

**ASSESSMENT OF THE HAZ-DUST HD-7204 REAL-TIME PERSONAL LIGHT-SCATTERING
PHOTOMETER FOR THE MEASUREMENT OF AIRBORNE INHALABLE DUST**

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ABSTRACT

The performance of the Haz-Dust HD-7204 direct reading light-scattering photometer was investigated in a small dust chamber for response to Calcium hydroxide dust across a wide concentration range. This was done to determine the difference between the real-time response and the built-in reference sampler, derive the average correction factor (CF) and examine its uncertainty, evaluate the linearity and understand the limitations in the sampling head design. The instrument response was compared with the built-in reference sampler. This was the IOM-type sampler, followed by the 37-mm single-hole cassette fitted with the MCE filter. The HD-7204 was factory calibrated to the ISO 12103-1 Fine Test Dust and designed to be predominantly responsive to dust of respirable size. There was a statistically significant difference between the real-time and the reference method (t-Score 3.09; p-value <0.05). The monitor significantly underestimated the measurement of inhalable concentrations for Calcium hydroxide. The mean CF was calculated at 1.95 ± 0.65 (CV 0.32). The application of the mean CF significantly improved the accuracy of the real-time data. The linearity was good across the entire concentration range (R 0.98); however, there might be a better monitor response at higher concentrations. The regression analysis indicated a very good fit (R^2 0.965), and the regression equation could be used as a reliable prediction model of exposure in the absence of reference method data. The design of the IOM-type sampling head had several limitations that could result in undersampling. The results demonstrated that the derivation of a valid CF is necessary to align the real-time response to the reference method. Overall, the performance of the HD-7204 is comparable to its alternatives. The monitor has several advantages and can be a powerful tool in exposure assessment if its limitations are fully appreciated and accounted for.

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INTRODUCTION

Occupational health protection agencies across the world set various occupational exposure limits (OELs) to regulate the exposure to hazardous substances and ensure the protection of workers' health. When OELs are legally binding, demonstrating compliance through exposure monitoring is often mandatory. Compliance monitoring requires collecting a certain number of aerosol samples of a defined size fraction in the worker's breathing zone to obtain a statistically robust exposure dataset to compare against the exposure limit (The British Standards Institution, 2019).

There are conventional validated methods for air sampling that allow for the collection of personal exposure samples for comparison against the OELs. In the UK, these are Methods for the Determination of Hazardous Substances (MDHS). For aerosols, it is typically MDHS14/4 "General methods for sampling and gravimetric analysis of respirable, thoracic and inhalable aerosols", and for volatile organic compounds, it is usually MDHS72 "Volatile organic compounds in air. Laboratory method using pumped solid sorbent tubes, thermal desorption and gas chromatography". These methods utilise an air sampling pump connected to a sampling head via tubing, fitted with a sampling media that captures the contaminant in the workers' breathing zone for subsequent gravimetric or chemical analysis. This type of analysis is known as the integrated sampling method and provides a time-weighted average (TWA) concentration over the sampling duration. Although this method is useful in comparing exposures against long-term (8-hour) and short-term (15-min) workplace exposure limits (WELs), it does not offer any resolution (e.g. 1, 10, 60 seconds). The integrated sampling method conceals valuable information that can be used to identify and control the specific sources of exposure, creating a need for a direct reading instrument capable of providing real-time monitoring data.

In the 1980s, a new type of sampling device became available – the direct reading instrument (DRI). The most common type of particulate DRI is a light scattering photometer (The British Standards Institution, 2010). For this type, the dust-laden air enters the sensing zone, where a beam of light illuminates it. Dust particles reflect this light in all directions (scatter), and the dust concentration can be determined from the intensity of this scatter. There are also other types of particulate DRIs, such as Piezobalance, TEOM, Beta Mass, and Optical Particle Counters. They have different operating principles from light-scattering

photometers and have specific advantages and disadvantages (The British Standards Institution, 2010).

DRIs can provide instantaneous results and drastically reduce the time between the monitoring event and the conclusion of compliance status. Thus, reducing the time and cost of a workplace exposure monitoring programme. In contrast with conventional sampling methods, DRIs allow for monitoring both peak (ceiling) and long-term exposures (15-min and 8-hour TWA). They have also proved helpful in assessing the efficiency of engineering controls and pinpointing the source of exposure in preliminary surveys when combined with visual video techniques (video exposure monitoring).

Although there were issues with specificity, the use of DRIs for monitoring gases and vapours had better acceptance due to their accuracy in response (Baron, 1994). However, the use of photometer-type DRIs for monitoring aerosols was not widely adopted due to the complexities in response to various particulates associated with their physical parameters, such as size, density, and refraction index.

Several studies evaluated the performance of various commercially available direct-reading dust monitors used for compliance monitoring (Kuusisto, 1983; Willeke and Degarmo, 1988; Tsai, Shih and Lin, 1996; Lehocky and Williams 1996; Thorpe and Walsh, 2002; Thorpe, 2006; Thorpe and Walsh, 2007; Thorpe and Walsh, 2013; Dado et al., 2017). The research confirmed a significant variation in monitors' response when challenged with various aerosols and differences in response between various devices when challenged with the same dust. It also highlighted the inability of many monitors to sample in the breathing zone and capture the EN481 and ISO 7708 defined aerosol size fractions (The British Standards Institution, 1993; The British Standards Institution, 1995). Nevertheless, these studies have demonstrated that when valid correction factors (CFs) are applied, DRIs could be used for personal exposure monitoring with a satisfactory degree of accuracy compared to conventional sampling methods.

In 2019, the Environmental Devices Corporation released a new real-time personal light-scattering photometer Haz-Dust HD-7204 (HD-7204). According to Environmental Devices Corporation (2019), the monitor aimed to overcome common flaws of existing DRIs, namely:

- the inability to sample EN 481 and ISO 7708 health-based size fractions;
- the inability to capture contaminants in the workers' breathing zone;
- the requirement for a separate sampling device to obtain the gravimetric/chemical reference sample.



Figure 1. Haz-Dust HD-7204 Real-time Personal Dust Monitor.

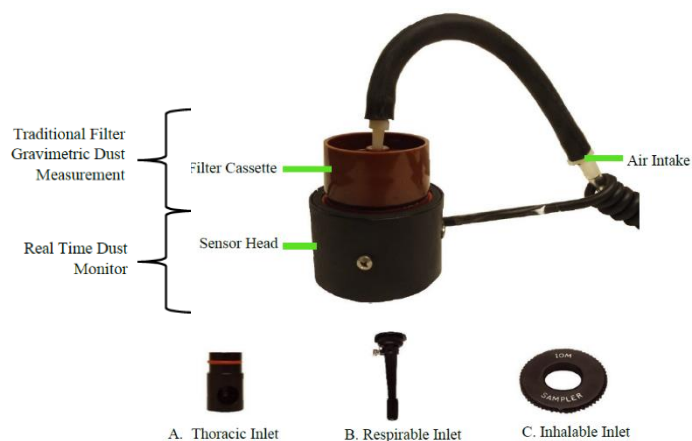


Figure 2. Components Used for the Traditional and Real-time Dust Monitor.

The HD-7204 overcomes these challenges by combining a conventional pumped gravimetric/chemical sampling method with light-scattering sensor technology. The sensor is integrated into a standardised IOM-type sampling head that can be fitted with a respirable (cyclone) or thoracic adaptor and connected to an air pump that supplies the required flow rate (Environmental Devices Corporation, 2019).

The device monitors the scattered light from the infrared emitter to calculate the concentration of an aspired aerosol. The HD-7204 is calibrated with the ISO 12103-1 Fine Test Dust (Arizona Road Dust) and will only provide accurate readings when challenged with the same test dust. For other dusts, the response of the HD-7204 monitor is expected to vary significantly depending on the aerosol's physical properties, such as density, colour, refractive index, and size, thus making it essential to apply a valid CF.

Although some previous studies have evaluated the response of similar devices (e.g. SKC Split 2, Haz-Dust IV), no research was available that assessed the performance of the HD-

7204 monitor. As such, the reliability of this monitoring device has not been independently verified beyond the manufacturer's claims.

This study attempted to evaluate the performance of the HD-7204 when used to monitor the inhalable Calcium hydroxide dust. The objectives were to assess the difference between the real-time response and the conventional sampling method, examine the linearity between the sensor response and the integrated reference sample across a wide sensing range, evaluate the degree of scattering in CFs, and derive a mean CF. Also, the intention was to examine the effect of dust concentration on linearity and investigate the limitations in the HD-7204 sampling head design that could affect sampling efficiency.

The HD-7204 monitor was challenged with Calcium hydroxide dust in a purpose-built small-scale dust chamber. A series of measurements were undertaken to collect in-line samples using the real-time sensor and the conventional gravimetric/chemical reference method. The results were subjected to statistical analysis to evaluate the aforementioned parameters.

Understanding the performance of the HD-7204 monitor will allow for direct comparison with other DRIs and provide the basis for an informed decision when selecting suitable and sufficient exposure monitoring equipment. A statistically valid correction factor for the HD-7204 monitor will provide an essential in-field calibration for real-time exposure monitoring when sampling for Calcium hydroxide. Consequently, this will eliminate the need for laboratory analysis and drastically reduce the time and cost of an exposure monitoring programme.

AIMS AND OBJECTIVES

This study aimed to evaluate the performance of the HD-7204 monitor across the aerosol concentration range expected to be encountered in occupational settings.

The objectives of the study were:

- To confirm/refute the existence of statistically significant difference in response between real-time and reference methods.
- To derive a statistically valid mean correction factor for the test dust (Calcium hydroxide).
- To determine the level of correlation between the real-time response and the built-in IOM-type sampler reference method.
- To assess the degree of dispersion in correction factors and understand its implications.
- To determine the net effect of applying the derived mean correction factor on precision.
- To evaluate the effect of the aerosol size and concentration on the linearity of the real-time response.
- To compare the performance of the HD-7204 to similar direct reading instruments.
- To examine potential limitations in the IOM-type sampling head design.

LITERATURE REVIEW

A considerable amount of research on direct reading dust monitors was undertaken between the 1980s and 2000s. These early studies had significant limitations, but nevertheless, they provided a fundamental understanding of photometer-type dust monitors' performance and highlighted the critical variables influencing their accuracy and precision.

Kuusisto (1983) studied CFs for numerous portable DRIs. His research showed a precision of <25% for six monitors with respect to common industrial aerosols. Another study by Tomb and Gero (1988) compared real-time aerosol monitor responses to various dusts. The aerosol type strongly affected the measured concentrations, and results varied by a factor of two at the extremes compared to the gravimetric method. Both studies showed that direct readouts could not be accepted as factual data, so CFs had to be applied.

Willeke and Degarmo (1988) evaluated the difference in DRIs response when operated in active and passive modes. They found that flow rate significantly affected sampling efficiency and the degree of internal wall loss.

