# What is the value of inhalable coal dust exposure monitoring?

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## ABSTRACT

The re-emergence of 'Black Lung' or Coal Workers Pneumoconiosis (CWP) in Queensland (Qld) after reporting it being absent for over three decades had cast doubts on the rigour placed in the medical diagnosis and personal exposure assessment data. As of July 2023, Resources Safety Health Queensland (RSHQ) has reported that 68 and 88 cases of CWP and silicosis respectively, across the Qld mining and allied industry since 1984. The Qld Government amended the Qld Coal Mining Safety and Health Regulation 2017 (CMSHR) to reduce the exposure limits for respirable coal dust from 3.0 mg/m$^3$ to a level of 1.5 mg/m$^3$, with a respirable silica dust limit of 0.12 mg/m$^3$ in 2017 to 0.05 mg/m$^3$. Current exposure limit for inhalable coal dust remained at 10 mg/m$^3$, with the application of extended shift exposure limit values for compliance determination purposes.

Mining industry worldwide spends a significant amount of technical and financial resources in dust sampling to assess the exposures of health hazards for effectiveness of 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 coal dust in mining industry. Since its inception in 1920s, the recommended occupational exposure limits of a substance have varied significantly between mining countries worldwide. Over the last two decades, international harmonisation of size-selective sampling curve and instruments which replicate human inhalation of dust particles have changed. This paper discusses the experiences of the inhalable coal dust sampling for exposure and compliance monitoring purposes in the coal industry and shares the shortcomings of current personal exposure monitoring, reporting, assessment and compliance determination challenges using extensive service provider exposure data. Further the paper implores the benefits of inhalable sampling and its value in the long-term personal dose-response curves, non-compliance to 'ideal' inhalable size-characterisation curve and understand potential level of risks. The investigation study indicates sufficient and prior due-diligence of sampler characterisation prior to its industry wide applications. Lastly, it is suggested that any adjustment of inhalable exposure limits using the inhalable samplers that do not meet the size characterisation standards may not benefit all the stakeholders in the industry, let alone compliance monitoring. Until then, what is the value of inhalable coal dust monitoring or how is it being enforced?

## INTRODUCTION

Monitoring of coal dust and silica dust in mines is an important task as part of the exposure management journey that requires reliable knowledge of dust sampling devices that intended to collect the harmful dust. There are various means of measuring dust, *viz* personal sampling, area sampling and engineering sampling. Knowledge of routine dust exposure limit values can help workers' and industry focus on protection of workers respiratory health. Against this background, the scrutiny of available sampling devices used for routine sampling and exposure assessment that provides improved accuracy is continuing and appropriate. This paper shares experience of introducing a new instrument for the exposure monitoring that is relevant to similar industries worldwide. In Australia, Inhalable dust is governed by the standard AS 3640. This paper attempts to investigate the 'inhalable' sampler performance, sampling data, proposed limits, issues and its ultimate use in the exposure assessment and medical diagnosis purposes.

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, Busch and Lynch, 1977; Kissell and Sacks, 2002). 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, Vincent and Mark, 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 or Inhalable dust, 13.5 mg of thoracic dust.

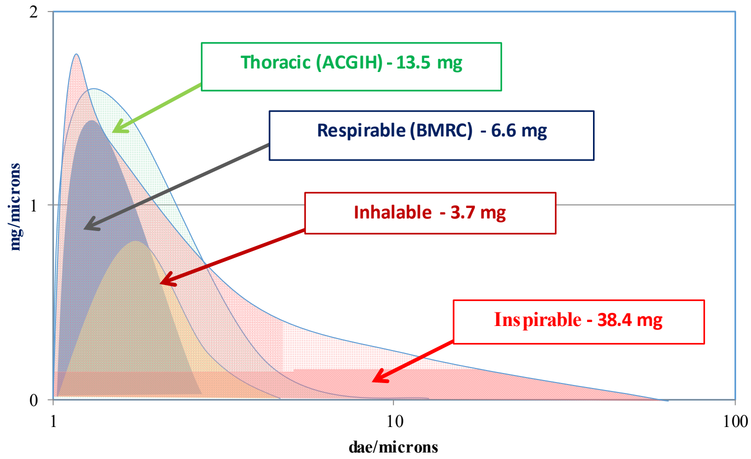


**FIG 1** – Illustration of typical respirable fraction of coal dust breathed.

A South African industry study for the introduction of any new dust-monitoring instruments for personal sampling in underground mines to be accepted by the key stakeholders, were required to meet the basic requirements (criteria) as outlined below (Belle, 2002, 2012):

- They must be intrinsically safe for use in underground mines.
- They must sample according to the accepted size-selective criteria at the specified flow rates.
- They must meet the ±25 per cent National Institute for Occupational Safety and Health (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.

The South African extensive multi-commodity mine study noted that the IOM respirable foam sampler failed to meet the NIOSH accuracy criteria and was not pursued further for use in South African mines (Belle, 2012). In Australia, personal respirable dust monitors are to meet the AS2985, definition of respirable dust with specific sampler flow rates mentioned in that standard. As a result of international harmonisation of size-selective dust criteria (ISO, 1995), led to replace the traditional '*total dust*' definition by '*inspirable*' that later termed as *'inhalable'* dust. Therefore, it is expected that the *inhalable* dust samplers are equally required and independently validated for coal dust to meet the following requirements for any sampling program in the coal mining industry, as inhalable coal dust sampling is practiced widely in the industry:

- ISO 7708:1995 (ISO, 1995) definition of Inhalable dust.
- AS 3640 (Standards Australia, 1989) Method for sampling and gravimetric determination of inhalable dust.
- British Method (Methods for the Determination of Hazardous Substances (MDHS, 2000)) 14/3 method for inhalable dust in air.

History of ‘total’ dust can be traced back to South African ‘sugar tube’ that can produce health effects after deposition anywhere in the body, including not only the lung but also other parts of the respiratory tract (eg the nasopharynx), as well as elsewhere in the body if the aerosol material is soluble (Walton and Vincent, 1998). In the USA or rest of the world, traditionally, dust sampling is carried out to measure ‘total’ and ‘respirable’ dust as outlined by NIOSH analytical methods. For ‘total dust’ sampling, a standard 37 mm cassette with a PVC filter membrane, which would collect airborne dust and small enough to fit through the cassette’s inlet opening of approximately 4 to 4.5 mm diameter is used. For respirable dust sampling in US mines, currently real-time gravimetric sampler that uses a size-selective HD type cyclone ahead of the filter cassette is used as a compliance device for coal dust exposure assessment.

Unlike harmful metal dust at very low concentrations, coal dust is hydro-phobic and known inhalable dust toxic health risk is less clearly understood. Currently in the USA, there are no personal occupational exposure limits (OEL) or personal exposure limits (PEL) for inhalable dust. Enforcement of those limits was suspended as the Final Rule on Air Contaminants Project (Occupational Safety and Health Administration (OSHA), 1989). While most of the exposure limits were originated in the USA, views submitted to OSHA (1989) when formulating generic ‘total’ dust or unregulated particulate limit were that there was no evidence of adverse health effects associated with exposure to these particulates. The submissions by the American Iron and Steel Institute at the time noted that effects of such exposures were found to be ‘short-term and immaterial’. OSHA has established an 8 hr TWA total dust limit of 10 mg/m$^3$ for all particulates having identified health effects in the toxicological literature but retained a 15 mg/m$^3$ ‘total’ dust limit for those particulates not specifically linked to health effects other than physical irritation (OSHA, 1989).

