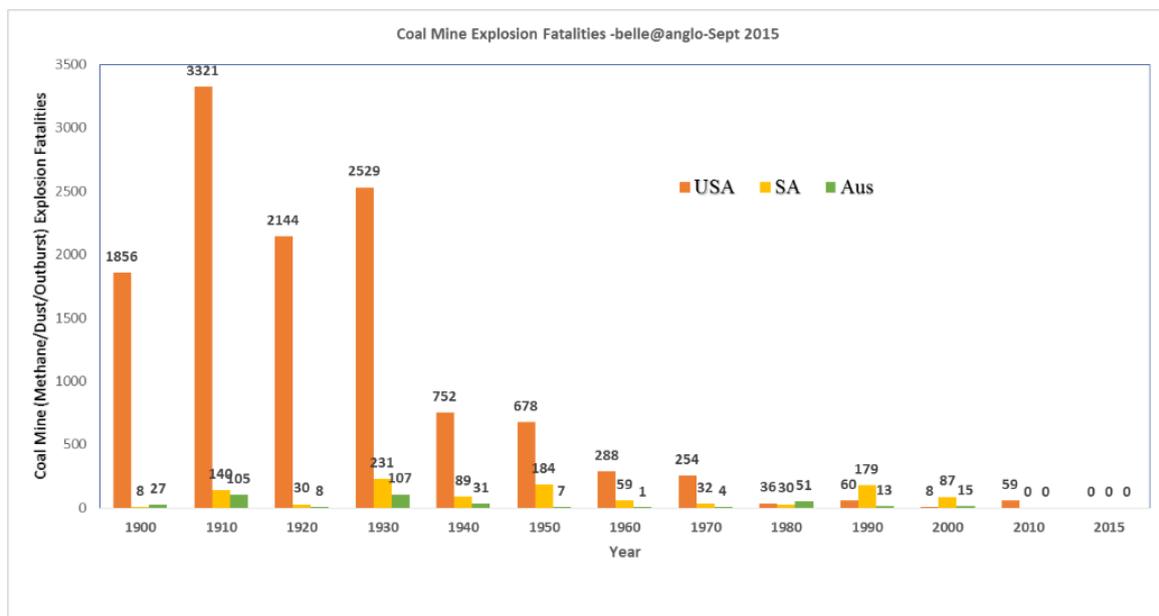


Figure 1: USA-SA-Australian coal mine explosion fatality statistics over the decades

The 12 m rule directive for dust exposure management states as follows (DME Directive, 1997):

1. “No continuous miner (CM) heading must be developed further than 12m from the last row of permanent support or from the point of auxiliary ventilation; and
2. Only ventilation systems that can ensure, at all times, a maximum dust reading of 5 mg/m^3 , measured at the driver’s position on the continuous miner (CM), must be employed.”

This paper reviews the origin of the CM engineering sample, its application and shortcomings and its current interpretation after two decades of implementation in South African coal mines.

Dust monitoring in South African Collieries

This section of the paper summarises the history of dust exposure monitoring and the changes that have taken place in the last two decades. Exposure monitoring and assessment is a complex system that requires clear understanding of the coal mining operation, monitoring practices, engineering

controls, ventilation system and dust generation dynamics. It is therefore increasingly necessary to measure the dust levels as accurately as practicable to assess the exposure, by using effective sampling techniques. Historically, the assessment of workers' dust exposure in South African coal mines was done by using various air samplers such as the Casella 10 mm cyclone, Gillian cyclones, GME008 Higgins-Dewell type South African cyclones, MSA cyclones, and CIP10 samplers. All these dust monitoring units were approved by the DME and operated at a conventional flow rate of 1.9 L/min, except for CIP-10, where the flow rate is 10.0 L/min. Due to its inherent measurement shortcomings (Belle, 2002), CIP10 samplers are no longer used in South African mines following an instruction by the DME. Currently South African coal mines must perform two types of dust sampling. In terms of the DME guideline for the assessment of personal exposure to airborne pollutants (August 2002), the results of the personal exposure sampling programme are to be submitted to the inspectorate quarterly. In terms of the Department of Minerals and Energy Affairs Guideline for a Code of Practice for the Ventilating of Mechanical Miner Sections in Coal Mines in terms of Section 34(1) of the Minerals Act 1991 (Reference GME 16/2/1/20 dated October 1994), also known as "Directive B7" or the "12 m rule", the results of gravimetric sampling performed daily at all operating CM sites, termed "environmental samples" in the directive, but commonly referred to as 'engineering sampling' must be submitted to the Directorate within four days.

Prior to 1998, dust samplers at all South African underground mines were operated at a flow rate of 1.9 L/min in agreement with the BMRC respirable convention (BMRC, 1952). However, according to the new ISO/CEN/ACGIH respirable dust curve with a 50% cut point (d_{50}) of 4 μm , the recommended flow rate is 2.2 L/min (Kenny, Baldwin and Maynard, 1998). Currently, mine dust sampler pumps draw 2.2 L/min of air through a mini-cyclone, which separates the airborne dust and collects only the fraction of respirable dust (<10 μm) on a pre-weighed filter. The dust samples are weighed on completion of the working shift and the procedure for determining the dust mass is followed according to DME guidelines (1995).

BACKGROUND TO ENGINEERING SAMPLING

This section of the paper provides background to various sampling definitions that are used in the mining industry. Occupational health exposure assessment refers to various sampling strategies over the years and relevant definitions of the sampling methods are summarized (Belle and Clapham, 2001) below:

Personal sampling: Is a method of sample collection whereby the dust sample collected is in the breathing zone of a mine worker while performing occupational duties during a work shift. In this sampling method, the worker wears the sampling train (cyclone, pump, tube, sample filter) for the entire work shift. Personal sampling results are most commonly used as the exposure or dose element in the development of dose-response relationships.

Area or environmental sampling: Is a method of sample collection whereby the dust sample taken at a fixed location at the workplace in an environment or area of interest that is not mobile. The dust sample reflects the average concentration in the area of interest and does not reflect the exposure of any worker in that area. The guideline for a code of practice for the ventilating of mechanical miner sections in coal mines (1994) noted that the sampler is to be placed in a stationary position inside the cab of the mechanical miner and referred to as environmental sampling. Area sampling should not be confused with the engineering sampling suggested in the Directive (1997) and the term "environmental" for the purpose of B7 is not correct.