In his review, Baron (1994) noted the lower popularity of direct-reading aerosol monitors compared to real-time gas and vapour monitors, which he attributed to the complexity of particulate properties that result in considerable variability in response. He acknowledged common flaws in monitor inlet design and a significant impact of internal wall losses, rendering results unreliable. However, important aspects such as linearity and correlation in sensor response were not captured due to the exploratory nature of his review. While the HD-7204 is designed to replicate validated sampling head designs, it can still suffer from internal wall losses, reducing the linearity in sensor response.

Tsai, Shih and Lin (1996) tested the response of different monitors to particulates with a similar size distribution. One of the monitors was found to have an accuracy within 10-16% of the reference method independent of dust material. However, "total dust" was used as a benchmark which had little value when compared against health-based OELs based on the EN 481 and ISO 7708 defined size fractions (The British Standards Institution, 1993; The British Standards Institution, 1995).

A later study by Lehocky and Williams (1996) compared the performance of respirable samplers to direct-reading aerosol monitors. They found that none of the monitors agreed identically with each other nor with a benchmark respirable sampler. However, the authors concluded that the tested instruments could still be used to measure coal dust based on the high coefficient of determination values indicated by regression analyses.

Early work by Thorpe and Walsh (2002) investigated the sources of variation in response of three portable direct reading dust monitors - MIE DataRam, Casella Microdust, and HAM. They acknowledged their major limitation that the CFs could vary significantly depending on the physical properties of the measured dust.

The monitors' response was compared to the response of the Higgins-Dewell (HD) cyclone sampler. Several tests were undertaken inside a dust tunnel with air velocities of 0.5 and 2 m/s. Stone, wood, MDF, and flour dust were selected as challenge aerosols. The test dust was introduced via a screw feed system. Some tests were undertaken in a calm air dust chamber where aerosols were introduced via a fluidised bed generator or screw feed system. A total of 38 samples were taken.

All monitors were generally found to show good linearity. CFs ranged between 0.91 and 6.77, depending on test conditions. Devices calibrated to SAE Fine, and Arizona Road Dust agreed closely with reference samples when challenged with respirable stone dust, which is similar to the factory calibration dust. On the other hand, Microdust calibrated to the Total Suspensible Particulate (TSP) consistently read higher, by up to a factor of 6.77. This highlights the importance of understanding the physical properties of the factory calibration dust and the measured aerosol when predicting a real-time monitor response.

DRIs responses were found to increase with the increase in mass median aerodynamic diameter (MMAD) of the challenge dust. This was explained by the fact that cyclones conforming to the EN 481 respirable convention curve will stop sampling particulates >12 μm while light-scattering sensors will continue to detect particles up to 30 μm in diameter.

Increased air velocity did not affect monitors' response when challenged with stone dust. However, for dusts with larger MMAD, an increase in air velocity resulted in a decreased monitor response. The impaction and inertia could potentially affect larger particles preventing them from reaching the sensor. The author confirms this assumption in a later

study (Thorpe and Walsh, 2007). It is reasonable to assume that an increase in particle size would affect the HD-7204 monitor response to a lesser extent since it relies on active sampling that reduces the significance of impaction and inertia. In addition, Mark, Lyons, and Upton (1993) have shown that at 2 m/s, cyclone samplers have increased sampling efficiencies and, therefore, would introduce bias when used as a benchmark.

When the monitors were exposed to very high concentrations, the optics became contaminated, significantly affecting their accuracy. This effect was more pronounced when attempting to measure a lower concentration after a high-level exposure event. Even after decontamination, one monitor showed a calibration factor 65% lower than the original value. Thus, overexposure may potentially result in permanent damage to optics. The HD-7204 may suffer the same fate as its sensor is not shielded from the incoming dust, so it is essential not to expose it above the sensing range ($>500 \text{ mg/m}^3$).

In his later work, Thorpe (2006) assessed the performance of five different personal direct-reading dust monitors for measuring inhalable dust. He acknowledged that an instrument calibrated to a standard dust would respond differently to various particulates depending on their physical properties, such as particle size, shape, and refractive index.

The evaluated devices were SKC Split 2, Thermo Electron DataRAM (pDR-1000), Respicon TM, Sibata PDS-2, and TSI Sidepak. Out of these five monitors, the design of SKC Split 2 has the closest resemblance to the HD-7204. Both monitors have a light scattering sensor built into the IOM-type sampling head, and both are capable of aspirating inhalable dust at the required flow rate. Options to sample for respirable and thoracic fractions are also available for both monitors. However, SKC Split 2 relies on size-selective foam plugs that are prone to undersampling with increased dust loading (Thorpe and Walsh, 2007). The HD-7204 employs size-selective adaptors with a non-filtering mode of action and thus should not suffer from this limitation.

Other monitors also claimed to be able to collect certain size fractions via size-selective adaptors, specific inlet designs, or integrated impactors. However, these did not conform to the EN 481 or ISO 7708 conventions curves, and all had non-standard sampling inlets making their use for compliance monitoring less valuable.

The responses to various dusts with different physical characteristics and MMAD (6 to 89.5 μm) were tested in a modified recirculating wind tunnel (Blackford and Heighington, 1986). The response of instruments to inhalable dust was compared with the IOM personal sampler. A Casella respirable cyclone sampler was used to benchmark the response to respirable dust. A uniform velocity profile of 0.5 m/s was established to avoid dust concentration gradients. The samplers and monitors were mounted onto a manikin. A multipoint injection system was used to generate dust within the tunnel.

It was found that all monitors greatly underestimated the inhalable concentration for all the tested dusts. The response of a light-scattering sensor decreased with the increase in particle size. All monitors showed good linearity. The SKC Split 2 generally had a higher response to all dusts of various sizes (CFs 5.03-181.82) compared to other instruments (CFs 6.02-588.24). The SKC Split 2 response to respirable dust was mixed depending on the similarity between the evaluated test dust and the factory calibration dust. The author found that the SKC Split 2 IOM-type sampling head suffered from dust losses amounting to an average loss of 55.9%. These losses were attributed to the poor rubber seal.

Reasonable extrapolations can be made between findings related to the SKC Split 2 and the HD-7204 monitors due to their design similarity. However, an identical response of two different sensors from different manufacturers cannot be guaranteed. Also, the magnitude of potential wall losses for the HD-7204 sampling head is unknown and should be evaluated separately.

A year later, Thorpe and Walsh (2007) compared three direct-reading monitors sampling actively, with size-selective adaptors, and passively. These were Microdust Pro, DataRam pDR-1000, and SKC Split 2. He highlighted that real-time monitors could accurately measure respirable dust when properly calibrated.

In contrast to his previous work, the monitors were tested inside a calm air dust chamber without a manikin. This decision was motivated by the findings of Kenny and Stancliffe (1999), who demonstrated that random errors in reference concentrations are easier to control within a small space. The temperature and relative humidity were not regulated but ranged between 21–23°C and 30–35%. As such, the author failed to capture the effect of atmospheric conditions on monitors' performance.

Two test dusts with the MMAD of 6 and 13 μm were used to evaluate the effect of particulate size on the real-time response. Such a narrow size range could only provide a limited conclusion, and the study would have benefited from selecting challenge dusts with a broader size range. Various aerosol generating methods were used to introduce test dusts. Samplers and monitors were placed on a turntable inside the chamber. Testing was carried out in passive, active, and active sampling with inhalable adaptors modes. The gravimetric analysis using the HD cyclone and the IOM sampler was used as a benchmark reference method.

All monitors showed good linearity for most of the dusts tested. All devices showed a lower response when operated actively with a cyclone adaptor compared to passive sampling without. An increase in particulate size had little effect on monitor readings when sampled actively using a cyclone adaptor. For active sampling using cyclone adaptors, CF ranged from 0.54 to 4.47. Microdust consistently showed a higher response than other monitors. This is due to Microdust being calibrated to the TSP, which approximates the inhalable particulate size fraction. This differs from the HD-7204, calibrated to Arizona Road Dust, which approximates the respirable particulate size fraction. Therefore, it is reasonable to expect a lower response from the HD-7204, which will require a higher CF.

All cyclone adaptors showed excellent linearity with the reference HD cyclone. The SKC Split 2 cyclone adaptor underestimated the dust concentration by 13% compared to the reference HD cyclone. This is potentially due to the increased distance that dust must travel before reaching the backup filter. The same may apply to the HD-7204 as the backup filter is located further behind the cyclone inlet. The gravimetric sample obtained using the SKC Split 2 inhalable dust adaptor closely correlated with the reference IOM sampler (within 2%). Thus, it is reasonable to expect the same level of correlation between the HD-7204 IOM-type sampling inlet and the reference IOM sampler.

In their latest work, Thorpe and Walsh (2013) assessed the behaviour of direct reading dust monitors used to measure inhalable size aerosols. These were DataRam pDR-1000, TSI Sidepak AM510, Casella Microdust Pro, Hund Respicon TM, and Thermo Fisher 3600 PDM (PDM) personal monitors.

Monitors were tested inside a dust tunnel on a manikin with a uniform velocity profile of 0.5 m/s. Dust was injected via a screw feed system coupled with a venturi pump. Barley grain dust, softwood, hardwood and flour dust, and aluminium oxide (Aloxite) powder were used as test dusts. The IOM sampler and the HD cyclone were used for benchmarking.

Experiments were also undertaken in occupational settings. The dusts encountered in these workplaces were broadly consistent with those generated in laboratory trials. A series of side-by-side samples were taken using various DRIs and PDM as a reference method to evaluate the effect of within-process particle size variation on CFs. The choice of the PDM monitor for use as the reference value is explained by empirical data that suggests a linear relationship between PDM and reference IOM concentrations. However, this relationship is not ideal (<1:1) and, as such, cannot be treated as an entirely “true” reference value.

The PDM and Respicon monitors showed good linearity compared with the reference IOM sampler and were relatively unaffected by changes in the physical properties of the dust. The Respicon results agreed within 6% of the reference IOM concentration. The remaining photometer type monitors significantly underestimated the inhalable fraction by up to 90%.

The change in dust size fraction had a significant impact on the CFs. The Respicon remained relatively unaffected when challenged with Aloxite dusts with the MMAD between 6 μm and 6 μm + 58 μm (CF 0.68 to 1.27). However, other inhalable monitors like Sidepak and DataRam showed considerable variation in response (CF 7.06 to 51.39 and 3.8 to 25.57) when challenged with the same dusts. This indicates that the sensor results can be unreliable if the particle size varies substantially. At the same time, if the composition of test dust remains unchanged, the use of an average CF may be acceptable.

The author attempted to apply an average CF to the DataRam measurements in the workplace setting, resulting in an overestimation of background and peak concentrations. When tested in a woodworking workshop, DataRam CFs were found to vary considerably depending on the work activity (CF 3.87-42.23), confirming unreliability when monitoring tasks that generate particles of various sizes.

The study concludes that the modified PDM and Respicon TM monitors were good candidates for personal inhalable samplers. However, the Thermo Fisher 3600 PDM has been discontinued, leaving Respicon as the only viable option for real-time personal inhalable dust sampling.

