Performance of a prototype personal dust monitor for coal mine use

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ABSTRACT: The personal dust monitor (PDM) is a sampling device developed for measuring the personal exposure to coal mine dust of mine workers. The device is based on proprietary technology known as the tapered element oscillating microbalance (TEOM) originally developed as a fixed- site environmental particulate mass monitor by Rupprecht and Patashnick Co., Inc., Albany, NY. Currently, the monitoring of exposure to coal mine dust relies on periodic samples taken by traditional coal mine dust sampling units that use a cyclone, filter, pump, and laboratory measurement of the filter mass. Better measurement of mine dust levels has been the goal of industry and labor for nearly two decades.

PDM technology offers accurate, end-of-shift and near real time assessment of worker dust exposure. Laboratory and underground tests compared measurements taken by a prototype PDM-2 (a two-piece TEOM) to the average of multiple personal dust samplers monitoring the same space. In the range of mass loadings between 0.5 and 4.0 mg/m^3 the PDM met a 25% accuracy criterion 95% of the time with 95% confidence. However, some questions still exist about potential bias between types of coal. The prototype two-piece device is in the process of being combined into a single unit that also contains the miners' cap lamp creating a more ergonomic dust sampling system.

1 INTRODUCTION

Sampling dust levels in mining presents specialized challenges because of the variable composition of the dusts and because mining involves constantly moving workplace (Hearl and Hewett, 1993). Monitoring of personal respirable dust exposure is an important step in eliminating many dust-related occupational illness and diseases. Currently, dust levels in mining are measured either gravimetrically, using filters and the accumulated dust mass in a given volume of air (Raymond et al. 1987), or through the use of instantaneous electronic dust monitors (Williams, and Timko 1984). The filter method takes several weeks to process before results are reported to the mine. This time delay, coupled with the constant change and movement inherent to the mining process, makes the filter measurement useful only as an historical data point. The results do not provide timely feedback to detect or correct excessively dusty conditions.

In a joint effort with the Mine Safety and Health Administration (MSHA), the NIOSH Pittsburgh Research Laboratory (PRL) has been working on an approved sampler for coal mining. Through a contract with Rupprecht & Patashnick Co., Inc. (R&P), CDC contract 200-98-8004, a sampler was developed based on the highly successful tapered element oscillating microbalance technology that is used worldwide for a number of commercial environmental sampling instruments. This study reports on results of laboratory and mine testing of the prototype Phase III, PDM-2. This instrument represents the first testing of a miniaturized person-wearable TEOM respirable dust sampler. Subsequent improved versions of this device are anticipated. This work compared the dust measurement accuracy and precision of the PDM-2 with that of the coal mine personal dust sampling unit, hereafter referred to as the personal sampler.

2 DESCRIPTION OF PDM-2 INSTRUMENT

The PDM-2 shown in Figure 1 is constructed in two parts. The lapel unit contains the inlet to a Dorr-Oliver 10-mm nylon cyclone, a U-shaped air heater section; the filter connected to a momentum compensated tapered element microbalance, and the computer. The belt unit contains a flow controlled pump, batteries, and data display. The cyclone has a custom fabricated shield to protect the inlet from direct water spray action and to reduce the sensitivity of the inlet to wind direction (Cecala et al. 1983).

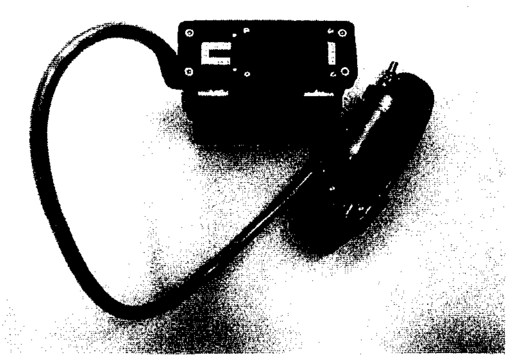

Figure 1. PDM-2 belt and lapel unit.

The weight of the total unit is 1.9 kg (4.3 lb). The lapel unit weighs about 0.45 kg (1 lb). The lapel unit measures 20 cm (8 in) long, 6.3 cm (2.5 in) wide, and 3.8 cm (1.5 in) thick. The belt unit measures 17.8 cm (7 in) tall, 15.2 (6 in) wide, and 5 cm (2 in) thick.

