The Effects of Low Quartz Mass Loading and Spatial Variability on the Quartz Analysis of Surface Coal Mine Dust Samples

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Monitoring the miner respirable quartz dust exposure for compliance with U.S. federal regulations is mandatory to protect the health of coal miners. However, there is no technique available for the direct measurement of the respirable quartz dust concentration in the mining environment. The only means to estimate the respirable quartz dust concentration is to perform an analysis of the respirable dust sample collected, which contains both coal and quartz dust as well as other mineral constituents. For samples collected at coal mines, the U.S. Mine Safety and Health Administration (MSHA) utilizes the P7 method for respirable quartz analysis.

The objectives of this work are to 1) evaluate the performance of the P7 method on field samples of low quartz mass loadings, 2) evaluate the magnitude of dust mass spatial variability within an enclosed cab environment, and 3) estimate the subsequent propagation of error in calculating the percentage of quartz over a broad range of mass and quartz filter loadings at a surface coal mine. These objectives were achieved by obtaining surface coal mine dust samples over a 9-month time period in enclosed cabs of three drills and three bulldozers. By measuring weighing precision and using reasonable estimates for sampler variability, the dust mass spatial variability component was calculated by difference. The results show that 1) the P7 method can be precise and linear with quartz mass loadings as low as approximately 5 μmg of quartz, 2) the dust mass spatial variability, even within an enclosed cab environment, is the dominant factor of variability in propagation of error in estimating the quartz content of the obtained dust samples on a percentage basis, and 3) weighing precision is not a significant factor in error propagation. In addition to the enclosed cab samples, samples from eight surface coal mine drills were collected at various locations exterior to the drill cab. Significant data scatter at these outside locations strongly suggests that the ambient dust mass spatial variability has a significant effect on the propagation of error in estimating quartz content of the dust samples on a percentage basis.

Keywords Quartz, Surface Mining, Drilling

Crystalline silica (quartz) dust has long been recognized as an occupational health hazard to the respiratory system,$^{(1-6)}$ responsible for the insidious disease known as silicosis. In underground mining, this quartz dust is created from several sources, which generally include, but are not limited to, cutting, drilling, or milling of rock material. In coal mining, this rock material may be found as an inherent mineral matter constituent of the coal, although this is usually not a significant source of quartz. The majority of the quartz is found in the immediate overlaying or underlaying rock strata that are frequently removed during the coal mining process. Also, significant rock inclusions, known as partings, occur within the coal seam itself and must of necessity be removed with the coal. Surface mining operations can also produce significant quantities of airborne respirable quartz due to the amount of overburden that must be removed by means of drilling, bulldozing, and haulage. In some instances, up to one hundred meters of overburden must be removed to access a meter of coal. In comparison with underground mining, the potential for quartz exposure is much greater in surface mining operations. This potential quartz exposure is especially important for drilling operations that involve crushing and pulverizing.

Monitoring the miner respirable dust exposure for compliance with federal regulations$^{(7)}$ is mandatory to protect the health of coal miners. If the quartz content of the dust sample is measured to be 5 percent or less, the respirable dust standard is 2.0 mg/m^3. If the quartz content exceeds 5 percent, the respirable dust standard is reduced according to the formula

$$\frac{10\ \text{mg/m}^3}{\text{percent quartz}} \qquad [30\text{CFR } 71.101]$$

This formula establishes a limit for exposure to respirable coal mine dust so that the concentration of quartz in the respirable coal mine dust does not exceed 0.1 mg/m^3. The formula uses a common method for reporting measured quartz content, i.e., as a percentage of the total respirable mass. However, mathematical operations performed with measured values result in propagation of error. In other words, if a quantity $V = V(x, y)$, then V is in error by an amount dV as a result of the errors dx and dy in the measured quantities x and y. Therefore, any calculated value of the percentage of quartz is subject to propagation of error.