Occupational sampling: An occupational sample is the dust sample taken during a work shift on individual workers who perform duties in a designated occupation and the terminology is used in US coal mines. This method of sampling measures the dust exposure for defined occupations as if one person performed the duties in that occupation for the whole working shift.

Engineering sampling: An engineering sample is the dust sample taken at the CM operator's position, which is not defined in the original DME directive (1997). The origin of the engineering sampling in South Africa can be traced back to a B7 directive (1997), requiring underground coal mines to reduce the dust levels to below 5 mg/m^3 for the sampling period at the operator's cab position on CMs. An engineering sample is the dust sample taken to characterise the emission source or suppression effectiveness of ventilation and dust control measures. The engineering sampler is switched on at the face area at the beginning of the shift while the cutting machine is standing and is switched off before leaving the face area at the end of the shift. It aims at evaluating both the management (administrative effectiveness) of the dust control system as well as effectiveness of the dust control system (engineering). An engineering sample (sample collected during the sampling period only) is the dust sample taken at the CM operator's position (Figure 2). The engineering sample is collected only while the engineering activity is taking place (in this case CM operation).

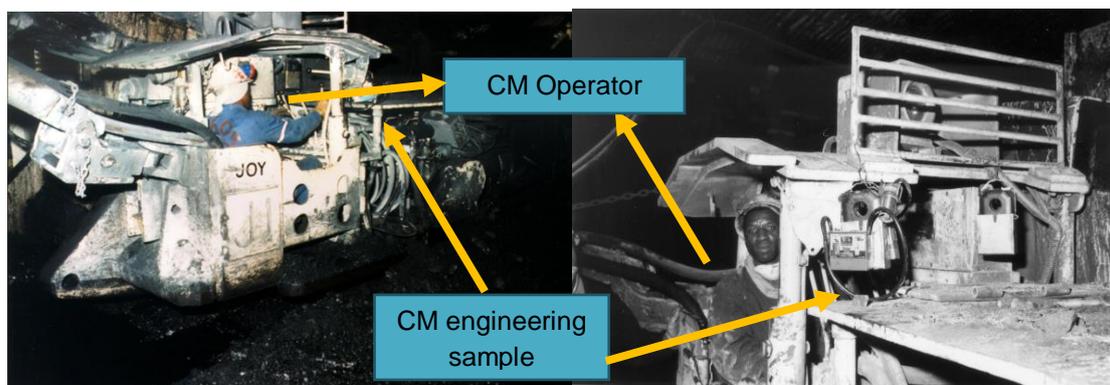


Figure 2: Position of samplers at the CM operator's position

What is of importance in the current context is that when the directive was instituted and promulgated during the late 1990s, the CM operator was on-board the machine. Currently, the majority or almost 90% of CM operations are done remotely where the operator is in fresh intake air. In addition, there was no guidance, in the B7 directive on the exact location of sampling with respect of the CM cab geometry other than "front of the CM cabin", as should be specified in evaluations of various engineering dust control systems.

Figure 3 shows the position of the instrument used to obtain a CM engineering sample, (i.e., location '1' in Figure 3) as per directive B7 that applied in Mine Health and Safety Council (MHSC) studies (Belle and Du Plessis, 1998). The choice of location-1 provides an indication of dust roll-back at the CM operator's position and the effectiveness of directional sprays and the ventilation system and of the CM dust control system when the CM is operated with an on-board scrubber and auxiliary ventilation system. Operating CMs 'remotely' as is common now allows the CM operator to be located in the fresh intake air (location R in Figure 3). With the switch over to remote operation and the operation of larger CMs, the position of the sampling device was also moved away to other locations towards the back of the CM (Locations 3, 4 and 5 in Figure 3). This has resulted in failure to adhere to the DME guideline (1994/1997) regarding compliance test requirements and has invalidated any comparison of the results obtained over the years. In some instances, a dust pump steel mesh box was built with engineering samples positioned inside it. During another dust control system study, two real-time dust samples were taken in front of the CM cabin (location 1 and 2). Results from these studies shown in Figure 4 highlight the difference in the dust cloud sampled by the monitors. This demonstrates the dynamics of the sampled dust cloud, in particular, the peak dust levels between the two real-time monitors when evaluating the effectiveness of the control system in managing the methane and dust hazards and the importance of the location of the CM engineering sample monitoring station.