In Australia, preliminary industry investigation through engagement with end users (including medical surveillance, (Newbegin, 2020, personal communications)) suggested that the application of the inhalable dust exposure monitoring program implemented at the coal mining operations and ‘where’ and ‘how’ these inhalable exposure results in relation to the general health of CMW are used is not clear, well understood, other than for compliance enforcement, where applied. In Australia, Safe Work Australia (SWA) notes that where no specific exposure standard has been assigned and the substance is both of inherently *low toxicity* and free from toxic impurities, exposure to dusts should be maintained below 10 mg/m$^3$, measured as inhalable dust (8 hr TWA) as per AS 3640. This has been the basis for the monitoring of ‘inhalable dust’ in the coal mining industry. Furthermore, the ambiguities in the differences in measured respirable and inhalable dust has not been scientifically explored. What is clear is that there is inadequate medical evidence for coal dust on the short- and long-term medical health effects associated with exposure to inhalable dust and the reason behind the suspension of ‘inhalable’ or ‘total’ coal dust PELs in US or most of the world is not known. It is noted that Australian Coal industry is carrying out relevant inhalable dust research.

## INHALABLE DUST, EXPOSURE LIMITS AND SIZE SELECTIVE CURVE

Based on the past epidemiological knowledge (Orenstein, 1960), it has been established that the respirable dust particle size distribution is critical due to its potential health effects and quantifying the risks. Respirable dust refers to particles that settle deep within the lungs that are not ejected by exhaling, coughing, or expulsion by mucus. Since these particles are not collected with 100 per cent efficiency by the lungs, respirable dust is defined in terms of size-selective sampling efficiency curves. This had led to internationally recognised respirable size-selective sampling widely known as the British Medical Research Council (BMRC) definition of the respirable dust fraction or Johannesburg curve with a median aerodynamic diameter of 5 μm collected with a 50 per cent efficiency (D50) (BMRC, 1952). In reality, these size-selective curves represent lung penetration of dust particles that dust sampling instruments attempt to replicate. The International Standards Organisation (ISO) in 1995 recommended that the definition of respirable dust follow the theoretical convention described by Soderholm with a D50 of 4 μm (ISO, 1995; Soderholm, 1989, 1991). An international collaboration for sampling harmonisation has led to the agreement on the definitions of health-related aerosol fractions in the work-place, defined as the inhalable, thoracic and respirable curve (ISO, 1995; ACGIH, 1985, 1999; CEN, 1993).

The American Conference of Governmental Industrial Hygienists (ACGIH) established an Air Sampling Procedures Committee to review available data on regional deposition of inhaled particles and on the collection efficiencies of sampling instruments in 1988. The committee recommended 'Inspirable' Particulate Mass applies to material which is hazardous anywhere in the respiratory tract (Phalen *et al*, 1988). The modern terminology has replaced the term 'inspirable' with 'inhalable' (Kenny, 2003). Inhalable dust refers to the particle size entering the mouth and nose during normal breathing and may be deposited in the respiratory tract. Vincent *et al* (1990) documented that the human respiratory system is an inherent effective size-selective aerosol sampler, and therefore, it is misleading to assume that all airborne particles will enter it. Large particles are excluded from entering the nose and mouth through inertial separation. Personal exposures to this definition of large size dust particles in the workplace may cause physical irritation and respiratory health effects. IARC Monogram (1997) noted that there is no consistent evidence supporting an exposure-response gradient for coalmine dust and stomach cancer.

Vincent *et al* (1990) observed that aspiration or some time referred to as 'inspired' is a function of a number of parameters, including particle size, external air speed, orientation to the prevailing air movement direction, and breathing rate and volume. However, for external wind speeds of a few metre per sec and lower, the probability of a particle entering the mouth or nose (termed inhalable dust particles) may be generalised as being around 100 per cent for dust particles with aerodynamic diameters of a few microns and below, reducing to around 50 per cent at 100 μm aerodynamic diameter. Figure 2 summarises the BMRC and ISO size-selective curves for dust sampling in mines (ISO, 1995; ACGIH, 1985) to demonstrate likely penetration of dust particle sizes to various regions of human respiratory system. It is important to note that it is not only a difference in the $D_{50}$ value but an entire size-selective curve. Interestingly, inhalable sampling for coal dust is rarely practiced worldwide except in Australia and potentially UK. In the early 2000s the ISO standards on respirable and inhalable dust have come to prominence with various sampling devices available for sampling and assessment. Most sampling instruments that purported to measure the 'total' dust were developed without regard to their sampling efficiency characteristics (Ramachandran, 2005). Anecdotally, there were suggestions recently, even to monitor 'thoracic' fraction dust sampling from some dust sampling service providers to the coal mining operations in Australia.

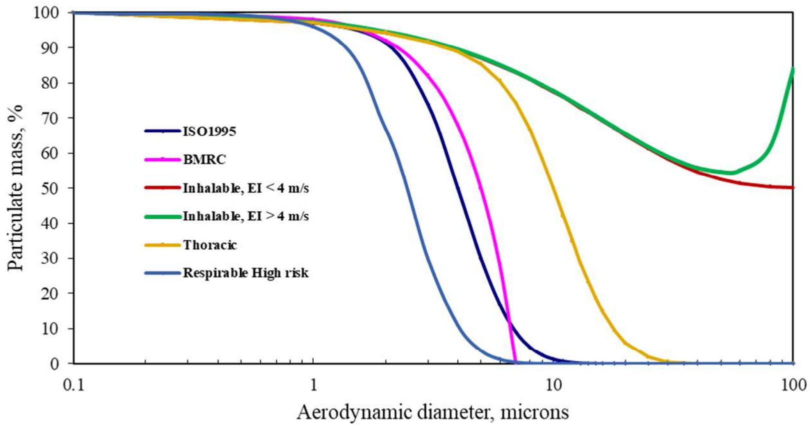


**FIG 2** – Respirable and Inhalable dust size selective characteristics (ISO, 1995; ACGIH, 1985).

The inhalable convention is based on particle penetration through the mouth and nose of a breathing mannequin over a range of wind speeds and orientations with respect to the wind, and is defined (Volkwein, Maynard and Harper, 2011; Maynard and Baron, 2004) as:

$$SI(d_{ae}) = 0.5 \times (1 + e^{-0.06*dae}) \quad (1)$$

for $0 < d_{ae} < 100$ μm. $SI(d_{ae})$ is the inhalable penetration fraction of dust particles entering the system as a function of aerodynamic diameter $d_{ae}$. It is to be noted that the Figure 2 for wind speeds > 4 m/s demonstrates the limitations of the prescribed ISO (1995) formula, which suggests that it should not be applied to particles with diameter of > 90 μm and win velocities U > 9 m/s. This very same size-characterisation curve implies the current use of inhalable samplers for air velocities under certain mining occupational environments where air velocities are > 4 m/s, as in the longwall face.

