Equivalency of a personal dust monitor to the current United States coal mine respirable dust sampler

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The United States National Institute for Occupational Safety and Health, through an informal partnership with industry, labor, and the United States Mine Safety and Health Administration, has developed and tested a new instrument known as the Personal Dust Monitor (PDM). The new dust monitor is an integral part of the cap lamp that coal miners normally carry to work and provides continuous information about the concentration of respirable coal mine dust within the breathing zone of that individual. Previous laboratory testing demonstrated that there is a 95% confidence that greater than 95% of individual PDM measurements fall within ± 25% of reference measurements. The work presented in this paper focuses on the relationship between the PDM and respirable dust concentrations currently measured by a coal mine dust personal sampler unit utilizing a 10 mm Dorr Oliver nylon cyclone. The United Kingdom Mining Research Establishment instrument, used as the basis for coal mine respirable dust standards, had been designed specifically to match the United Kingdom British Medical Research Council (BMRC) criterion. The personal sampler is used with a 1.38 multiplier to convert readings to the BMRC criterion. A stratified random sampling design incorporating a proportionate allocation strategy was used to select a sample of mechanized mining units representative of all US underground coal mines. A sample of 180 mechanized mining units was chosen, representing approximately 20% of the mechanized mining units in production at the time the sample was selected. A total of 129 valid PDM/personal sampler dust sample sets were obtained. A weighted linear regression analysis of this data base shows that, in comparison with the personal sampler, the PDM requires a mass equivalency conversion multiplier of 1.05 [95% C.I. (1.03, 1.08)] when the small intercept term is removed from the analysis. Removal of the intercept term results in a personal sampler equivalent concentration increase of 2.9% at a PDM measurement of 2.0 mg m^{-3}.

1. Introduction

Measurement of workplace respirable dust concentration is an essential first step in eliminating lung disease caused by over exposure to dust. In the United States (US), The Federal Coal Mine Health and Safety Act of 1969, the predecessor of the Federal Mine Safety and Health Act of 1977,[1] mandates that respirable coal mine dust levels be monitored and controlled to a maximum of 2 mg m^{-3} or below for a working shift, provided quartz levels remain at or below 5%. To date, this monitoring process has relied upon a coal mine dust personal sampler unit (hereafter referred to as personal sampler or CMDPSU in figures and tables) utilizing a pre weighed 5 μm pore polyvinyl chloride (PVC) filter, preceded by a 10 mm Dorr Oliver nylon cyclone, operated at a flow rate of 2.0 L min^{-1} to collect a sample in the mine environment. The personal sampler historically includes an empirically de rived[2] 1.38 multiplier to convert readings to the United King dom British Medical Research Council (BMRC) criterion.[3]

In consultation with labor, industry, and government, the US National Institute for Occupational Safety and Health (NIOSH) issued a contract to Rupprecht and Patashnick Co., Inc. (now Thermo Fisher Scientific Corporation), Albany, NY, USA, (CDC Contract 200 98 8004) to develop a Personal Dust Moni tor (PDM). The PDM is based on existing environmental ambient air monitoring instruments, the latter of which has achieved global acceptance for use in air quality monitoring networks. The key feature of this monitor is that it directly measures the mass of dust on a filter, regardless of dust composition, size, or physical characteristics. This contract work successfully miniaturized the air quality monitor's sensor and incorporated the sensor into a prototype, person wearable dust monitor that provides accurate end of shift respirable dust con centration data to miners.[4] Through a protocol developed by a partnership of labor, government and industry, previous work[5] verified that the PDM laboratory accuracy met the NIOSH

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criterion.[6] This report describes the underground full shift per formance of the PDM compared to the personal sampler.

2. Methods

2.1 Criteria for mine selection

A stratified random sampling design was used to select me chanized mining units that were representative of all US underground coal mines. The sampling base was developed using information extracted from the US Mine Safety and Health Administration (MSHA) Standardized Information System and reflected all producing mechanized mining units as of September 27, 2004. The selected sample of mechanized mining units was partitioned into mutually exclusive strata that reflected the type (MSHA bituminous coal district) and mining method (potentially related to size distribution) of the dust in underground coal mines. Because of the mine selection process, any mine dust size distribution effects are accounted for, on average, in the data analyses. Of the total mechanized mining unit population, only a small percentage employed longwall and other (*e.g.*, scoop) mining methods (6% and 3.5%, respectively), with the balance being continuous mining sections. A proportionate allocation strategy with different sampling rates among the strata was used to ensure that the composition of the sampled mechanized mining units was approximately representative of the composition of the popu lation. A sample of 180 was chosen to represent approximately 20% of all mechanized mining units in production at that time. The sample was randomly selected using the Survey Select procedure from the SAS system for the statistical analysis of data (SAS Institute, Inc., Cary, NC, USA).