Currently, no technique is available for the direct gravimetric or real-time measurement of the respirable quartz dust concentration in the mining environment. The only means to estimate the respirable quartz dust concentration is to perform an analysis of the respirable dust sample collected, which contains both coal and quartz dust as well as other mineral constituents. The techniques used for routine estimation of the quartz content of a respirable dust sample,(8) recommended by the National Institute for Occupational Safety and Health (NIOSH), are the infrared Method 7603 and X-ray Method 7500.(9) The Mine Safety and Health Administration (MSHA) employs the P7 infrared method to estimate the quartz content of a respirable coal mine dust sample.(8) The MSHA and NIOSH infrared methods are similar, but with some differences noted in the sample preparation. Airborne dust samples from metal and nonmetal mines are analyzed by MSHA using Method 7500. The recommended weight gain range for coal mine quartz dust analysis (P7) is between 0.5 and 2.0 mg, with a minimum quartz mass of 25 μg.(8) The original work (performed by SRI International under contract to NIOSH) on which the method was based produced test samples of mixed dust which had no less than 70 μg of quartz. Mass loadings in that same study achieved light quartz loadings down to 27 μg only when pure quartz material was used. Thus, there has always been an issue about the performance of the P7 method on field samples of low quartz mass loadings.

To estimate the effect of dust mass spatial variability in the calculation of quartz percentage in a variety of occupational settings, it is informative to provide an estimate of the minimum value the dust mass spatial variability can reasonably assume in any environment. If this minimum value is known, then it can be presumed that the effect of dust mass spatial variability will be at least as great and, therefore, the calculation of quartz percentage will be affected accordingly. Sampling in underground mine environments is not the best method to provide an estimate of the effect of minimum dust mass spatial variability on error propagation. Large dust concentration gradients may be present due to a variety of causes, such as ventilation airflow patterns and turbulence induced by water spray action and machine movement. Also, improvements to closely regulate and control the volumetric flow rate of dust sampling pumps now allow for a more accurate estimate of minimum dust mass spatial variability.

The objectives of this work are to 1) evaluate the performance of the P7 method on field samples of low quartz mass loadings, 2) evaluate the magnitude of dust mass spatial variability within an enclosed cab environment, and 3) estimate the subsequent propagation of error in calculating the percentage of quartz over a broad range of mass and quartz filter loadings at a surface coal mine. These objectives were achieved by obtaining surface coal mine dust samples over a long-term time period in enclosed cabs of three drills and three bulldozers.

EXPERIMENTAL METHODS

Two different sampling procedures were examined. Procedure A was the weekly collection and P7 quartz analysis of samples within enclosed cabs on drills and bulldozers at a mine for a 9-month period, using very strictly controlled sampling equipment. A surface coal mine located in West Virginia which consistently operated blasthole drills and bulldozers equipped with environmental cabs was selected for the study. The rotary drills sampled were two Ingersoll-Rand DM50Es and a DrillTech D40K. The bulldozers sampled were a Caterpillar D9H, D10N, and a D11N. Procedure B involved the collection and P7 quartz analysis of samples taken outside of the cabs of various drills at different mines under slightly less strict control of the sampling equipment, as will be defined under Procedure B.

During both procedures, a broad range of weather conditions were encountered because of seasonal variations. These conditions consisted of 1) rain, snow, or no precipitation, 2) dry or muddy ground conditions, and 3) ambient temperatures ranging from 20 to 85°F. The effect of these environmental factors was eliminated by calculating the standard deviations and coefficients of variation (*CV*, defined as the standard deviation divided by the mean, × 100 percent) relative only to the mean of simultaneously acquired samples.

Sampling Procedures—Procedure A

In procedure A, for one shift each week during the period from November 1997 to August 1998, a sampling package, consisting of four gravimetric personal samplers mounted side-by-side on a rack, was located in the cab of one of three drills and bulldozers each. Because of the small physical size of the cabs on both the bulldozers and the DrillTech drill, the sampler packages were located within approximately 2 feet of the operator's breathing zone. On the Ingersoll-Rand DM50E drills, the cabs were somewhat larger and the sampler packages were located within approximately 3 feet of the operator's breathing zone.

Each personal sampler consisted of a 10-mm Dorr Oliver nylon cyclone and a Dupont Flowlite pump. For each cyclone, individual parts were numbered so that each exact cyclone would be used with the same numbered pump. Additionally, each cyclone maintained its same respective position on the rack on which it was located. Each week prior to sampling, each pump was calibrated under load (unused filter cassette + cyclone in a sealed 1-gallon jar) to within ±1 percent of 2.0 L/min. Overall, calibration of all pumps had a CV of 0.5 percent. Sampling times for all samples was greater than 420 minutes.