In Australia, the term inhalable dust sampling applies to both non-toxic and toxic dusts. Exposure standards for dusts are measured as inhalable dusts unless there is a notation specifying an alternate method, eg silica. In Australia, inhalable dust is defined as same (Table 1) as in ISO 7708:1995 and must be measured according to AS 3640-2009 (Standards Australia, 2009). It is to be noted the Australian health regulations refer to AS 3640-2009 and not ISO 7708:1995. AS 3640-1989 originally recommended either the Casella seven-hole sampler or the IOM sampler for personal sampling of inhalable fraction of airborne dust. The AS 3640-2009 notes that providing the airborne particulate does not contain other hazardous components, compliance with the exposure standard for dusts not otherwise classified should prevent impairment of respiratory function. Where no specific exposure standard has been assigned and the substance is both of inherently low toxicity and free from toxic impurities, exposure to dusts should be maintained below 10 mg/m$^3$, measured as inhalable dust (8 hr TWA). As expected, the exposure standard for dusts or particles not otherwise classified (PNOC) should not be applied where the particulate material contains other substances which may be toxic or cause physiological impairment at lower concentrations. For example, where a dust contains asbestos or crystalline silica, like quartz, cristobalite or tridymite, exposure to these materials should not exceed the exposure limit values for such substances.

**TABLE 1**

Inhalable dust definition as per ISO 7708:1995/AS 3640-2009.

| Particle equivalent aerodynamic diameter (µm) | Inhalable convention,% for wind speeds < 4.0 m/s | Inhalable convention,% wind speeds > 4 m/s |
|---|---|---|
| 0 | 100 | 100 |
| 1 | 97 | 97 |
| 2 | 94 | 95 |
| 3 | 92 | 92 |
| 4 | 89 | 90 |
| 5 | 87 | 87 |
| 6 | 85 | 85 |
| 7 | 83 | 83 |
| 8 | 81 | 81 |
| 9 | 79 | 79 |
| 10 | 77 | 78 |
| 11 | 76 | 76 |
| 12 | 74 | 75 |
| 13 | 73 | 73 |
| 14 | 72 | 72 |
| 15 | 70 | 71 |
| 16 | 69 | 69 |
| 18 | 67 | 67 |
| 20 | 65 | 65 |
| 25 | 61 | 62 |
| 30 | 58 | 59 |
| 35 | 56 | 57 |
| 40 | 55 | 56 |
| 50 | 52 | 55* |
| 60 | 51 | 55* |
| 80 | 50 | 62* |
| 100 | 50 | 84* |

* ISO (1995) inhalable size-selective curve limitations for air velocities > 4 m/s and risks of inhalable samplers where air velocities exceeds 4.0 m/s (see Figure 4).

The origins of inhalable sampler, which is used in Australia, as shown in Figure 3, can be traced back to the aspiration measurements on breathing mannequin research by the Institute of Occupational Medicine (IOM) by Mark and Vincent (1986). There have been various further studies on the shortcomings of IOM inhalable sampler, sample collection and interference, influence of environmental conditions that is expected to follow the ISO (1995) inhalable size convention with particles up to 100 µm aerodynamic diameter (Liden and Kenny, 1994; Kennedy *et al*, 1995; Aitken and Donaldson, 1996; Smith, Bartley and Kennedy*,* 1998; Roger *et al,* 1998; Li and Lundgren, 1999; Liden and Bergman, 2001; Aizenberg *et al,* 2001). Despite these shortcomings, and in the absence of any other inhalable guidance sampler, it's been accepted in the UK, followed by Australia as a gravimetric method for determining inhalable dust levels (Health and Safety Executive, 1997; Safe Work Australia, 1995).

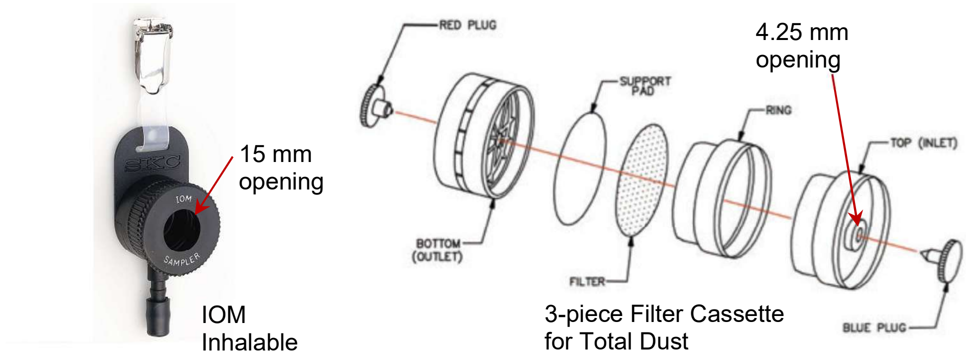


**FIG 3** – IOM inhalable sampler and the total dust filter cassette.

The operational issue of 'wall deposits' that is the dust attached to the sampler walls or surfaces was discussed by Harper and Demange (2007) for both IOM sampler and the traditional closed-face 37 mm cassette used in the USA. While no sampler may match the ISO (1995) conventions, understanding the size-ranges collected by the inhalable sampler in the field or manufacturer's size selective curves or sampler bias as a function of test aerosol distributions (Bartley and Breuer, 1982; Liden and Kenny, 1992; Maynard and Kenny, 1995) or dust concentration level is important for practical reasons for workers to understand their risk, operators to improve on controls or to the regulators to adjudge the risk limits.

Both inhalable and total dust samplers operate at a recommended flow rate of 2.0 lpm without any size-selective devices. Inhalable sampler has a larger open circular inlet (15 mm) with a lip that protrudes 1.5 mm outwards, with an aim to minimise the potential for particles deposited on the outer surfaces of the inlet to be carried into the sampler. The 'total' dust closed face three-piece filter cassette has an opening inlet size of 4.25 mm.

Considering the disproportionate attention given in some quarters of the globe to the inhalable sampling and potential limits for inhalable dust, some scrutiny has come. For example, Volkwein, Maynard and Harper (2011), Harper and Muller (2002) and Harper, Akbar and Andrew (2004) have observed that the upper limit of the size range of interest (100 µm) is an *arbitrary* selection, and particles larger than this can be airborne and therefore are available for possible inhalation. Specifically, this single factor of 'upper size' limit alone can be a significant driver in the dust concentration determination values during exposure assessment or compliance determination. They had argued that the inhalable convention does not account for mouth breathing potential and many other physiological variables due to changes in workforce age distribution, fitness, gender, ethnicity, and so on (Liden and Harper, 2006). Adding to the diverse parameters is the coal mining operational environment where the turbulent air velocity conditions of 3 to 5.0 m/s, against the original surface industrial calm air sampler performance evaluation settings of 0.1 to 0.3 m/s (Baldwin and Maynard, 1998; Liden, Juringe and Gudmundsson, 2000; Aitken *et al,* 1999; Kenny *et al,* 1999). What is definitive is that these inhalable samplers and their suitability is not evaluated for underground coal mining conditions where the legislative requirement of minimum air velocity requirements > 0.3 m/s, with normal air velocity ranges of 3 to 5 m/s, that are deployed to dilute and manage safety risks associated with the flammable gases.