Other required components are the battery charger for the lithium ion batteries that connect through a charging port on the belt unit, and a personal computer (lap top or desk top) that accesses the lapel unit computer through a port on the side of the lapel unit. Windows-based software was provided by R&P to upload and download data from the lapel unit. The PDM-2 memory has the capacity to store 128 parameters at one-minute intervals, for an entire 12-hour shift.

3 TEST AEROSOLS

Four types of coal aerosols were used in the laboratory Marple chamber. These were Pittsburgh Seam A, Pocahontas, Illinois #6 obtained from the Penn State Coal Collection, and a commercially available ground coal called Keystone. Only Keystone was used in the longwall gallery testing. Underground tests were conducted in the Pittsburgh (PA), Eagle (WV), and Blue Creek (AL) coal seams. Characterizations of the airborne size distributions were measured with Marple personal cascade impactors for all coal types tested in the Marple chamber.

4 MASS LOADING PROTOCOL

Two identical PDM-2 prototypes, designated units 12 and 14, were available for this study and were always run simultaneously. The mass determined by each PDM-2 dust monitor was compared with the average mass of four standard personal samplers. The personal sampler filters were preweighed at the PRL controlled atmosphere-weighing facility according to established procedures. Filter blanks used the average of three filter blanks for the Marple chamber and underground data and the average of two filter blanks for the longwall gallery data. All filters were returned to the PRL weighing facility for post-mass determination using identical procedures to the preweighing.

Flow-controlled MSA Elf Escort pumps were calibrated at the beginning of a each coal type test in the Marple chamber, before the longwall gallery testing, and before each underground mine test. A Gilibrator, primary standard, flow meter was used to establish a flow rate of 2.0 ±1% lpm using an equivalent pressure restriction of the cyclone and filter assembly. Flow rates of the PDM-2 were checked and recalibrated (if required) each day using the Gilibrator attached to the bottom of a sealed inlet cyclone that was substituted for the PDM-2 cyclone.

During the programmed warm-up, an airflow check was usually conducted. Units were then placed into the Marple chamber, or placed into a Lippmann chamber (Blachman and Lippmann, 1974) that was used to reduce spatial variability, and then transported by car to the longwall test gallery; alternatively, for underground sampling, the instruments were placed into the Lippmann chamber at the mine prior to being carried underground. At the conclusion of each test, final cumulative concentration data from the belt screen display were recorded, airflow rates with loaded filters were then checked, and the units' memories were downloaded to a PC. These data were then translated into an ASCII text file that was read with a spreadsheet program. Units were then cleaned, new filters installed, and prepared for the next test.

The data files were then coordinated with the run times of the gravimetric data. Because the start time of the gravimetric samplers did not always match the automatic start times of the PDM-2 units, the mass of the PDM-2 at the gravimetric start time was subtracted from the PDM-2 end time mass. Gravimetric samplers were always started after the 30-minute warm-up cycle. Gravimetric start and stop times were ±1 minute and PDM-2 times were to the nearest previous minute (i.e., 2 min. 59 sec. was recorded as 2 min.)

5 MARPLE CHAMBER

Chamber tests were conducted under well-controlled conditions and assessed the best performance that can be expected from the PDM-2. Chamber temperature varied between 23° and 25° C. Relative humidity varied between 42 and 61%.

Personal sampling cyclone and filter holders were arrayed in a 1 m (39-in.) diameter circle around a central point in the chamber about 0.5 m (19 in) above the table, and the two PDM-2 units were placed 180 degrees apart within the array. The array slowly rotated 356 degrees and then reversed on a continuous basis so that each sampler inlet was exposed to an identical location in the chamber. A total of 19 gravimetric filters were used for each test. There were four sets of four filters for testing and three control filters. The control filters were handled in a fashion identical to the experimental filters with the exception that the end caps were not be removed. Calibrated Elf Escort pumps (Mine Safety Appliance Co.) were used to power the personal sampling cyclone filter units. The PDM-2 and Elf units were placed in the Marple chamber and operated under battery power as if being used in a mine.