Sampling Procedures—Procedure B

For procedure B, samples from eight surface coal mine drills were collected at various locations exterior to the drill cab. Sampler packages consisted of either two, three, or four gravimetric personal samplers mounted side-by-side on a tripod. Each personal sampler consisted of a 10-mm Dorr Oliver nylon cyclone and a Dupont Flowlite pump. Prior to sampling, each pump was calibrated to within ±5 percent of 2.0 L/min.[(10)] However, cyclone and pump assignment was random with respect to position and location. The samplers were used in dust source evaluations of drills and therefore were moved as necessary to maintain position within the drill dust emissions. Sample times ranged from 73 to 475 minutes, depending on the severity of dust emissions.

SAMPLE ANALYSIS

After desiccation for 15 minutes and equilibration to weighing room conditions, each dust sample was pre- and post-weighed on a Mettler M3 balance for mass gain. Weighing room conditions were maintained at temperatures between 70 and 74°F. Relative humidity differences between pre- and post-weighings varied between 0 and 30 percent. Because of these fluctuations, a set of eight control filters was weighed weekly over a 15-month period to estimate the weighing precision used in the present analysis.

For procedure A, the number 2 sample of the four taken at each location was analyzed by the P7 infrared method[(8)] for respirable quartz at the NIOSH Pittsburgh Research Laboratory. The number 2 sample was chosen so that the same cyclone sampler was collecting the sample at the same location within the cab and on the sampler rack, thus minimizing a source of unexplained variation. The remaining three dust samples were combined into a composite sample before P7 analysis to determine if a bias due to sample mass existed. The P7 analysis performed at the NIOSH laboratory is periodically verified to be in agreement with the P7 procedure used by MSHA. In addition, each P7 analysis was replicated three times to estimate the precision of the method.

For procedure B, P7 analysis was performed on each sample. Because of the established precision of the P7 method, replicate scans were performed only on certain filters for verification.

STATISTICAL METHODS

A common practice for reporting measured quartz mass is as a percentage of the total respirable mass. However, since mathematical operations performed with measured values result in propagation of error, any calculated value for percentage of quartz is subject to propagation of error. For multiplicative or divisional operations, the propagation of error, in terms of standard error (σ_m), can be expressed as[(11)]

$$\left(\frac{\sigma_{m_z}}{Z}\right)^2 = \left(\frac{\sigma_{m_A}}{A}\right)^2 + \left(\frac{\sigma_{m_B}}{B}\right)^2 \qquad [1]$$

where

$$\sigma_{m_z} = \frac{\sigma_z}{\sqrt{N}}, \quad \sigma_{m_A} = \frac{\sigma_A}{\sqrt{N}}, \quad \sigma_{m_B} = \frac{\sigma_B}{\sqrt{N}},$$

$$Z = Z(A,B), \ A,B \text{ independent, measurable quantities.}$$

After substitution and elimination of N, the number of samples, it can be shown from the definition of CV that, for cab samples,

$$CV^2_{\text{cab}} = CV^2_{\text{P7}} + CV^2_{\text{package}} \qquad [2]$$

where CV_{P7} and CV_{package} are the coefficients of variation of the quartz mass measurement and the respirable dust measurement, respectively, in the calculated percentage of quartz. The same formulation applies for procedure B samples outside of the cab, yielding a measure for CV_{outside}.

Several assumptions made in this derivation are i) σ_m for the quartz mass and dust mass measurements are sufficiently small so that the quartz percentage can be considered a linear function in the mass range ($M \pm \sigma_m$); ii) the measurements of the quartz mass and dust mass are independent; iii) the errors in the measurements of the quartz mass and dust mass are independent. Assumption (i) will be shown in the Results section to be valid. It is important to note that this assumption does not need to apply to either CV_{P7} or CV_{package} since these values, although useful measures of error, are not the fundamental measures of error in statistics. The CV of any measurement is a measure of relative, not absolute, dispersion. As long as the original measure of error (σ or σ_m) satisfies assumption (i), the derived equation for CV_{cab} is valid. Assumption (ii) is valid because there generally is no relationship between the quartz mass and the dust mass from test to test. These mass values are largely determined by the geology, which can vary significantly from test to test and can be considered random variations. Assumption (iii) usually follows from assumption (ii). However, the validity of assumption (iii) is assured in this work because the quartz mass and dust mass are determined by strictly independent methods.