2.2 Testing procedures

Planning and implementation of this segment of the testing was performed by NIOSH, in close cooperation with MSHA headquarters, district offices, and field offices. A sampling schedule was developed after the list of candidate mines and mechanized mining units was compiled. This schedule also introduced a degree of randomness in that, whenever possible, certain selected mines from different MSHA field offices and/or districts were combined into one trip. The mine sampling was conducted from October, 2004 through August, 2005.

Each sampling package contained (1) a PDM, pre pro grammed to begin an 8 h sample at the selected mine's shift start time and operating at 2.2 L min^{-1}; (2) two dust samplers using Dorr Oliver cyclones, one operating at 2.0 L min^{-1} and the other at 1.7 L min^{-1}; and (3) a Marple cascade impactor operating at 2.0 L min^{-1}. The Marple impactor is a miniatur ized eight stage cascade impactor intended to provide particle size distributions of sampled aerosol and sufficiently small as to be wearable as a personal sampler. The cyclones, impactor, and the PDM sampling inlet were mounted inside a specially constructed Lippmann sampling canister[7,8] with a single inlet. This procedure ensured that all samplers were exposed to the same atmospheric conditions. Flow controlled Mine Safety Appliances Escort Elf® pumps were calibrated to 2.0 ± 0.02 L min^{-1} and 1.7 ± 0.017 L min^{-1} for the cyclone samplers prior to each trip using a Gilibrator (Sensidyne Inc., Clear water, FL, USA) primary standard flow meter. An equivalent pressure restriction for the respective samplers was used dur ing pump calibration. Flow rates for all samplers were checked prior to each trip and post checked for proper calibration to ±1%. The post check calibration also served as pre calibra tion for the following trip. Sampling locations were chosen where miners typically worked. Data for the cascade impactor and 1.7 L min^{-1} Dorr Oliver sampler will not be included in this report because they are not pertinent to the present objective. Analysis of those samplers will be the focus of a future publication.

The PDM was pre programmed to automatically begin sampling at the pre determined shift start time and turn off eight hours later. Gravimetric samplers were manually started and stopped within 3 min of the PDM start/stop times. In the event that the PDM display indicated a projected end of shift concentration of 1.5 mg m^{-3} or greater at any time during the sampling period, a HEPA filter was placed into the inlet of the Lippmann canister and all samplers finished running the 8 h period without collection of additional airborne dust into the canister. The purpose of the 1.5 mg m^{-3} concentration limit was to minimize the possibility of overloading the impactor.

2.3 Samplers

2.3.1 PDM. The PDM[4,5] is a pre commercial (not for general sale) model 3600 PDM using a tapered element oscillating microbalance (TEOM®) mass sensor. The PDM uses Teflon® coated fiberglass (nominal 15 mm diameter) filter media TX40H120WW, (Pallflex Products Corp., Putnam, CT, USA) manufactured into special plastic holders that mount on the end of a vibrating hollow tapered element. The device is intended to be virtually "invisible" to the miner, as a replacement for the cap lamp and battery currently employed in mines. Fig. 1(a) illustrates the PDM device with accompanying charger/PC interface docking station. The docking station is used to simultaneously communicate with PC software for programming and retrieving stored data in the instrument and to recharge its batteries for the next work shift. Fig. 1(b) shows the PDM components. The enclosure of the PDM is hardened to withstand the harsh conditions found in the mine environment, with the system designed to meet MSHA drop test requirements for cap lamps,[9] as well as intrinsic safety approval requirements.[10] An illuminated data display on the top of the PDM continuously shows the dust concentration for the previous 30 min, cumulative mass con centration to that point in the shift, and a projected end of shift concentration. A full description of the PDM system configuration, air flow path, flow measurement and control, battery configuration, data acquisition, and mass measure ment technique has been previously described[5,11] and will not be presented here. Additionally, extensive laboratory and replicate sampling data from ten underground coal mines to establish the accuracy and precision of the PDM have been previously reported.[5]

The PDM instrument samples, analyzes, and calculates mass based concentrations of respirable dust. It is acknowl edged that there may be some negative bias (defined as [measured concentration ÷ true concentration] 1) in the