Dado et al., (2017) evaluated the performance of the Microdust Pro CEL 712 (in passive mode), and the HD-7204 predecessor model Haz-Dust IV fitted with a GS-3 cyclone inlet. Their study challenged the DRIs with a wood dust produced by sanding a beech plank with an orbital sander fitted with 80-grade sanding paper. The test dust was manually introduced into the chamber and dispersed using a fan. A reference IOM sampler fitted with a respirable foam insert was placed near the monitors' sampling inlets to ensure uniform exposure to generated test dust concentrations. Eight parallel samples were taken for 20 minutes for each device to derive average correction factors.

Both monitors showed good linearity compared to the gravimetric reference sample, although the Haz-Dust IV demonstrated a higher coefficient of determination (R^2 0.967 vs. R^2 0.907). The Haz-Dust IV underestimated the respirable dust concentration (CF 2.07) while the Microdust overestimated it (CF 0.75), emphasizing the importance of field calibration of photometer-type dust monitors. This difference in response was attributed to different types of dust used in factory calibration (Arizona Road Dust vs. Total Suspended Particulate).

Both monitors had narrow dispersion of correction factors demonstrated by a low coefficient of variation (CV) - a CV of 10.4 for the Haz-Dust IV and a CV of 15.6 for the Microdust. The low dispersion in the sensor response means the adjusted concentration values have less potential to be overestimated or underestimated when a mean CF is applied to the real-time data.

Although this study provided the evaluation of the device that most closely resembled the HD-7204, it had several significant limitations. One of them was the use of a GS-3 Cyclone size selector. Cyclone size selector ensures that only a pre-defined respirable aerosol size fraction (50% cut-off point at 4.25 μm) enters the sensing zone of the monitor. The Haz-Dust IV is calibrated using Arizona Road Dust against NIOSH method 0600 for respirable dust. Therefore, the use of a Cyclone adaptor resulted in a smaller deviation from the CF of

1. This is contrary to the IOM sampling head used in this study, which aspired significantly coarser inhalable dust fraction (50% cut-off point at 100 μm). Coarser aerosols produce less light scatter, resulting in poorer monitor response (Thorpe, 2006).

A significant concern raised the short sampling duration of 20 min. The collected samples were analysed gravimetrically, and the reference IOM sampler time-weighted average results ranged between 0.9 and 3.6 mg/m^3 . The gravimetric analysis has a relatively high analytical limit of detection (LOD) for low sampling volumes. For example, one UK laboratory (Marchwood Scientific Ltd) offers a gravimetric analysis with a LOD of 0.2 mg for the UKAS accredited MDHS 14/4 method (McCann, 2022). To detect the 0.9 mg/m^3 concentration using the method with such LOD, one had to collect at least 222 litres of air, resulting in a minimum 111-minute sample when sampled at 2 litres/min. The described 20-minute samples would only be capable of detecting concentrations $>5 \text{ mg}/\text{m}^3$.

It is possible that the gravimetric method used by Dado et al. (2017) had a LOD lower than the one offered by the UKAS accredited laboratory. However, there was no reference made to the specifics of the analytical method and the LOD, apart from mentioning it being analysed by weighing. The absence of such details significantly reduced the confidence in the obtained results.

Another limitation of this study was the placement of the reference IOM sampling head in relation to the monitors' sensor heads. Although the effort was made to locate them as close as possible, there were inevitably some spatial concentration gradients as the dust was manually generated. The design of the dust chamber did not provide for uniform dust distribution across the entire area; therefore, identical concentrations could not be guaranteed within the space between sampling heads (10-15 cm). This limitation could have been addressed using the integrated gravimetric sampling within the Haz-Dust IV IOM-type sampling head. However, this monitor feature was not utilised, and a separate external IOM sampler was used.

Additionally, the way the challenge dust was generated has raised some concerns. In the process of orbital sanding, the beech dust was likely to be mixed with the dislodged particles from the sanding paper. As such, the derived CF was for the monitor response to

the beech dust mixed with 80-grade sanding paper particles and not for the pure beech dust; therefore, it could not be applied to tasks involving pure beech dust.

The gravimetric reference sample was collected using the IOM sampling head fitted with a foam size-selective adaptor. In contrast, the Haz-Dust IV monitor was fitted with the SKC GS-3 cyclone inlet. The foam adaptor is known to be prone to undersampling as its capturing efficiency increases with increasing dust deposition (Thorpe and Walsh, 2007). Due to the difference in sampling efficiencies between these size-selective adaptors, the results could not achieve a 1:1 ratio even if exposed to exact concentrations of the factory calibration dust. As such, the comparison of the monitors' real-time response to the reference sample could not be deemed "like for like".

Finally, the Microdust was not fitted with any size-selective adaptor and was sampling passively. Therefore, the comparison of its response to the reference IOM sampler equipped with the respirable size-selective SKC GS-3 cyclone inlet was somewhat meaningless.

Literature Review Summary

Multiple studies evaluated the relationship between the response of real-time monitors and parallel reference gravimetric samplers, confirming a high degree of linearity but stressing a wide variation in CFs. Several studies assessed DRIs similar in design to the HD-7204 monitor, like SKC Split 2 and Haz-Dust IV; however, none of them evaluated the performance of the HD-7204 monitor. This study was undertaken close the existing gap by studying the response of the HD-7204 monitor to inhalable dust to confirm its adequate performance when used for exposure monitoring.

METHODOLOGY

HAZ-DUST 7204 Overview

This instrument measures the intensity of the scattered light to determine dust concentration. According to the manufacturer, the HD-7204 is the world's first personal dust monitor to combine traditional filter techniques with a real-time monitoring method (Environmental Devices Corporation, 2019).

It is operated actively by combining the sampling head with an integrated personal air sampling pump that introduces particles into the sensing chamber. The sampling pump is capable of supplying flow volumes between 1 and 5 l/min. A 25 mm or 37 mm filter cassette can be fitted behind the sensor to allow concurrent gravimetric/chemical analysis to determine the reference dust concentration. The monitor is placed on a worker's belt, and the sensor can be mounted in the worker's breathing zone. The instrument comes with the following attachments:

- An SKC IOM Sampling Inlet for measuring the inhalable fraction.
- An SKC Respirable Dust GS Cyclone for measuring the respirable fraction.
- A Thoracic Sampling Inlet for monitoring the thoracic fraction.

According to Environmental Devices Corporation (2019), the sensing range is 0.001-500 mg/m³ for the particle size range from 0.1 to 100 µm. The instrument displays instantaneous particulate exposure levels (mg/m³), as well as the time-weighted average (TWA), short-term exposure limit (STEL), minimum (Min), and maximum (Max) levels on a coloured LED monitor integrated into the sampling pump. The data can be logged in 1, 4, 10, or 60 seconds averaging intervals; and up to 43,000 data points can be stored.

The HD-7204 monitor is factory calibrated using the ISO 12103-1 Fine Test Dust (Arizona Road Dust). This dust has a nominal size of 0-80 microns and a 50% volume fraction at 10 µm. It does not precisely follow the EN481 respirable convention curve. Nevertheless, it is closer to the EN481 respirable size fraction than the ISO 7708 inhalable size fraction (The British Standards Institution, 2016; The British Standards Institution, 1995). The built-in touch screen menu allows programming the monitor with a CF that can be applied to real-time measurements to perform in-field dust-specific calibration.

According to the HD-7204 specifications, the gravimetric concentration and the real-time TWA readout will match (+/-10%) when the monitor is challenged with the factory calibration dust. For other dusts the response of the HD-7204 monitor will vary significantly depending on the physical properties of the aerosol, such as density, colour, refractive index, and size, thus making it essential to derive and apply a valid CF. The device also offers infield calibration to verify that the instrument is within +/-10% of factory calibration via the calibration span reference accessory.

Sample Size and Power of the Study

The reviewed literature expressed the difference between the response of DRIs and the reference method as correction factors: the ratio of reference gravimetric/chemical analysis and real-time dust monitor data. Some studies included correlation graphs to visualise the difference between the two methods at various concentrations. However, none of the reviewed papers presented the raw data measured in mg/m^3 for both methods. As such, these values had to be manually extracted from correlation graphs.

Thorpe (2006) included the SKC Split 2 monitor in his study, which closely resembled the HD-7204. Therefore, his results were used to calculate the required sample size using paired t-test to infer the statistically significant difference in response of the HD-7204 monitor to the gravimetric analysis reference method.

In the study by Thorpe (2006), a total of 29 inhalable samples (MMAD 7.7-63.1 μm) were assigned to Group 1 (real-time data), and 29 samples were assigned to Group 2 (gravimetric data). Group 1 had a mean value of 5.72 mg/m^3 and a SD of 7.33. Group 2 had a mean value of 70.17 mg/m^3 and a SD of 68.86. The positive correlation coefficient was calculated at 0.67.

The acceptable Alpha value was set at 0.05. The Power value was set at 0.90 to allow an excellent ability to detect a real relationship/difference between the two methods. Using The Biomath online calculator (Snedecor and Cochran, 2021), it was estimated that a total of 13 samples would be required (Figure 9 in Appendix) to establish the presence/absence of statistically significant difference between the two monitoring methods.

Test Dust

The study was undertaken at a chemical company specialising in crop protection products manufacture. The company handles various chemical substances such as raw materials, intermediates, by-products, water treatment chemicals, lubricants, and final commercial products. The information on these products is stored in a local Safety Data Sheets (SDS) database. The database was reviewed to identify the most suitable candidate substance to challenge the HD-7204 monitor.

It was decided that the test aerosol should satisfy the following selection criteria to be suitable for the study:

- It had to be a solid powder – to allow easy aerosol generation within the dust chamber.
- It had to not be carcinogenic, mutagenic, reprotoxic (CMR); asthmagenic; or severely toxic – to reduce the potential consequences of accidental exposure during the experiment.

Table 1 presents the outcome of the initial screening according to these criteria.

Table 1. The List of Hazardous Substances.

Criterion	Number of Qualifying Substances
Total number of substances used on site AND	305
Physical form – solid powder AND	36
Not CMR, asthmagenic, or severely toxic	23

Out of 23 qualifying substances, “Calcium Hydroxide 98%” supplied by Atom Scientific Ltd was selected as the most suitable. The main component of this product (98%) was Calcium hydroxide (CAS 1305-62-0) with small quantities of trace elements. The product comes in fine dry powder form. Its relative density is 2.24 g/mL and pH 12.4-12.6. The material mean particle size was unknown. Calcium hydroxide is not CMR, asthmagenic, or severely toxic, and it bears the following hazard statements:

- H315 - Causes skin irritation;
- H318 - Causes serious eye damage;
- H335 - May cause respiratory irritation.

Calcium hydroxide has an UK long-term (8-hour TWA) workplace exposure limit of 5 mg/m³ for an inhalable size fraction and 1 mg/m³ for a respirable size fraction. It also has an UK short-term (15-min) workplace exposure limit of 4 mg/m³ for a respirable size fraction. According to the supplier, 100% of the product had a particle size <500 µm, and 95% of the material was <75 µm. Calcium hydroxide was used at the Effluent Treatment Plant, where it was offloaded from a road tanker via a bespoke powder handling system.

Dust Chamber

The tests were carried out in an improvised small-size dust chamber (30x20x18 cm) made of a transparent storage container. The closing lid was airproofed with a rubber seal to minimize dust leakage. The aerosol was generated by a manually operated Birchmeier Bobby 0.5 powder duster used in gardening. The duster loaded with the test substance was attached to the dust chamber through a small opening in the container wall.

