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Testing a revised inlet for the personal dust monitor

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Abstract

A person-wearable dust monitor that provides nearly real-time, mass-based readings of respirable dust was developed for use in underground coal mines. This personal dust monitor (PDM) combined dust sampling instrumentation with a cap lamp (and battery) into one belt-wearable unit, with the air inlet mounted on the cap lamp. However, obsolescence of belt-carried cap lamp and batteries in coal mining ensued and led end users to request that the cap lamp and battery be removed from the PDM. Removal of these components necessitated the design of a new air inlet to be worn on the miner's lapel. The revised inlet was tested for dust collection equivalency against the original cap-mounted inlet design. Using calculated inlet respirable fractions and measured dust mass collection, the performance of the two inlets is shown to be similar. The new inlet requires a 1.02 factor for converting dust masses obtained from it to equivalent masses collected from the original inlet.

Keywords

Coal mine dust sampling; inlet; personal dust monitor

Introduction

Since the promulgation of the Federal Mine Safety and Health Act of 1969, exposure of underground miners to coal mine dust has resulted in coal workers' pneumoconiosis (CWP) being the direct or contributing cause of 75,000 deaths and the distribution of over $44 billion in black lung benefits.[1] This Act set a 2.0 mg/m^3 limit on allowable concentrations of respirable dust in the coal mining workplace and also mandated the use of a coal mine dust personal sampler unit (CMDPSU)[2] to measure miners' exposure concentrations. By gravimetric measurements on its collection filter, the CMDPSU is used to determine an average mine dust concentration to which workers were exposed over an 8-hr work shift.

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However, because of the continued incidence of CWP in mine workers, in 1996 the Secretary of Labor established the Federal Advisory Committee on the Elimination of Pneumoconiosis among Coal Mine Workers. The Committee recommended that the National Institute for Occupational Safety and Health (NIOSH) research improved sampling instrumentation for use in the mining industry.[3] In response, NIOSH led the development of the personal dust monitor (PDM), in consultation with labor, industry and government.

The Model 3600 PDM (Figure 1A), manufactured by Thermo Fisher Scientific (Franklin, MA; hereafter Thermo), is a personal dust monitor certified under 30 CFR Part 74 for use in underground coal mines that provides coal miners with nearly real-time measurements of coal dust concentrations in their breathing zones. This enables miners to monitor and reduce their exposure during their work shift, by modifying their position relative to the dust source and adjusting dust controls. The Model 3600 PDM has been described in detail elsewhere.[4–6] In brief, it includes a tapered element oscillating microbalance (TEOM), a size classification device (Higgins-Dewell cyclone), air heaters, pump, pump battery, electronic control boards, a display screen, a mining cap lamp, cap lamp battery, and air sampling inlet. The cap lamp was originally incorporated into the device, in consultation with end users, to make the PDM less intrusive to the miner. The Model 3600 PDM is a replacement for the cap lamp and battery normally carried during underground work, having dimensions and weight similar to a lead-acid type miner’s cap lamp battery.[5] To best integrate the dust sampling technology with the lighting source, an inlet was created to be adjacent to the cap lamp (hereafter called original inlet), mounted on the miner’s hard hat (Figure 1B). Previous work concluded that inlets placed at either the cap lamp or lapel locations accurately measured the miner’s exposure to respirable coal mine dust as measured at the nose; however, there is a slight difference between measurements made at the cap lamp and more conventional lapel inlet locations.[7]

In the years since the PDM was initially designed, lighting and battery technology improved greatly, leading to the introduction of light-emitting diode (LED) based cap lamps. The new LED systems improve the lighting conditions, reduce the battery capacity requirements, and allow for a lighter and more compact system design,[8] eliminating the need for a belt-wearable battery and power cord. This lighting improvement has now been adopted by the large majority of underground mines, with very few still using lead-acid batteries to power cap lamps. The use of compact cap lamp systems is now the industry norm, and the size and weight of the PDM with the incorporated cap lamp system is much greater than recently adopted LED lighting technology. With the widespread adoption of this new lighting technology, industry asked NIOSH to initiate research into removing the camp lamp and related battery from the PDM, reducing its weight and making it more acceptable to underground miners. This research resulted in the PDM 3700 (Figure 1C). The PDM 3700 is a modification of the PDM 3600 in which the power take-off, cap lamp and cap lamp battery have been removed, along with the cap-mounted inlet. To accommodate charging of only one battery instead of two, a modified model of the instrument recharger was produced. In addition, the instrument firmware was revised to better serve in a mine compliance application. Among the changes made to PDM design, only the inlet revision could affect instrument performance. By removing the original cap lamp from the PDM, it became necessary to create a revised inlet with performance similar to the original inlet, thus minimizing the impact of the inlet revision.

