A revised conversion factor relating respirable dust concentrations measured by 10 mm Dorr-Oliver nylon cyclones operated at 1.7 and 2.0 L min^{-1}

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Accurate measurement of workplace respirable dust concentration is an essential step in eliminating lung disease in any occupational setting. In the United States (U.S.) coal mining industry, this measurement process has relied upon a personal sampler that includes a 10 mm Dorr-Oliver (DO) nylon cyclone operated at a flow rate of 2.0 L min^{-1} to collect a respirable dust sample. Dust concentrations measured with this sampler are multiplied by 1.38, which was empirically derived, to convert them to measurements approximating the United Kingdom British Medical Research Council (BMRC) definition of respirable dust upon which the health effects of coal mine dust are based. The International Organization for Standardization (ISO) subsequently refined the respirable dust definition and the U.S. National Institute for Occupational Safety and Health (NIOSH) 1995 Criteria for a Recommended Standard presented a conversion multiplier of 0.857 to apply to the 2.0 L min^{-1} DO (in addition to the 1.38 multiplier) to obtain equivalent ISO concentrations, as approximated by the 1.7 L min^{-1} DO. However, the conversion multiplier 0.857 was derived indirectly from a limited size distribution data set rather than a direct comparison of the DO samplers. The present analysis focuses on providing a more accurate conversion multiplier derived from direct comparisons of the 2.0 L min^{-1} (with 1.38 BMRC equivalency multiplier) and 1.7 L min^{-1} DO cyclones. A weighted linear regression analysis of this database suggests that a more accurate estimate of the conversion multiplier is 0.815.

1. Introduction

Accurate measurement of workplace respirable dust concentration is an essential first step in eliminating lung disease caused by overexposure to dust in any occupational setting. More accurate measurements can be made by minimizing random error and, perhaps more importantly, minimizing measurement bias. In the United States (U.S.), 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 the quartz content of the airborne respirable dust remains at or below 5%. To date in the U.S. coal mining industry, this measurement has relied upon a personal sampler unit that includes a 10 mm diameter Dorr-Oliver (DO) nylon cyclone operated at a flow rate of 2.0 L min^{-1} to collect a respirable mine dust sample.

Particle collection according to size by the DO cyclone operated at 2 L min^{-1} sampling airflow rate was initially considered in the U.S. to approximate particle deposition in the human lung and became an early definition of respirable dust for the U.S. coal mining industry. However, earlier studies relating the

prevalence of lung disease to exposure to respirable coal mine dust were conducted in the United Kingdom (U.K.) using a different type of sampler. The horizontal plate elutriator associated with the U.K. sampler classified mine dust according to a different particle size function, which came to be known as the British Medical Research Council (BMRC) definition[2] of respirable dust and adopted by the U.K. Mining Research Establishment (MRE) as the method used to relate coal mine dust concentrations to worker health effects. Subsequent comparison studies[3] arrived at a multiplier of 1.38 to convert the U.S. personal sampler [2.0 DO] estimates of respirable dust concentrations to equivalent BMRC estimates (hereafter referred to as [2.0 DO]$_{BMRC}$, measured in mg m^{-3}). It is understood that [2.0 DO]$_{BMRC}$ = 1.38 × [2.0 DO]. The U.S. coal industry has retained use of the BMRC definition.

More recently, Soderholm[4] developed a theoretical model to characterize human lung penetration of all dust sizes. This model was adopted by the International Organization for Standardization[5] (ISO) and is that organization's definition of respirable dust. This definition of respirable dust has also been adopted by the European Committee for Standardization[6] (CEN), the American Society for Testing and Materials[7] (ASTM) and the American Conference of Governmental Industrial Hygienists[8] (ACGIH).