Given a package of four samplers, the total variation in the mean of those samplers is a measured quantity. Knowing reliable estimates for sampler pump, cyclone, weighing, and P7 analytical variation, the remaining variation due to dust mass spatial variability is determined by difference. For the variations of the sampling pump, cyclone sampler, gravimetric analysis, spatial distribution of dust, and the P7 method for quartz mass measurement associated with calculated values of percentage of quartz, CV^2_{package} can be expressed as

$$CV^2_{\text{package}} = CV^2_{\text{weighing}} + CV^2_{\text{cyclone}} + CV^2_{\text{pump}} + CV^2_{\text{spatial}} \qquad [3]$$

Assumptions in the derivation of Eq. 3 are: iv) the errors represented by each term are multiplicative or divisional and not additive; v) σ_m for the individual components are sufficiently small so that the dust mass concentration can be considered a linear function in each range of error, for example, the mass range ($M \pm \sigma_m$); vi) the error terms are strictly independent. Assumption (iv) can be validated from the equation used to calculate CV_{package}:

$$\text{Dust concentration, (mg/m}^3) \propto \frac{\text{Dustmass, (mg)}}{\text{Pump flow rate, } (L/\text{min}) * \text{ sampling time, (min)}} \quad [4]$$

which shows the multiplicative/divisional nature of the terms used in Eq. 3. In addition, it is assumed that any spatial variability associated with the quartz fraction of the airborne dust is negligible in comparison to CV_{spatial} for the total airborne respirable dust. Quartz fraction spatial variability could not be determined from this work due to the required sample destruction to obtain a single and composite quartz analysis for each sampler package. Assumption (v) will be shown to be reasonable in the Results section, due to the smallness of the standard deviations presented. Assumption (vi), although not strictly true, is sufficiently valid for the degree of precision required in this work. For example, CV_{pump} and CV_{cyclone} are not strictly independent in the sense that cyclone size-fractional dust penetration is a function of the pump flow rate. However, the change in dust concentration created by cyclone-to-cyclone variation can reasonably be assumed to be significantly larger than the change in dust concentration caused by fluctuations in pump flow rate. Although not explicitly stated in Eq. 4, the cyclone variability is multiplicative due to the definition of cyclone penetration, i.e., throughput/input. It is further assumed that errors in the time measurement are so small in comparison to the other error terms that they may be legitimately excluded.

Combining Eqs. 2 and 3, the sum of the terms

$$CV_{\text{P7}}^2 + CV_{\text{weighing}}^2 + CV_{\text{cyclone}}^2 + CV_{\text{pump}}^2$$

resulting from the appropriate substitutions, 1) represents the method variability, 2) is independent of the term CV_{spatial}^2, and 3) has been previously documented. The NIOSH Accuracy Criterion[(12)] requires that a sampling and analytical method be sufficiently accurate such that measurements by the method will come within 25 percent of the corresponding true air concentrations at least 95 percent of the time. In terms of the CV, a method meets the NIOSH Accuracy Criterion if the true total CV is equal to or less than 12.8 percent. Since it is not possible to determine the "true" concentration or CV, it is usually required that there be a 95 percent confidence that the above conditions will be met. The P7 method was developed and was found to be a NIOSH-classified B method meeting the above criteria in a single laboratory.[(8)]

One useful method of estimating the dust spatial variability component is to empirically establish, with a large quantity of data, an upper confidence limit for the standard deviation S_{limit} associated with CV_{cab}. Having obtained this value, it will be shown that measured values for the remaining error terms S_X can be subtracted from S_{limit} according to the root-mean-square (RMS) formula to estimate the dust spatial variability component. Determination of S_{limit} can be accomplished by regression analysis of the data. To analyze the data, it is necessary to note that error values can assume any value within an absolute boundary or upper limit defined only by an infinite number of measurements. It is assumed in this analysis that the amount of data is sufficient to allow for a reasonable approximation to this boundary, analogous to an empirically derived upper confidence limit. The appropriate strategy is to choose only the outermost points of the data set as the best choice for the equation governing the error propagation and the upper confidence limit. The method chosen to evaluate the magnitude of the spatial variability of the dust concentration in the enclosed cab environment is to perform a regression of Eq. 2 using the respirable dust mass on each filter analyzed for quartz as the independent variable. The equation chosen for regression (SigmaPlot, SPSS, Inc., Chicago) is Eq. 2, presented in the form

$$CV_{\text{cab}} = \left(CV_{\text{P7}}^2 + \left(\frac{S_{\text{limit}}}{x}\right)^2\right)^{1/2} \quad [5]$$

where

CV_{P7} = P7 analytical replication coefficient of variation,
S_{limit} = estimated regression standard deviation, mg
x = respirable dust mass, mg, on filter analyzed for quartz.