The duster output was manually controlled by a bellow-type feed mechanism. The amplitude and speed of the handle stroke dictated the concentration of the generated dust cloud. This manual mechanism created peak concentrations but allowed for controlling the time-weighted average concentration recorded by the monitor inside the dust chamber to desired levels. Both sampling methods (real-time and gravimetric/chemical) were built into one sampling head; thus, the spatial difference in dust concentrations within the dust chamber should not result in different exposure levels for the two sampling methods. The dust chamber was located inside a laboratory fume cupboard fitted with a local exhaust ventilation to capture any dust escaping from the chamber.

The HD-7204 sampling head was placed on a podium opposite the duster inlet at a 90-degree angle to avoid deposition of aerosol by direct impaction. This set-up allowed the sampling head to be situated in the centre of the generated dust cloud while avoiding overwhelming the light-scattering sensor. The cable and the air sampling tube were fed

through the sidewall, and the portal was made airtight using tape. The HD-7204 was positioned outside the dust chamber to avoid unnecessary contamination. The complete set-up is presented in Photo 1 and Photo 2 below.

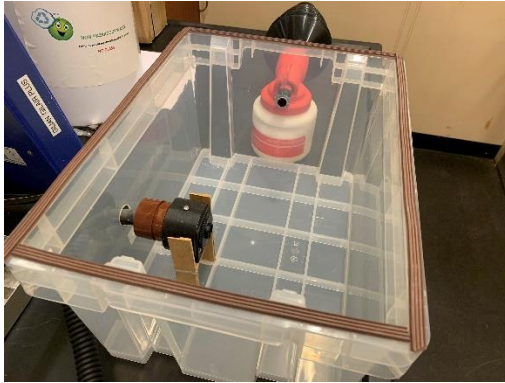


Photo 1. Dust Chamber (Open).



Photo 2. Dust Chamber (Closed).

Test Procedure

The monitor was span checked and zeroed prior to testing, and programmed to log every second. The HD-7204 flow calibration was undertaken to ensure the air was drawn through the sampling head at 2 l/min using a calibrated bubble flow meter before the sampling. The Birchmeier Bobby 0.5 powder duster was loaded with 500 grams of Calcium hydroxide and attached to the dust chamber wall orifice. The HD-7204 IOM-type sampling head was fitted with a two-part cassette pre-loaded with a 37 mm MCE filter and placed on a podium inside the dust chamber with the lid closed.

Once the experimental assembly was complete, the sampling commenced. Depending on the desired concentration, a certain number of bellows strokes were applied to generate a dust cloud. The real-time TWA response was monitored to adjust the number and strength of bellow strokes to adhere to the pre-determined target TWA concentration. When the required volume of air was collected, the HD-7204 was stopped, and one minute clearance period was observed to allow for sufficient dust settling to reduce the risk of exposure when opening the dust chamber. The dust chamber lid was opened, and the sampling head was removed. The sampling train flow rate was measured again to ensure the values were within +/- 5% of the initial flow rate. The pre-loaded cassette would then be removed without opening and stored for shipping at room temperature.

This procedure was repeated 13 times by adjusting the generated dust concentration levels to allow for the collection of samples across the sensing range of the device (0.001 mg/m³ – 500 mg/m³). Although the HD-7204 sensing range goes up to 500 mg/m³, the focus was on the lower end of the sensing range (0.1 mg/m³ – 12 mg/m³), which is more likely to be encountered in a modern workplace environment.

It was initially planned to use the MDHS 14/4 gravimetric analysis method as a reference method to compare the response of the HD-7204 monitor to the “true” exposure data. However, the limit of quantification (LOQ) for the gravimetric method was 0.2 mg. Such a poor LOQ would’ve resulted in a sampling time of 1000 minutes to achieve the lowest target concentration of 0.1 mg/m³. Due to the manual mechanism of aerosol generation (manually operated duster), sustaining low airborne target concentrations for such a prolonged duration would not be practicable. Therefore, an alternative reference method with a better LOQ was required.

The Inductively Coupled Plasma (ICP) method of analysis was considered over the gravimetric method as it could offer a better LOQ resulting in shorter sampling times. An external occupational hygiene laboratory (Marchwood Scientific Ltd) offered a UKAS accredited OSHA ID-125G Metal and Metalloid Particulates in Workplace Atmospheres ICP Analysis method for Calcium. The declared LOQ for this method was 0.004 mg. This analytical method allows for the detection of Calcium on the sample media and subsequent calculation of Calcium hydroxide based on the molecular weight of the entire element (Figure 3).

Chemical formula:				
<input type="text" value="Ca(OH)2"/>				<input type="button" value="Calculate"/>
#	Atom	Molar Mass (MM) (g/mol)	Subtotal Mass (%)	Subtotal Mass (g/mol)
1	Ca	40.08	54.09	40.08
2	O	16.00	43.19	32.00
2	H	1.01	2.72	2.02
Total Molecular Weight:				<input type="text" value="74.09"/>

Figure 3. Inferring Calcium Hydroxide Concentration from Calcium Analysis.

As the test dust consisted of pure Calcium hydroxide (~100% by weight), the calculated concentrations using the ICP method were equivalent to those that would have been

obtained using the conventional gravimetric method. This allowed a direct comparison of the HD-7204 filter media concentration with the gravimetric results from the previous studies. In this study, the OSHA ID-125G ICP analysis is referred to as the reference method.

The OSHA ID-125G method requires submitting at least one field blank for each set of air samples to ensure the absence of cross-contamination (OSHA, 2000). All collected samples were submitted to the external laboratory (Marchwood Scientific Ltd). The minimum sampling duration was calculated to ensure sufficient filter loading to allow for the analysis above the limit of detection (LOD). Table 2 presents the target real-time TWA concentrations and the estimated minimum sampling duration required.

Table 2. Target TWA Concentrations and Minimum Sampling Duration.

Sample No	Reference Method TWA (mg/m³)	Min Sampling Duration (min)
1	0.1	20
2	0.3	6.5
3	0.5	4
4	1	2
5	2	1
6	3	<1
7	5	<1
8	8	<1
9	12	<1
10	18	<1
11	25	<1
12	40	<1
13	60	<1
14	100	<1
FB	-	-

Statistical Analysis

Fourteen samples plus one field blank were collected across the range of target concentrations. Generally, the desired concentration levels were achieved for the minimum sampling duration. The field blank was handled exactly like all the other samples but with no air drawn through. Correction factors were calculated for each sample by

dividing the reference method concentration by the real-time data. The mean correction factor was derived by adding all individual CFs and dividing them by the total number of samples (14). The mean CF was used to evaluate the average difference between the HD-7204 real-time response and the reference method and to assess the tendency of the monitor to underestimate or overestimate the exposure compared to the reference method.

A paired t-test was undertaken to understand whether the observed difference between the two exposure analysis methods was statistically significant and not by chance. This test is used when we are interested to know the difference between two variables (real-time and reference method) for the same subject (sample collected with the HD-7204 monitor). The paired t-test had the following hypothesis:

Null hypothesis: The HD-7204 mean concentration observed using the real-time method is equal to the mean concentration observed using the reference method.

Alternative hypothesis: The HD-7204 mean concentration observed using the real-time method is NOT equal to the mean concentration observed using the reference method.

The t-score measures the size of the difference relative to the variation in the sample data. The greater the magnitude of the t-score, the greater the evidence against the null hypothesis. The closer the t-score is to 0, the more likely there is no significant difference.

If the p-value is less than the significance level ($p < 0.05$) and the t-score is above 0, the data provides strong evidence to conclude that the difference between the means of the two methods exists and is not by chance; thus, the null hypothesis can be rejected. Rejecting the null hypothesis would confirm the requirement for correcting the observed real-time data with the derived mean CF.

Pearson's correlation coefficient (R) is a statistical test that measures the relationship between two continuous variables. It provides information about the magnitude of correlation as well as the direction of the relationship. Pearson's correlation coefficient was determined to establish how accurate the HD-7204 real-time response was across the desired range of possible concentration (linearity) and whether it tends to overestimate or underestimate airborne concentrations.

The coefficient of determination (R^2) was also calculated to understand if the regression slope can be used as a reliable predictor of reference method concentration. The standard deviation (SD) of calibration factors was calculated to establish the uncertainty surrounding the mean correction factor. Knowing the standard deviation helps to understand the level of dispersion and its effect on the corrected concentration values when compared against the occupational exposure limits. The coefficient of variation (CV) was calculated for the HD-7204 to compare the observed dispersion in CFs to other DRIs from previous studies.

The improvement in precision following the application of the mean CF was calculated by subtracting the difference between the corrected real-time data and the reference method data expressed as a percentage of the reference method and comparing it to the difference between the initial real-time data and the reference method data expressed as a percentage of the reference method. Any change in the corrected real-time concentration towards the reference value was considered a beneficial increase in precision. For example, if prior to applying the average CF the real-time data underestimated the reference concentration by 50%, and after applying the average CF the real-time data overestimated the reference concentration by 25%, this would be considered a 25% increase in precision (25% vs. 50% off from the reference value).

RESULTS

The results of the real-time response and corresponding reference method concentrations are displayed in Table 3. Summary statistics are presented in Table 4. Statistical data from the previous studies can be found in the Appendix.

Sample 5 was discarded due to the sampling error – a loose IOM sampler lid that resulted in air leaks leading to undersampling. The lid had a short thread length and came loose during the calibration process when it was fitted with the flow meter adapter. This was noted immediately post sampling, and precautions were taken to avoid this error for the subsequent samples.

Table 3. Reported Concentrations for Real-Time Data and Reference Method.

Sample No	Real-Time TWA (mg/m ³)	Reference Method TWA (mg/m ³)	Correction Factor (real-time/reference)
1	0.1	0.2	2.0
2	0.31	1.0	3.2
3	0.48	1.3	2.7
4	1	2.4	2.4
5*	2.04	1.1	0.5
6	3.09	3.4	1.1
7	5.31	7.8	1.5
8	8.15	18	2.2
9	13.3	25	1.9
10	16.59	43	2.6
11	24.99	30	1.2
12	40.05	63	1.6
13	57.52	97	1.7
14	97.9	130	1.3
FB	N/A	N/A	N/A

*Discarded

Table 4. Summary Statistics.

Mean CF	Pearson's Coefficient (R)	Coefficient of Determination (R ²)	t-Score	Significance (p-value)	CF SD	Coefficient of Variation (CV)
1.95	0.982	0.965	3.09	0.0093	0.65	0.32

DISCUSSION

The Difference in Real-Time vs. Reference Sampling Methods

The t-test was undertaken to confirm whether the average response of the light-scattering sensor was significantly different from the average response of the reference method, and it was not by chance. Based on the presented literature review, the HD-7204 sensor was expected to underestimate the reference concentration. The monitor response is dictated by the degree of light scatter that would be higher for particles finer than the factory calibration dust and lower for coarser aerosols. The HD-7204 was factory calibrated with the ISO 12103-1 Fine Test Dust approximating the EN481 respirable size fraction. The real-time response could be observed in both directions (underestimating or overestimating) depending on the size of the test dust (finer or coarser than the factory calibration dust). Since the size of the test aerosol was not clearly defined, it was decided to carry out a two-tailed t-test to also account for the possibility of real-time data overestimating the “true” concentration.