Preliminary research by NIOSH included inlet designs that used simple steel tubes of various diameters, bent forward at a 90° angle. Although they collected dust masses similar to the original inlet, they were eliminated as candidates after discussions with Thermo, because they were judged as too difficult to keep directed in a forward direction and would also require mounting brackets that would be excessively heavy. Thermo selected an alternate, similar-performing candidate as the choice for replacing the original inlet, because it avoided these difficulties and easily clipped to a miner's clothing. The new inlet (hereafter called revised inlet) (Figure 1D) was designed to attach and hang from the miner's lapel, just as is done with the CMDPSU, which has longstanding use industry-wide to measure coal dust exposure. Therefore, the positioning of the revised inlet is more typical for industrial hygiene practice, would be highly consistent with the established predecessor, and likely to produce measurements readily comparable to historical data collected with CMDPSU. The objective of this article is to report results comparing the dust collection performance of the revised inlet to that of the original inlet and determine any equivalency factor needed in transitioning from one inlet design to the other. Because the effect of changing locations has already been evaluated in previous literature,[7] this topic is not addressed in this article.

Methods

Inlet characteristics

Both the original and revised inlets are of metal construction, the former of brass and the latter of stainless steel. The original inlet is attached by means of a fixed brass bracket to the side of the cap lamp. Using a toothed clip, the revised inlet is attached to a cloth lapel or tab of a miner's clothing. The original inlet body is oriented horizontally when attached to a miner's cap and has a tapered inner bore, while the revised inlet body is oriented vertically when hanging from a miner's garment and has a straight inner bore. The original inlet points in the same direction as the miner's face and the revised inlet points outward from the miner's chest, so both inlets can be described as facing forward when worn by a miner. Conductive silicone rubber tubing attaches to the rear of the original inlet, on a barbed hose fitting, while this tubing attaches at the bottom of the revised inlet, on a polished cylindrical tube adapter, as shown in Figure 2. Multiple lengths of tubing ranging from 121.9–167.6 cm (48–66 in) were offered for the original inlet, to accommodate miners of different height. However, for this research a tubing length of 92.7 cm (36.5 in) was selected and used throughout the testing on both inlets. This length is similar to the tubing length utilized with the CMDPSU.

Testing procedures

The performance of the two inlet designs was compared using two metrics: respirable fractions and collected coal dust masses (mass loadings). The methodology used for each metric is described below.

Respirable fractions

The penetration efficiencies of the original and revised inlets were evaluated with a commonly used method for characterizing size selectors' performance.[9–12] An aerosol composed of glass microspheres (Cospheric, Santa Barbara, CA) was injected into a calm air chamber, at a constant rate, using a TSI 3400A fluidized bed dust generator (TSI Inc., Shoreview, MN). The material in the generator was an equal-mass combination of two microsphere products with different distributions: one set of spheres had a median diameter of 3 μm and 90% of the spheres were smaller than 8 µm; the second set had a median diameter of 10 µm and 90% of the spheres were smaller than 18 µm.

Before entering the chamber, the charge of the aerosol was neutralized by a TSI 3012A Aerosol Neutralizer. The mass concentration of the glass aerosol was kept constant at 2 mg/m^3 and the aerosol particle size was log-normally distributed (2.72 µm MMAD, 1.53 GSD).

The chamber was of cylindrical fiberglass construction (0.45-m diameter, 2.4-m height) supplied with compressed, filtered air at a flow rate of 20 L/min. The flow rate was controlled by an F-4100 Rotameter (Gilmont Instruments, Barrington, IL) and the air was introduced into the chamber through eight radial inlets at the top. The generated aerosol was fed at a constant rate and introduced into the chamber at the same cross-sectional position as the filtered air, to aid in adequate mixing. The relative pressure of the chamber was maintained at −2.49 Pa (−0.01 in H2O) measured by a Magnehelic gauge (Dwyer Instruments, Michigan City, IN).