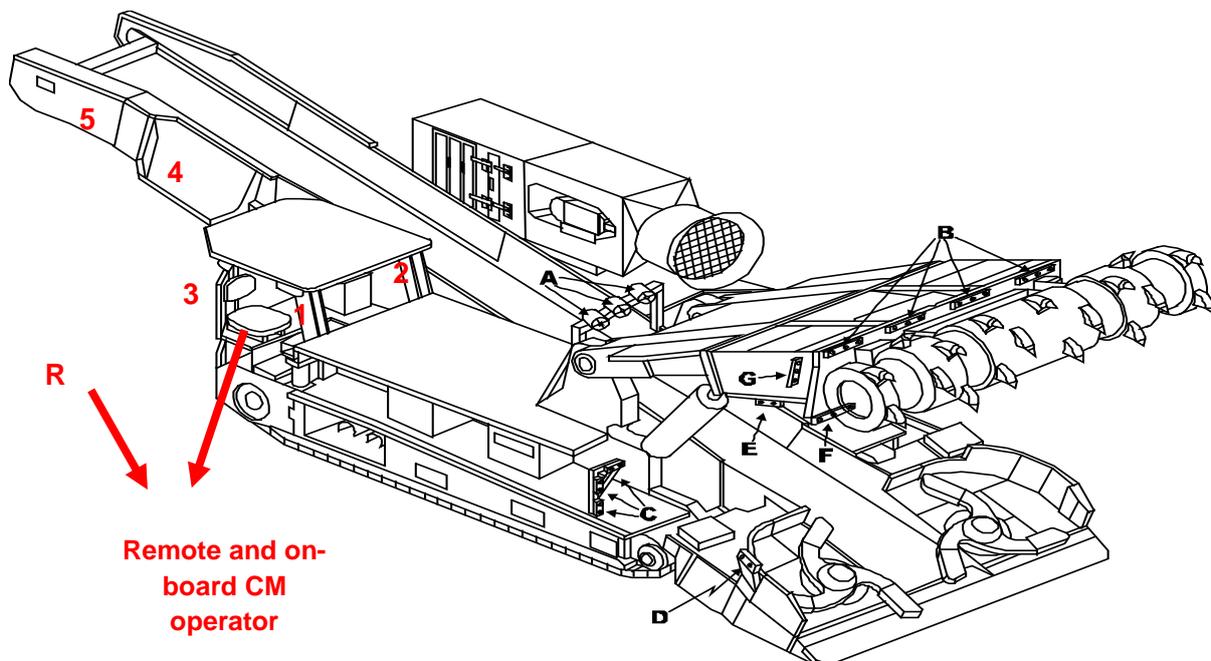


Figure 3: Position of samplers at the CM operator's position-Circle 1
(Source: Belle and Du Plessis, 1998)

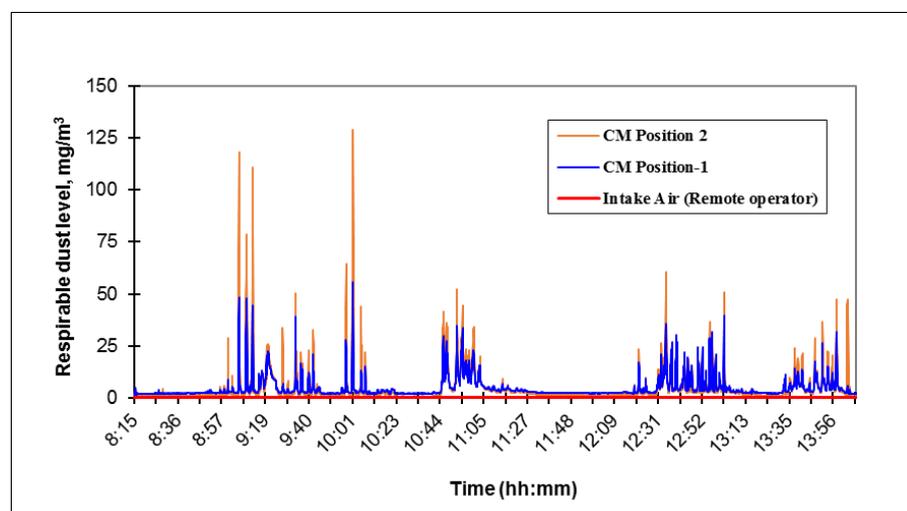


Figure 4: Real-time dust levels monitored for sample locations (1 and 2) identified in Figure 3

In the above example, despite the dust samplers being located approximately 60 cm from each other, the dust cloud monitored by the instruments was different. Such variability in measured peak dust levels shows the complexity and doubtful validity of any conclusions that may be drawn from this sampling. In this specific example, the engineering sample dust level was 4.75 mg/m^3 (average of peak flammable gas level was 0.12 %) with a shift production of 1020 tons. If the CM was to be operated under remote control, the CM operator would be standing in the fresh intake air (dust concentration measured at 0.29 mg/m^3). The position of the dust samplers used in the engineering area sampling is crucial in determining the effectiveness of dust control systems. This can easily be illustrated by positioning a sampler at different locations, e.g. closer to the flight conveyor, CM cutter head. Comparisons between dust sampling results therefore require consistent positioning of the samplers. Further examination of the concentration-time data from underground trials shows how real-time dust sampling instruments placed at a distance of less than a meter from each other in the CM operator's cabin actually monitor two different dust streams (Figure 4). In this example, Hund-2 was positioned inside the operator cabin, towards the CM flight conveyor, while Hund-1 was

positioned inside the cabin towards the clean air side. The conversion factor for the Hund data was obtained from the gravimetric samples collected at the Hund-1 position. The average concentration levels from the two Hunds for the total sampling period were expected to be similar. Further analysis of the Hund data for a specific cutting period shows that the measured dust exposure levels differed as the monitors sampled two different dust streams near the CM cabin (Table 1). This clearly illustrates that a face worker can be exposed to different dust concentration clouds and refutes the view that the dust exposure level within even a small area is fixed. This illustration gives an idea of the complex nature of sampling, analysis and interpretation of the dust concentration values obtained in the field.

Table 1: Concentration levels at the CM operator

Specific Cutting Period	CM Operator Concentration Level, mg/m ³	
	Hund-1	Hund-2
Period 1	5.38	6.37
Period 2	4.99	4.88
Period 3	6.70	6.43
Period 4	5.84	6.68

Ultimately, the above results give an idea of the serious difficulties of dust measurement, with many challenges in obtaining the consistency required when comparing with a set limit for effectiveness of controls.

Typically, engineering samples are used to identify failures of engineering controls and such sampling is not a common practice elsewhere in the world for routine and daily sample data collection as practiced in South Africa. In order to compare the concentration of dust measured for similar CM operations data from a development heading (Figure 5) in a US coal mine is used. Dust concentrations were measured at the left and right rear corners of the continuous miner and at the remote miner operator location, with and without the additional side sprays in operation (Goodman, 2000). The results clearly show the significant differences in the measured dust concentrations on-board the CMs and for the CM operator at the remote position. Regardless of the dust control system operation (on or off), the ratio of fixed location area sampling to CM remote operator was high, i.e., 3.69:1 (sprays off) and 4.30:1 (sprays on) referenced to the left rear corner sampling position. Table 2 highlights the engineering dust concentrations greater than 5 mg/m³ measured by this NIOSH research study (Goodman, 2000).

