Mining, Metallurgy & Exploration (2024) 41:719–725
https://doi.org/10.1007/s42461-024-00934-2

Equivalency of PDM3700 and PDM3600 Dust Monitors

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Received: 7 July 2023 / Accepted: 28 January 2024 / Published online: 28 February 2024

Abstract

The PDM3600 and PDM3700 are two closely related person-wearable dust monitors manufactured by Thermo Fisher Scientific. Both are based on tapered element oscillating microbalance technology and provide nearly real-time, mass-based readings of respirable dust concentrations. From a monitoring perspective, the primary difference between the models is the PDM3600 has an integrated cap lamp with attached inlet, while the PDM3700 has no cap lamp and a revised inlet attaches to the worker's lapel. Using coals of varied origin and employing a wide range of concentrations, side-by-side measurements from these instruments were collected under controlled laboratory conditions and then compared. By use of ordinary least squares and weighted least squares regression methods, followed by mixed model analysis, results suggest there is no statistically significant or practical difference in instrument performance. The two monitors are equivalent for the field dust concentration measurements for which they were designed.

Keywords Personal dust monitor · Coal mine dust sampling

1 Introduction

In 1996, the Secretary of Labor established the Federal Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers, because of the continuing incidence of that occupational lung disease. The Committee recommended [1] that the National Institute for Occupational Safety and Health (NIOSH) research improved sampling instrumentation for the mining industry. In response, NIOSH led the extended effort to develop the personal dust monitor (PDM), in consultation with labor, industry, and government. The first such commercial instrument, the PDM3600 (Fig. 1), manufactured by Thermo Fisher Scientific (Franklin, MA; hereafter Thermo), is a personal dust monitor certified under 30 CFR Part 74 [2] for use in underground coal mines. It 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 each work shift, by modifying their work location/position when possible relative to the dust source and adjusting mine dust controls when applicable.

The PDM3600 has been described in detail elsewhere [3–5]. In brief, it includes a tapered element oscillating microbalance (TEOM), a size classification device (Higgins-Dewell cyclone), air heaters, pump, general instrumentation 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, based upon recommendations of underground miners, intending to make the PDM less intrusive to wear. Therefore, the PDM3600 is both a dust monitor and 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 [4]. To integrate the dust sampling technology and the lighting source into one instrument, an air inlet was created to be adjacent to the cap lamp (Fig. 2) that mounts on the miner's hard hat.

Subsequent to the initial design of the PDM3600, the introduction of cap lamps utilizing light-emitting diodes (LEDs) led to improved lighting conditions, reduced battery capacity requirements, and allowed for lighter and more compact system designs [6]. This new lighting technology eliminated the need for a belt-wearable battery and power

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Fig. 1 Fully assembled PDM3600 (left) and PDM3700 (right) dust monitors

Fig. 2 The original PDM3600 inlet (left) and revised PDM3700 inlet (right)

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 PDM3600 with the incorporated cap lamp is much greater than recently adopted LED lighting technology. With the widespread adoption of new LED systems, 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 PDM3700 (Fig. 1), which is also certified under 30 CFR Part 74 [2].

The PDM3700 [7] is a modification of the PDM3600 in which the power take-off, cap lamp, cap-mounted inlet, and cap lamp battery have been removed. To accommodate charging of only one battery instead of two, a modified version of the instrument recharger was produced. In addition, the instrument firmware was revised to better serve in a mine compliance application and an internal software factor was adjusted by 2% to better interpret measurements with the new design. Among the changes made to the PDM3600, only inlet revision could affect instrument performance. By removing the original cap lamp assembly to create the PDM3700, it became necessary to create a modified inlet [8] with performance similar to the original inlet, minimizing the effect of inlet revision.

The revised inlet (Fig. 2) uses a toothed clip to attach to the miner's lapel, the same method as is used with the Coal Mine Dust Personal Sampler Unit, 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 and is very consistent with the established inlet predecessor. Both the original and revised inlets are of metal construction, the former of brass and the latter of stainless steel. Conductive silicone rubber tubing attaches to the rear of the original inlet, on a barbed hose fitting, while this same tubing attaches at the bottom of the revised inlet, on a polished cylindrical tube adapter. 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. In view of the fundamental instrument similarities and modest differences, the objective of this paper is to report results comparing the dust measurement performance of the two PDM models and determine if they are functionally equivalent.