Calm air conditions were maintained, with a downward air velocity of 2 mm/sec. For each test session in the chamber, measurements were taken to ensure that the aerosol in the sampling zone of the chamber was spatially and temporally stable and uniform.

The glass aerosol was measured using a TSI 3321 Aerodynamic Particle Size (APS) analyzer (TSI Inc.), both in the chamber and downstream of the inlet being evaluated. A system of valves was used to alternate sampling between the chamber aerosol and the output from the inlet. The inlets were tested at 2.2 L/min (standard PDM airflow) with total flow rate entering the APS analyzer at 5 L/min.

For both inlet types, the APS measured stable size-segregated particle number concentrations with (W) and without (WO) the tested device in-line. The following series of seven settings was used for each individual experiment (10 scans, 20 sec per scan): WO_1-W_1-WO_2-W_2-WO_3-W_3-WO_4. Penetration by particle size was then calculated as the particle number concentration measured with the tested inlet (W) divided by the background concentration (WO), using the mean of the number concentrations immediately preceding and following the inlet measurement. In this manner, particle penetration was determined for an inlet, using a plain stainless steel tube as a reference. The plain tube was 4 cm long with a 4-mm internal diameter. The plain tube and the inlets were positioned in the chamber so that the particles entered the tube or the inlets horizontally.

The penetration data gives information, for each particle size, of the percent of particles passing through the specific inlet. Because the PDM has a size selection device (a cyclone) after the inlet, which only allows the passage of respirable particles and removes large particles, the measured penetration values were corrected with the size-selection function of the International Organization for Standardization (ISO)/Comité Européen de Normalisation (CEN)/ACGIH® respirable convention curve.[13] The respirable inlet penetration data was obtained by multiplying the raw penetration data with the function value for the respirable convention, at each particle size. The resulting value provides the percent of respirable particles passing through the specific inlet and subsequently the cyclone.

Coal dust mass collected with both inlets

The relative performance of the two inlets was tested using side-by-side gravimetric measurements of 12 original inlets and 12 revised inlets, both manufactured and supplied by Thermo. Samples of respirable coal dust, aerosolized in a Marple calm air chamber,[14] were collected on pre-weighed PVC membrane filters (5-μm pore, 37-mm diameter) in two-piece cassettes. Environmental conditions in the chamber during the testing were 22–24 °C and 44–53% RH. Airflow to aerosolize the bulk coal dusts was provided through a Miller-Nelson HCS-501 Flow, Temperature, and Humidity Control System (Miller-Nelson Inc., Livermore, CA). Using a TSI 3400A Fluidized Bed Aerosol Generator and TSI 3012A Aerosol Neutralizer (TSI Inc.), a stable target concentration was established before starting the sampling and was maintained over the full sampling period. Inlets were arranged in a circular alternating pattern, and the sampling turntable within the Marple chamber was continuously rotated to ensure uniform exposure for the inlets. Figure 3 shows the inlet positioning and internal arrangement during Marple chamber testing.

Conductive tubing (Thermo part no. 32–006785-0050) of 0.48-cm ID, cut to 92.7-cm length, connected each tested inlet to a HD-BGI-4CP cyclone (Mesa Labs, Butler, NJ), which is the cyclone used in the PDM. The flow rate for each sampling unit was maintained at 2.2 L/min using a critical orifice. The flow rate was verified for each sampler at the beginning of each test series with each different coal dust. The inlets were compared using three different coal dusts, at three targeted mass loadings of 0.4 mg, 1.2 mg, and 2.6 mg for each dust. These mass loadings correspond to the 5%, mean, and 95% coal mine dust exposure concentrations reported in the Mine Safety and Health Administration (MSHA) database.[15] Table 1 summarizes coal types and particle size distributions for these dusts, when aerosolized in the Marple chamber and measured by Model 290 Marple cascade impactors, as previously recorded elsewhere.[6] The tests were run for 8 hr and different mass loadings were produced using different mass concentrations in the chamber, as monitored by a Thermo TEOM 1400AB unit. The testing for each coal dust at each mass loading was performed three times, resulting in a total of 27 tests. Using 12 of each inlet design per test, this provided 324 total raw data values per inlet type.