The mean difference between the two methods was calculated at 11.79 mg/m³. The t-value was calculated at 3.09 with a two-tailed p-value of 0.0094. By conventional criteria, this difference was considered to be statistically significant (p-value <0.05). This means that the two in-line sampling methods would yield significantly different mean results, which could not occur by chance. As such, the real-time light-scattering sensor method cannot be used as a reliable predictor of “true” concentration without the correction for the reference method concentration. However, the light-scattering sensor method can still be used as an approximate indicator of increasing or decreasing concentrations even without applying any correction factors.

Linearity and Regression Analysis

The responses of the HD-7204 monitor were plotted against the reference method concentrations, which are shown in Figure 4. The solid line represents the best fit, and the dotted line represents the 1:1 relationship. The HD-7204 monitor consistently underestimated the test dust concentration compared to the reference method.

Correction factors ranged between 1.1 and 3.2, with the mean CF calculated at 1.95. The field blank was reported as <LOD, indicating no signs of cross-contamination.

The real-time response of the HD-7204 showed very good linearity compared to the reference method, demonstrated by the high Pearson's correlation coefficient (R 0.98). Such a high coefficient indicates a very strong positive relationship meaning that both real-time data and reference method concentrations are expected to move together in the same direction by the same percentage on most occasions.

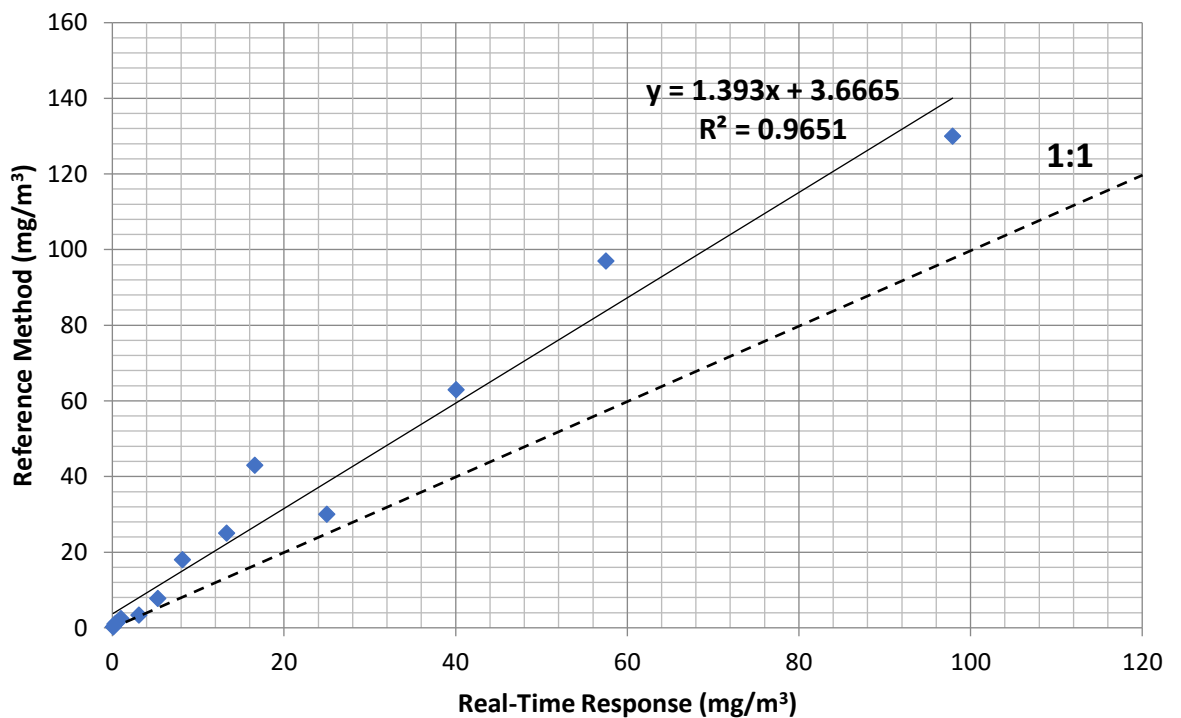


Figure 4. HD-7204 Regression Analysis.

The regression analysis presented in Figure 4 indicated a very good fit (R^2 0.96). The coefficient of determination, also known as “goodness of fit,” can be interpreted as the percentage of time (96%) the predicted value will fall on the regression analysis slope. A very good fit indicates that the regression equation can be used as a reliable prediction model of “true” exposure when obtaining future real-time data without using the reference method.

The regression line in Figure 4 intercepts the Y axis at around 4 mg/m³. This is because the regression equation predicts that the reference method concentration will always be somewhat higher than the real-time response of the HD-7204. Although this is true, in the

context of exposure monitoring, this is not possible to have reference method concentration above the real-time response at null exposure. When the HD-7204 is “zeroed” prior to its use with a special HEPA filter attachment, its real-time response reads zero, as the HEPA filter does not allow any aerosol to pass through the sensing chamber onto a sampling media. As such, the reference method cannot be $>0 \text{ mg/m}^3$ when the real-time sensor shows 0 mg/m^3 . Therefore, the regression line intercept must be set at 0 mg/m^3 to account for this fact. Subsequently, this correction slightly lowers the predicted concentration for the reference method (Y axis). The amended regression analysis is presented in Figure 5.

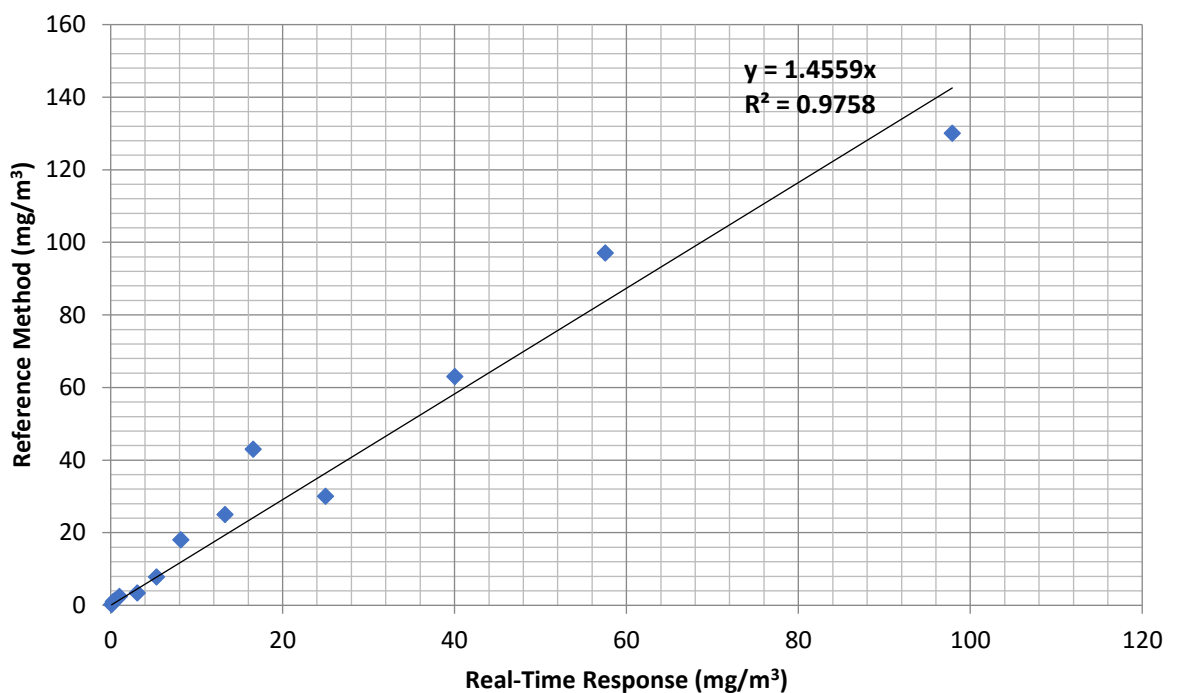


Figure 5. HD-7204 Regression Analysis (Intercept).

Particle Size of Calcium Hydroxide

The absence of well-defined particle size of the test dust (Calcium hydroxide) restricts the analysis of the HD-7204 linearity and prevents the comparison of its performance to other DRIs. It has been previously demonstrated that linearity for a similar DRI (SKC Split 2) remains largely unaffected (R 0.98-0.99) when challenged with aerosols with MMAD 7.7-21.1 μm (Thorpe, 2006). However, there was a significant drop in linearity (R 0.94) when the DRI was challenged with a coarse aerosol (MMAD 63.1 μm). Therefore, the MMAD of

Calcium hydroxide would be required to understand if the observed linearity in the HD-7204 response (R 0.98) is comparable to its alternatives challenged with similar size dust.

Nevertheless, it was attempted to approximate the size of Calcium hydroxide through inferences made in the experimental correction factors and some limited data provided by the material supplier. The product size information provided by the supplier states that the entire material (100%) has a particle size <500 μm and that 95% of the material is <75 μm . This information confirms that Calcium hydroxide was not a very coarse test dust which removes the need to compare the observed linearity in the HD-7204 (R 0.98) to observed linearity in a similar DRI (SKC Split 2) challenged with a coarse dust (MMAD 63.1 μm ; R 0.94).

Further inferences can be made by examining the derived mean CF (1.95) for the HD-7204. Coarser aerosols have a lower degree of light scatter. Since the instrument operates by measuring the intensity of the scattered light, the response is expected to be lower, resulting in higher correction factors. A correction factor >1 indicates that the MMAD of the challenge aerosol (Calcium hydroxide) was above the MMAD of the ISO 12103-1 A2 calibration dust (MMAD 9.1 μm).

Although the derived mean CF was >1, it was not excessively high, which would have signalled that the MMAD of Calcium hydroxide was grossly above the MMAD of the 12103-1 A2 calibration dust. For example, Thorpe (2006) recorded CFs of up to 342 for a similar SKC Split 2 monitor challenged with Aloxite 320 (MMAD 63.1 μm). Therefore, based on these observations, it can be assumed that the MMAD of Calcium hydroxide was somewhere between 9.1 and 63.1 μm and most likely approaching the lower range.

Dispersion in Correction Factors

The standard deviation of the mean correction factor (1.95) was calculated at 0.65. Such a dispersion in CFs could potentially lead to erroneous conclusions when testing compliance with OELs. Underestimation could lead to erroneously accepting the unacceptable risk, while overestimation could lead to unwarranted investment in exposure controls and additional work restrictions. This effect of uncertainty could be demonstrated by applying

the mean CF to sample number 5 (3.09 mg/m^3), resulting in a corrected value of 6.02 mg/m^3 , which is above the inhalable WEL of 5 mg/m^3 . However, due to the uncertainty surrounding the average CF, the corrected value could, in fact, lie anywhere between 4.01 and 8.03 mg/m^3 (CF 1.95 ± 0.65). As such, it is possible to underestimate or overestimate the corrected aerosol concentrations when applying the average CF. Therefore, it is essential to consider whether applying one SD takes the adjusted value below or above the OEL and the subsequent implications. If, after applying the SD, the corrected value range crosses the OEL boundary, it may be worth labelling it as having a low/medium/high level of uncertainty depending on how far the uncertainty range spans below/above the OEL.