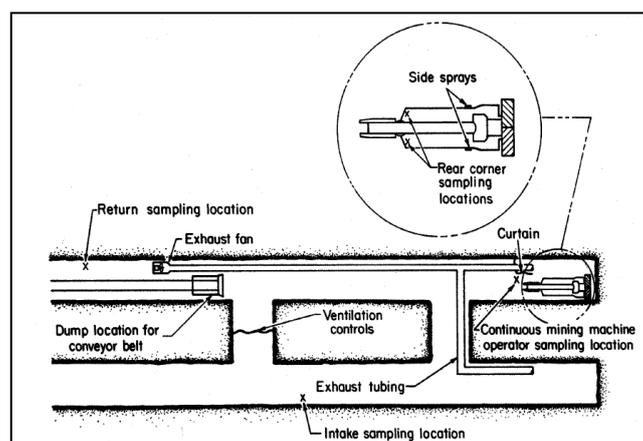


Figure 5: Remote operator location in a US underground bord and pillar section (Source: Goodman, 2000)

Table 2: Relationship between CM mounted fixed sample and remote operator from a US coal mine (Goodman, 2000).

Dust Control	Sample Location	Number of Samples, #	Sample time, minutes	Average dust, mg/m ³	Fixed/Remote CM Ratio, #
Side sprays Off	Left rear corner	2	321	9.74	3.69
	Right rear corner	2	321	4.58	1.73
	Machine operator	2	103	2.64	1.00
Side sprays On	Left rear corner	2	338	8	4.30
	Right rear corner	2	340	4.4	2.37
	Machine operator	2	120	1.86	1.00

Myths about CM engineering sample results as coal dust explosion diagnostic tool

Over the years, there have been various misleading views on the value of collecting engineering samples daily and of comparison with the stated limit value of 5 mg/m³. One such view is that 5 mg/m³ limit value can be a diagnostic metric to assess the coal dust explosion risk. The author has attempted to clarify this claim in the context of minimum dust levels required to initiate dust explosions. Coal dust is both a health and an explosion hazard and the key differentiator between these is particle size. Coal dust is less homogeneous compared to industrial dusts and has a complex structure which affects the propagation of a coal dust explosion. For health risk assessments, mean particle sizes of 4 µm (D₅₀ value) is of significance with the current coal dust exposure limit of 2 mg/m³. On the other hand, for dust explosion risk assessment, mean particle sizes of 20 µm (D₅₀ value) are used at least in explosion simulation test facilities such as Kloppersbos. There are various values on minimum dust explosion initiation limit values that can be found in the literature based on type of ignition source used, and laboratory limitations. One of the known lowest dust explosion initiation concentration value is 37 g/m³ or 37000 mg/m³. In addition, the commonly used Kex value to determine the explosibility of coal dust at Kloppersbos uses the dust level of 500 g/m³ or 500,000 mg/m³. Based on this critical and irrefutable scientific evidence, it is to be noted that the current B7 'engineering CM sample' value of 5 mg/m³ cannot be used as an input to assess the coal dust explosion risk assessment.

The levels of respirable and explosive dust formed during the coal mining process will depend on the inherent dustiness of the coal seam, pre-drainage of coal seams for methane, the array of cutting tools used and the design of the mining machine used. It is not easy to find documentary evidence of measured dust levels at the coal face of mines globally. This is due to the challenges of collecting samples or the conditions. In the dust explosion research work by Landman (1992), it was documented that the dust levels measured by Kachan, Kocherga and Kolchinsk in the Donbass basin coal mines in the Ukraine were recorded as between 4.6 g/m³ to 12.3 g/m³ at a distance of 0.5 m from the coal face, with 19.8 g/m³ to 25.8 g/m³ being the maximum. With water sprays the dust level around the cutting pick remains high at 9.2 g/m³, but falls to 0.4 g/m³ to 3.6 g/m³ when 0.5 m from the face. However, there was no mention of the sampling techniques used in the study. Based on dust measurement experiences at various coal faces, it is considered that these dust value can be very subjective, especially when taking samples while the CM is cutting with dust control systems operational, i.e., sprays, scrubbers.

Landman (1992) also reported gravimetric samples of the dust clouds surrounding CM drums measured by Chamber of Mines research Organisation (COMRO) from various collieries in South Africa. The recorded values varied substantially, with mean particle sizes of between 20 and 50 microns. It is to be noted that the dust concentration values are to be used just as a guidance and not as an absolute figure as the sampling during coal cutting is very unsafe and complex and values can vary enormously due to the type of dust gradient used from coal face to outbye area. The dust

concentrations observed varied substantially in a wide band from 1.7 g/m³ to a 160 g/m³, but values could possibly be higher. Landman (1992) has reported that high dust concentrations with methane far below its lower explosive limits can result in hybrid mixtures that are extremely sensitive to ignition. The most explosible mixtures for methane occur at the stoichiometrically balanced point of 9.5 % methane, and for coal dust depends on the properties of the coal under investigation. For washed Ermelo coal dust mixed with air, stoichiometric balance is achieved at 625 g/m³ of coal dust, for un-washed Ermelo coal at 670 g/m³, for washed Springfield coal at 928 g/m³ and for un-washed Springfield coal at 1033 g/m³.

For point source ignition, the lower explosive limit of a methane/air mixture is 5.2 %, but 1.4 % is the maximum allowed by law, resulting in a methane safety factor of 3.71. Similarly, if the lower explosive limit of Ermelo dust for volumetric chemical ignition is 75 g/m³ (Landman, 1992), limiting concentrations to about 20 g/m³ will also result in a safety factor 3.75. If the engineering CM dust value is seen as the limiting dust level for explosion prevention, the safety factor would be 15,000. For hybrid mixtures, which can be defined as a combination of two different phase components, namely gas and dust (solid) material in air, Bartknecht (1987) reported that at 2% methane concentration, the Lower Explosive Limit (LEL) of coal dust drops by 64%. Therefore, the safety factor in this discussion would drop down to 9,600 from 15,000.

The information evidenced above clearly show that the engineering CM dust concentration limit of 5 mg/m³ is well below the minimum dust explosibility level needed to initiate dust explosion in a coal face and therefore the use of this limit as a proxy measure for dust explosion risk is not deemed feasible.

RELATIONSHIP BETWEEN PERSONAL VS CM ENGINEERING SAMPLE DATA ANALYSES- DISCUSSIONS

The consistent application of the Directive (1997) represents almost two decades' worth of engineering sample collection by all underground coal mines in South Africa. In an effort to provide some relevance to this work, a pairwise analysis of the engineering and personal CM operator sample data was carried out in order to evaluate the relationship between CM engineering and CM operator sample results. The dust levels presented throughout this paper reflect respirable gravimetric dust measurements taken over a full working production period. Although the original engineering sampling definition was meant for the production period only, some of the engineering sampling periods were greater than 8 hours. It was assumed that the dust samples as collected underground were weighed and the procedure for determining the particulate mass was followed according to DME guidelines (DME, 1995). A total of 200 pairwise samples were available from two different random data periods Year 2005 and Year 2015 to evaluate and identify any significant differences in findings.