After testing was completed, a weighted least squares (WLS) regression model was used on pooled data from all 27 tests, to quantify how the mass measured with revised inlets compared to the mass measured with original inlets. The 12 individual revised inlet values from each test were paired with the mean original inlet value calculated from the same test, the mean original values serving as “reference” values. Assigning revised inlet values to the abscissa (x-axis) and the original inlet values to the ordinate (y-axis) directly provided a regression slope that is the adjustment factor for translating revised inlet values to correlated original inlet values, without the need for further calculations. The WLS weighting was the inverse of the mean original inlet mass, inverse weighting being a common weighting method (see online Supplemental materials).

Results and discussion

Respirable fractions

Figure 4 shows the effect of the two inlet designs on the respirable fraction of the glass aerosol. The ISO/ACGIH respirable convention was applied, by particle size, to the penetration data of the original and revised inlets. The respirable fraction data presented in the figure represent the averages for three inlets of each type.

There was little difference in the calculated respirable fractions between the two inlet types, Figure 4 suggests that for smaller particles, the penetration was higher for the original inlet, while for larger particles it is higher for the revised inlet. Overall, the revised inlet seemed to generate respirable penetration values closer to the international respirable convention. It is important to note that for the PDM, the respirable fraction is obtained using a Higgins-Dewell cyclone in line after the inlet. This current calculation, shown in Figure 4, is only intended to show that both inlets have a similar effect on the Higgins-Dewell performance. The size-by-size errors bars for the respirable penetration data indicate that the difference for the two inlets are within the individual inlet type variability and thus switching them will have only an insignificant effect on the cyclone performance and ultimately on the dust exiting the cyclone and assessed by the monitor.

Inlet equivalency factor

Table 2 provides the summary statistics for the WLS regression and Figure 5 presents the related regression line and equation. As shown, the coefficient of determination R^2 was greater than 0.99, indicating that more than 99% of the variation in original inlet mass loadings can be explained by revised inlet loadings. The small, statistically significant non-zero intercept is of no practical consequence, non-zero values being common in dust research, and −0.013 mg being less than 1% of the dust collected at the exposure limit of 1.5 mg/m^3 over a work shift. Based on the 1.018 value of the slope (with detailed derivation in the online Supplemental materials), it was determined that 1.02 would be used as the multiplying factor in making the revised inlet performance equivalent to that of the original inlet.

A change in inlet configuration can create significant changes in the characteristics of the aerosols being sampled. Vincent (2007)[16] discusses several potential influences, including turbulence, electrostatic forces, and inlet geometry, which may affect the collection efficiency of the sampler. This current research addressed these concerns through measuring the overall collection efficiency of particles in freestream air after the inlet, which is identified by Vincent as the method to use for measuring a sampler’s performance.[16] The utility of an empirical investigation is that a valid equivalency factor can be derived, irrespective of the details of inlet revision. The data reported here show that in total, the changes in inlet geometry resulted in a minor total difference of 2% in collection efficiency between the original and revised inlet designs.

Conclusion

The Model 3600 PDM with the original inlet has been demonstrated to be an accurate, direct reading instrument suitable for use in the underground coal mine environment.[4,5] With the advancement of lighting technology and the resulting abandonment of belt-carried cap lamp batteries in underground mining, industry requested that the cap lamp and related battery be removed to improve the comfort of miners wearing the PDM. As a result, it became necessary to design a new inlet for the PDM, which was separate from the cap lamp. In this study, a newly designed inlet was tested and its sample collection performance compared against the original inlet design. The data presented here, using both inlet respirable fractions as well as coal dust mass loadings, show that the performance of the two inlets is similar and that the revised inlet would require a 1.02 factor for converting masses obtained from it to equivalent masses from the original inlet.