2 Methods

The relative performance of the two PDM types was tested using side-by-side concentration measurements of three PDM3700 units and three PDM3600 units. Air volumes bearing respirable coal dust were generated in a Marple calm air chamber [9] (Fig. 3). Environmental conditions in the chamber during testing were 22–24 °C and 44-53% RH. Airflow to aerosolize the bulk coal dusts, proceeded through a TSI (Shoreview, MN) 3400A Fluidized Bed Aerosol Generator and TSI 3012A Aerosol Neutralizer, with additional dilution airflow treated using a Miller-Nelson HCS-501 Flow, Temperature, and Humidity Control System (Livermore, CA). Instrument inlets were arranged in a circular alternating pattern at the same horizontal level, pointing toward the center of the chamber. The six inlets attached to a copper ring, with 60° separation between adjacent inlets (Fig. 4). The turntable base/floor inside the Marple chamber was set for continuous rotational oscillation to ensure more uniform exposure for the inlets. The design and operation of the chamber minimizes dust concentration gradients, as may occur in less controlled field use, from factors such as varying mine conditions, uneven

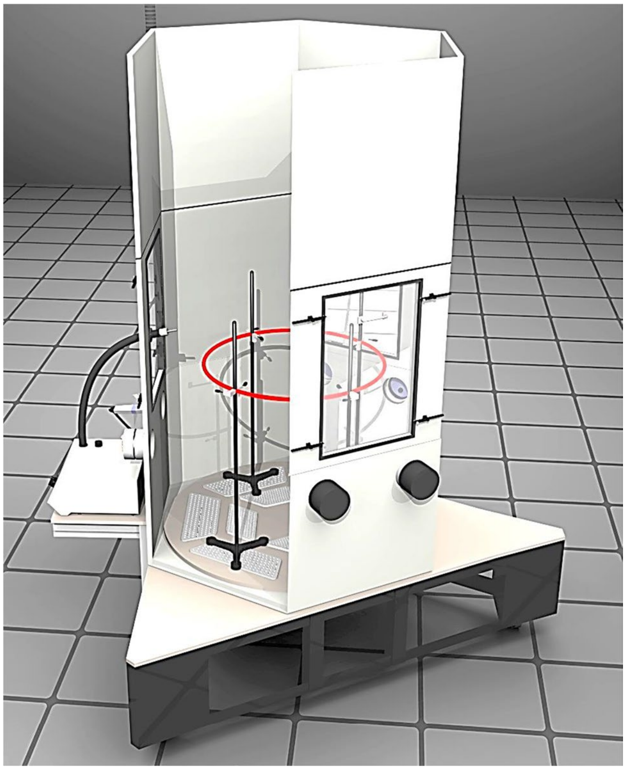

Fig. 3 Cutaway drawing of the Marple chamber. Instrument inlets were attached to a copper ring, shown in red at mid-level interior