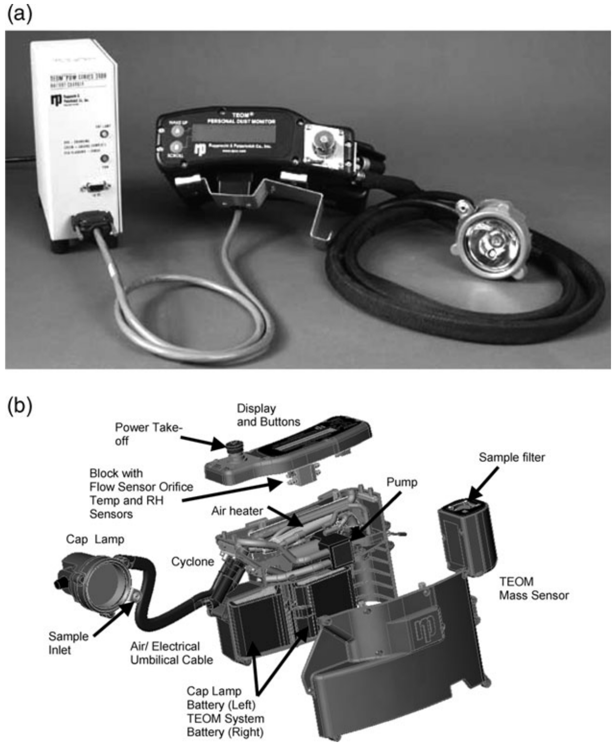

Fig. 1 (a) Pre commercial PDM connected to docking station used for charging and communication with a PC using an RS 232 interface. (b) PDM internal components.

use of the PDM associated with particle losses that take place in the sampling path between the cyclone exit and the sensing zone of the instrument. This may be corrected empirically by reference to experimental data in specific situations. Prior testing[5] of the pre commercial PDM instrument found that the PDM consistently underestimated mass, based on com parison to reference mass samples using identical inlet config urations and Higgins Dewell cyclones. Established scientific protocol requires measurement correction for systematic error (bias) prior to analysis. Therefore, these systematic measure ment errors were used to calculate an average bias correction factor prior to regression analysis.[12,13]

Additionally, prior work has documented that the PDM filter has a characteristic average positive thermally induced filter bias during an 8 h sampling period. This value was determined by random filter selection from various filter lots and is due to heating effects acting on the filter.[14] The data of this work were also corrected for this bias, prior to regression analysis. While this filter induced bias is trivial for an indivi dual measurement, it is significant when many low mass measurements are combined in the regression analysis.

2.3.2 Cyclone gravimetric reference. Each sampler consisted of a Mine Safety Appliances 37 mm diameter, pre weighed 5 µm pore PVC filter, preceded by a 10 mm Dorr Oliver nylon cyclone.

2.4 Analytical gravimetric imprecision

Gravimetric analysis was performed on a Mettler Toledo UMT2 microbalance for the personal sampler samples. Weighing was done in the NIOSH Pittsburgh Research Laboratory at 22.8 + 0.4 °C (73 ± 0.7 °F) and 53 ± 2% RH. All samples were pre and post weighed, employing control filters. Two filter cassettes were used as controls for the personal sampler. Average blank control filter masses were used to correct the filter mass results for each test. Because sampling packages were deployed to numerous mines simul taneously, the control filters could not accompany the sam pling packages to the mines. However, this is considered a minor factor compared to differences in weighing room con ditions between pre and post weighings. All sample and control filters were desiccated and allowed to equilibrate to room conditions. However, small cyclical fluctuations in room conditions are not totally corrected by the control filters because: (1) the control filters cannot be weighed at the same moment as the sample filters, and (2) the pre and post weighings are not performed at the same time in relation to the cyclic variation of the room conditions. Since the pre and post weighings are not time correlated with the cyclic varia tion, there is an uncorrectable, but minor, random variation. Therefore, several estimates for the weighing imprecision will be provided.