For each coal type three tests were conducted to achieve a range of dust concentrations from about 0.2 to 4 mg of MRE equivalent mass. All gravimetric filters were started at the beginning of the test, but sets of four filters were turned off at intervals to encompass the desired range of mass loadings. The PDM electronic file was then used to determine the mass at the corresponding gravimetric sampling intervals. In this way, each test resulted in four PDM to gravimetric data pairs. Mass loadings ranged from 0.2 mg/m^3 to 4 mg/m^3.

6 GALLERY

The full-scale longwall gallery model at PRL enabled the assessment of the PDM-2 under less controlled conditions and in the presence of water spray mist. Performance of the device in motion was also evaluated. The full-scale model testing also enabled the performance and logistics of the Lippmann chamber to be assessed prior to underground testing.

The gallery was operated using Keystone coal dust, commercially available in large quantities required for gallery testing, with constant water and ventilation flow rates. Gallery water flow rate was 65 gpm @ 80 psi with a ventilation rate between 280 and 300 fpm. A powered continuous loop of chain conveyor was used to simulate a person's movement within the tailgate area of the gallery.

A total of 14 tests were conducted in the gallery. The Lippmann chamber contained four personal dust samplers and two PDM-2 units. Two control filters were used for each test. As with the laboratory testing, the target range of masses for equivalent concentrations ranged from 0.2 to 4 mg. The same setup and download protocol were followed for these tests with the exception of battery charging.

7 UNDERGROUND TESTING

Four evaluations were conducted in underground U.S. coal mines. Two coal mines were in the Pittsburgh seam, (which included coal similar to that used in the laboratory test), one in a longwall section, and one in a continuous mining section. One coal mine was in the Eagle seam in central WV and the fourth used diesel-powered face haulage and was in the Blue Creek seam in AL. Full-shift underground testing was conducted. Two PDM units, four personal gravimetric sampling filters, and two control filters were placed inside the Lippmann chamber. All units were turned on as they entered the portal, then were carried to the face for an 8-hour shift, and then were returned to the portal where the units were turned off. One test at each mine was conducted for 10 hours.

For all sampling, a NIOSH team was responsible for transporting the instruments at all times and shadowing a designated high-risk occupation for the entire shift. The readings from the PDM were used to estimate mass loadings such that a range of concentrations from 0.2 mg/m^3 to 4 mg/m^3 was achieved. To achieve higher mass loadings, it was occasionally necessary to move to a higher dust area.

8 DATA ANALYSIS AND STATISTICS

Reduced data compared the difference between the average of the gravimetric filter mass loadings to the individual PDM-2 mass loadings in a pair wise manner. Data were converted to MRE equivalent mass using the factor of 1.38. In the case of the PDM-2, this conversion takes place in the K factor constant, which converted oscillation frequency into mass. In the case of the personal gravimetric samplers, this conversion was made following the mass calculation.

The average gravimetric filter mass measurement and each PDM-2 mass measurement constituted one paired measurement. The ratio of the paired measurements was computed, and the accuracy criteria method of Kennedy et al. (1995) was used with the addition of a method to account for the inaccuracy of the reference method. For these tests, the concentration ratio for each data pair was calculated by dividing the individual PDM mass by the average value for the personal sampler mass. The individual concentration ratios were then averaged over appropriate data sets (i.e., laboratory, mine, overall, etc.) and the relative standard deviation was calculated.

To reduce the impact of error in the personal gravimetric measurement, the experimental pooled estimate of the relative standard deviation of the gravimetric samplers was subtracted from the relative standard deviation of the ratios. Bias was then calculated based on the mean concentration minus one. Accuracy was then estimated from the chart provided by Kennedy et al. Confidence limits were then calculated based on the method used by Bartley (2001) using a non-central Student-t test. A linear regression analysis was also done for each data set and for the overall data. This analysis used the Excel regression format.

9 RESULTS

Presented here are results of the PDM to personal sampler mass comparison from the Marple chamber for the four coal types, longwall gallery, underground mine data, and overall summary data. Also included are the results for the temperature, tilt, zero, and shock testing.