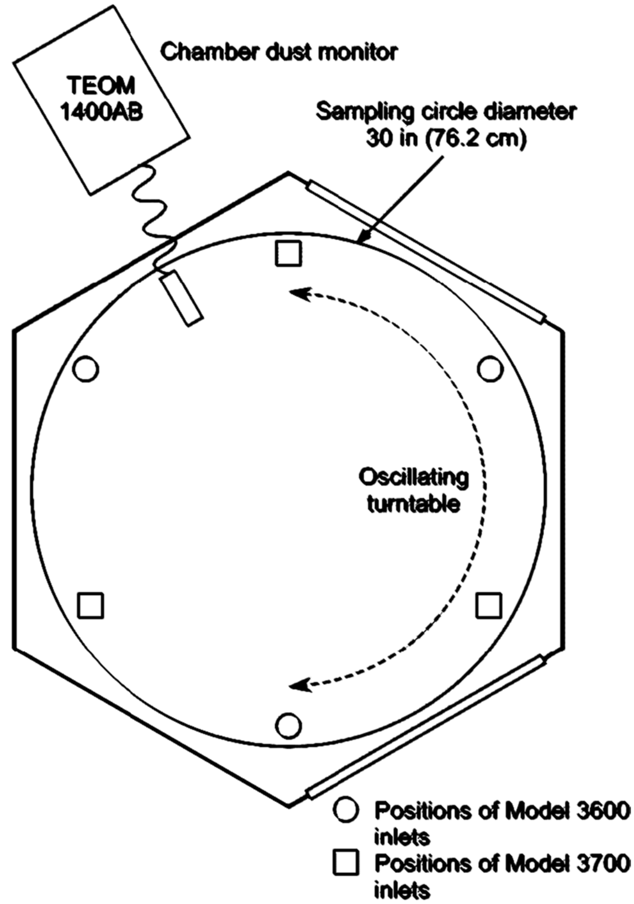

Fig. 4 Schematic showing the radial arrangement of instrument inlets in the Marple chamber. Inlet openings were pointed toward the chamber's center

airflow, and inlet positioning. Therefore, a better environment is provided in the chamber for accurately comparing instrument performance.

Dust generation began when the instruments' 35-min warm-up period was complete and began recording data. Each test had a target mass for final instrument-collected dust, corresponding to the targeted average dust concentration for that test. The target concentration was established early in the test, dust feed, and airflow manipulated to maintain the concentration, as monitored by a Thermo TEOM 1400AB unit. Each test was of 8-h duration, with PDM data files downloaded and examined afterward. The dust concentration value at the end of each file, i.e., the final reading, provided the data values used in the instrument comparison. Instruments were cleaned between tests and fresh TEOM filters installed.

Conductive tubing (Thermo part no. 32-006785-0050) of 0.48 cm (0.19 in) ID, cut to 92.7 cm (36.5 in) length, connected each PDM3700 inlet to its cyclone, reflecting how this model would be deployed in mines. PDM3600 units have been available with options for different lengths for the inlet tube/cap lamp cable, to fit miners of various heights. The units in this testing had tube/cable lengths of 121.9 cm (48.0 in), the most common option. PDM3600 units had their cap lamps on during testing, representing mine usage.

A careful mass-measurement calibration was performed on each PDM instrument before testing began. The flow rate for each instrument was calibrated at 2.2 l/min and verified before each series of tests with each coal dust. The instruments were compared using three different coal dusts, at eight targeted dust concentrations of 0.2, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, and 4.0 mg/m^3 for each dust. These test targets were implemented in a randomized order and generally correspond to previous validation testing [3, 4] that spanned the concentration range expected in the field. Table 1

Table 1 Coal dust types and particle size distributions

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 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 [3]. The combined 24 tests (three coal dusts at eight concentrations) provided 72 total raw data values per PDM model.

After data from all tests were pooled, an ordinary least squares (OLS) regression model was used for the initial examination of how the concentration measured with PDM3700 units and the concentration measured with PDM3600 units compared. The three individual PDM3700 values from each test were paired with the mean PDM3600 value from the same test, the mean PDM3600 values serving as "true" values. This repeats the procedures applied in a previous study [8] that compared the performance of revised and original inlets. Next, a weighted least squares (WLS) regression model was applied to the same pooled data in which the weighting was the inverse of the mean PDM3600 concentration, inverse weighting being a common weighting method. The data was paired in the same manner as with the previous OLS regression. To provide context for and clarify the results of the above regressions, further smaller-scale regressions were then performed between data from two individual PDM units of the same model. There are twelve combinations in which such regressions may be performed. A statistical software optimization routine was used to select and apply the weighting for each same-model regression, taken from a wide range of possible inverse powers of the ordinate values.

Finally, linear mixed model analysis focusing on main effects was used to test the equivalence of the PDM3700 and the PDM3600. Linear mixed models can be used to test both fixed and random effects [10]. An effect is labeled as fixed if all the levels or categories of interest are investigated in the study. For example, instrument model would be considered a fixed effect in the current analysis because the researchers' interest was limited to comparing the PDM3700 and the PDM3600. On the other hand, an effect is labeled as random if the levels or categories investigated in the study are considered to be a random sample from a larger population of possibilities, and the researcher's interest is in estimating the variability among levels or categories rather than in comparing only certain specific levels or categories. In the current study, variability among target masses and dust types were each treated as a random effect because the researchers' interest was not limited to only the specific target masses and dust types that were tested. An advantage of mixed model analysis is that the results are robust with violations of distributional assumptions [11].