No cyclone sampler collects dust strictly according to either the BMRC or ISO definition of respirable dust, and specific cyclones that are used will exhibit varying degrees of bias, depending on the size distributions of challenge aerosols. The [2.0 DO]$_{BMRC}$ sampler currently used in the U.S. has bias relative

to both the ISO and the BMRC definitions of respirable dust.[9] The same DO cyclone operated at a flow rate of 1.7 L min^{-1} and without the 1.38 multiplier (hereafter referred to as [1.7 DO], measured in mg m^{-3}) has been previously reported[9–11] to have low bias relative to the ISO definition. However, it must be observed that this reported low bias is based on idealized laboratory tests utilizing particle counting at very low levels of challenge aerosol directly from the cyclone outlet. Performance of [1.7 DO] under actual dust sampling conditions could exhibit negative bias, for example, due to particulate loss or loading within the cyclone itself[12] and possibly within the cyclone/filter transition zone.

To relate cyclone performance with international definitions of respirable dust, the National Institute for Occupational Safety and Health (NIOSH) document, Criteria for a Recommended Standard,[13] presents a conversion multiplier of 0.857 to apply to [2.0 DO]$_{BMRC}$ measurements to obtain equivalent [1.7 DO] values as an approximation of the ISO definition. At the time the 0.857 conversion multiplier was calculated, the best available data was limited size distribution data from eleven underground coal mine sections obtained using a Marple 298 personal cascade impactor. This is a miniaturized eight-stage cascade impactor intended to provide particle size distributions of sampled aerosol and it is sufficiently small so as to be a wearable personal sampler. The conversion multiplier was derived indirectly by first using the ISO respirable definition to calculate an equivalent respirable mass concentration to associate with each impactor stage. The cumulative result of this calculation was then compared to the cyclone-defined respirable mass concentration measured by [2.0 DO]$_{BMRC}$. To support the analysis, the NIOSH Criteria Document[13] cites another independent analysis[14] of particle size distributions using Marple 298 and 260 impactors obtained from various studies over a 10-year time period. The resultant conversion multiplier obtained from that analysis was 0.85, similar to the Criteria Document result.

The present work represents a direct comparison between [2.0 DO]$_{BMRC}$ and [1.7 DO] and should provide a more accurate conversion multiplier than previously derived. Such a relationship, however, has more significance than a mere conversion value between two different samplers. For example, it would permit conversion of historical U.S. Mine Safety and Health Administration (MSHA) coal mine respirable dust exposure data to near-ISO equivalency, as estimated by [1.7 DO], in the event that MSHA would make the transition to the ISO definition at some future time in the interest of regulatory enforcement. Also, the ISO definition of respirable dust is acknowledged to be a better approximation of alveolar deposition than the BMRC definition. Of epidemiological interest, the conversion multiplier provides consistency and a means to place the U.S. historical data on the same international basis with which exposure and epidemiological data from other countries could be compared. Although exposure limits themselves cannot be directly compared from country to country because of differences in measurement strategies, the current work does provide a common point of comparison adopted by the international community regarding the health effects of exposure to respirable coal mine dust.

Of a more general and widespread concern, the Marple cascade impactor is used in many different industrial hygiene applications outside of mining and it has generally been accepted that data obtained with this impactor is more or less accurate. Therefore, this work presents the opportunity to examine the accuracy of the Marple cascade impactor. Additionally, the work presents an analytical method of sampler comparison which is beyond ordinary regression and is not limited only to dust samplers. This method is particularly useful when data exhibit constant coefficient of variation with an inherent constant variance term at small values of either variable.

2. Methods

2.1 Criteria for mine selection

A stratified random sampling design was used to select mechanized mining units that were representative of all U.S. underground coal mines. The sampling base was developed using information extracted from the MSHA Standardized Information System, reflecting 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 coal type (MSHA bituminous coal district) and mining method. Therefore, because of the mine selection process, many potentially confounding effects such as mine dust size distribution or coal type are accounted for, on average, in the data analyses. Of the total mechanized mining unit population, only a small percentage employed longwall and other mining methods (6% and 3.5%, respectively) with the balance being continuous mining sections. A proportionate allocation strategy was used to ensure that the composition of the sampled mechanized mining units was approximately representative of the composition of the population. 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).