2.5 Analysis

Weighted regression is the method of choice to stabilize the variance for data analysis by estimating the relationship between the variance and the independent variable. Appendix A† describes the mathematical representation and weight variable estimation. It should be noted that, since the overall purpose is to predict contaminant concentration from an imprecise measurement in the PDM, there is no need to specifically consider random measurement error in the pre dictor variable. Additionally, it can be demonstrated that the random error in the PDM can be classified as one of the embodiments of the Berkson case. The Berkson case describes several classes of measurement procedure in which random error in the predictor variable has no effect on the regression analysis. Weighted regression was performed using Sigma Plot v.9.0.[15]

3. Results

3.1 PDM bias correction

A bias correction factor for internal dust loss within the PDM was estimated from previous empirical work.[5] A negative bias of 6.6% for laboratory data from instrument testing was calculated. This bias correction is not applied to the tabular data of Tables B 1 and B 2 in Appendix B.† However, all subsequent data analysis will include this PDM bias correction as well as the thermal zero drift bias correction of 25.5 µg (0.024 mg m^{-3} for an 8 h sample).[14]

3.2 Gravimetric limit of quantification

Determination of the traditional limit of quantification (LOQ)[6] requires determining the standard deviation (S_W) in nine consecutive weighings of a blank filter. It was determined that S_W 1.4 µg and LOQ 14 µg in a single weighing. However, quality control procedures involving control room filters used only in the balance room document that the total standard deviation (S_T) due to (S_W) and the cyclic fluctuations in weigh room conditions during the course of this study was S_T 4.1 µg. Applying traditional formulae for propagation of error in the personal sampler filter dust mass gains (including an average of 2 control filters) yields S_{filter} $1.8478 \times S_T$ 7.6 µg. For an 8 h sample, this value corresponds to ${}_0\sigma$ 0.011 mg m^{-3}, suggesting an LOQ 0.11 mg m^{-3} for the personal sampler.

3.3 In-mine testing results

Table B 1† lists all data included in the analysis, sorted in order of increasing PDM measurements. Of 180 total projected samples, 129 valid PDM/personal sampler pairs were collected. Although the number of valid samples obtained was less than the target value, the actual sample data base obtained was closely proportional to the original mine distribution by district. Table B 2† lists 9 entire data sets excluded for technical or procedural errors. It is again noted that the PDM values in Tables B 1 and B 2† do not include any bias corrections.

3.4 Data analysis

3.4.1 Weight variable estimation. Analysis of the raw mine replicate sampling data of Volkwein *et al.*[5] show that the relative standard deviation (RSD) of the different samplers can be generally described by the equation

$$RSD = RSD_0 \quad A(mg^{\ 1}\ m^3) \times X_{sampler}(mg\ m^{\ 3})\ (R^2 < 0.1), \quad (1)$$

with slopes (A) typically less than 0.05 in magnitude. The RSD is also called the coefficient of variation (CV). The low R^2 and the small slope of the data demonstrate general independence of the RSD on sampler concentrations above $X_{min} \approx 0.3$ mg m^{-3}. Constant RSD necessarily implies variance increasing with the square of the mean. Given this relationship, a partial weighting factor to correct the regression for the increasing variance is ($1/X^2$). It should be noted that the magnitude of the intercept constant (RSD_0) in eqn (1) is not important in establishing the weighting factor for two reasons. First, the only statistical requirement is proportionality between standard deviation and mean. Second, the intercept term incorrectly implies constant RSD as the concentration approaches zero.

The small negative slope indicates the presence of a constant variance term becoming more prominent at sampler concentrations less than 0.3 mg m^{-3}. Iteration of eqn (A 3) (see Appendix A),† with $({}_0\sigma)^2$ fixed by weighing imprecision, converged quickly to a solution within 4 iterations, yielding.

$$\sigma_T^{\ 2} \quad (0.011\ mg\ m^{-3})^2 + 0.0155X^2. \quad (2)$$

3.4.2 Weighted regression. Fig. 2 shows the scatter plot relationship between the personal sampler and the PDM. The iterated weighted regression without the y intercept term is included. In general, the data clearly indicate a linear relationship with multiplicative errors between the two instruments. Regression weight variable estimates were obtained using eqn (2).

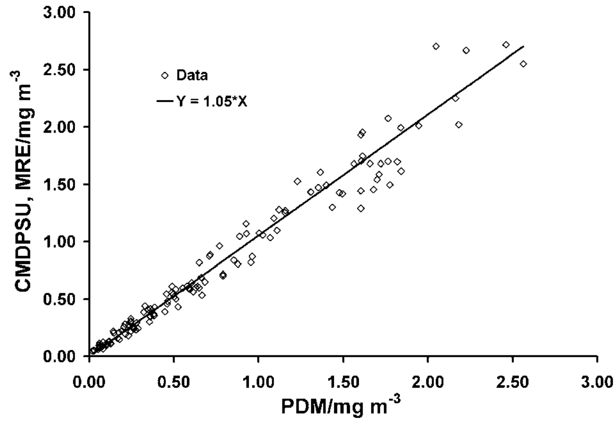

Fig. 2 CMDPSU data plot with PDM bias corrections. CMDPSU data incorporate 1.38 multiplier historically used to estimate BMRC/MRE equivalency. Weighted regression statistics are presented in Table 1.