Figure 6 provides the relationship between engineering and personal CM operator sample values for different periods in two decades of sampling. The poor relationship between the engineering and personal CM operator samples is evident from these results. Similarly, Figure 7 shows the frequency distribution of the ratio between CM engineering and personal samples for the two sampling periods in the last two decades. It was noted that in the pre-2010 era, nearly 43% of the samples exceeded the ratio of 5:1, while post 2010, 22% of the samples exceeded this value. The key reasons for the extreme concentration ratios and significant differences in engineering and personal exposure levels can be attributed to the following:

- The outbye location of CM engineering samples (Figure 3) and off-board CM operator and different size of CM types impacting the dust gradient from the coal face and the engineering sample location.
- Human errors associated with the engineering and personal sampling process underground.
- Impact of stone dusting during engineering and personal sampling significantly affecting the interpretation of the measured dust levels as identified by Belle and Phillips (2013).

- Improved ventilation system and scrubber operation to improve the efficiency of the dust size-capture profile resulting in reduced dust levels

During a number of field studies, the following observations were made with regard to misuse of samplers. The problems observed include: incorrect sample pump and cyclone handling procedures, inconsistent positioning of samplers on the machine, sample pump not switched on, pump operating at flow rates of 1.4 l/min or below, sample pump pipe not connected properly, coarse dust holder (cap on bottom of cyclone) missing, sample pumps forgotten in lamp room, waiting place, on the top of auxiliary ventilation devices like a force fan and jet fan, lack of discipline and little or no knowledge of operating procedures and reason for sampling and/or benefit to operator not being clear. During frequent visits underground at a number of mines, it was found that the pumps were not switched on – this could have been the result of either pump failure or poor discipline.

As noted from the regression equation with a very poor correlation for both of the two periods, for a 2 mg/m³ personal Occupational Exposure Limit (OEL), the resulting engineering CM dust sample value would be 1.37 mg/m³ and 1.35 mg/m³ respectively against the expected CM engineering sample Directive (1997) value of 5 mg/m³. This further demonstrates the failure of the original rationale on the derivation of the 5 mg/m³ engineering CM dust limit value as an indication of personal exposure level of CM operator or face area workers.

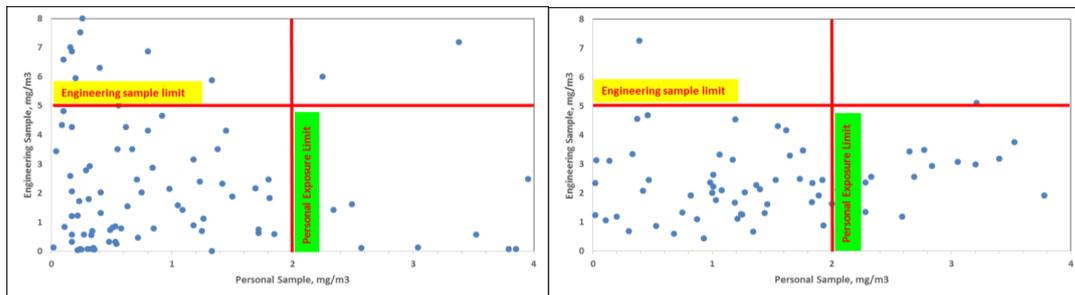


Figure 6: Relationship between CM engineering and personal samples

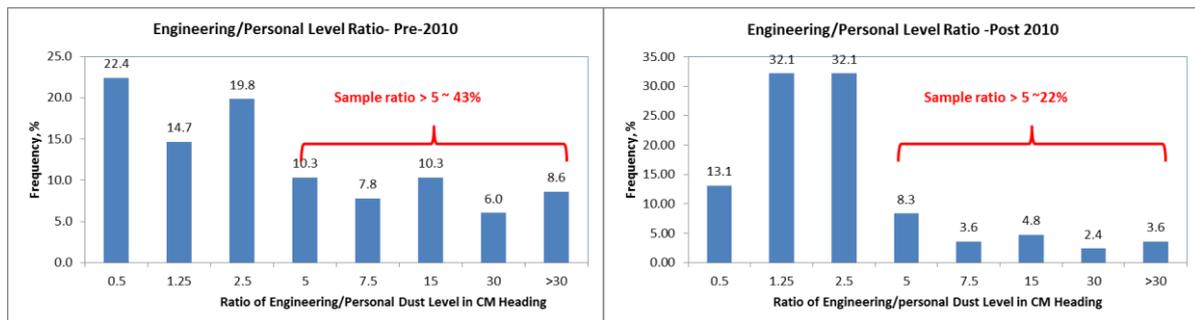


Figure 7: Frequency distribution of ratio of CM engineering and personal samples

USE OF CM ENGINEERING SAMPLING FOR PERSONAL EXPOSURE ASSESSMENT

Various studies have indicated that personal sampling provides the best estimate of worker exposures and of the temporal and spatial variability in those exposures for use in dose-response models. Leidel *et al.* (1977) recommended that, for accurate assessments, the personal exposure measurements must be taken within the worker's breathing zone. The inaccuracy incurred in using area sampling for measuring dust exposure of mining machine operators in US coal mines is well documented by Kissell and Sacks (2002). They recommended that the worker exposure is best assessed using 'personal sampling' rather than 'area or engineering sampling' techniques using evidence based on US coal mine studies. However, experience of personal and area dust

measurement in the narrow reef and humid conditions of very deep gold mines in South Africa suggests that area sampling can be an option where a clear dust gradient can be established with minimum variability between the two sampling techniques (Belle, 2002). The following studies reflect the extent of and the possible reasons identified for using personal sampling for exposure assessment:

- A comparative study of personal and fixed-point (area) samplers by Breslin, Page and Jankowski (1983) reported the coefficient of variation of measured mine dust concentration to be typically less than 20%.
- Listak *et al.* (1999) concluded that there was little predictive correlation between fixed-location area samples on CMs to operator breathing zone samples. This US study noted that if the fixed-point dust level was 1.5 mg/m^3 , then the 95% confidence level predicted operator dust levels at the boom hinge point and in the operator breathing zone exposure could vary from zero to 2.6 mg/m^3 .
- Divers *et al.* (1982) conducted a three-shift dust study in a US coal mine operated using remote control machines. Their study showed that the mean ratio of respirable dust samples taken at the cab and at the remote control operator location was 30.7.
- Kissell and Sacks (2002) have shown that a wide variation in dust levels between samplers located within a few feet (less than about 1.5m) of each other, i.e., fixed sampler was within 18 inches (45cm) to 30 inches (75cm) from the machine operator.
- Similar observations were made when the engineering samplers and real-time monitors were positioned between the front two poles of the CM operator cabin as shown in Figure 2.
- Table 3 shows the results of the four published US coal mine studies and the South African study reported in this paper. Table 3 provides enough information to calculate a mean concentration ratio (F/O) between the fixed location (F) and the CM operator (O).

**Table 3: Summary of mean ratio of fixed and personal sample
(Source: Kissell and Sacks, 2010)**

Published Study	No. of Mines	Mean ratio of Fixed/Personal sample	Relative standard deviation (RSD)
Kost and Saltsman, 1977	6	3.53	0.81
Divers <i>et al.</i> , 1982	1	30.7	0.21
Kissell and Jankowski, 1993	5	4.15	0.45
Listak <i>et al.</i> , 1999	5	3.07	0.59
This Study*	8	7.19	2.41

* This is discussed in the next section of the paper.

Based on the above Table 2, it can be concluded that the studies fail to meet the 25% accuracy criterion for which the average relative standard deviation (RSD) is 0.89 reinforcing the view that the fixed-location area samples cannot predict the personal dust exposure of a CM operator.

Derivation of 5 mg/m^3 engineering sample limit and its flaws

As noted before, the B7 directive of the DME stipulated an engineering sample compliance dust limit of 5 mg/m^3 as part of the B7 Directive sampling programme. It is most unfortunate that there was no guidance on behalf of the DMR to provide clarity on the purpose of the sample or on the basis of the 5 mg/m^3 limit. There has been confusion between this limit and the personal exposure limit value of 2 mg/m^3 . Despite this, there were ad-hoc suggestions that the engineering sample limit value was based on the regulated personal OEL of 2 mg/m^3 for coal dust. Based on the personal communications at the time (Rowe, 1997), it was noted that the 5 mg/m^3 engineering limit approximates the personal exposure limit of 2 mg/m^3 due to an estimation that the CM generally operates for only 40% of the shift, i.e., 192 minutes. A further assumption was made that there would

be no further exposures to coal dust following the completion of the cutting cycle of the CM despite knowing that the fresh intake air dust levels in the travel road also contain respirable dust. It is also to be noted that the derivation of the value or its assumptions as applied in South Africa is not practiced in other parts of the world.

$$\text{Engineering Dust level} = \frac{(\text{Personal dust OEL} + \text{Intake dust level}) \times 480}{40\% \text{ of CM production period} = (0.4 \times 480)} \quad (1)$$

In the above equation, the DMR (Rowe, 1997) had assumed that the CM cutting time in a shift is 40 % of 480 minutes, i.e., 192 minutes, that the intake dust level to the CM section would be 0.0 mg/m^3 and that the personal occupational exposure limit for coal dust is 2 mg/m^3 . Substituting these values in the above equation would result in an engineering sample limit value of 5 mg/m^3 . What can be ascertained is that there is no other scientific rationale for the value of 5 mg/m^3 . For example, if the production period is increased to 50% or 240 minutes, the expected engineering dust levels should be reduced to 4 mg/m^3 without changes to the engineering control system. Based on this background, it is to be assumed that under ideal conditions, the ratio of engineering and personal sample is 2.5, i.e., 5 mg/m^3 divided by 2 mg/m^3 . There seems to be no other scientific reasoning beyond the mere assumption of the CM cutting cycle duration and fresh air dust concentration levels of zero mg/m^3 . Figure 8 shows the relationship between the engineering CM sample limits for various production periods. With the suggested reduction of coal dust OEL to 1.5 mg/m^3 , application of the above concept would result in an engineering CM sample limit of 3.75 mg/m^3 for a 40% CM cutting time in a shift.