The revised inlet has been incorporated into the manufacture of the PDM and is a design feature of the Thermo Model 3700, which was certified by NIOSH for use in underground coal mines. On February 1, 2016, the underground coal mining industry began using the Model 3700 PDM to collect respirable dust samples to comply with requirements of the respirable dust rule[17] that was recently promulgated by MSHA.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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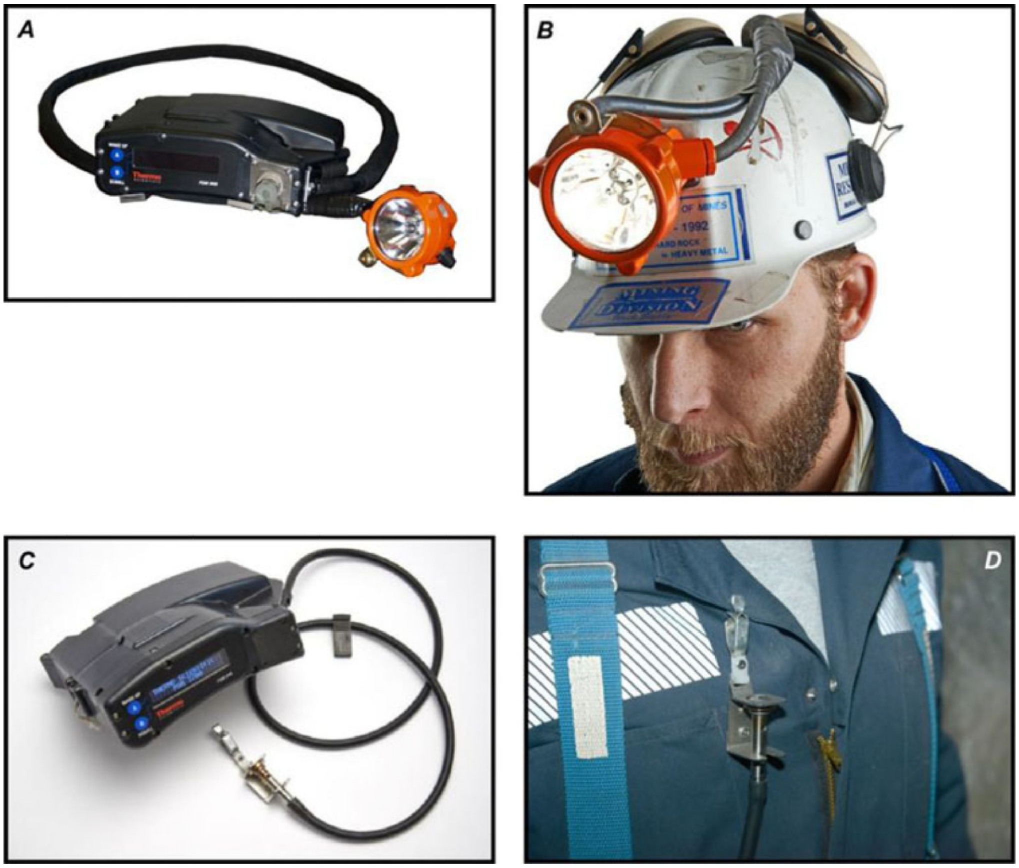

Figure 1.
Pictures of the instruments and associated inlets for the PDM 3600 (A, B) and PDM 3700 (C, D).

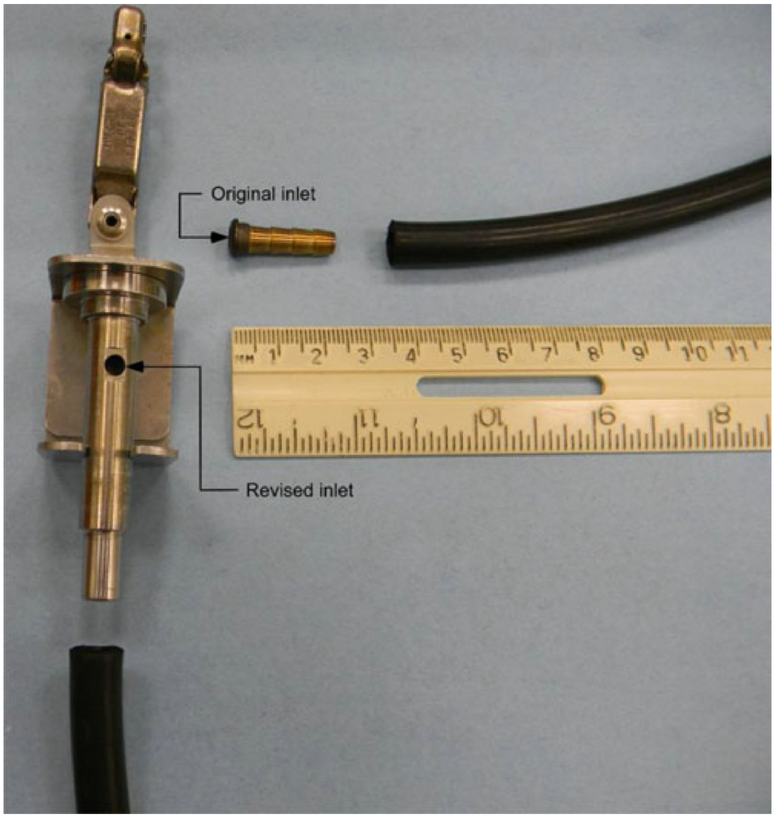

Figure 2.
Picture of the original and revised inlets.