The coefficient of variance was calculated at 0.32. It was used to compare the degree of dispersion in the HD-7204 CFs to other DRIs such as SKC Split 2, DataRAM, Sidepak, Sibata PDS-2, and Microdust. The data was extracted from Thorpe (2006) to calculate CVs derived for aerosols within the approximated particle size range of Calcium hydroxide (9.1 and $<63.1 \mu\text{m}$). The data from Dado et al. (2017) was also added to the comparison; however, the size fraction of the test dust was unknown. As such, the results for the Microdust should be treated with caution. The compiled data was used to understand how the observed dispersion in CFs of the HD-7204 compared to other real-time dust monitoring devices, and it is presented in Table 5.

Table 5. CV of the HD-7204 and Other DRIs (Thorpe, 2006; Dado et al., 2017).

Monitor	MMAD (μm)	CV	Average CV
HD-7204	≈ 9.1 - <63.1	0.32	N/A
SKC Split 2	17.5	0.42	0.23
	19.8	0.19	
	20.3	0.18	
	21.1	0.14	
DataRAM	17.5	0.34	0.19
	19.8	0.11	
	20.3	0.19	
	21.1	0.10	
Sidepak	17.5	0.41	0.23
	19.8	0.07	
	20.3	0.24	
	21.1	0.28	
Sibata PDS-2	17.5	0.44	0.19
	19.8	0.16	
	20.3	0.04	
	21.1	0.12	
Microdust	Unknown	0.16	N/A

The coefficients of variance ranged from 0.04 to 0.44. The highest CV (CV 0.34-0.44) was observed for the dust with MMAD 17.5 μm (Aloxite 800). The correction factors for other test dusts (MMAD 19.8 to 21.1 μm) showed a lower deviation from the mean (CV 0.04-0.28). It is difficult to directly compare the dispersion of the HD-7204 to other DRIs as the exact MMAD of Calcium hydroxide was unknown.

If one assumed the size of the Calcium hydroxide was around 17.5 μm , it would be concluded that the dispersion in correction factors observed in the HD-7204 (CV 0.32) is lower than in other monitors, except for Microdust; thus, making it a more precise DRI. However, if the actual MMAD of Calcium hydroxide was 19.8 to 21.1 μm , it would be concluded that the HD-7204 is significantly less precise than its alternatives. Therefore, no definitive conclusion could be made other than the CV of the HD-7204 falls approximately within the observed CV range of other DRI. There are no defined acceptable CV values for

DRIs; however, the lower the value, the better the precision and higher the confidence in the derived mean CF.

Cauda (2021) described the correction factors derivation methodology for real-time optical monitors in the NIOSH manual. His guidance suggests that if the range of correction factors is within 10%–15% of the average, the conditions for the different tests may be considered consistent. If the range is much higher than 15%, the user should refrain from developing a field-calibration factor even with consistent conditions. Following this NIOSH guidance would result in rejecting the derived mean correction factor for this study as the highest CF was 64% above and the lowest CF was 43% below the mean CF, even though the increased precision in real-time data could be demonstrated.

Application of Mean Correction Factor and Effect on Precision

Overall, the application of the derived mean correction factor (1.95) substantially improved the precision of the real-time data obtained with the HD-7204 monitor (Table 6). The precision of 9 out of 13 samples was improved up to 47.5%. However, after applying the mean correction factor (CF 1.95), the precision of 3 out of 13 samples significantly decreased. One sample had a negligible decrease in precision (-0.85%), although it was considered positive since it provided a slight overestimation. The overall effect of applying the derived mean CF can be regarded as positive as all of the non-corrected data underestimated the true concentration. While those 3 samples with reduced precision overestimated the actual concentration, in the context of occupational hygiene, it can be considered a preferable outcome compared to underestimating.

Nevertheless, the improvement in corrected concentrations still resulted in some degree of underestimation, although significantly less than before applying the mean CF. It can be argued that a safety factor should be incorporated when using the derived mean CF. Such a safety factor could be one SD (0.6) added to the mean CF. If the corrected results (real-time data multiplied by mean CF + SD) are < OEL, it could be concluded with a high degree of confidence that the actual exposure levels do not exceed the OEL. Undoubtedly the addition of one SD will bring a degree of conservatism. Therefore, professional judgment

should be exercised to understand whether such conservatism is desirable in specific circumstances.

Table 6. Application of the Mean CF and the Effect on the Real-time Data Precision.

Real-Time Concentration (mg/m ³)	Reference Method Concentration (mg/m ³)	Concentration with Applied Mean CF (mg/m ³)	Original Precision (% off the reference method)	Post-Calibration Precision (% off the reference method)	Precision Improvement after Calibration (%)
0.1	0.2	0.20	-50	-2.50	47.5
0.31	1.0	0.60	-69	-39.6	29.4
0.48	1.3	0.94	-63.1	-28.0	35.1
1	2.4	1.95	-58.3	-18.8	39.6
3.09	3.4	6.03	-9.1	+77.2	-68.1
5.31	7.8	10.35	-31.9	+32.8	-0.85
8.15	18	15.89	-54.7	-11.7	43.0
13.3	25	25.94	-46.8	+3.7	43.1
16.59	43	32.35	-61.4	-24.8	36.7
24.99	30	48.73	-16.7	+62.4	-45.7
40.05	63	78.10	-36.4	+23.9	12.1
57.52	97	112.16	-40.7	+15.6	25.0
97.9	130	190.91	-24.7	+46.9	-22.2

The Effect of Concentration on Monitor Response

There appeared to be a slight tendency for a better monitor response (lower CFs) at higher dust concentrations (Figure 6). The scatter plot of the reference method concentrations against the derived correction factors demonstrated a moderate negative correlation (R = 0.395). However, this was not deemed significant due to the limited sample size (n=13; p-value 0.181). This observation suggests that the real-time sensor response might not be linear at the higher range of concentrations. The potential explanation for this sensor behavior could be that the ratio of respirable to inhalable dust increases with the overall increase of generated dust concentration. Since the HD-7204 is calibrated with the ISO 12103-1 Fine Test Dust, which approximates respirable size fraction, a better response to higher respirable dust concentrations is expected. This change in respirable to inhalable

ratio could be attributed to the dust generating method (manual duster), or this could be an established behavior of any dust cloud at increasing concentrations regardless of the aerosol generating method. This assumption could be confirmed by utilising an aerodynamic particle sizer like TSI Model 3321 or an optical particle counter like TSI Model 3330. Non-linear response at higher dust concentrations could introduce an unacceptable margin of error when mean CF is applied to real-time readings. A larger sample size would allow for a better power of the study to determine if a statistically significant decrease in linearity exists at the higher aerosol concentrations.

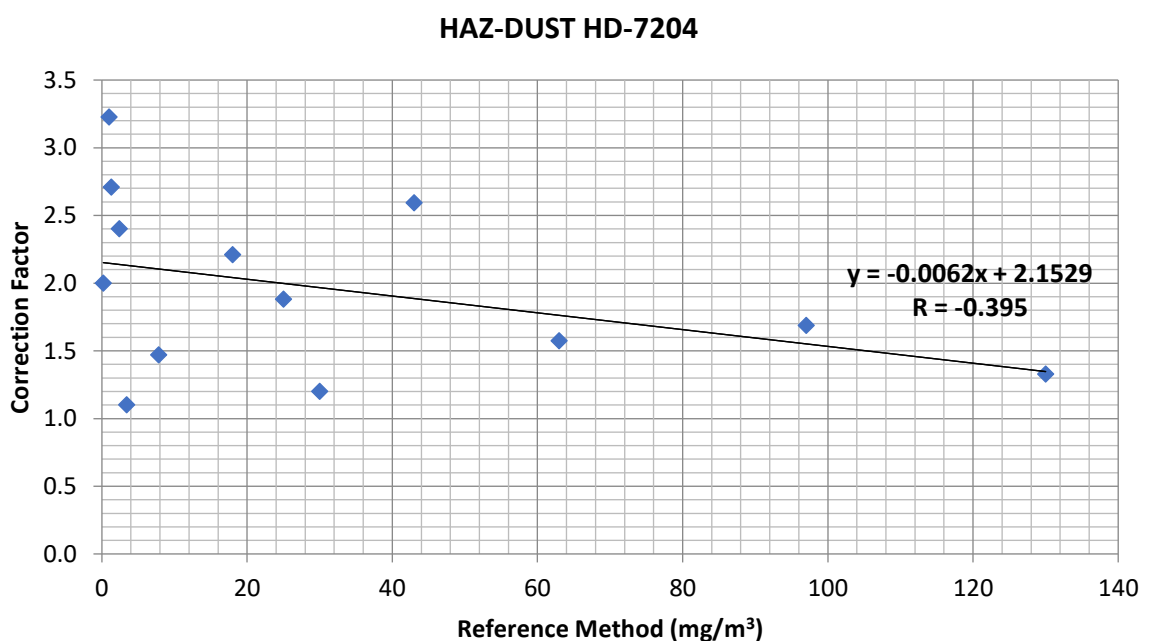


Figure 6. Reference Method Concentrations vs. CFs Regression Analysis (HD-7204).

Comparison of the HD-7204 Performance to Similar Devices

The established approximate size of the test dust allowed us to compare the linearity of the HD-7204 with other previously studied DRIs. The coefficients of determination (R^2) calculated for various DRIs responding to inhalable aerosols with MMAD between 9.1 and <63.1 μm were extracted for comparison against the R^2 value calculated for the HD-7204 responding to Calcium hydroxide. Thorpe (2006) provided R^2 values for SKC Split 2, Dataram, Sidepak, and Sibata PDS-2 monitors challenged with aerosols with MMAD of 17.5 μm (Aloxite 800), 19.8 μm (pine dust), 20.3 μm (stone dust), and 21.1 μm (coal dust). Dado

et al. (2017) provided R^2 values for the Microdust monitor challenged with beech wood dust generated through manual sanding; however, its MMAD was not stated. As such, a comparison of its R^2 should be exercised with caution. The extracted coefficients of determination are presented in Table 7.

Table 7. R^2 Values of Various Real-time Monitoring Devices (Thorpe 2006; Dado et al., 2017).

Dust Monitor	Coefficient of Determination (R^2)
HD-7204	0.965
Microdust	0.907
SKC Split 2	0.968 - 0.992
DataRAM	0.983 - 0.999
Sidepak	0.977 - 0.998
Sibata PDS-2	0.951 - 0.997

The linearity of the HD-7204 approximates that of similar design DRI SKC Split 2 as well as Sibata PDS-2. The HD-7204 linearity is lower than that of DataRAM and Sidepak. The R^2 value of the Microdust was considerably lower than that of the HD-7204. This can be explained by the difference in the composition of the calibration dust. The Microdust is calibrated with Total Suspended Particulate that approximates the inhalable fraction; thus, it may have a poorer response to particles of respirable size.