Table 1 shows the regression statistics for analyses with and without the intercept term. Although it is not quantifiable, the y intercept 0.018 mg m^{-3} term is statistically significant at the 0.05 significance level ($t_{intercept}$ 4.35 > $t_{critical}$ 1.98). Removal from the regression can have a significant effect on the slope and the calculation of respirable dust concentration. For comparison, regression without the intercept yields slope 1.05 [95% C.I. (1.03, 1.08)]. Because t_{slope} 3.82, the hypothesis [slope 1.00] is rejected and the PDM would use a 1.05 conversion factor to be an equivalent measure of the personal sampler.

3.4.3 Consideration of regression intercept terms. Ideally, in the absence of bias one would expect both instruments to read zero or to average zero for a very large data set when no dust is present. When this does not occur, there are several different schools of thought regarding treatment of an intercept term. One philosophy is that, in many cases, the intercept is not considered meaningful for two reasons. First, the intercept is usually beyond the range of the data and assigning any

Table 1 CMDPSU (with 1.38 conversion factor) *vs.* PDM. Weighted regression results on bias corrected PDM data

Statistic	Value	95% C.I.	90% C.I.
PDM designated predictor (independent) variable			
Intercept y_0/mg m ^{3}	0.018	(0.010, 0.026)	(0.011, 0.025)
$S_{intercept}$	0.004		
$t_{intercept}$	4.35		
Slope	1.01	(0.98, 1.04)	(0.98, 1.04)
S_{slope}	0.017		
t_{slope}(*wrt* 1.0)	0.52		
y_0 removed			
Slope	1.05	(1.03, 1.08)	(1.03, 1.08)
S_{slope}	0.014		
t_{slope}(*wrt* 1.0)	3.82		
Regression ${}_0\sigma$/mg m ^{3}	0.011		
Regression CV	12.4%		
$t_{critical}$(.05)	1.98		
$t_{critical}$(.10)	1.66		
N	129		

significance to an extrapolation beyond the data is suspect. Second, the intercept can be highly influenced by error inherent in the data. Therefore, a case could be made for simply ignoring an unmeasurable intercept.

Another school of thought is that in a regression, the intercept and slope are correlated. If, in particular, the intercept term is not statistically significant, it offers no useful information and should be removed from a subsequent regression. The issue is not quite so clear cut when the intercept is statistically significant but unmeasurable. In this case, performing the regression without the intercept may have a significant effect on the slope parameter, depending on the level of significance associated with the intercept. Because consideration of the intercept term is often an end user decision, the analysis is presented with and without the intercept term in the regression.

Additional insight regarding the intercept term can be obtained using independent data obtained by Volkwein *et al.*[5] This independent data set was obtained in the same manner as the present data, with the exception that, although data was collected in every mining district, the mines were not selected in a proportional manner. Even though this proportionality is a very important consideration, the independent data is useful. The weighted linear regression result was a statistically significant intercept of 0.020 and slope of 1.05. Given that the present work has an intercept of +0.018, it could reasonably be inferred that the intercept terms are merely a result of error inherent in the data and should be removed from the regression. Removal of the intercept term in the independent data results in a slope of 1.02. Although this is slightly outside the present confidence interval (1.03, 1.08), the difference is somewhat exaggerated by rounding error (1.024 *vs.* 1.026). In any case, being somewhat conservative would be preferable to basing the health of miners on a statistical consideration. This would provide justification for not including the intercept term in the regression.

4. Conclusions

An accurate, direct reading dust monitor for use in coal mines has been demonstrated in underground coal mine environments. In the current, as tested, PDM configuration and calibration, weighted regression analysis indicates that a linear relationship between the PDM and the personal sampler can be established. The conversion factors are applicable only after applying the PDM internal dust loss and filter thermal bias corrections to the raw PDM measurements for an 8 h sampling period. However, it is noted that the filter thermal bias correction is negligible at most respirable dust concentrations of interest, being only 2.4% at a concentration of 1.0 mg m^{-3}. It is recommended that the manufacturer document and implement the measured bias corrections to the mass concentration calculations of the PDM instrument.

The results indicate the suitability of the PDM for in mine use to assess respirable dust concentrations defined in accordance with the currently used personal sampler. This fact, together with the advantages of a direct reading end of shift instrument, provides strong justification for adoption of the PDM as a primary in mine sampling device.