2.2 Testing procedures

Sampling instruments were grouped into a sampling package. Each sampling package contained (1) a Personal Dust Monitor (PDM),[15–17] pre-programmed to begin an 8 h sample at the selected mine shift start time and operated at 2.2 L min^{-1}; (2) two dust samplers using DO cyclones, one operated at 2.0 L min^{-1} and the other at 1.7 L min^{-1}; and (3) a Marple 298 cascade impactor prepared according to standard procedures and operated at 2.0 L min^{-1}. The PDM is a belt-wearable combination cap lamp and real-time sampling instrument using a tapered element oscillating microbalance (TEOM®) mass sensor. Dust classification in the PDM is performed by a Higgins-Dewell cyclone. Each DO cyclone sampler consisted of a Mine Safety Appliances (Cranberry, PA) 37 mm diameter, pre-weighed 5 μm pore PVC filter preceded by a 10 mm DO nylon cyclone. It should be noted that the PVC filter is contained within a plastic cassette so that wall deposits are retained with the filter and not lost. The DO cyclones, impactor, and the PDM sampling inlet were mounted inside a specially constructed Lippmann sampling canister[16–18] with a single inlet to minimize spatial variability. This procedure ensured that all samplers were exposed to essentially the same atmospheric conditions by minimizing

spatial variation. Flow-controlled Mine Safety Appliances Escort Elf ® pumps were calibrated to ± 1% for the DO cyclone and impactor samplers prior to each mine test using a Gilibrator (Sensidyne Inc.,Clearwater, FL) primary standard flow meter. An equivalent pressure restriction for the respective samplers was used during pump calibration.

Sampling locations were chosen where miners typically worked. Data for the PDM has been previously analyzed and reported.[17]

2.2.1 Analytical gravimetric imprecision. Gravimetric analysis was performed on a Mettler-Toledo UMT2 microbalance. Weighing was done at controlled ambient conditions of $22.8 \pm 0.4\,°C$ ($73 \pm 0.7\,°F$) and $53 \pm 2\%$ RH. All samples were pre- and post-weighed with control filters. Two filter cassettes were used as controls for each sampler. To correct for potential differences (*e.g.*, temperature and humidity variations) in weighing room conditions between pre- and post-weighings, average blank control filter masses were used to correct the filter mass results for each test. All sample and control filters were desiccated and allowed to equilibrate to room conditions prior to weighing.

2.2 Analytical model

An iterative weighted regression was the method of choice previously reported[17] according to the model

$$[1.7\ \mathrm{DO}] = (a[2.0\ \mathrm{DO}]_{\mathrm{BMRC}})\varepsilon_1 + {}_0\varepsilon_0 \qquad (1)$$

where a = regression slope and assuming zero (statistically insignificant or unmeasurable) intercept, ε_1 = a normally distributed random multiplicative error term with unity mean and constant variance $(\sigma_1)^2$ resulting from in-canister spatial variation in the concentration, coupled with sampling error of the personal sampler, and ${}_0\varepsilon_0$ = a normally distributed random additive error term with zero mean and constant variance $({}_0\sigma)^2$ resulting from weighing imprecision as the true concentration approaches zero.

Appendix B† presents the general analytical model and method of weight variable estimation. The $[2.0\ \mathrm{DO}]_{\mathrm{BMRC}}$ was chosen as the independent predictor variable to correspond with the designation in the NIOSH Criteria Document.[13]