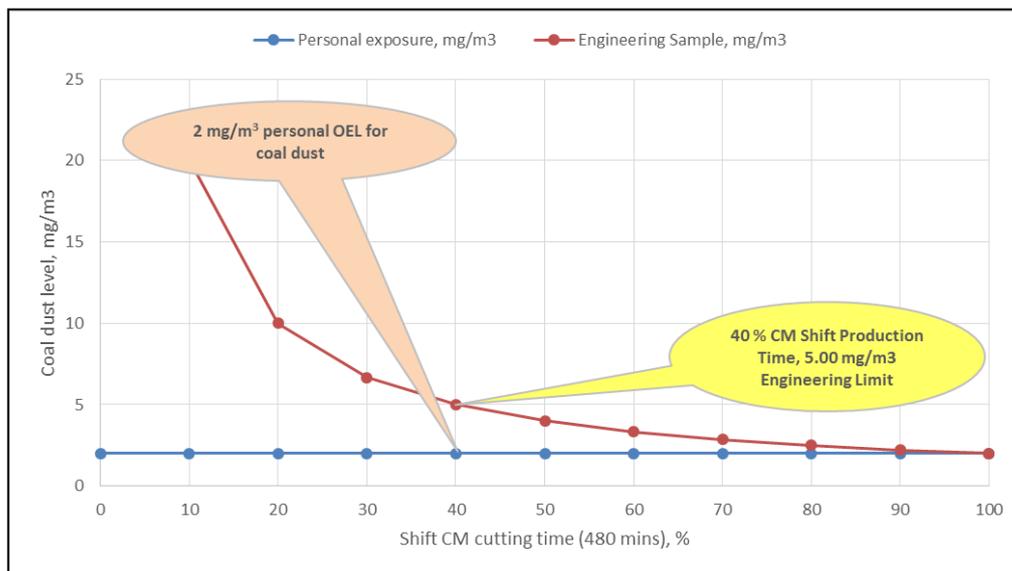


Figure 8: Relationship between engineering sampling limit and CM production time

Based on the reported results of engineering sample values well below 3 mg/m^3 , would indicate that only one of the following is true, i.e., the production period is increased or the sampling location is different. What is therefore certain is that the engineering sampling location in this context is simply not representative of the effect on the remote operator. Therefore, considering that the sample location, as identified, is the same, achieving an engineering concentration of 2.5 mg/m^3 would entail the assumption of a production time of nearly 80% of the shift (6.4 hours or 384 minutes) which, from current experience, is not justifiable. In addition, the basis of the initial calculation used to derive the 5 mg/m^3 limit, assumed that the shift lengths were in the region of 8 hours and cutting times around 40% of the shift. However, the derived engineering sampling results are extrapolated to full shift duration and sometimes up to 540 minutes. The above evidence suggests that the engineering sample values as stated in Directive B7 cannot be compared to the personal respirable coal dust OEL of 2 mg/m^3 .

Establishing an accuracy criterion and statistical analyses

The need for an exhaustive pair-wise statistical comparison was not carried out as the available data show glaringly obvious conclusions that the engineering to personal ratio not equal to 2.5. As part of this evaluation, an effort was made to validate if the measurement made using 'engineering sampling' technique will provide what the remote CM operator is exposed to breathing, i.e., personal exposure. Due to the presence of dust gradients represented by the ratio between engineering and personal samples if the operator was located in the cabin, one could have attempted to establish a relationship for an engineering sample's possible use as a proxy for the personal exposure value. In order to establish the engineering sample accuracy criterion standards, for all comparison purposes, the dust level measured by the 'personal CM operator sample' was considered the "true" exposure level. Therefore, the concentration ratio of the "engineering sample" to the 'personal CM operator' sample was calculated. If the variability in the concentration ratio is small, then one can consider accepting the "engineering sampler" for its continued use.

In order to validate the use of an engineering sample as a value for personal exposure assessment, the NIOSH accuracy criterion of $\pm 25\%$ (Kennedy *et al.*, 1995) and the European Community standard accuracy criterion of $\pm 50\%$ (CEN. 1994) is used. As part of the data analyses, concentration ratios of engineering and personal dust level of pairwise data from 8 different mines were created with the denominator being the personal exposure value and the numerator being the engineering sample value. The average and standard deviations of the concentration ratios of each of the mines was calculated. The corresponding Relative Standard Deviation (RSD) values were obtained and compared with the accuracy criterion to validate the acceptance or rejection of NIOSH/CEN accuracy standards. The RSD was calculated from the standard deviation and the mean concentration ratio. In a normally distributed data set 95.45% of the measurements fall within \pm two standard deviation (or ± 1.96 *standard deviation). This would represent that for the $\pm 25\%$ criteria with a mean value of 100, then $1.96s = 25$ and $s=12.755$. Therefore, the RSD value for the $\pm 25\%$ criteria is equal to 0.127 or less. Similarly, for $\pm 50\%$ criteria with a mean value of 100, then $1.96s = 50$ and $s=25.51$ and the RSD value for $\pm 50\%$ criteria is equal to 0.25 or less.

Table 4 show the summary statistic of dust concentration levels for the 200 pairwise engineering-CM operator data obtained from 8 different mines over two different periods spanning two decades as an assessment of the benefits and shortcomings of using engineering sampling. Ideally, as per the DMR directive (1997), the ratio of engineering sample to CM operator sample at the current coal dust OEL is 2.5. From the summary statistics (Table 4), it can be seen that there is an absence of any relationship between the two sampling techniques and any useful value in using engineering samples for this purpose. For example, for Mine A, the average of ES/PS ratio is 6.99 against the ideal value of 2.5. Overall, the CV of the ratio between the sampler dust concentrations was above the NIOSH and CEN accuracy criteria.

Table 4: Accuracy criteria for the mean concentration ratio between engineering and personal samples

Mine	A	B	C	D	E	F	G	H	Overall
PS mg/m ³	2.14	1.78	0.72	2.90	1.66	2.58	2.03	0.79	2.00
ES mg/m ³	2.43	2.86	3.45	3.44	3.97	3.05	2.77	4.05	3.00
# of samples	63	50	6	29	21	8	13	10	200
Avg. ES/PS Ratio	6.99	10.72	5.25	7.30	4.88	1.80	2.14	7.41	7.19
Min. ES/PS Ratio	0.06	0.02	0.24	0.02	0.23	0.30	0.60	0.24	0.02
Max. ES/PS Ratio	118.00	86.00	12.73	108.22	31.38	5.03	10.19	36.24	118
SD	20.91	18.45	4.82	20.88	7.50	1.52	2.57	12.05	17.36
RSD	2.99	1.72	0.92	2.85	1.54	0.85	1.20	1.63	2.41

* PS-Personal CM sample; ES-Engineering CM sample.

COST OF SAMPLING AND USE OF NIOSH PDM3700 REAL-TIME MONITOR AS AN ALTERNATIVE TO CM ENGINEERING SAMPLE

Dust sampling and exposure assessment is part of an expensive pathway to eliminating dust related lung-diseases. As required by regulations and directives, if properly carried out, exposure assessment can result in significant benefits to the mining industry. Uncertainties in mandatory sampling requirements and failure to review vast sample data sets has led to mines continuing to collect many thousands of samples (personal or engineering) with significant annual costs. A paper by Belle and Thomson (2005) estimated the cost of personal and engineering dust sampling for the coal mining industry. In addition, a high level costing of dust control and ventilation was also carried out using models that excluded the cost of the human resources utilised in the sampling programme. From the sampling-control cost model it was evident that the cost of monitoring in the coal mining industry is higher than the dust control costs. Therefore, it is evident that focusing the financial resources on dust control rather than monitoring would surely benefit the industry further by reducing exposure. In addition, the use of new technologies may still assist in meeting the sampling requirements.