Since the design inception of personal gravimetric samplers or cyclones, most to all sampler evaluations were carried out under 'calm air conditions' which is understood to be < 0.1 m/s air velocity to legislated minimum air velocities of 0.3 m/s for underground working environment. Baldwin and Maynard (1998) had noted that typically 80 per cent of the working conditions would have air velocities of up to 0.3 m/s, which influences the efficiencies of personal samplers. However, in modern coal mining conditions, the reality is that air velocities would be an order of magnitude higher or 'turbulent' conditions than these samplers that were designed and evaluated. Figure 4 shows the underground coal mining turbulent air velocity conditions, an operational reality, against laboratory evaluation conditions, which would have impact on sampler performance efficiencies.

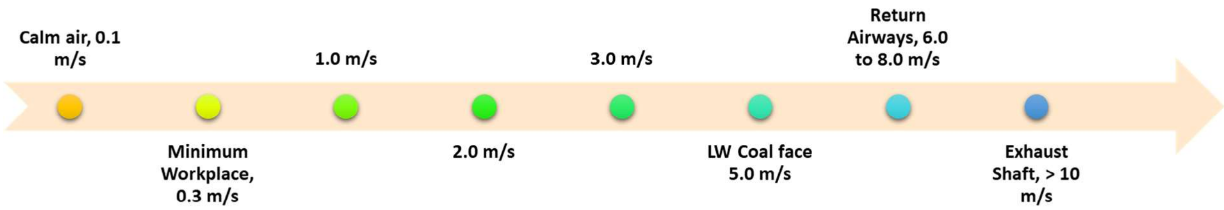


**FIG 4** – Laboratory personal sampler evaluation conditions < 0.3 m/s (Baldwin and Maynard, 1998) against underground coal mining ventilation conditions.

In the absence of clear evidence of past medical investigations in relation to coal dust, there are misperceptions and interpretations of health risk definitions used in the literature for respirable and inhalable coal dust. However, what is unquestionable is the critical importance of inhalable monitoring of toxicity of traditional low concentration high risk hygroscopic metal dust (cadmium, led) to asses known health impacts and inhalable exposure data as part of medical diagnosis. The influence of non-conformance to size-selective sampling, flow rates, and measured dust levels and compliance determination has been recently unearthed in Australia that led to the changes to selection of appropriate respirable dust sampler for use (Belle, 2017, 2018). However, this paper attempts to understand if there is a such similar sampler bias in IOM Inhalable coal dust sampler which has a 15 mm diameter inlet orifice, where particles are aspirated into and collected over a 25 mm filter, which is operated at 2.0 Lpm of flow rate.

Following paragraphs provide a glimpse of what could possibly have been the rationale behind inhalable coal dust sampling in Australia, with almost no studies on coalmine inhalable dust monitoring. In the absence of scientific due diligence or apparent significant benefits of inhalable coal dust may potentially lead to unverified confidence in dust controls, when used alongside with respirable dust data.

- Considering the health risks associated with the inhalable wood dust, Hinds (1988) noted a sampling method that accurately measures the amount of inhalable wood dust, including particulate deposited in the nose, is therefore desirable for the evaluation of worker exposures to airborne wood dust. Mark and Vincent (1986) observed that inhalable sampling method is expected to collect more particulate mass than the total dust method.
- A surface lead smelter study (Spear *et al*, 1997) with side-by-side personal aerosol sampling with 'total' (37 mm sampler) and inhalable (IOM personal sampler) showed the ratio, expressed as IOM (mg/m$^3$)/37 mm (mg/m$^3$) of individual paired samples were consistently greater than unity with values ranging from 1.39 to 2.14 aligned with IOM samplers collecting large particles than the 37 mm sampler of airborne dust (Mark *et al*, 1994; Kenny, 1995).
- A second lead smelter study (Spear *et al*, 1998) showed the mean mass ratios of inhalable to respirable for different workplaces with likely differing aerosol environment measured as per the ACGIH/ISO/CEN particle size-selective criteria varied from 4 to 10 using the personal inhalable dust spectrometer (PIDS).
- In a carpenter shop exposure study on wood dust, Martin and Zalk (1998) described a comparison of sampling results from air monitoring conducted using total dust and inhalable dust sampling methodologies for the evaluation of wood dust exposures for its association with the health effects referring to the Australian study (Pisaniello, Connell and Muriale, 1991). The Australian health study reference noted that the potential health effects from exposure to wood

dust include pulmonary function changes, allergic respiratory responses (asthma), and cancer of the nasal cavity and paranasal sinuses. The Safe Work Australia standards (1995) for inhalable wood dust exposure for hardwood and softwood are 1 mg/m$^3$ and 5 mg/m$^3$ respectively and historically 'total' wood dust exposures were measured (Alwis, 1998).

- Martin and Zalk (1998) concluded that the total dust sampling method underestimates the 'true total' inhalable aerosol and suggested that the existing inhalable sampling method needs further research and development before it can be accurately applied for evaluations for wood dust exposure assessment.
- Further two studies related to wood dust (Kim and Lee, 1996; Perrault, Cloutier and Drolet, 1996) reported that Inhalable/total dust ratios of 1.9 to 2.8 and 0.2 to 11.3 respectively and were dependent on dust concentration levels and the type of industry (Navy and Marine Corps Public Health Center (NMCPHC), 2020).
- Vincent *et al* (1997) suggested guidelines for use where it is deemed desirable to adjust exposure data to account for the change in exposure assessment rationale (based on generalisation of results of comparisons between 'total' aerosol as measured using the 37 mm sampler and inhalable aerosol as measured using the IOM sampler) with values 1 to 2.5 and for similar exposure groups, found to take values from close to unity to as large as 4.
- A US defence study (Clinkenbeard *et al*, 2010) that collected breathing-zone air samples for chromium collected for workers engaged in corrosion control maintenance operations on several types of aircraft at several US Air Force bases using pairwise modified 37 mm total dust sampling cassette with an IOM inhalable dust sampler. This approach utilised total chromium as a sensitive surrogate indicator of total aspirated mass. Linear regressions showed that the modified 37 mm cassette over-samples aerosol by 35 per cent compared to the IOM inhalable sampler when a wide range of aerosol concentrations and compositions for multiple field locations are sampled. This is the only study that potentially suggests that total sampling underestimates the dust levels when compared with IOM inhalable sampler.
- Liden *et al* (2000) carried out parallel inhalable personal dust sampling with the open-face filter cassette and the IOM sampler dust for nine types of organic dust. Parallel samples numbering 749 were obtained from 152 plants. The coefficient of regression for each subset ranged between 0.2 and 0.7. Based on the results of this study and the difference in sampling efficiency for large particles between the two samplers, it was concluded that the numerical value of the OEL for inhalable dust may be set at approximately ***twice*** the numerical value of the corresponding limit value for 'total dust'. If this were to be applied to coal dust, this would suggest that the inhalable limit value would be 20 mg/m$^3$, considering the current total dust limit value of 10 mg/m$^3$. This outcome in reality may not be beneficial to coalmine workers, considering the respirable coal dust limit is reduced by half in 2018.
- A field study (Demange *et al*, 2010) on metal exposure results comparing a 37 mm Closed-Face Cassettes and IOM Samplers, noted consistency to those published elsewhere with a ratio IOM/total dust of much higher than 1.
- Verma (1984) studied the measured 40 sets of side-by-side sampling relationship between Inhalable dust using overburden respiratory burden (ORB) sampler developed by Ogden and Birkett (1978), total dust and respirable dust by 10 mm nylon cyclone operated at 1.7 Lpm matching ACCGIH curve and MRE horizontal elutriator (Casella 113A) operated at 2.5 Lpm matching BMRC curve, in an area (static) sampling program at eight selected ferrous and non-ferrous foundries In the foundry environments surveyed, study noted that the total dust correlated highly with the inhalable dust concentration ($R^2$ = 0.94). The determined relationship from the field evaluations showed that Inhalable/total dust ratio was found to be less than 1.0.
- A Canadian steel industry (including welding) Hexavalent Chromium contaminant exposure assessment study (Shaw *et al*, 2020) showed that inhalable/total dust ratio was found to be 2.2.
- The IARC had classified carbon black as a possible human carcinogen (IARC, 1996) and further literature suggested that inhalation of elemental carbon black may be associated with