3 Results and Discussion

Table 2 reports the summary statistics for the OLS regression derived from the pooled PDM concentration data. The coefficient of determination, R^2, is greater than 0.99, indicating that the relationship between the independent and dependent variables is highly linear. The slope value of 0.999 is highly statistically significant and suggests that the two PDM models provide fully equivalent measurements. Also, there is statistically significant intercept of 0.070. As will be discussed below, a ready explanation is available for the nonzero intercept, so that it has less importance in our evaluation.

As is common with dust measurements, greater data spread (Fig. 5) occurs at higher concentrations than at lower concentrations. Therefore, one of the underlying assumptions for conducting an OLS regression is violated, specifically, homogeneity of variance. As the next step, WLS regression was applied to the pooled data, to mitigate the heteroskedacity and to provide a presumably more accurate regression. As stated earlier, the weighting employed in the WLS regression was the inverse of the mean PDM3600

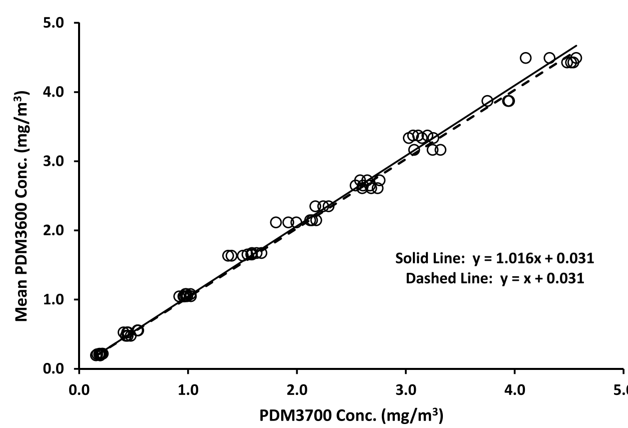

Fig. 5 WLS regression (solid line) for pooled PDM coal dust concentration measurements (dashed line is for comparison)

Table 2 Results of OLS regression model

R^2	SEE	Slope	Slope 95% LCL	Slope 95% UCL	Intercept	Intercept 95% LCL	Intercept 95% UCL
0.993	0.108	0.999	0.979	1.018	0.070	0.025	0.115

p(slope) <0.0001; p(intercept) = 0.003

SEE standard error of the estimate, *LCL* lower confidence limit, *UCL* upper confidence limit values. Inverse weights are commonly chosen, but there is no single "correct" weighting for WLS methods and varying weightings can cause minor differences in resultant slopes and intercepts.

Table 3 reports the summary statistics for the WLS regression and again the coefficient of determination, R^2, was greater than 0.99. This regression produces a slope of 1.016 and intercept of 0.031, with both values being statistically significant. Figure 5 shows the graphed line for the WLS regression and a comparison line having the same intercept, plotted upon the pooled data of this study. In this instance, the small 0.031 mg/m^3 intercept, being about 2% of the exposure limit of 1.5 mg/m^3 over a work shift, is of no practical significance. The LCL of the slope is 1.001 that may be regarded as coinciding with 1.000. Certainly, any small deviation from a unity slope would be substantially less than the sum of other forms of sampling variability generally experienced in the field [12]. The same may also be said for the intercept having a small nonzero value.

A unique confounding bias factor for PDMs can result in nonzero intercepts, even when they are compared among themselves. PDM filters are mounted on top of the vibrating TEOM tube and are heated to reduce humidity content in the collected dust sample. Each heated filter will produce a small mass measurement bias, likely from the polymer composition experiencing a minor relaxation from the heating, which then slightly affects the TEOM frequency. This has been discussed in earlier research [13]. Each individual filter, used only once and then discarded, produces a small unique bias. In comparing two groups of PDM measurements, one might expect their average biases to be similar, but there would be no guarantee of this, and certainly they would not be identical. Therefore, the heating-related filter bias would cause an offset between the two groups of measurements, which would result in a nonzero intercept and also possibly affect the slope.