Unfortunately, the R^2 value from Dado et al. (2017) for the HD-7204 predecessor model HAZ-DUST IV could not be used to compare the performance of the two models as the monitor was fitted with a cyclone adaptor. The cyclone adaptor acts as a size selector by ensuring only a pre-defined aerosol size distribution (EN481 respirable convention curve) enters the light scattering sensor. This removes the variability in the monitor's response due to fluctuating aerosol size composition, ensuring a stable flow of aerosol closely resembling the calibration dust. As a result, the observed mean CF deviates less from the default correction factor of 1, and the coefficient of determination is closer to unity. Overall, there is a lack of research on the HD-7204 predecessor model HAZ-DUST IV to allow a proper comparison of their performance.

Sampling Head Design Limitations

The IOM-type design of the HD-7204 sampling head was not identical to the original IOM sampler, which could have resulted in different collection efficiency. The device sampling head had the IOM sampling face and inlet design but was followed by a light-scattering sensor connected to a single hole 37 mm cassette (Photo 3 and 4).



Photo 3. IOM-type HD-7204 Sampling Head.



Photo 4. 37-mm Cassette Fitted to the Sensor Head.

This assembly could result in a wall loss within the sensing chamber of a light-scattering sensor that is longer than the tunnel of the original IOM inlet. Consequently, a portion of the aspired aerosol may not reach the opening of the 37 mm cassette to be deposited on the filter media. This would result in a lower filter weight/concentration, causing an underestimation of the airborne exposure levels.

In the IOM sampling head design, once aspired, the aerosol travels through a short tunnel directly onto a 25 mm filter media. Therefore, the transition between the IOM inlet to a single hole 37-mm cassette within the HD-7204 sampling train could result in a double size selection, potentially leading to undersampling of aerosols larger than 20 μm (Figure 7).

Previous work by Cherrie (2011) confirms that the closed-face 37 mm cassette underestimates the inhalable fraction significantly for particles >20-25 μm . These “total dust” samplers tend to undersample large particles compared to the ISO 7708 inhalability curve. On the other hand, the IOM sampling head closely follows the ISO 7708 inhalable size fraction curve even for particles >20-25 μm . As such, a sample collected using the IOM sampling head will have a greater mass concentration than a sample collected on a 37-mm

cassette. Since the HD-7204 sampling head is essentially a train consisting of these two sampling heads, the difference in collection efficiencies will be lost somewhere in the sensing chamber. This raises the question if a sample collected using the HD-7204 IOM type sampling head can be treated as a genuine inhalable sample.

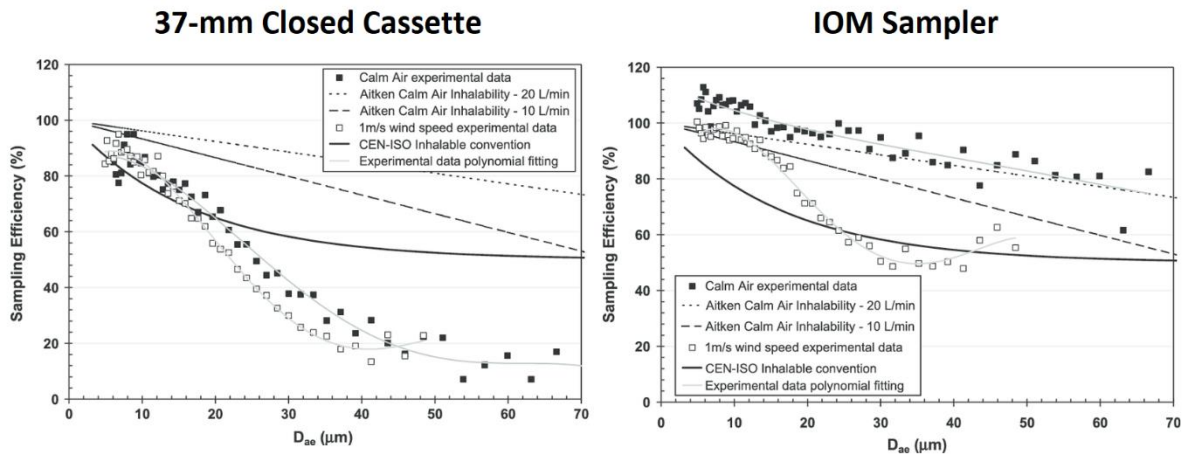


Figure 7. Sampling Efficiency of 37-mm Closed Cassette vs. IOM Sampler (Görner et al., 2010).

Also, the design of the HD-7204 sampling head does not allow for its outward placement facing away from the worker's body. It only provides for the inlet positioning facing downward. The orientation of the sampling head to the wind was found to affect the collection efficiencies of various sampling heads, including the IOM type (Aizenberg et al., 2001). This effect is due to distorted aerosol flow leading to impaction and interception of particles. The sampling efficiency of the IOM sampling head is designed for a certain level of particle inertia. The increased wind velocity increases particles' inertia, leading to poorer aspiration rates. Inertia forces are also greater where aerosol flow diverges sharply due to sampling head positioning leading to poorer aspiration (Gardiner and Harrington, 2005). If the sampling head faces the air stream directly, it may lead to increased deposition due to direct impaction. These factors, however, did not influence this study as a special holder was constructed to ensure the inlet was held at a 90-degree angle from the horizontal plane, and there was no significant air movement within the dust chamber.

These HD-7204 sampling head features may reduce the confidence in the reference method results collected via an in-line sampler. The undersampling of particles $>20 \mu\text{m}$ may result in a significant underestimation of personal exposure levels expressed as the total

weight of the sampled aerosol (mg) since larger, heavier particles have a more significant contribution to the overall weight of the sampling media.

The downward orientation of the HD-7204 sampling head may result in additional undersampling for particle sizes near the upper boundary of the inhalable fraction and beyond it when used in the field (Aizenberg et al., 2001). This may further exacerbate the undersampling of larger particles caused by the size selection of the built-in 37-mm cassette. Therefore, erroneous conclusions about the acceptability of exposure may be drawn, putting workers' health at risk.

As such, it should not be assumed that the in-line sampling via the IOM-type HD-7204 inlet provides identical sampling efficiency to the original IOM sampler. A side-by-side sampling using the original IOM sampler at the correct orientation may be required to obtain accurate reference concentration. Alternatively, the use of a special IOM adaptor that eliminates the 37-mm cassette and allows fitting the sampling head at the right angle would reduce the uncertainty (Figure 8). However, this IOM adaptor would not result in complete alignment with the IOM sampler due to the extended length of the inlet tunnel within the sensing chamber.



Figure 8. IOM Adapter for the HD-7204 Sampling Head.

Limitations and Further Work

This study focused on the response of the HD-7204 to inhalable dust only. However, the HD-7204 can be fitted with respirable and thoracic adaptors. The use of these size-selective adaptors may reveal important differences in the monitor response, such as changes in linearity and dispersion of correction factors that were not evident using the inhalable

adaptor only. It would be prudent to undertake sampling of the same test dust with respirable and thoracic adaptors to compare the obtained data and establish the differences in the monitor response.

The small sample size (n=13) did not allow for a statistically significant conclusion (p-value 0.18) on the degree of linearity at the higher range of aerosol concentrations. As such, the decrease in linearity at the higher concentrations can only be suggestive. Assuming the linearity remains approximately the same or higher (R=-0.395), at least 13 additional samples would need to be collected to achieve satisfactory significance (p-value <0.05). These additional samples should be collected at a higher concentration range (>60 mg/m³) where a reduction in linearity is suspected. Additionally, the presumed increase in respirable to inhalable particle ratio with increasing dust cloud concentration should be confirmed using an aerodynamic particle sizer or an optical particle counter. This will help to understand the root cause of a seemingly better response of the HD-7204 at higher concentrations.

The HD-7204 monitor was challenged with only one type of aerosol. This did not allow us to explore the variation in the monitor's response to dust of various sizes. From the derived mean CF 1.95, it can be implied that the test aerosol was somewhat coarser than the factory calibration dust (ISO 12103-1 Fine Test Dust), which approximates the EN481 respirable size fraction convention curve. However, it should not be very coarse based on the material information provided by the supplier (product size 100% - 500 µm, 95% - 75 µm). Considering the presented literature review, it can be expected that the linearity will vary depending on the aerosol size. As such, it would be beneficial to challenge the HD-7204 monitor with aerosols of different sizes to understand its response to coarser and finer particles other than Calcium hydroxide.

This study utilised the built-in capacity for reference in-line sampling within the IOM-type sampling head fitted with the light-scattering sensor. As previously described, this HD-7204 IOM-type sampling head differed in design from the IOM sampling head, which could have potentially resulted in undersampling. To minimise the effect of this limitation, it would be prudent to replicate this study using the HD-7204 IOM adaptor, thus eliminating the problem of double size selection (IOM + 37-mm cassette). Alternatively, a side-by-side sampling using a separate IOM sampling head as a reference could be undertaken. In this

case, the current design of the dust chamber would not be adequate as it does not allow for generating a uniform dust cloud across the area where two sampling heads are located. Therefore, using a more sophisticated dust tunnel similar to the one used by Thorpe (2006) should be considered if a side-by-side sampling method is chosen.

Some data from previous studies, such as gravimetric and real-time concentrations for various challenge dusts, was not available in raw format and had to be manually extracted from graphs and charts. Although all effort was made to ensure the correct export of this data, the manual extraction inevitably introduced a margin of error in the calculation of correction factors, correlation coefficients, and coefficients of variation for various monitors from previous studies (Thorpe, 2006; Dado et al., 2017). To mitigate this limitation, requesting experimental data from the authors of these previous studies would be required.

CONCLUSION

A method for generating aerosols of pre-determined concentration inside a small dust chamber has been developed. This has enabled us to investigate the response of the HD-7204 real-time monitor to Calcium hydroxide test dust.

The HD-7204 real-time response was compared to the built-in reference method to understand the mean difference between the two methods of analysis. The mean results of the two methods were found to be statistically different and not by chance. As such, the null hypothesis was rejected, and it was confirmed that the real-time data obtained using the HD-7204 monitor should be adjusted with a valid correction factor.

The HD-7204 real-time response was found to underestimate the concentration of the test dust compared to the reference method. The real-time data displayed a good level of correlation with the reference method and was found to be linear. The observed level of linearity in the HD-7204 response approximated the linearity of similar direct reading instruments evaluated in previous studies.

A potential decrease in linearity was observed with the increasing dust concentration, which could be attributed to the changing ratio of respirable to inhalable particle composition and the factory calibration dust. The regression analysis indicated a good fit; thus, regression equation could be used as a reliable prediction model of "true" exposure in the absence of the reference method data.

A degree of dispersion observed around the mean correction factors could have resulted in erroneous conclusions about the level of risk. As the precise size of the test dust was not known, no definitive conclusion could be made about the performance of the HD-7204 other than that the observed variation in the monitor response fell within the observed variation ranges of similar direct-reading instruments. Additionally, the observed dispersion in correction factors could invalidate the derived mean correction factor if the NIOSH guidance has to be followed.