In comparison to the personal sampler, the PDM would require a mass concentration equivalency conversion multiplier of 1.05 [95% C.I. (1.03, 1.08)] when the small intercept term is removed from the analysis. Removal of the intercept term results in a personal sampler equivalent concentration increase of 2.9% at a PDM measurement of 2.0 mg m^{-3}.

5. Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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Appendix A

Mathematical representation

Comparison of the PDM to the personal sampler was made using regression analysis. The data indicate an error term increasing with the independent variable, or multiplicative error, in addition to the required constant additive error term. As a result, the total sum of squares will largely be influenced by the large dependent variable values and lead to an analysis bias. This situation is typical of data collected with dust sampling instrumentation[1] and there are several different remedial data transformations to eliminate, or at least minimize, the non-constant variance problem.

The general equation used by Eagleson and Muller[2] to represent only multiplicative errors can be written as:

Eq. A-1 $$Y = g(X)*(\varepsilon_1).$$

In the present analysis,

Y = a personal sampler response variable,
$g(X)$ = some function of the PDM predictor variable (X),
ε_1 = a normally distributed random multiplicative error term, mean = 1 and variance resulting from in-canister spatial variation in the concentration, coupled with sampling and analytical error of the personal sampler.

The only requirement is that g(x) be a smooth function. Eq. A-1 can also be expressed in terms of the usual error term ε_0 with mean = 0, with inclusion of an additive error term, as

Eq. A-2 $$Y = g(X)*(1+\varepsilon_0) + {}_0\varepsilon_0 = g(X) + g(X)*(\varepsilon_0) + {}_0\varepsilon_0,$$

where

${}_0\varepsilon_0$ = a normally distributed random additive error term with mean = 0 and constant variance $({}_0\sigma)^2$, resulting from weighing imprecision as the true concentration approaches zero.

A decision for g(X) representing the true underlying model for the data must be made. The model should agree with similar published data, previous experience, and be based on sound statistical arguments. Intuitively, one would expect, in the absence of measurement bias, a linear and monotonic relationship (and ideally with zero intercept, unity slope) between different instruments designed and developed to measure the same true but unknown quantity. In this case, that quantity is the airborne respirable coal mine dust concentration.

Weight variable estimation

Weighted regression can directly stabilize the variance if the variance function can be estimated. There are numerous weighting factors that can be used in regression analysis, the more common of which are (1/X) and ($1/X^2$).[3,4] The data of this investigation were used to internally estimate the variance relationship of the personal sampler with the independent PDM variable. Typical $1/X^2$ weighting assumes that dependent variable variance increases proportionally with X^2 over the entire range of independent variable. However, at low concentration values there is the limiting error term ($_0\varepsilon_0$) due to weighing imprecision. The constant variance $(_0\sigma)^2$ of this error term is known quite accurately for the personal sampler samples and is presented in the Results section. It is readily seen that the proper weight variable is the reciprocal of the true total variance σ_T^2, given by

Eq. A-3 $$\sigma_T^2 \approx (_0\sigma)^2 + (RSD)^2 * X^2,$$

where RSD can be considered to be the variation of the dependent variable about the regression.

The process for estimating the proper weight variable is iterative, using the following procedure for the personal sampler data:

Step 1: An initial regression of Eq. A-2 using $1/X^2$ weighting is performed to establish initial weight variables, where $g(X) = Y_0 + a*X$.
Step 2: Using the definition of variance, the values $(Y_i - Y_{ip})^2$, representing the variance between the measured Y_i and predicted Y_{ip} from the initial regression of step 1, are calculated.
Step 3: The plot of $(Y_i - Y_{ip})^2$ vs X_i is fit with the function of Eq. A-3. The second weight estimation is then approximated point-by-point as $1/\sigma_T^2$.
Step 4: Perform a weighted regression with the new weight variable.
Steps 2-4 are then repeated with each new estimate of weight variable and $(Y_i - Y_{ip})^2$ until convergence to a solution.