certain measures of respiratory morbidity (Gardiner *et al*, 1993). Therefore, inhalable carbon black measurement trends were studied using IOM inhalable sampler by Van Tongeren, Kromhout and Gardiner (2000) in the European Carbon Black Manufacturing Industry for overexposure assessment and review of limits.

- Görner *et al* (2010) had carried out an assessment of inhalable dust exposure using five different personal inhalable aerosol samplers in European laboratory wind tunnels under calm air and below 1.0 m/s air velocities using polydisperse glass-beads' test aerosol. Samplers tested were IOM sampler (UK), two versions of CIP 10-Inhalable samplers, 37 mm closed face cassette sampler (USA), 37 mm cassette fitted up with an ACCU-CAP™ insert (USA), and Button sampler (USA). Compared with CEN–ISO–ACGIH sampling criteria for inhalable dust, the experimental results show fairly high sampling efficiency for the IOM sampler. Significant differences between moving air and calm air sampling efficiency were observed for all the studied samplers. What are unknown in this study are the differences in the measured inhalable concentration levels between various inhalable samplers, when exposed to different dust levels, as in the operations. In comparison, for operating coal mining conditions, the air velocities are four times higher than those referred to by Görner *et al* (2010).
- Area sampling performance of six inhalable aerosol samplers was studied using monodisperse, solid particles by Li, Lundrgren and Rowell-Rixx (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).
- A German study (Wippich *et al*, 2020) to determine conversion functions from inhalable to respirable dust fractions of 15, 120 parallel measurements in German Database with no reference to coal dust concluded that all conversion functions are power functions with exponents between 0.454 and 0.956 and the data do not support the assumption that respirable and inhalable dust are linearly correlated in general.
- IOM report had recommended the Inhalable IOM sampler and Higgins-Dewell Samplers as suitable candidate samplers for measuring personal respirable dust exposure measurements for the Nickel (Ni) industry (Jiménez, Tongeren and Aitken, 2012) based on the historic IOM studies.

## AUSTRALIAN OPERATIONAL EVALUATIONS

In Australia, RSHQ data shows the respirable dust limits changed from 3.0 mg/m$^3$ in 2017 (CWP cases re-identified in 2015) to 2.5 mg/m$^3$ in 2018 and 1.5 mg/m$^3$ in 2020 for coal dust. However, there were no changes made to the inhalable dust. In a knowledge share (Figure 5) at the Dust and Respiratory Health forum of 2020, showed an interesting profile of average respirable and inhalable dust levels in a longwall face. While, the respirable dust levels followed the changes in the OEL values, inhalable dust levels did not make a difference at the longwall face. From a worker exposure perspective and engineering control perspective, this is contradictory. Dust suppression efficiency decreases with decreasing particle size (herein respirable dust), and dust control efficiency increases with increasing particle size of the airborne dust. Secondly, higher inhalable average dust values can be attributed to dust sampling program or sampling instrument deficiencies at the anonymous site, although collected D50 of inhalable dust is an order of magnitude higher. While these issues are not readily addressed, it brings into the fore, questioning the value of inhalable sampling and its use or interpretation. It cannot be sure if there is any reasonable worker exposure assessment can be made. Furthermore, there is lack of clarity on the use of divergent worker dust exposure assessment data outcomes on any medical diagnostic significance, let alone the suggestion for pursuing thoracic coal dust sampling.


**FIG 5** – Relationship between measured respirable and inhalable dust over the years (Source – Qld Dust Forum, 2020).

Another annual survey data of respirable and inhalable dust is shown in Figure 6. The mean respirable coal dust concentration for the period was 0.75 mg/m$^3$, while the average inhalable dust concentration for the period was 10.41 mg/m$^3$, with few higher measured inhalable dust values, exceeding the limit value of 10 mg/m$^3$. What can one make out of the situation based on the inhalable dust data? In the USA, the total dust limit of 10 mg/m$^3$ was equivalent to 2 mg/m$^3$ with less than 5 per cent of silica present in the sample. Figure 7 shows an example of inhalable sample dust collected for high concentration values of 17 mg/m$^3$ and 48 mg/m$^3$. Confidence in these measured inhalable dust levels were questionable, in terms of visibly larger chunks of agglomerated dust on the filters. Situations such as these and absence of past coalmine studies, provoke questions in relation to the value of collecting inhalable dust or the samplers that were used during the collection or how they could be related to compliance respirable dust that is effectively controlled.

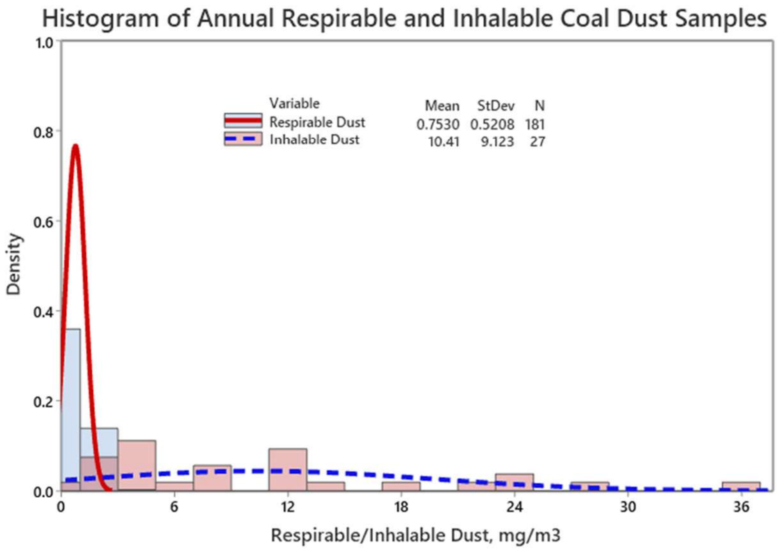


**FIG 6** – Example of relationship between measured respirable and inhalable coal dust.

**FIG 7** – Examples of inhalable coal dust sample filters with measured dust levels of 48 mg/m$^3$ (left) and 17 mg/m$^3$ (right).

## FIELD EVALUATIONS OF SIDE-BY-SIDE INHALABLE, RESPIRABLE AND TOTAL DUST SAMPLERS

Considering the above practical anomalies and differences in measured inhalable dust levels found, a field evaluation comprising of pairwise sampling of inhalable, total and respirable dust samplers was carried out. The samplers were operated as per the sampler operating instructions, which are aligned with the ISO 1995 methodology. This section of the paper discusses the results (Table 2) of the field evaluations on surface of the inhalable, and total dust samplers against the respirable samples collected. A total of 81 filters including blanks were collected and the dust samples were weighed, and concentration levels were determined at an independent accredited Australian laboratory facility with the limit of reporting (LOR) is 0.01 mg.