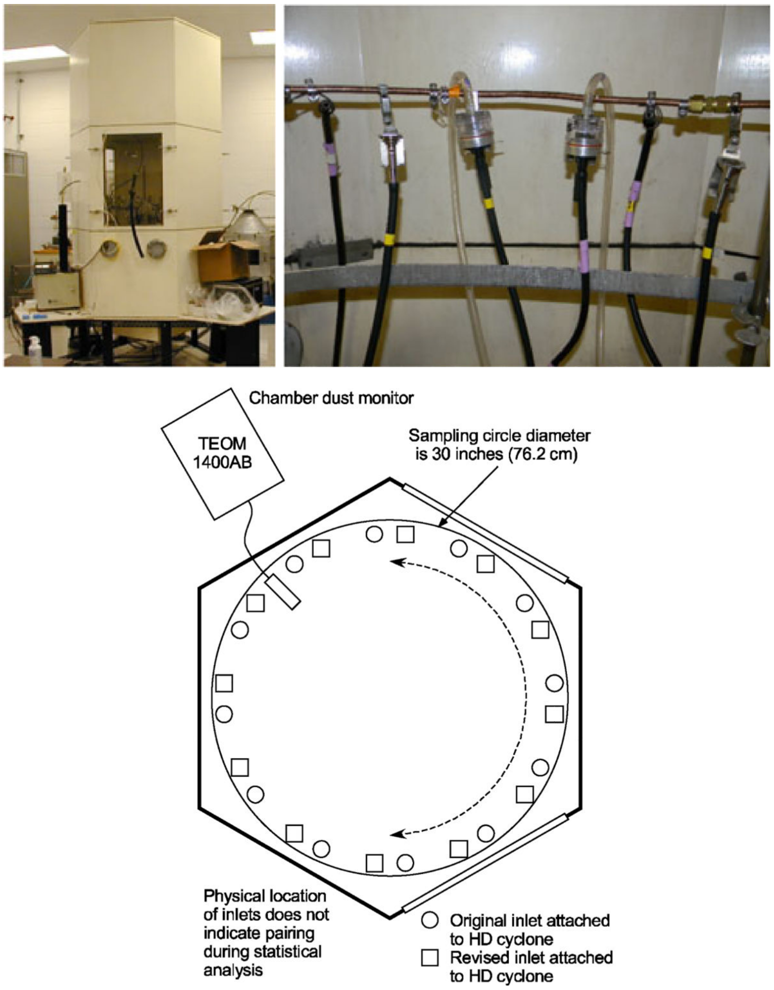

Figure 3.

Picture of the Marple chamber at PMRD (upper left), inlet positioning (upper right) and arrangement scheme within the chamber (lower).