9.1 *Marple chamber*

A summary of the results for all Marple chamber testing is in Figure 2. The figure displays the calculations for the linear regression and correlation coefficient for each coal type. Also displayed on the figure is the ideal 1:1 comparison line. Table 1 contains the mass median aerodynamic particle size and geometric standard deviation for each of the coals used in the Marple chamber testing.

9.2 *Longwall gallery testing*

Figure 3 contains the linear regression and correlation coefficient for the longwall gallery tests. Note that both PDM-2 units gave essentially parallel lines to the 1:1 response, with a positive offset of about 0.10 mg. Data for November 28 were not obtained for unit 14 due to a mechanical failure of a microswitch that turns the tapered element off when the PDM is opened in order to change the filter. This broken switch prevented the tapered element from oscillating. Subsequent tests were able to be conducted by wedging the broken switch into the on position. This also required the filter to be changed with the tapered element oscillating, but this has no effect on test results.

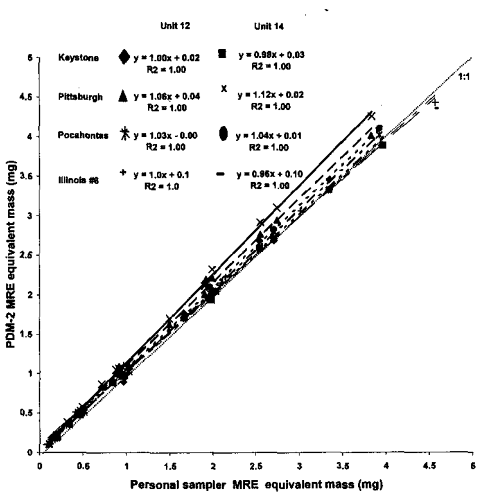

Figure 2. PDM-2 response to individual coal types.

Table 1. Size distribution of Marple chamber aerosols.

	MMAD um	GSD
Keystone	3.91	3.05
Pittsburgh	5.31	2.20
Illinois #6	7.54	3.08
Pocahontas	3.93	2.63

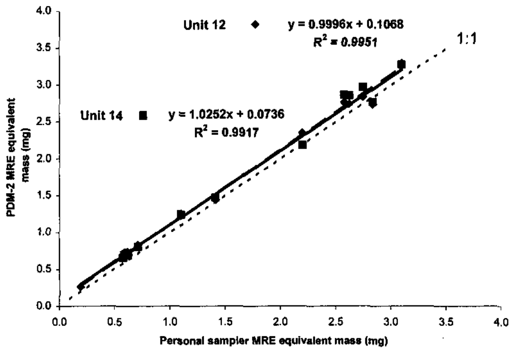

Figure 3. Longwall gallery regressions.

The starting mass loadings of the PDM-2 for this testing were occasionally negative. Reasons for this were unknown at the time, but subsequent analysis showed that this was related to ambient temperature. Other parameters in the data file suggest that the oscillation frequency of the tapered element was valid and therefore, the negative value was considered a valid zero point and the mass added (rather than subtracted) to the ending mass for the test. The maximum mass added in this manner was 0.0587 mg.

Use of the Lippmann chamber in this testing reduced spatial variability. The average relative standard deviation for the personal gravimetric sampler in the longwall gallery data was 6.1%. This value is similar to that obtained in the Marple chamber tests, where the average RSD was 5.67.

9.3 *Underground testing*

Figure 4 shows the linear regressions and correlation coefficients for all of the individual mine and instrument results. Note that the individual results with larger deviation from the 1:1 correspondence also have a reduced correlation coefficient. Mines 1 and 4 were in the Pittsburgh coal seam near the Pennsylvania and West Virginia border. Mine 2 was in the Eagle seam of central West Virginia. Mine 3 was a diesel powered face haulage equipped mine. The use of the Lippmann chamber resulted in an average RSD for the mine testing of 4.32%.

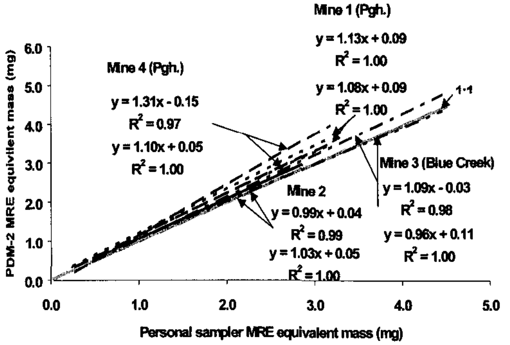

Figure 4. Individual mine response. Regression equations are for units 12 and 14 respectively.