**TABLE 2**

Field measurement of three-way sample results of inhalable, respirable and total dust concentrations.

| Pair No | Inhalable (I) | Respirable (R) | Total (T) | I/R | T/R | T/I |
|---|---|---|---|---|---|---|
| 1 | 1.239 | 0.645 | 1.880 | 1.92 | 2.92 | 1.52 |
| 2 | 1.271 | 0.713 | 1.411 | 1.78 | 1.98 | 1.11 |
| 3 | 2.384 | 0.398 | 1.832 | 6.00 | 4.61 | 0.77 |
| 4 | 0.747 | 0.664 | 1.207 | 1.12 | 1.82 | 1.62 |
| 5 | 1.804 | 0.368 | 1.748 | 4.91 | 4.75 | 0.97 |
| 6 | 2.869 | 0.299 | 1.659 | 9.60 | 5.55 | 0.58 |
| 7 | 3.030 | 1.185 | 3.978 | 2.56 | 3.36 | 1.31 |
| 8 | 1.503 | 0.800 | 2.500 | 1.88 | 3.12 | 1.66 |
| 9 | 1.541 | 0.486 | 0.708 | 3.17 | 1.46 | 0.46 |
| 10 | 1.667 | 0.473 | 2.163 | 3.52 | 4.57 | 1.30 |
| 11 | 0.081* | 0.458 | 1.390 | 0.18 | 3.03 | 17.10 |
| 12 | 0.879 | 0.377 | 1.617 | 2.33 | 4.29 | 1.84 |
| 13 | 0.214 | 0.155 | 0.026 | 1.37 | 0.16 | 0.12 |
| 14 | 0.733 | 0.174 | 0.725 | 4.21 | 4.16 | 0.99 |
| 15 | 0.131 | 0.037 | 0.074 | 3.52 | 1.98 | 0.56 |
| 16 | 0.202 | 0.015 | 0.073 | 13.75 | 4.95 | 0.36 |
| 17 | 0.105 | 0.081 | 0.048 | 1.30 | 0.60 | 0.46 |
| 18 | 5.008 | 0.717 | 5.942 | 6.98 | 8.28 | 1.19 |
| 19 | 1.060 | 0.622 | 0.385 | 1.71 | 0.62 | 0.36 |
| 20 | 4.058 | 0.947 | 1.650 | 4.29 | 1.74 | 0.41 |
| 21 | 1.993 | 1.062 | 1.275 | 1.88 | 1.20 | 0.64 |
| 22 | 12.532 | 0.787 | 6.141 | 15.92 | 7.80 | 0.49 |
| 23 | 13.293 | 1.200 | 5.072 | 11.07 | 4.23 | 0.38 |
| 24 | 10.081 | 2.913 | 11.449 | 3.46 | 3.93 | 1.14 |
| **Average** | **2.85** | **0.65** | **2.29** | **4.52** | **3.38** | **1.56** |

* Unusual sample result.

For the gravimetric results, there were issues with loose dust, torn filter and switching filters. Those samples where cases of suspected pump failure or terminated prematurely in some inhalable/total samples were not part of the analyses. A total of 24 pairwise sampling results were available and they were taken over four sampling periods. There were some samples of very high inhalable dust levels with relatively moderate to high total and respirable dust samples (Pairs 22, 23 and 24). These 'high' inhalable dust levels (more than twice of the 'total dust') samples are probably due to large dust particles were deposited into these inhalable dust sample heads as these IOM samplers have much larger sampling inlet (15 mm) than the 'total dust' (the three-piece cassette) with 4.25 mm inlet. Sampling observations noted that large dust particles at higher dust loads were visible near the dust sources where some of the samples were collected. The relationship between the measured values obtained from the side-by-side inhalable-respirable, inhalable-total, total-respirable and inhalable-total dust levels collected under similar test conditions is shown in Figure 8. There was no statistical comparison between these samplers was made, as these samplers are designed and operated to different size-selective performance characteristics. From the plot it is observed that all field 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.

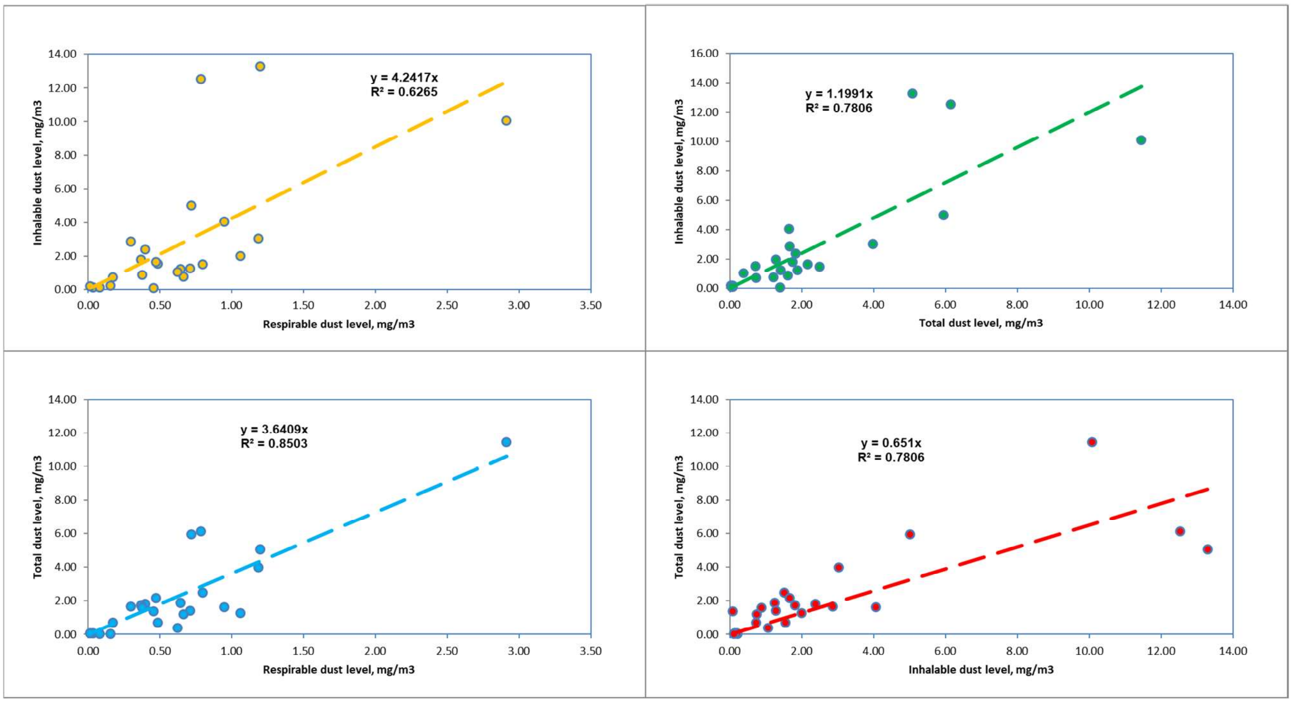


**FIG 8** – Relationship between respirable-inhalable-total dust for the three-way samples.

The review of sample data shows the large variation between sampled values using the IOM and total dust samplers depends on the size of large/chunky particles. Inhalable and Total values for sampler 24 are completely different from samplers 22 and 23: inhalable levels are similar but the total dust level for sampler 24 is more than double higher than other two samplers. The existing Inhalable and total dust samplers without size selective device are not able to obtain a confident relationship for any assessment of dust conditions. Even for compliance purpose, different site and operation could generate different varieties of particles with varied large particles. The high sampled concentrations doesn't mean high health hazards because a large amount of collected particles are greatly larger than 100 micron (D50).