3. Results

3.1 Gravimetric limit of quantification

Quality control procedures, involving control room filters used only in the weighing room, document that the standard deviation (S_W) due to weighing imprecision and the cyclic fluctuations in weighing room conditions during the course of this study was $S_W = 4.1\ \mu g$. Propagation of error in the personal sampler filter dust mass gains (including an average of 2 control filters, designated W_C) using

$$S_T^2 = S_{W_{pre}}^2 + S_{W_{post}}^2 + \frac{S_{W_{C-pre}}^2}{\sqrt{2}} + \frac{S_{W_{C-post}}^2}{\sqrt{2}} \qquad (2)$$

yields $S_T = 1.848 \times S_W = 7.6\ \mu g$. For an 8 h sample, this value corresponds to ${}_0\sigma = 0.008\ \mathrm{mg\ m^{-3}}$ applicable to measured values of $[1.7\ \mathrm{DO}]$. This value was used to estimate ${}_0\sigma$, necessary for estimating the appropriate weight variable in the regression analysis.[17]

3.2 Analysis

Tables 1 and 2 (see Appendix A) present the regression results and sampler data, respectively. Fig. 1(a) shows a scatter plot of the data with a high degree of linearity and a slight degree of the typical multiplicative error. An initial weighted regression yielded a very small intercept of $-0.006\ \mathrm{mg\ m^{-3}}$. Although statistically significant at the 95% significance level ($t = -3.83$), the intercept is below any level of measurement certainty and has very little effect on the slope when regression is performed without the intercept. Therefore, the iterative weighted regression was performed through the origin. The final result yielded a conversion multiplier of 0.815 (95% C.I. = [0.804, 0.824]), which is statistically different ($t = -7.48$) from the value of 0.857 reported in the NIOSH Criteria Document.[13] Table 1 additionally shows the regression value of d, from which σ_1 and the coefficient of variation (CV) are calculated, as per Appendix B,† from

$$d = a^2\mathrm{CV}^2 = \sigma_1^2 \qquad (3)$$

4. Discussion

Differences in particle size distribution between mines or coal-type bias likely are not contributing factors in the difference between the present direct comparison and the Criteria Document[13] or the analysis by Hewitt.[14] This is suggested by the fact
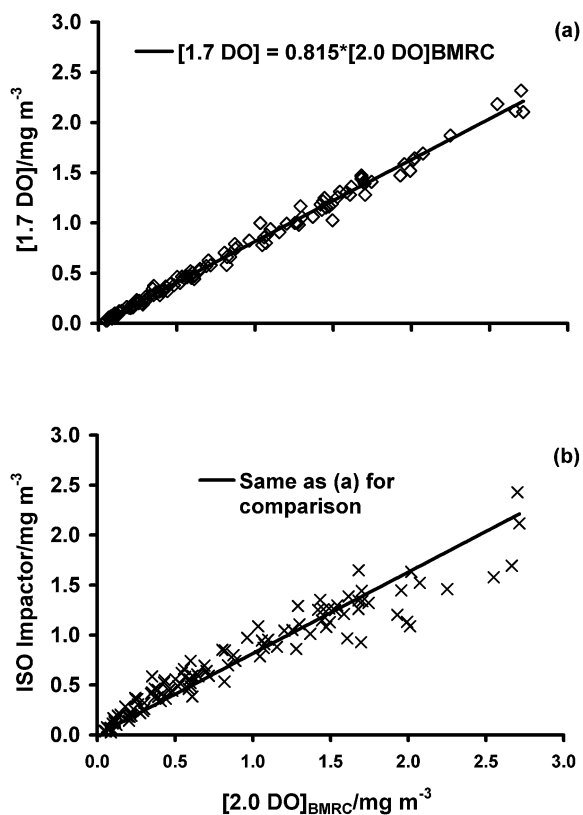
Fig. 1 (a): Fitted line to the paired cyclone data. (b): Substitution of [1.7 DO] data by the ISO calculation from impactor data. The regression line shown is that of part (a) to establish a common comparison.