The mean correction factor was derived from 13 collected samples. It was demonstrated that applying this mean correction factor to the real-time data positively affected the precision of exposure estimates. However, some adjusted values still underestimated the

actual level of exposure, and it could be argued that one standard deviation should be added to the mean correction factor as a safety margin. It was also demonstrated that applying the mean correction factor could result in overestimating exposure; thus, professional judgement should be exercised when the adjusted real-time data minus one standard deviation falls below the OEL.

The design of the HD-7204 IOM-type sampling head was found to have several limitations. The most significant was the IOM-type sampling inlet followed by a 37-mm single-hole cassette that could result in a double size selection and undersampling of particles >20-25 μm leading to a lower deposition onto a sampling media. The downward pointing direction of the IOM-type sampling inlet on the default HD-7204 sampling head could also impact the sampling efficiencies; thus, using a separate forward-facing IOM adaptor should be considered.

Overall, the HD-7204 is a promising direct reading instrument with a major advantage of “all in one” sampling. It is the only available model that incorporates the personal sampling pump and light-scattering sensor within the size-selective sampling head fitted with a filter media, eliminating the need for a second parallel reference sampling. Its performance is comparable to similar real-time monitoring devices and is adequate for the intended use as a personal exposure monitor if limitations are appreciated and accounted for. Further work is required to understand these limitations and their impact on the performance of the HD-7204 monitor.

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APPENDIX

Paired t-test	
Find sample size: If you know the mean difference and its standard deviation, use this form to find the number of subjects you need.	Find effect size: If you know the number of subjects and the standard deviation of the change, use this form to find how small a difference you can detect.
Mean difference: <input type="text" value="64.46"/> Standard deviation: * <input type="text" value="64"/> Click here for sample size: <input type="button" value="Result"/> You will need <input type="text" value="13"/> subjects	Number of subjects: <input type="text"/> Standard deviation: * <input type="text" value="64"/> Click here for effect size: <input type="button" value="Result"/> You can show a difference of size <input type="text"/>
* If you don't know the SD of the difference <input type="button" value="Click here"/> If you know the SD of each of the two measures and the correlation coefficient, we will calculate the SD of the difference for you. Measure 1 SD: <input type="text" value="7.33"/> Measure 2 SD: <input type="text" value="68.86"/> R: <input type="text" value="0.672"/> <input type="button" value="Calculate"/>	
For different power or significance level, change the fields below: Alpha: Prob(reject H_0 when H_0 is true) <input type="text" value="0.05"/> <input type="button" value="v"/> Power: Prob(reject H_0 when H_1 is true) <input type="text" value="0.90"/> <input type="button" value="v"/>	
Choose another study design 18/12/2021, 15:39:56 Contact: sfh2@columbia.edu Source: G.W. Snedecor & W.G. Cochran Statistical Methods (7th ed., p. 104)	

Figure 9. Minimum Sample Size Calculations for the t-Test.

Significance Level:

- 0.01
- 0.05
- 0.10

One-tailed or two-tailed hypothesis?:

- One-tailed
- Two-tailed

Difference Scores Calculations

Mean: 11.79

$\mu = 0$

$$S^2 = SS/df = 2273.7/(13-1) = 189.48$$

$$S^2_M = S^2/N = 189.48/13 = 14.58$$

$$S_M = \sqrt{S^2_M} = \sqrt{14.58} = 3.82$$

T-value Calculation

$$t = (M - \mu)/S_M = (11.79 - 0)/3.82 = 3.09$$

The value of t is 3.089034. The value of p is .00938. The result is significant at $p < .05$.

Figure 10. Results of the t-Test.

Best-fit values	
Slope	1,393 ± 0,07986
Y-intercept	3,666 ± 2,774
X-intercept	-2,632
1/Slope	0,7179
95% Confidence Intervals	
Slope	1,217 to 1,569
Y-intercept	-2,438 to 9,771
X-intercept	-7,649 to 1,631
Goodness of Fit	
R square	0,9651
Sy,x	8,035
Is slope significantly non-zero?	
F	304,3
DFn,DFd	1,11
P Value	< 0,0001
Deviation from horizontal?	Significant
Data	
Number of XY pairs	13
Equation	$Y = 1,393 * X + 3,666$

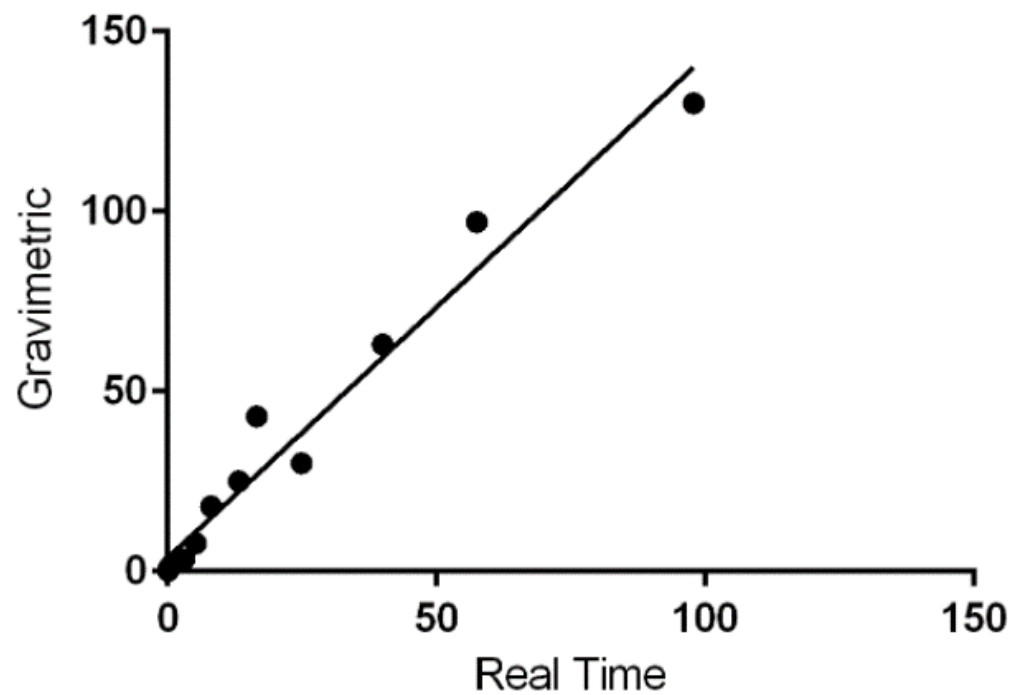


Figure 11. Results of Regression Analysis.

R Score:

-0.39

N:

26

Significance Level:

0.01

0.05

0.10

The P-Value is .048884. The result is significant at $p < .05$.

Figure 12. The Number of Samples Required for a Statistically Significant Conclusion on the Degree of Linearity at the Higher Concentration Range.

SKC SPLIT 2						
CF	Real time (mg/m3)	Gravimetric (mg/m3)	MMAD	Correlation Coefficient		
4.8	10.8	52	7.7	Aloxite 1200		
4.2	7.2	30				CV
5.0	2	10			0.92	0.18
6.7	1.2	8			5.14	
5.1	35.9	182			0.999	R2
8.0	1	8	17.5	Aloxite 800		
7.9	1.9	15				
15.0	6	90				
24.2	4.8	116			14.7	CV
15.3	11.6	178			6.20	0.42
18.0	17	306	0.982	R2		
8.0	0.5	4	19.8	Pine		
11.5	2.6	30				
10.5	4.2	44			11.1	CV
13.8	3.7	51			2.11	0.19
11.8	8.5	100			0.991	R2
7.3	1.1	8	20.3	Stone		
12.0	4	48				
9.7	7.4	72			9.9	CV
10.8	8.8	95			1.74	0.18
9.8	13.8	135			0.993	R2
9.1	0.55	5	21.1	Coal Dust		
11.9	1.6	19			11.4	CV
11.5	3.4	39			1.64	0.14
13.0	6	78			0.998	R2
342.9	0.07	24	63.1	Aloxite 320		
135.2	0.355	48			209.7	CV
155.9	0.59	92			93.44	0.45
205.0	0.722	148			0.948	R2

Figure 13. Statistical Analysis of SKC Split 2.

DataRam						
CF	Real time (mg/m3)	Gravimetric (mg/m3)	MMAD	Correlation Coefficient		
14.5	0.55	8	17.5	Aloxite 800		
12.5	1.2	15				
25.7	3.5	90				
33.1	3.5	116			22.9	CV
25.1	7.1	178			7.84	0.34
26.4	11.6	306			0.992	R2
20.0	0.2	4	19.8	Pine		
24.0	1.25	30				
20.0	2.2	44			20.6	CV
21.0	2.43	51			2.23	0.11
17.9	5.6	100			0.995	R2
7.7	1.04	8	20.3	Stone		
13.6	3.54	48				
11.2	6.45	72			10.9	CV
10.9	8.75	95			2.09	0.19
11.2	12.03	135			0.995	R2
10.0	0.5	5	21.1	Coal Dust		
12.7	1.5	19				
12.0	3.25	39			11.8	CV
12.4	6.3	78			1.21	0.10
12.7	12	152			0.9997	R2

Figure 14. Statistical Analysis of DataRam.

Sidepak						
CF	Real time (mg/m3)	Gravimetric (mg/m3)	MMAD	Correlation Coefficient		
11.4	0.7	8	17.5	Aloxite 800		
10.7	1.4	15				
29.5	3.05	90				
31.4	3.7	116			21.7	CV
23.6	7.55	178			8.80	0.41
23.5	13	306			0.988	R2
15.4	0.26	4	19.8	Pine		
17.6	1.7	30				
17.3	2.55	44			16.8	CV
		51			1.21	0.07
		100			0.9997	R2
5.5	1.45	8	20.3	Stone		
9.0	5.31	48				
8.2	8.75	72			7.6	CV
		95			1.84	0.24
		135			0.994	R2
6.3	0.8	5	21.1	Coal Dust		
8.3	2.3	19				
9.8	4	39			7.7	CV
6.4	12.2	78			1.67	0.22
		152			0.9807	R2

Figure 15. Statistical Analysis of Sidepak.

Sibata						
CF	Real time (mg/m ³)	Gravimetric (mg/m ³)	MMAD	Correlation Coefficient		
53.3	0.15	8	17.5	Aloxite 800		
50.0	0.3	15				
136.5	0.85	116				
101.7	1.75	178			94.9	CV
133.0	2.3	306			41.75	0.44
					0.982	R ²
40.0	0.1	4	19.8	Pine		
54.5	0.55	30				
51.8	0.85	44			48.8	CV
68.0	0.75	51			7.72	0.16
62.5	1.6	100			0.9984	R ²
25.8	0.31	8	20.3	Stone		
27.4	1.75	48				
28.8	2.5	72			27.0	CV
26.2	3.63	95			1.18	0.04
27.0	5	135			0.998	R ²
38.0	0.5	19	21.1	Coal Dust		
32.5	1.2	39				
30.6	2.55	78			35.0	CV
39.0	3.9	152			4.10	0.12
					0.9856	R ²

Figure 16. Statistical Analysis of Sibata.