The coefficient of determination values (R2), a quantitative measure of variation attributed, between the inhalable-respirable, total-respirable and inhalable-total dust sample pairs were 0.63, 0.85, and 0.78 respectively. The plot shows a nominal linear relationship and there is a significant difference between the measured dust levels by the inhalable, total and respirable samplers. For the study, the average measured levels (excluding pair #11) of the inhalable, respirable and total dust are 2.97 mg/m$^3$, 0.66 mg/m$^3$ and 2.33 mg/m$^3$ respectively for the field test conditions. The linear relationship model shows relatively poor relationship between Inhalable and respirable sample dust data. When comparing the inhalable and total dust data, excluding large concentration values of 10 mg/m$^3$ for pair # 22, 23 and 24, it is observed that the measured dust levels were approximately 1.5 mg/m$^3$ by the two samplers. This brings to the question, the impact of inhalable samplers at higher dust concentrations with large coal dust clouds and what it means if these samples were to be operated at higher concentration values or dusty conditions, that yielded wide results of inhalable sampler results.

For average inhalable or total concentration below 2 mg/m$^3$, the measured differences between inhalable and total dust sample values are relatively small. If one were to use the respirable dust standard of 1.5 mg/m$^3$, using the relationship between the inhalable and respirable sample data, measured inhalable dust levels would be below 5 mg/m$^3$ for the evaluated conditions, despite the current limit of 10 mg/m$^3$. What is clear from the data set is that at higher dust levels, the confidence in measured inhalable dust is lowered, let alone size characterisation studies associated with it. Therefore, the question, what is the value of inhalable dust sampling and the associated data, if there are no regulatory consequences.

## PARTICLE SIZE ANALYSES OF INHALABLE AND TOTAL DUST SAMPLES

In order to understand the particle size distribution (PSD) of collected inhalable and total dust, samples were analysed in an accredited laboratory, where the minimum particle mass required for the PSD analysis is 10 mg. The PSD analyses involved sample preparation to collect enough samples for analyses and coal dust samples on the filters were dispersed in the distilled water/ethanol by sonication. The PSD analyses was performed on Master Sizer 3000 on batch of filter samples that had high filter loading and contains a large amount of dust sample on each filter. In each PSD measurement test, the sample was repeatedly measured five times and D10, D50, D90 and D100 were measured. For example, D10 is the diameter of the particles at which 10 per cent of the sample's volume is comprised of particles with a diameter less than this value. For each type of dust, only four sample filters were processed, which has resulted in an enough amount of dust sample for PSD analysis. The sample preparation ie the dust detachment and dispersion in the solvent was conducted by sonication for a short duration about 5–10 mins. Table 3 and Figure 9 show the sample distribution of the collected inhalable and total dust samples from the field. Based on the analysed size analyses results, following observations are made:

- Maximum particle diameter of the inhalable samples had a mean size value of 450 μm, against the ISO 1995 standard, with larger diameter particles contributing to the increased mass concentrations of dust.
- Similarly, total dust sample data displayed bi-modal particle size distribution with maximum size range of the first mode distribution with an average of 116 μm.
- Average D50 of the collected inhalable dust sample was 16.9 μm, which is greater than the average D50 value of the total dust samples analysed, ie 10 μm, possibly attributed to the inhalable sampler inlet diameter and further contributing to the higher measured dust concentration levels, against the D50 of respirable dust of 4 μm.
- Furthermore, the Relative Standard Deviation (RSD) values of the particle sizes for inhalable sampler were higher than that of total dust.
- One of the key inferences from the Inhalable coal dust sample analyses is that perceived upper limit of 100 μm collected by the inhalable sampler is potentially misleading, as it is observed that the inhalable samples can collect significantly larger than 100 μm that is airborne and therefore are available for possible inhalation. The consequence of this finding is the implication of the existing exposure limit value of 10 mg/m$^3$ as the factor of 'size' alone can be a significant driver in the concentration values in exposure assessment or non-compliance.

**TABLE 3**

PSD analysis of Inhalable coal dust sample.

| Inhalable Dust # | $D_{10}$ (μm) | $D_{50}$ (μm) | $D_{90}$ (μm) | $D_{100}$ (μm) | Total Dust # | $D_{10}$ (μm) | $D_{50}$ (μm) | $D_{90}$ (μm) | $D_{100}$* (μm) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5.57 | 18.3 | 68.6 | 666 | 15 | 3.25 | 10.1 | 56.5 | 127 |
| 2 | 5.22 | 17.0 | 55.1 | 516 | 16 | 3.19 | 10.1 | 60.0 | 127 |
| 3 | 4.96 | 16.4 | 54.0 | 454 | 17 | 3.12 | 9.83 | 53.6 | 111 |
| 4 | 4.72 | 15.7 | 45.9 | 163 | 18 | 3.12 | 9.98 | 78.5 | 98.1 |
| Mean size | 5.12 | 16.9 | 55.9 | 450 | Mean size | 3.17 | 10.0 | 62.1 | 116 |
| RSD (%) | 7.11 | 6.69 | 16.8 | 47 | RSD (%) | 2.03 | 1.35 | 18.1 | 12 |

* presence of bi-modal size distribution.

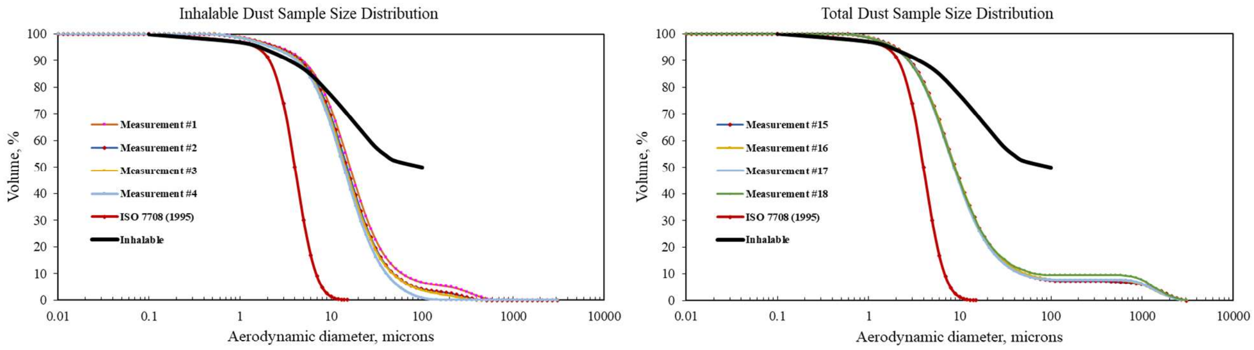


**FIG 9** – Particle size distribution of inhalable and total dust samples.

# CONCLUSIONS

The re-emergence of 'Black Lung' or CWP in Queensland (Qld) after reporting it being absent for over three decades had cast doubts on the rigour placed in the medical diagnosis and personal exposure assessment data. As of July 2023, RSHQ has reported that 68 and 88 cases of CWP and silicosis respectively, across the Qld mining and allied industry since 1984. The Qld Government amended the Qld CMSHR 2107 to reduce the exposure limits for respirable coal dust from 3.0 mg/m$^3$ to a level of 1.5 mg/m$^3$, with a silica dust limit of 0.12 mg/m$^3$ in 2017 to the current limit of 0.05 mg/m$^3$. Current exposure limit for inhalable coal dust remained at 10 mg/m$^3$, with the application of extended shift exposure limit values for compliance determination purposes.