Further insights are provided by the comparisons of two instrument units of the same model, summarized in Table 4. Eight of the twelve same-model regressions have slopes deviating from unity by 0.026 or more. This suggests that the 1.016 slope of the WLS regression is an ordinary outcome and that there is no more difference in the performance between different PDM models than there is between PDMs of the same model. Also, four of the 12 same-model regressions have intercepts deviating from zero by 0.030 or more. This suggests that the 0.031 intercept of the WLS inter-model regression (or the 0.070 intercept of the OLS regression) is less significant than first impression or the p-value suggest, because even same-model regressions have similar nonzero intercepts. The same-model comparisons performed here show results consistent with our previous experience [3, 4] that in laboratory Marple chamber tests

Table 3 Results of inter-model WLS regression model

R^2	SEE	Slope	Slope 95% LCL	Slope 95% UCL	Intercept	Intercept 95% LCL	Intercept 95% UCL
0.996	0.070	1.016	1.001	1.032	0.031	0.011	0.050

p(slope) = 0.049; p(intercept) = 0.002

SEE standard error of the estimate, *LCL* lower confidence limit, *UCL* upper confidence limit

Table 4 Results of same-model WLS regressions

PDM model	Units compared (Y vs. X)	Weighting used	R^2	SEE	Slope	Intercept
3700	1 vs. 2	$Y^{-1.50}$	0.999	0.029	0.956	0.034
	2 vs. 1	$Y^{-1.25}$	0.999	0.032	1.045	-0.036
	1 vs. 3	$Y^{-1.75}$	0.998	0.034	0.946	0.006
	3 vs. 1	$Y^{-1.75}$	0.999	0.035	1.053	-0.006
	2 vs. 3	$Y^{-1.75}$	0.999	0.030	0.990	-0.030
	3 vs. 2	$Y^{-1.75}$	0.999	0.030	1.008	0.030
3600	1 vs. 2	$Y^{-1.50}$	0.999	0.022	1.026	-0.009
	2 vs. 1	$Y^{-1.50}$	0.999	0.022	0.974	0.009
	1 vs. 3	$Y^{-1.75}$	0.998	0.034	1.027	-0.003
	3 vs. 1	$Y^{-1.75}$	0.998	0.035	0.970	0.004
	2 vs. 3	$Y^{-1.75}$	0.999	0.034	1.002	0.005
	3 vs. 2	$Y^{-1.75}$	0.999	0.034	0.995	-0.005

Underlined entries: Slopes varying most from 1.000 and intercepts varying most from 0.000

SEE standard error of the estimate

Table 5 Results of mixed model type III tests of fixed effects

Source	Numerator df	Denominator df	F	Sig.
Target mass	7	127.147	2073.191	<0.001
PDM model	1	4.052	3.933	0.117
Dust type	2	127.077	1.933	0.149

Dependent variable: dust conc

df degrees of freedom, *Sig.* significance (*p*-value)

PDM concentration readings can vary by several percent between individual instrument units.

Results of the mixed model analysis are reported in Table 5. The strongest effect, as shown by the size of the *F*-value, was for the main effect of target mass, indicating that it has the greatest influence on concentration readings. This is an expectable result because mass loading, the researcher's choice in establishing a dust level in the Marple chamber, would have a stronger influence on a dust monitor concentration reading than either the type of dust or the instrument model. A desirable result was that the main effect of PDM model was not significant ($p = 0.117$), indicating that there is no overall difference between the instrument types. A significant effect would suggest that readings for one instrument were systematically higher or lower than readings for the other when readings were averaged over target mass and dust type. There was non-significance for the main effect of dust ($p = 0.149$), although significance here would likely only have reflected that dust types with different particle sizes (Table 1) can influence how readily dust concentration can be established and maintained in the Marple chamber.

The study has a few limitations. It is of small scale, with three units of each PDM model. However, the number of optimally functioning units simultaneously available of both types was hampered by the aging population of PDM3600 units and the full production transition to the PDM3700 design. Furthermore, any PDM is a much more complex assembly than that used in the previous inlet study [8]. As such, any small variation in the instruments' numerous components may slightly affect the outcome. Also, the instruments' mass measurement and flow calibrations each have accuracies of about 0.5% if care is exercised. Finally, experience has shown that the dust mass concentration variation inside the Marple chamber is typically within 2–3%. These factors can individually and cumulatively be confounding influences in characterizing minimal performance differences between instruments of very similar designs; they may introduce seemingly small differences where none truly exist. The appearance of a small nonzero intercept cannot be eliminated, nor can it be fully corrected, as it depends on the behavior of individual filters. However, the common appearance of nonzero intercepts in the same-model comparisons argues for its lack of importance in inter-model comparisons. The range for slopes of the same-model comparisons also argues that a unity slope for the inter-model comparison is not strictly required.