Table 1 Regression results for cyclone comparison

Statistic	Value	95% CI
$[2.0\ DO]_{BMRC}$ designated predictor variable		
Intercept y_0/mg m^{-3}	−0.006	
$S_{intercept}$	0.002	
$t_{intercept}$	−3.83	
Slope a	0.828	
S_{slope}	0.008	
y_0 removed		
Slope a	0.815	(0.804, 0.826)
S_{slope}	0.006	
t_{slope} (wrt 0.857)	−7.48	
$t_{critical}(0.05)$	1.98	
$_0\sigma$/mg m^{-3}	0.008	
d	0.00187	
$\sigma_1 = \sqrt{d}$	0.043	
$CV = \sigma_1/a$	5.3%	
N	131	

that the Criteria Document and the Hewitt analysis obtained virtually identical results. Considering that the Hewitt analysis was based on some 400 impactor data sets collected over several years by different people and that the data base for the NIOSH Criteria Document had 52 impactor data sets from 11 sections in 7 mines, it would seem extremely coincidental for both studies to have identical size and coal type biases and yielding identical conversion factors. The common denominator between those two studies was the Marple impactor. The 131 sample set of the present direct comparison was statistically representative of the mining industry and tends to average out size distribution and coal type effects uniformly when seeking a conversion multiplier to apply to the entire U.S. coal industry.

Fig. 1(b) shows the respirable dust concentration calculated from the Marple impactor according to the ISO definition. The calculation was made in similar fashion as calculated in the NIOSH Criteria Document[13] by assigning the appropriate ISO respirable fraction to each impactor stage. It should be noted that the particular method of estimating these ISO concentrations is not important in the context of this work because it would apply equally to all samples and any resulting bias incurred would be constant. Qualitatively, there is one notable and important point concerning Fig. 1(b) and that is a concentration-dependent negative bias producing the downward curvature. The observed non-constant negative bias occurs independently of the manner in which an ISO respirable concentration is estimated from the stage masses collected. The linear regression line shown in Fig. 1(b) is the same as in Fig. 1(a) to provide a common reference point. Because of evidence that the impactor data is biased, it is provided only in graphical form for the purpose of demonstrating that there is an increasing underestimation of the respirable dust concentration with increasing concentration as measured by $[2.0\ DO]_{BMRC}$. Size distribution information derived from the impactor data, such as median size and geometric standard deviation, are rendered quite meaningless because of the displayed negative bias increasing with increasing mass concentration. Extracting any useful information from impactor data requires the instrument to be operating properly, properly calibrated, and linear with respect to mass concentration. Because a linear relationship is expected

with such data we presume that some concentration-related or mass loading bias is the source of the non-linearity.

As noted above, it is observed that overall there is downward curvature in Fig. 1(b). This downward curvature is not likely to be the result of impactor overloading. If it is presumed that impactor overloading occurred, the expected effect on the data would produce a relationship that curves *upward*, not downward. One explanation in terms of overloading can be eliminated as follows. One must consider each impactor stage, beginning with the first, when excessive dust attempts to deposit on each substrate. The phenomenon generally has the result of an effect known as "particle bounce" or "blow off" within impactors.[19] The high velocity air stream carrying the dust particles to the substrate will actually begin to dislodge the dust accumulated on the substrate, and a portion of this dislodged dust will be carried on to the following stage substrate(s). Since each subsequent stage corresponds to a smaller aerodynamic size, and therefore a larger respirable size fraction, it is obvious that a biased increase in accumulated mass on a subsequent stage would necessarily result in a positive, rather than negative, bias in measured impactor respirable dust concentration. In the absence of concentration-dependent impactor bias, one would reasonably expect a linear relationship instead of the apparent downward curvature indicated. It should be noted that this curvature is made apparent, in large part, by the preponderance of data obtained in this study. A much more limited set of data likely would not exhibit the curvature because the high degree of multiplicative error (variance increasing with concentration) in the impactor data could easily conceal any curvature.