In the absence of clear evidence of past medical investigations in relation to coal dust, there are misperceptions and interpretations of health risk definitions used in the literature for respirable and inhalable coal dust. However, what is unquestionable is the critical importance of inhalable monitoring of toxicity of traditional low concentration high risk hygroscopic metal dust (cadmium, lead) to assess known health impacts and inhalable exposure data as part of medical diagnosis. The influence of non-conformance to size-selective sampling, flow rates, and measured dust levels and compliance determination has been recently unearthed in Australia that led to the changes to selection of appropriate respirable dust sampler for use. Therefore, this paper attempts to understand if there is a such a similar sampler bias in IOM Inhalable coal dust sampler in terms of its size-selective characteristics when used in coal mining environment.

Mining industry worldwide is spending significant amount of resources in sampling safety and health hazards to ensure adequate control measures are being implemented. Over the years, size-selective sampling curve and instruments which replicate human inhalation have also changed along with dust compliance limits between various mining countries worldwide. Most mining countries sample for respirable dust, however sampling of inhalable dust in mining industry is carried out in very few countries like Australia.

This paper summarises comparative performance through dust concentration results evaluated under field conditions between the Inhalable, total and the 'reference true' Higgins-Dewell UK reference sampler operated in accordance with the to the CEN/ISO/ACGIH size-selective curve at a flow rate of 2.2 L/min (ISO 7708) as side-by-side static samplers. The results of the evaluation are relevant to Australian mines in the context of practices of inhalable personal dust exposure monitoring. The following conclusions can be drawn from these inhalable, total and respirable sampler evaluations:

- The field evaluation was unable to calculate average bias map using the particle size distribution data, due to complex and likely aerosol distributions encountered during the comparative sampling of inhalable dust samples. Based on experiences of monitoring side by side real-time coal dust in the South African coalmines have shown the presence of distinct dust clouds attributed to the dynamic ventilation systems attributed to the significant differences in the measure dust levels.
- Inhalable dust samplers on average measured higher dust levels than 'total dust' samplers. However, there is no consistent relationship between respirable and inhalable sampler measured dust concentrations.
- Using the current coal dust respirable exposure limit of 1.5 mg/m$^3$, the estimated inhalable coal dust levels, using the inhalable and respirable relationship obtained with this work would be 4.4 mg/m$^3$.
- As noted by overseas researchers, it is agreed that dust sampler performance can be influenced by airborne dust concentrations, size-characteristics of airborne dust, sampling environment, air velocities and turbulence, sampler orientation that cause degree of uncertainty in measured dust levels. Considering these variable properties, expert judgement is applied to determine compliance with regulatory limits, or the use of data for risk assessment and management of dust control.
- The presence of few coal dust particles of 500 µm to 1000 µm collected by IOM inhalable sampler would have mass value of > 1 mg that definitely skews the measured inhalable dust levels (see Figure 8). While there has been progress in the inhalable dust assessment in the known cancer-causing metal dust types, value of inhalable coal dust is questioned, until a practical relationship is established at the current coal dust exposure limit of 10 mg/m$^3$. In the interim, comparing the inhalable to respirable dust is unhelpful. On the other hand, it is possible that the current respirable dust collection may not be the reflection of the true dust control at the operations.

It is recognised that the monitoring of inhalable dust for those substance (eg cadmium, lead, manganese) that have immediate human body reaction upon entering the breathing space with known dose-response curve evidence is critical for measuring the likely harm. In this context, there has been no discussions in the Australian industry in relation to the inhalable coal dust sampling (Newbegin *et al*, 2020) as there is great uncertainty exist and what action must be taken based on the findings presented in the paper. The continued cases of CWP and silicosis in the industry do not provide the confidence in the control effectiveness, which is a lever for predicting future cases of lung diseases and problems at hand. From a medical diagnosis perspective, it is not known, how the inhalable coal dust results are used in the assessment outcome. Notwithstanding the doubts expressed about the inhalable dust measurement, the disparities between inhalable and respirable dust levels indicate that monitoring problems persist in the area of inhalable sampling in the coal mining industry or questions persist on the value of inhalable coal dust sampling data in the mining industry.

Based on the findings of this work, the use of 'inhalable dust' or 'respirable dust' as a criterion or 'key health performance indicator' in evaluating or validating the effectiveness of coal dust control systems or worker's exposure assessment would be problematic, considering contradictory outcome of inhalable and respirable exposure assessment data. This finding is significant in verifying the dust control effectiveness of workers' protection. From an operational perspective, the implications of this findings are significant when compliance and epidemiological determinations are made by using the current approach of using personal inhalable coal dust measurements.

It is hoped that the findings in this paper will assist in navigating with appropriate questions on 'inhalable coal dust sampling' and more importantly, how and where these results are being used by the medical profession or compliance enforcement purposes. In the absence of past studies or references on inhalable coal dust sampler studies in Australia, complicates the approach to the pursuit of reduction in the exposure limits from the existing 10 mg/m$^3$ to an unknown limit. It is suggested that additional 'controlled' studies replicating underground ventilation conditions be pursued to understand the deficiencies of the inhalable sampling requirements, inhalable size-selective sampler performance curves, compliance determination of worker exposure assessment using inhalable samplers, criterion used for dust control effectiveness using inhalable and respirable data.

The field observations and the exposure data presented herein for the coal industry suggests that the science behind the inhalable sampler may not be well understood yet and require further decomposition and design review of current inhalable sampler may be needed. Despite these findings and insights from this paper, the coalmine worker's expectations for a workplace of health and safety should not be obscured as the reduction of harmful dust is the primary critical control action, while the measurement forms the secondary action. The comparative field evaluation experience shared in this paper suggests sufficient due diligence and prior evaluation of any new instruments for industry wide applications be carried out. 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. In the case of inhalable coal dust sampling this is not evident. Finally, it is the consistent approach to inhalable sampling, instruments used, availability of exposure data relationship between respirable and inhalable to develop and understand to correct systematic biases in sampling which in the longer term assists in exposure determination and for continued formulation of dose-response relationships. Until then, what is the value of inhalable coal dust monitoring or how is it being enforced?

## 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, amendments to the exposure limits and need for data for continued development of dose-response relationships to improve safety and health of workers. Various inputs of all relevant parties are clearly acknowledged. This paper and the work contained herein is an effort to improve the exposure monitoring and improve engineering controls in workplaces.

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