In this analysis, S_{limit} is the regression constant of interest and can be considered to represent an empirically derived upper confidence limit to the net dust mass standard deviation due to all variation sources. These include sampling pump variability, cyclone variability, weighing imprecision, and dust mass spatial variability within the sampling environment (defined as the enclosed cabs of the equipment). It will be seen in the Results section that S_{limit} can indeed be considered a constant. An additional use of Eq. 5 is that, given estimates of other variability components, a sensitivity analysis of weighing error can be easily performed. This will be done in the Results section.

Having determined S_{limit} as a constant from the CV_{cab} regression, the analysis is no longer bound to use CVs for the individual error terms in Eq. 3 for CV_{package} in spite of the multiplicative/divisional nature of these error terms. Given that 1) S_{limit} is approximately constant, 2) the sampling pump flow rate error is small in comparison to the other CV terms and can be ignored, 3) the standard deviations of cyclone penetration, weighing error, and spatial variability are expressed in terms of mass changes, and 4) the standard deviations are largely independent of mass over the range of masses in the data, then Eq. 3 must be true for all mass values and reduces to the RMS of the individual standard deviations. As will be seen in the Results section, the pump error can legitimately be ignored. This is also a required condition to allow using the RMS of the individual standard deviations because the units of pump error are volumetric flow and not mass. Although the standard deviation RMS equations presented in the Results section appear to represent additive error propagation, they in fact remain as describing multiplicative error propagation.

This analysis for CV_{cab} remains conservatively low in that any additional measurements producing a CV_{cab} beyond the estimated upper confidence limit will show the nonlinearity in the CV_{cab} vs dust mass curve occurring at a larger dust mass value. Also, any exceptions to assumptions (i)–(vi) will result in CV terms of higher order which are not accounted for in Eq. 3. For example, inter-variable dependency results in non-orthogonality of the error vectors. This produces higher-order terms determined by the degree of inter-dependency. An alternative view of the effect of inter-variable dependency is that non-independent and completely correlated errors are combined by algebraic addition and not RMS addition, which has the effect of generating a larger total error. Since the variables in this study are likely to have low partial correlation, the effect of higher-order terms is likely to be minimal.

RESULTS

The precision for a single weighing is estimated from the control filters to be no more than 0.020 mg standard deviation. Since sample filters were batch-weighed in short time frames, long-term variations in weigh room humidity and temperature would likely be minimized, producing a standard deviation lower than 0.020 mg. The maximum standard deviation in net filter weight gain, determined by pre- and post-weighing, is estimated by the formula for additive propagation of errors to be

$$S_{\text{weighing}} = \{(0.020)^2 + (0.020)^2)\}^{1/2} = .028 \text{ mg} \qquad [6]$$

Since the sampler pump pooled CV_{pump} was 0.5 percent for initial calibration and assuming that flow control was adequately maintained by the pump during the sampling period, it can reasonably be considered as insignificant and will be ignored.

Based on the replicate analyses of each sample analyzed for quartz, the single-sample P7 analysis had a pooled CV_{P7} of 2.2 percent and the composite samples had a pooled CV_{P7} of 2.0 percent on a quartz mass basis. The more conservative value of 2.2 percent was chosen for the regression of Eq. 5.

Procedure A

Sixty valid (i.e., no known sampling malfunctions) single and 55 valid composite quartz samples were obtained during the study and are summarized in Table I. The data do not suggest any benefit to classifying the data according to the particular piece of equipment being used. Therefore, analysis is based upon the total number of samples obtained. The smaller number of composite samples reflects the fact that, in some cases, the individual filter weight gains were large enough that too much mass would be present on the composite sample of three filters. This weight gain is especially critical for surface mine samples, where most of the dust mass on the filter is non-combustible mineral matter. The average mass variability of the sampler packages, expressed by pooling the values of CV_{package}, was 12.3 percent for the drill samples and 39.3 percent for the dozer samples.

Figures 1 and 2 show the results of a comparison between the single and composite samples in terms of micrograms of quartz as determined by P7. The composite values represent the average of three filters. It is apparent that the P7 method is precise and linear with quartz mass loadings as low as approximately 5 μg of quartz in field samples.