In addition to the direct vs indirect difference in sampler comparison, there is another problematic difference between the current and previous NIOSH studies. In using the impactor data, the total respirable mass calculation can be made in several ways. One is by assigning a respirable fraction to a single value, the stage cutpoint, for each impactor stage. However this method is at best a crude approximation because there are only nine size fractions in the impactor. Another more detailed method would be a numerical integration across all sizes associated with each impactor stage, weighted by the respirable fraction associated with each size. Although an improvement, this method is still an indirect calculation of ISO concentrations with the assumption that the [1.7 DO] is a close approximation to the ISO definition.

5. Conclusions

The work presented in this paper focuses on providing a more accurate conversion multiplier than previously reported in the literature, using an independent direct comparison of the 2.0 L min^{-1} Dorr-Oliver cyclone (BMRC equivalent) and the 1.7 L min^{-1} Dorr-Oliver cyclone. The sampler data were obtained in 131 underground coal mines and proportionately distributed to be representative of the entire U.S. underground coal mining industry. The revised conversion multiplier of 0.815 (95% C.I. = [0.804, 0.824) is statistically different from the value of 0.857 previously reported by NIOSH. Although the change is not large, conversion using the previous value of 0.857 would overestimate the respirable concentration by about 5%. For example, at $[2.0\ DO]_{BMRC} = 2.0$ mg m^{-3} the ISO equivalent would be

1.71 mg m^{-3} using 0.857, compared to 1.63 mg m^{-3} using the revised multiplier.

Because of the industry-representative database and derivation of the conversion multiplier without use of the potentially biased Marple cascade impactor, the present result is considered to be more reliable. Therefore, historical U.S. coal mine respirable dust exposure data can be more accurately converted to near-ISO equivalency, as estimated by the 1.7 L min^{-1} Dorr-Oliver cyclone.

The Marple cascade impactor is used in many different industrial hygiene applications outside of mining and it has generally been accepted that data obtained with this impactor is more or less reliable. The current work is the first evidence known to the authors suggesting this may not be the case by demonstrating impactor negative bias which increases with increasing mass concentration. The source of the suggested bias is currently being investigated.

The current work presents a statistically valid analytical method of sampler comparison which is beyond ordinary regression and is not limited only to dust samplers. This is particularly true when data exhibit constant coefficient of variation with an inherent constant variance term at small values of either variable. The analytical method also provides the means to estimate the coefficient of variation of the data about the regression function.

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 National Institute for Occupational Safety and Health.