4 Conclusion

The PDM3600 was previously demonstrated to be an accurate, direct reading instrument, suitable for monitoring the dust exposure of coal miners [3–5]. The advancement of lighting technology led to revising the design of this instrument into the PDM3700, for which the cap lamp and related battery were removed. This reduced the weight of the instrument and improved the comfort of those wearing it. In this study, the revised instrument was tested and its sample measurement performance compared against the original instrument design. The WLS results presented here, using measured coal dust concentrations, show that the PDM3700 and PDM3600 produce measurements no more different than that seen in comparisons between units of the same model. OLS results suggests the instruments provide entirely equivalent readings. Furthermore, mixed model analysis indicates there is no statistically significant difference in their performance. The two instruments can be considered equivalent for dust concentration measurements in their intended field application.

Thermo's PDM3600 is no longer in production. The PDM3700 is now the model designated for compliance sampling in coal mines and was certified by NIOSH for this use. As of February 1, 2016, the underground coal mining industry began using the PDM3700 to collect respirable dust samples to comply with requirements of the respirable dust rule [14] promulgated by the Mine Safety and Health Administration.

Acknowledgements The authors would like to acknowledge and thank NIOSH technician William (Joe) Archer for his skill and conscientious effort in performing laboratory procedures.

Data Availability The data that support the findings of this study are available on request from the corresponding author, [SEM]. The data are not publicly available due to US Government data use restrictions.

Declarations

Competing Interests The authors declare no competing interests.

Disclaimers The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

References

1. U.S. Department of Labor, Mine Safety and Health Administration, Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers. 1996. Recommendation Nos. 8 and 17, p. 34-42
2. (2010) Coal Mine Dust Sampling Devices. Fed Reg 75(65):17512–17529
3. Volkwein JC et al (2004. DHHS (NIOSH) Pub. No. 2004-151, RI 9663) Performance of a new personal respirable dust monitor for mine use. U.S. Dept. of Health and Human Services, Centers for Disease Control, Nat'l Inst. for Occup. Safety and Health, p 20
4. Volkwein JC et al (2006. DHHS (NIOSH) Pub. No. 2006-145, RI 9669) Laboratory and field performance of a continuously measuring personal dust monitor. U.S. Dept. of Health and Human Services, Centers for Disease Control, Nat'l Inst. for Occup. Safety and Health., p 47
5. Page SJ et al (2008) Equivalency of a personal dust monitor to the current United States coal mine respirable dust sampler. J Environ Monit 10(1):96–101
6. Sammarco JJ et al (2009) Technological aspects of solid-state and incandescent sources for miner cap lamps. IEEE Trans Ind Appl 45(5):1583–1588
7. Thermo Fisher Scientific, Model PDM3700 Personal Dust Monitor (user manual), Part Number 42-009904-3700. https://tools.thermofisher.com/content/sfs/manuals/EPM-manual-PDM3700.pdf (25Mar2016, downloaded 28Oct2022). 140
8. Mischler SE et al (2019) Testing a revised inlet for the personal dust monitor. J of Occup and Environ Hyg 16(3):242–249
9. Marple VA, Rubow KL (1983) An aerosol chamber for instrument evaluation and calibration. Am Ind Hyg Assoc J 44(5):361–367
10. Verbeke G, Molenberghs G (eds) (1997) Linear mixed models in practice (ebook). Springer, New York, USA, pp 11–22
11. Schielzeth H et al (2020) Robustness of linear mixed-effects models to violations of distributional assumptions. Methods Ecol Evol 11(9):1141–1152
12. Breslin JA, Page SJ, Jankowski RA (1983. RI 8740) Precision of personal sampling of respirable dust in coal mines. U.S. Dept. of Interior, Bureau of Mines, p 12
13. Page SJ, Tuchman DP, Vinson RP (2007) Thermally induced filter bias in TEOM mass measurement. J Environ Monit 9(7):760–767
14. Department of Labor (2014) Lowering miners' exposure to respirable coal mine dust, including continuous personal dust monitors. Fed Reg 79(84):24814–24994