9.4 *Data analysis and statistics*

Reduced data compared the difference between the average of the gravimetric filter mass loadings to the individual PDM-2 mass loadings in a pair wise manner. Data were converted to MRE equivalent mass using the factor of 1.38. In the case of the PDM-2, this conversion takes place in the K factor constant, which converted oscillation frequency into mass. In the case of the personal gravimetric samplers, this conversion was made following the mass calculation.

The average gravimetric filter mass measurement and each PDM-2 mass measurement constituted one paired measurement. The ratio of the paired measurements was computed, and the accuracy criteria method of Kennedy et al. (1985) was used with the addition of a method to account for the inaccuracy of the reference method. For these tests, the concentration ratio for each data pair was calculated by dividing the individual PDM mass by the average value for the personal sampler mass. The individual concentration ratios were then averaged over appropriate data sets (i.e., laboratory, mine, overall, etc.) and the relative standard deviation was calculated.

10 DISCUSSION

Fundamentally, the objective of this study is to determine how well the PDM agrees with the personal sampler. We use the accuracy criteria method of Kennedy et al. to describe such comparisons, and the accuracy criteria statistical calculations are supplemented by a correction for the experimentally determined relative standard deviation of the personal gravimetric samplers. This correction results in the relative standard deviation of the ratios being reduced by between 0.04 and 0.09. Accuracy can then be calculated from the corrected relative standard deviation and bias of the ratios. This results in calculations of the upper (95%) and lower (5%) confidence limits. According to Kennedy et al., an instrument meets the accuracy criteria if the 95% upper confidence limit is 0.25 or less and if the absolute bias is no greater than 0.10. However, if the method's lower confidence limit exceeds 0.25, the method does not meet the accuracy criteria. If neither of these conditions exist, the results are inconclusive and additional research will be required to accept or reject the method.

One of the difficulties of filter dust sampling and testing the equivalency of devices is the loss of measurement precision at low filter mass loadings. Kogut et al. (1997), for example, demonstrate that measurement precision for 16 measurements inside of a Lippmann-type chamber decreased significantly at mass loadings of less than about 0.5 mg. As mass levels decrease, the imprecision of the reference mass measurement increases. At low mass loadings, it is not possible to determine if the error in the pair-wise difference is attributable to the gravimetric sampler, the PDM-2, or a combination of the two instruments.

10.1 *Accuracy analysis*

Table 2 summarizes the accuracy criteria calculations for every pair-wise comparison measured as well as logical subsets of the data. For all data collected, the accuracy analysis of the data is inconclusive at the 95% confidence interval because the upper confidence interval exceeds 0.25. We can neither accept nor reject that the PDM-2 meets a 25% accuracy criteria. However, when the imprecision of the reference gravimetric samplers is taken into consideration, by examining only the data greater than 0.5 mg/m^3, the analysis indicates that the PDM-2 meets the 25% accuracy criteria because the upper confidence interval is less than 0.25.

For the subset of mine data greater than 0.5 mg/m^3, the accuracy analysis is inconclusive because the lower confidence interval is less than 0.25. It must be noted, however, that mine data results, are strongly influenced by the two mines in the Pittsburgh seam, where the bias[1] between the PDM and gravimetric samplers varied from 0.15 to 0.27. Three of the four individual instrument results from the other two mines meet the accuracy criteria, although the sample size for confidence interval testing is quite small (n<8).

10.2 *Temperature effects on accuracy*

During the laboratory testing the data indicated a dependency between mass and temperature. The data showed that for every degree centigrade drop in temperature, the PDM-2 apparent mass measurement increased by about 5.5μg. The converse

[1]Bias equals the mean concentration ratio minus 1.

Table 2. Accuracy criteria data.