Appendix A

Table 2 Underground cyclone data

MSHA district	Field office	mg m^{-3} [2.0 DO]$_{BMRC}$	[1.7 DO]
6	Whitesburg, KY	0.047	0.029
4	Pineville, WV	0.055	0.028
7	Barbourville, KY	0.048	0.032
6	Whitesburg, KY	0.063	0.052
6	Elkhorn City, KY	0.097	0.073
5	Norton, VA	0.078	0.068
6	Elkhorn City, KY	0.114	0.085
6	Pikeville, KY	0.088	0.048
4	Logan, WV	0.088	0.075
5	Norton, VA	0.124	0.085
5	Norton, VA	0.065	0.059
2	Indiana, PA	0.109	0.060
6	Martin, KY	0.098	0.073
4	Pineville, WV	0.209	0.161
2	Kittanning, PA	0.104	0.100
9	Delta, CO	0.129	0.114
5	Norton, VA	—	0.086
2	Ruff Creek, PA	0.132	0.121
5	Norton, VA	0.112	0.083
2	Kittanning, PA	0.113	0.083
9	Craig, CO	0.220	0.159
9	Castle Dale, UT	0.205	0.154
4	Princeton, WV	0.160	—
11	Hueytown, AL	0.208	0.161
5	Norton, VA	0.149	0.125
4	Logan, WV	0.224	0.168
2	Ruff Creek, PA	0.257	0.201
8	Benton, IL	0.282	0.188
7	Jacksboro, TN	0.195	0.154
2	Kittanning, PA	0.180	0.164
8	Hillsboro, IL	0.276	0.198
9	Castle Dale, UT	0.301	0.235
11	Hueytown, AL	0.331	0.276
2	Ruff Creek, PA	0.220	0.194
10	Beaver Dam, KY	0.308	0.234
9	Craig, CO	0.246	0.201
4	Logan, WV	0.262	0.223
4	Madison, WV	0.244	0.232
4	Pineville, WV	0.233	0.216
6	Whitesburg, KY	0.295	0.216
2	Johnstown, PA	0.246	0.225
3	Morgantown, WV	0.387	0.318
8	Benton, IL	0.441	0.320
11	Hueytown, AL	0.408	0.325
3	Morgantown, WV	0.303	0.264
5	Norton, VA	0.415	0.322
6	Pikeville, KY	0.352	0.282
8	Hillsboro, IL	0.346	0.344
8	Vincennes, IN	0.390	0.314
4	Madison, WV	0.404	0.325
4	Logan, WV	0.368	0.308
4	Madison, WV	0.369	0.303
7	Hindman, KY	0.354	0.373
3	St. Clairsville, OH	0.429	0.366
7	Harlan, KY	0.392	0.279
10	Madisonville, KY	0.546	0.453
6	Martin, KY	—	0.327
7	Hazard, KY	0.459	0.394
6	Martin, KY	0.482	0.378
4	Madison, WV	0.558	0.475
5	Vansant, VA	0.612	0.441
7	Hindman, KY	0.543	—
6	Phelps, KY	0.520	0.403
5	Vansant, VA	0.503	0.463
8	Benton, IL	0.587	0.469
4	Logan, WV	0.434	—
3	Morgantown, WV	0.599	0.458
9	Delta, CO	0.614	0.480
4	Madison, WV	0.595	0.452
2	Ruff Creek, PA	0.588	0.518
7	Barbourville, KY	0.644	0.523
10	Beaver Dam, KY	0.565	0.458
6	Pikeville, KY	0.601	0.500
4	Pineville, WV	1.370	1.061
5	Norton, VA	0.612	0.468
2	Kittanning, PA	0.600	0.504
8	Hillsboro, IL	0.819	0.581
4	Pineville, WV	0.689	0.570
2	Johnstown, PA	0.533	0.466
6	Phelps, KY	0.650	0.542
11	Hueytown, AL	0.875	0.741
3	Bridgeport, WV	0.888	0.760
9	Delta, CO	0.965	0.825
5	Norton, VA	0.717	0.578
6	Phelps, KY	0.703	0.626
8	Vincennes, IN	0.841	0.661
9	Craig, CO	0.805	0.703
10	Beaver Dam, KY	1.046	0.778
9	Price, UT	1.156	0.907
4	Mt. Carbon, WV	1.070	0.800
6	Whitesburg, KY	0.822	0.661

Table 2 (Contd.)

Table 2 (*Contd.*)