Appendix B

Table B-1 Valid area sample raw data without PDM bias corrections

		mg m^{-3}				
MSHA District	**Field Office**	**PDM**	**Void**	**CMDPSU**	**Void**	**Notes**
6	Whitesburg, KY	0.041	-	0.047	-	
4	Pineville, WV	0.050	-	0.055	-	
7	Barbourville, KY	0.050	-	0.048	-	
6	Whitesburg, KY	0.073	-	0.063	-	
6	Elkhorn City, KY	0.076	-	0.097	-	
5	Norton, VA	0.080	-	0.078	-	
6	Elkhorn City, KY	0.080	-	0.114	-	
6	Pikeville, KY	0.080	-	0.088	-	
4	Logan, WV	0.095	-	0.088	-	
5	Norton, VA	0.100	-	0.124	-	
5	Norton, VA	0.100	-	0.065	-	
2	Indiana, PA	0.115	-	0.109	-	
6	Martin, KY	0.119	-	0.098	-	
2	Kittanning, PA	0.126	-	0.104	-	
9	Delta, CO	0.129	-	0.129	-	
5	Norton, VA	0.130	-	-	0.004	(a)
2	Ruff Creek, PA	0.134	-	0.132	-	
5	Norton, VA	0.140	-	0.112	-	
2	Kittanning, PA	0.143	-	0.113	-	
9	Craig, CO	0.155	-	0.220	-	
9	Castle Dale, UT	0.158	-	0.205	-	
4	Princeton, W VA	0.180	-	0.160	-	
11	Hueytown, AL	0.186	-	0.208	-	
5	Norton, VA	0.190	-	0.149	-	
4	Logan, WV	0.204	-	0.224	-	
2	Ruff Creek, PA	0.213	-	0.257	-	
8	Benton, IL	0.220	-	0.282	-	
7	Jacksboro, TN	0.222	-	0.195	-	
2	Kittanning, PA	0.240	-	0.180	-	
8	Hillsboro, IL	0.240	-	0.276	-	
9	Castle Dale, UT	0.248	-	0.301	-	
11	Hueytown, AL	0.253	-	0.331	-	
2	Ruff Creek, PA	0.254	-	0.220	-	
10	Beaver Dam, KY	0.254	-	0.308	-	
9	Craig, CO	0.265	-	0.246	-	
4	Logan, WV	0.265	-	0.262	-	
4	Madison, WV	0.272	-	0.244	-	
4	Pineville, WV	0.280	-	0.233	-	
6	Whitesburg, KY	0.284	-	0.295	-	
2	Johnstown, PA	0.292	-	0.246	-	
3	Morgantown, WV	0.323	-	0.387	-	
8	Benton, IL	0.330	-	0.441	-	
11	Hueytown, AL	0.348	-	0.408	-	
3	Morgantown, WV	0.355	-	0.303	-	
5	Norton, VA	0.360	-	0.415	-	
6	Pikeville, KY	0.360	-	0.352	-	
8	Hillsboro, IL	0.360	-	0.346	-	
8	Vincennes, IN	0.360	-	0.390	-	
4	Madison, WV	0.369	-	0.404	-	
4	Logan, WV	0.376	-	0.368	-	
4	Madison, WV	0.379	-	0.369	-	

7	Hindman, KY	0.380	-	0.354	-	
3	St. Clairsville, OH	0.383	-	0.429	-	
7	Harlan, KY	0.440	-	0.392	-	
10	Madisonville, KY	0.449	-	0.546	-	
6	Martin, KY	0.451	-	-	0.395	(b)
7	Hazard, KY	0.452	-	0.459	-	
6	Martin, KY	0.455	-	0.482	-	
4	Madison, WV	0.475	-	0.558	-	
5	Vansant, VA	0.480	-	0.612	-	
7	Hindman, KY	0.485	-	0.543	-	
6	Phelps, KY	0.490	-	0.520	-	
5	Vansant, VA	0.500	-	0.503	-	
8	Benton, IL	0.500	-	0.587	-	
4	Logan, WV	0.513	-	0.434	-	
3	Morgantown, WV	0.540	-	0.599	-	
9	Delta, CO	0.563	-	0.614	-	(c)
4	Madison, WV	0.570	-	0.595	-	
2	Ruff Creek, PA	0.579	-	0.588	-	
7	Barbourville, KY	0.588	-	0.644	-	
10	Beaver Dam, KY	0.596	-	0.565	-	
6	Pikeville, KY	0.610	-	0.601	-	
5	Norton, VA	0.620	-	0.612	-	
2	Kittanning, PA	0.628	-	0.600	-	
8	Hillsboro, IL	0.630	-	0.819	-	
4	Pineville, WV	0.640	-	0.689	-	
2	Johnstown, PA	0.644	-	0.533	-	
6	Phelps, KY	0.660	-	0.650	-	
11	Hueytown, AL	0.686	-	0.875	-	
3	Bridgeport, WV	0.689	-	0.888	-	
9	Delta, CO	0.741	-	0.965	-	
5	Norton, VA	0.760	-	0.717	-	
6	Phelps, KY	0.760	-	0.703	-	
8	Vincennes, IN	0.820	-	0.841	-	
9	Craig, CO	0.842	-	0.805	-	
10	Beaver Dam, KY	0.852	-	1.046	-	
9	Price, UT	0.888	-	1.156	-	
4	Mt. Carbon, WV	0.890	-	1.070	-	
6	Whitesburg, KY	0.914	-	0.822	-	
3	Morgantown, WV	0.921	-	0.872	-	
4	Mt. Hope, WV	0.960	-	1.076	-	
9	Price, UT	0.979	-	1.059	-	
6	Pikeville, KY	1.020	-	1.035	-	
7	Barbourville, KY	1.041	-	1.203	-	
7	Jacksboro, TN	1.058	-	1.100	-	
7	Harlan, KY	1.070	-	1.280	-	
7	Jacksboro, TN	1.103	-	1.255	-	
3	Bridgeport, WV	1.103	-	1.271	-	
10	Madisonville, KY	1.171	-	1.528	-	
10	Madisonville, KY	1.244	-	1.435	-	
4	Logan, WV	1.285	-	1.473	-	
4	Madison, WV	1.297	-	1.607	-	
7	Harlan, KY	1.330	-	1.491	-	
6	Whitesburg, KY	1.362	-	1.301	-	
6	Martin, KY	1.401	-	1.428	-	
3	Morgantown, WV	1.419	-	1.420	-	
4	Madison, WV	1.482	-	1.680	-	
5	Norton, VA	1.520	-	1.291	-	