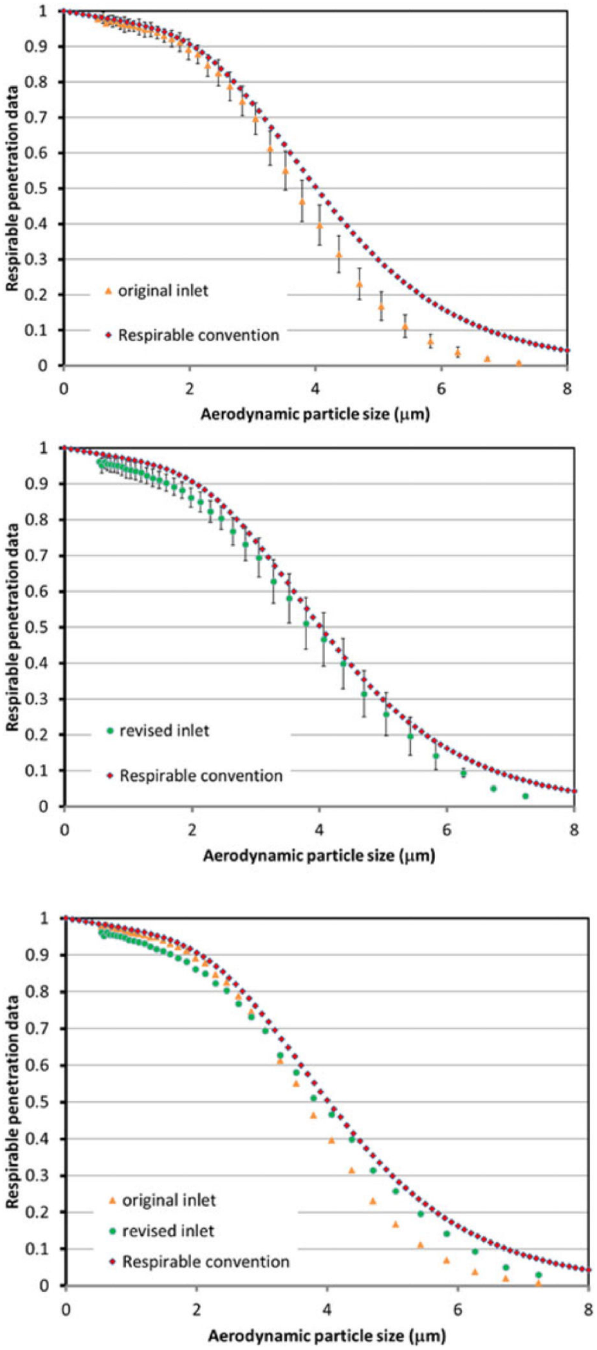

Figure 4.

Respirable penetration data for the two inlets tested, together with the ISO/CEN/ACGIH respirable convention curve: original inlet (top); revised inlet (center); both inlets (bottom).

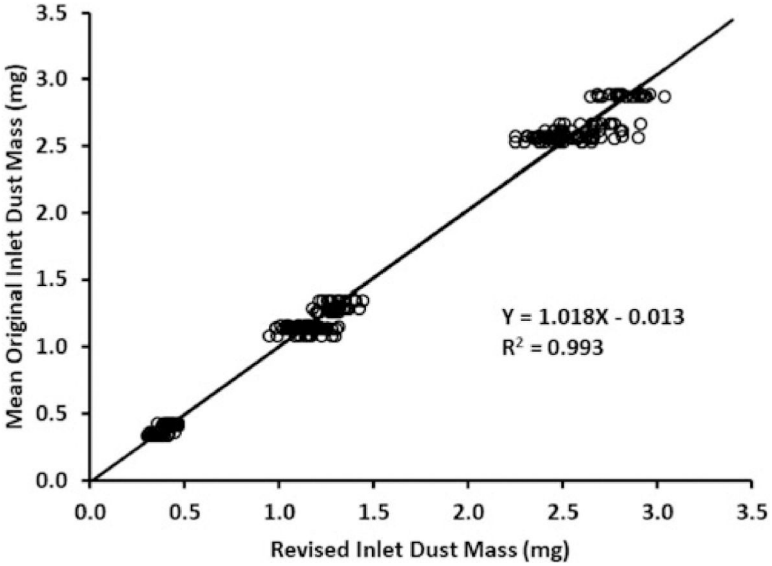

Figure 5.

Weighted least squares regression of pooled coal dust mass data.

Table 1.

Coal dust types and their particle size distributions.

Types and Sizes of Test Coal Dusts		
Name (Seam)	**MMAD (μm)**	**GSD**
Pocahontas No. 3	4.21	2.77
Illinois No. 6	5.71	2.23
Pittsburgh	11.05	2.77

MMAD - Mass median aerodynamic diameter

GSD - Geometric standard deviation

Table 2.

Summary statistics for weighted least squares (WLS) regression model.

WLS Model Summary Statistics							
R^2	**SEE**	**Slope**	**Slope 95% LCL**	**Slope 95% UCL**	**Intercept**	**Intercept 95% LCL**	**Intercept 95% UCL**
0.993	0.068	1.018	1.008	1.027	−0.013 [*]	−0.022	−0.003

[*] $p < 0.05$

SEE - Standard error of the estimate; LCL - Lower confidence limit; UCL - Upper confidence limit.