| MSHA district | Field office | mg m^{-3} | |
		[2.0 DO]$_{BMRC}$	[1.7 DO]
3	Morgantown, WV	0.872	0.790
4	Mt. Hope, WV	1.076	0.881
9	Price, UT	1.059	0.856
6	Pikeville, KY	1.035	0.999
7	Barbourville, KY	1.203	0.993
7	Jacksboro, TN	1.100	0.939
7	Harlan, KY	1.280	0.982
7	Jacksboro, TN	1.255	0.999
3	Bridgeport, WV	1.271	1.001
10	Madisonville, KY	1.528	1.257
10	Madisonville, KY	1.435	1.217
4	Logan, WV	1.473	1.164
4	Madison, WV	1.607	1.279
7	Harlan, KY	1.491	1.187
6	Whitesburg, KY	1.301	1.058
6	Martin, KY	1.428	1.129
3	Morgantown, WV	1.420	1.184
4	Madison, WV	1.680	1.437
5	Norton, VA	1.291	1.165
6	Phelps, KY	1.445	1.248
8	Vincennes, IN	1.930	1.472
4	Logan, WV	1.705	1.281
3	Oakland, MD	1.956	1.585
5	Vansant, VA	1.746	1.410
6	Elkhorn City, KY	1.681	1.461
6	Pikeville, KY	1.455	1.153
4	Mt. Hope, WV	1.543	1.311
7	Harlan, KY	1.586	1.307
5	Norton, VA	1.680	1.473
8	Vincennes, IN	—	1.507
7	Jacksboro, TN	1.700	1.392
7	Hazard, KY	2.074	1.692
7	Harlan, KY	1.496	1.026
7	Barbourville, KY	1.697	1.409
4	Mt. Hope, WV	1.993	1.519
7	Barbourville, KY	1.616	1.360
7	Harlan, KY	2.012	1.627
7	Hindman, KY	2.702	2.318
7	Hindman, KY	—	1.219
6	Martin, KY	2.250	1.869
4	Mt. Carbon, WV	2.020	1.645
6	Pikeville, KY	2.666	2.115
4	Pineville, WV	2.715	2.105
4	Logan, WV	2.550	2.185

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A Revised Conversion Factor Relating Respirable Dust Concentrations Measured by 10 mm Dorr-Oliver Nylon Cyclones Operated at 1.7 and 2.0 L min^{-1}

Appendix B

B-1 General analytical model

As a result of multiplicative errors arising from various errors associated with the personal sampler[B1], the total sum of squares in regression analysis will primarily 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[B1], and there are several different remedial data transformations available to eliminate, or at least minimize, the non-constant variance problem.

Weighted regression was the method of choice previously reported[B2] to stabilize the variance for data analysis according to the model

Eq.B-1 $$Y = g(X)\varepsilon_1 + {}_0\varepsilon_0,$$

where

Y = a response variable,
$g(X) = aX,$ and
a = regression slope, assuming zero (statistically insignificant or unmeasurable) intercept.

The only requirement in Eq. B-1 is that $g(X)$ be a smooth, arbitrary function of the predictor variable (X). Intuitively, one would expect, in the absence of measurement bias, a linear and monotonic relationship (ideally with zero intercept and unity slope) between different instruments designed and developed to measure the same true but unknown quantity.

Weighted regression can directly stabilize the variance if the variance function can be estimated. Typical $1/X^2$ weighting assumes that the dependent variable variance increases proportionally with X^2 over the entire range of independent variable, resulting in constant coefficient of variation (CV). However, at low concentration values there is the limiting error term (${}_0\varepsilon_0$) due to weighing imprecision.

B-2   Weight variable estimation

The constant variance (${}_0\sigma)^2$ of ${}_0\varepsilon_0$ can usually be determined with sufficient accuracy. It can readily be shown by calculating Var(Y), using the method of expectation values, that the proper weight variable is the reciprocal of the total variance σ_T^2, given by

Eq. B-2
$$\sigma_T^2 = (_0\sigma)^2 + [(g(X)CV]^2,$$

$$= (_0\sigma)^2 + (aCV)^2 X^2,$$

where

From Eq. B-2, *CV* can be considered to be the variation of the dependent variable about the regression line.

The process for estimating the proper weight variable is iterative, using the following procedure for estimating the relationship between the dependent variable variance and the independent variable:

Step 1: An initial regression of Eq. B-1 using $1/X^2$ weighting is performed to establish initial weight variables, where $g(X) = aX + Y_0$.
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. B-2, represented by the model

Eq. B-3
$$(Y_i - Y_{ip})^2 = c^2 + dX^2$$

using $1/X^2$ weighting. The second weight estimation is then approximated point-by-point as $1/\sigma_T^2$.
Step 4: A weighted regression is next performed 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. If intercept Y_0 is shown to be irrelevant due to statistical insignificance, being an unmeasurable quantity, or some other justification, steps 1-4 are repeated with $Y_0 = 0$.

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