Data Set	Unit No.	Number n	bias	rsd	Accuracy	Confidence Intervals Lower 5%	Upper 95%
All Data	12	97	0.089	0.091	0.25	0.23	0.28
All Data	14	96	0.099	0.083	0.25	0.23	0.28
Data >0.5 mg	12	71	0.078	0.076	0.21	0.19	0.24
Data >0.5 mg	14	71	0.088	0.066	0.21	0.19	0.23
Laboratory and Gallery	12	65	0.076	0.074	0.21	0.18	0.24
Laboratory and Gallery	14	65	0.087	0.070	0.21	0.19	0.24
Laboratory and gallery > .5 mg	12	47	0.067	0.059	0.17	0.15	0.20
Laboratory and gallery > .5 mg	14	47	0.078	0.063	0.19	0.17	0.22
All Mine Data	12	32	0.117	0.118	0.33	0.28	0.41
All Mine Data	14	31	0.124	0.102	0.31	0.27	0.38
Mine data >0.5 mg	12	27	0.100	0.094	0.27	0.23	0.34
Mine data >0.5 mg	14	26	0.108	0.077	0.25	0.21	0.30

was also true, that temperature increase resulted in mass decrease. This was initially attributed to changes in specific humidity in the air. Subsequently, R&P identified that an electronic circuit was temperature-sensitive and this caused the mass measurement to change in response to temperature. When the data from the gallery and mine testing are examined in view of the temperature sensitivity, the agreement between the PDM and personal samplers improves.

The observed mass dependence on temperature also had the effect of introducing bias to the mine results from both Pittsburgh seam mines. The other mine tests were conducted in warmer areas of the country where the intake temperatures were not that extreme. In the Pittsburgh seam mines, however, sampling was conducted during winter months and thus the mine temperatures, especially intake haulage, were quite cold. The sampling protocol required portal-to-portal sampling and the test start was always prior to entering the elevator after emerging from a warm indoor area. At the end of the test, the final reading was taken while the instruments were still cold from the mine air. The result of this protocol was that the final mass measurement was taken from a cold instrument relative to the initial mass measurement. This accounted for about a one third of observed bias in the Pittsburgh seam mines.

11 CONCLUSIONS & RECOMENDATIONS

The analysis of all data showed that when the prototype PDM-2 was compared to the currently used personal samplers the results are inconclusive to conclude that the device meets or does not meet a 25% accuracy criterion. There are two primary reasons why the results are inconclusive: First is the imprecision of the reference samplers at mass loadings less than 0.5 mg/m^3; second is the high bias found in the subset of mine data.

However, evaluating subsets of the data shows that if more precise reference samplers were available, then it is likely that the analysis would conclude that the PDM-2 meets the accuracy criteria. Data also show that the individual PDM-2 units did not meet the accuracy criteria in the mine tests because of high bias. This high bias was especially associated with the Pittsburgh coal type. A portion of this bias could be accounted for because of the temperature problems seen throughout these tests. A smaller, but similar bias was also noted for the laboratory results with the Pittsburgh coal where there was no temperature effect. Additional testing should clarify this result.

Analysis shows that the temperature sensitivity of the PDM-2 electronics did contribute to the observed bias from the Pittsburgh seam mine tests. However, we cannot be certain if the observed bias in the mine can be entirely explained by temperature since our laboratory data on temperature effects on mass is limited. Presumably the instrument manufacturer can eliminate the temperature sensitivity of the electronics, and additional testing must be conducted to determine if other sources of bias may exist.

The high regression correlation coefficients and low relative standard deviation of the data support the usefulness of the instrument in predicting respirable coal mine dust levels. If particular coal-type bias is still found with the improved electronics, this may be corrected with a specific coal-type calibration constant incorporated into the instrument's electronics or software.

Overall, these prototype PDM-2 test results demonstrate the successful miniaturization of the commercial TEOM technology into a person wearable respirable dust monitor. The absolute accuracy determination of the PDM-2 was hampered by inaccuracy of the reference methods and temperature dependence of the electronics. The results presented here, however, warrant further refinements of the technology to produce a coal mine dust monitor that provides accurate end of shift and short-term dust measurements. Furthermore, this new technology presents an opportunity to combine the dust monitor into the miner's cap lamp in a way that provides an accurate, easy to wear dust sampler.

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