6	Phelps, KY	1.520	-	1.445	-	
8	Vincennes, IN	1.520	-	1.930	-	
4	Logan, WV	1.522	-	1.705	-	
3	Oakland, MD	1.529	-	1.956	-	
5	Vansant, VA	1.530	-	1.746	-	
6	Elkhorn City, KY	1.570	-	1.681	-	
6	Pikeville, KY	1.590	-	1.455	-	
4	Mt. Hope, WV	1.610	-	1.543	-	
7	Harlan, KY	1.620	-	1.586	-	
5	Norton, VA	1.630	-	1.680	-	
8	Vincennes, IN	1.650	-	-	0.481	(d)
7	Jacksboro, TN	1.669	-	1.700	-	
7	Hazard, KY	1.670	-	2.074	-	(c)
7	Harlan, KY	1.680	-	1.496	-	
7	Barbourville, KY	1.720	-	1.697	-	
4	Mt. Hope, WV	1.740	-	1.993	-	
7	Barbourville, KY	1.742	-	1.616	-	
7	Harlan, KY	1.840	-	2.012	-	
7	Hindman, KY	1.934	-	2.702	-	
7	Hindman, KY	1.972	-	-	1.515	(b)
6	Martin, KY	2.042	-	2.250	-	
4	Mt. Carbon, WV	2.060	-	2.020	-	
6	Pikeville, KY	2.100	-	2.666	-	
4	Pineville, WV	2.320	-	2.715	-	
4	Logan, WV	2.415	-	2.550	-	
4	Pineville, WV	-	0.610	1.370	-	(e)
4	Pineville, WV	-	0.120	0.209	-	(e)

(a) Cyclone hose off when opened can

(b) Cyclone pump out of calibration

(c) light rockdusting

(d) possible pre-weigh error on 2.0 L min^{-1} filter--outlying data point

(e) PDM flow restriction

Table B-2 Excluded area sample raw data without PDM bias corrections

		mg m^{-3}		
MSHA District	**Field Office**	**PDM**	**CMDPSU**	**Notes**
2	Ruff Creek, PA	-	-	(a)
3	Bridgeport, WV	16.465	14.361	(b)
3	Bridgeport, WV	0.885	0.778	(c)
3	Bridgeport, WV	1.842	1.911	(a)
4	Mt. Carbon, WV	-	-	(d)
4	Mt. Hope, WV	3 930	4.714	(e)
5	Norton, VA	1 340	1.406	(a)
6	Martin, KY	0.174	0.228	(f)
6	Whitesburg, KY	0.520	0.411	(g)

(a) PDM failed
(b) PDM filter overload error after 4 hr 42 min
(c) PDM TE fail/remove error after 7 hr 10 min
(d) PDM did not start.
(e) PDM greater than twice the protocol limit.
(f) Sample terminated early, mine shut down by inspector.
(g) heavy rockdusting

References

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