In summary, in the absence of a meaningful relationship between the personal dust exposure and engineering sampling and wastage of resources, this study suggests that continuation of the CM sampling has no relevance. An alternative system to the engineering dust sampling program can be using permanent 'real-time' monitors at appropriate locations such as section returns and to take remedial actions using established models on dust levels in coal mine sections. In this regard, the studies on evaluating the use of real-time monitoring such as PDR1000, Hund, SKC Split-2 was carried out by the MHSC (Belle, 2002) in multi-commodity mines. The PDR1000 is the evolution of MiniRam (based on the light scattering principle) commonly used by the USBM/NIOSH mine studies in the 1980s and used as an engineering tool with a correction factor. The PDR1000 has been used as a Passive Sampler was evaluated in South African Coal, Gold, Platinum, Diamond mines to understand the engineering controls and not as a compliance tool. It should also be considered that the PDM3700 is an active real-time sampler that operates using a Higgins-Dewell (HD) size classifier prior to the dust concentration being read by the TEOM. This results in it being one of the best real-time dust monitors that can provide both the effectiveness of the engineering controls as well as personal exposure levels. Other benefits of the PDM-3700 are that it provides real-time temperature data, i.e., DBT and WBT and it is used as a real-time DPM sampler with NIOSH DPM Filter (Gillies, Wei and Belle, 2014).

A total of 955 samples were collected by a coal operator in the concurrent use of both a personnel worn PDM3700 and a gravimetric sampler. This data set supported the NIOSH results. The data shows that the average concentration measured by the gravimetric method (0.83 mg/m^3) was virtually identical to the PDM3700 with an average value of 0.82 mg/m^3 . Scientific studies conducted by NIOSH demonstrated the suitability of the PDM3700 to perform as a compliance personal sampling monitor or if required as an engineering sampler in CM section returns. Therefore, the choice of the PDM3700 personal real-time dust monitor for personal dust exposure management and as a replacement to engineering sampling is definitely a leading practice in the management of the dust hazard. It is recommended that the appropriate SABS certificates for its use in South African operations are obtained and that this device and a new sampling strategy are introduced into our mines.

CONCLUSION

The introduction and intervention by the DME (1997) directive has led to significant positive changes to dust control systems employed in South African coal mines. Previous analysis (Belle and Phillips, 2003) of the CM engineering dust levels indicated that the mere application of the 12 m rule on its own does not solve dust problems, but meticulous and regular maintenance and application of available state-of-the-art dust control technologies, effective dust control strategies and best practices, will ensure the reduced worker exposure. It also identified that the introduction of remotely

controlled CMs in the section would effectively lower the duration, severity and intensity of workers' exposure to coal dust.

Currently, South Africa is the only mining country where regulator prescribed engineering samples are collected every day and in some places sampling even exceeds the requirement. The basis of the engineering sample limit value of 5 mg/m³ does not have any scientific basis for relating it to the personal exposure levels. While the original rudimentary based engineering sample directive has assisted the industry to seek innovative dust control solutions, they do not provide any value in exposure assessment. Therefore, they must be reviewed with the objective of its discontinuation, as there is no relationship between engineering sampling and personal sampling the motive behind its continued use has to be seriously questioned, especially where resources are scarce.

Based on this investigation, it is considered that the continued use of CM engineering sample results is promoting misinformation about personal dust exposure of CM operators and multiplying the confusion on engineering sampling techniques. As part of this study, an attempt was made to identify the relationship between daily CM engineering sample and the CM operator personal exposure values. This paper has clarified the myths about sampling frequency benefit ratios and identified shortcomings and improvement opportunities in the management of the exposure levels in underground coal mines and these are summarized below:

- The study has demonstrated that the fixed-location CM engineering sample cannot predict the personal shift dust exposure of a CM operator. The South African study has shown that the average RSD value of over 2.41 against a measured value of 0.58 from the US coal mine studies demonstrates that engineering samples are totally unsuitable for any personal exposure assessment. Based on two decades of sampling and its poor correlation between engineering and personal samples, it is recommended that engineering sampling should be discontinued and replaced with measurement of remote operator personal exposure data that provides superior information towards dust exposure management.
- The commonly held belief that the engineering sample results are an indication of coal dust explosion risk is totally flawed.
- The performance of ventilation and dust control systems in a section can be achieved by current operating alternatives such as on-board methane sensors, CM water and pressure flow monitoring devices, scrubber monitors, section intake and return real-time air velocity monitors in addition to regulatory manual check-lists, start-up shift inspections and standard operating procedures.
- From an analyses of the cost of monitoring and engineering controls, it is evident that the operating cost of dust monitoring in coal mining industry is higher than the dust control costs. Therefore, it is essential that efforts be made to re-focus financial resources into dust control as this would result in reducing exposure and the use of real-time monitoring would equally meet the sampling requirements.
- The currently held perception that the 1997 DMR directive with an inherent requirement to operate the CMs with on-board scrubbers is flawed and, in addition, creates a continual noise hazard at the coal face. This particular requirement has prevented the coal mining industry from considering other leading practices, such as exhaust ventilation or force-exhaust ventilation systems as practiced elsewhere in the coal mining world. For example, coal mines in both the USA and Australia continue to operate up to 125 m long development headings using exhaust ventilation systems in managing very gassy and pre-drained, dusty coal seams.
- It is suggested that with the availability of new real-time technology such as the NIOSH PDM3700 engineering sampling can be replaced with personal exposure monitoring and effectively utilize the value add personal exposure assessment results to also evaluate the engineering controls.
- The NIOSH PDM3700 is a well proven personal –real-time dust compliance monitoring tool that is currently used by MSHA for compliance monitoring and has been introduced in Australian coal

mines. The PDM3700 not only provides an indication of the engineering control performance but also provides a valid sample for quarterly regulatory dust data submissions for other Homogenous Exposure Groups (HEGs) and critical occupations such as the roof bolt operator and shuttle car operator.

In summary, the focus of this paper is to review two decades of CM engineering sampling experience, perceptions and improvement opportunities. In addition, the status of daily collection of engineering samples, their subsequent use and relevance in managing coal dust exposure and explosion risk management is shown to be questionable. The paper highlights the strategic opportunities that could be better employed to improve the workplace in South African coal mines. It is suggested that the knowledge demonstrated in this paper be used to drive step-changes in sampling requirements by introducing flexibility for mines in approaching the measurement and management of personal exposure in coal mines.

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