Figure 3 plots the error propagation, represented by CV_{cab}, present in the quartz percentage calculation as a function of the sample mass. In Figure 3, both the positive and negative values of CV_{cab} obtained from sampler #2 are shown. (As a matter of note, negative CV's are not typically mentioned but they are entirely valid mathematically since the equation for CV_{cab} involves a square root. Additionally, from the definition of CV, one can have both (+) and (−) standard deviations, since average values are typically expressed as "mean value" ± "standard deviation.") The heteroskedastic nature of the sampling is clearly evident, showing that CV_{cab} is not constant across the mass range below 1.6 mg of dust. The data scatter below 0.3 mg is classic for multiplicative error propagation, illustrating that errors can assume any value within an absolute boundary which is dependent on all components of variation. Regression of Eq. 5 on the outermost points of the data set (identified in Table I) produced a value of $S_{\text{limit}} = .072$ mg. The validity of representing S_{limit} as a regression constant is established by the fact that for the data in Table I the standard deviations S_{package} of the sampler packages are quite linear and highly uncorrelated with the average package dust mass across the mass range 0.03 mg to 1.6 mg, as shown in Figure 4. Regression of S_{package} against the average mass (one obvious outlier excluded) produced the equation $y = 0.016x + 0.021$, $R^2 = 0.15$, showing only a 1.6 percent change in S_{package} over a five-fold change in dust mass. When $x = 0$ (no filter mass collected), the predicted standard deviation is 0.021 mg. This corresponds to the condition when no sample is taken and the only error present is the weighing error, measured to be 0.020 mg for a single weighing since there is no need for two weighings. Thus, this is further supportive evidence that established the validity of the measured error in a single weighing as well as assuming the quantity of data to be sufficient for interpreting S_{limit} to represent a suitable upper confidence limit.

Using S_{weighing} from Eq. 6 and the formula for multiplicative error propagation valid for all mass values, the remaining variability consisting of cyclone and dust mass spatial variability within the cabs can be estimated. This remaining variability is

TABLE I

Summary of in-cab sample quartz analysis and resultant coefficients of variation (CVs) for percentage of quartz (single sample) calculation

Single	Combined			Data		Regression^{A}	
Average of 3 scans		Net dust weight, mg	$CV_{package}$	$+CV_{cab}$	$-CV_{cab}$	$+CV_{cab}$	$+CV_{cab}$
μg quartz	μg quartz		pct	pct		0.02 mg^{B}	0.001 mg^{C}
3.8	4.0	0.031	13.4	13.5	−13.5		
21.3	21.9	0.038	29.9	30.0	−30.0		
9.2	9.5	0.064	50.5	50.6	−50.6		
5.6	8.7	0.068	9.1	9.5	−9.5		
18.2	19.1	0.069	109.6	109.6	−109.6	104.8	96.5
12.9	10.8	0.084	24.9	25.0	−25.0		
7.7	12.6	0.084	26.0	27.3	−27.3		
27.2	27.1	0.089	12.8	12.9	−12.9		
43.8	41.0	0.100	8.1	8.3	−8.3		
0.0	1.9	0.100	68.7	68.7	−68.7	72.3	66.6
13.1	12.2	0.102	15.8	15.8	−15.8		
36.2	34.5	0.111	22.2	22.4	−22.4		
30.5	33.7	0.114	12.0	12.0	−12.0		
46.1	58.1	0.114	11.3	11.3	−11.3		
56.1	54.2	0.118	22.9	23.0	−23.0		
12.7	12.5	0.119	37.6	37.7	−37.7		
13.0	12.6	0.121	12.1	12.2	−12.2		
46.5	44.4	0.123	21.6	21.6	−21.6		
29.0	29.0	0.125	8.9	8.9	−8.9		
13.9	14.3	0.125	10.1	10.5	−10.5		
20.3	15.8	0.136	29.7	29.8	−29.8		
42.1	46.1	0.137	18.1	18.1	−18.1		
55.2	50.2	0.142	38.5	38.5	−38.5		
73.3	75.7	0.147	6.2	6.5	−6.5		
52.1	50.8	0.149	14.5	14.5	−14.5		
17.0	16.7	0.161	14.3	14.5	−14.5		
23.0	22.7	0.164	12.4	12.5	−12.5		
44.0	44.9	0.180	26.8	27.0	−27.0		
4.0	4.7	0.183	30.8	31.0	−31.0		
13.2	14.8	0.185	52.3	52.4	−52.4	39.1	36.0
39.9	40.5	0.185	6.5	6.6	−6.6		
92.2	95.2	0.192	11.6	11.7	−11.7		
51.6	46.1	0.197	6.6	6.6	−6.6		
28.1	31.1	0.217	7.5	8.7	−8.7		
73.2	76.1	0.225	22.2	22.2	−22.2		
51.6	51.4	0.239	7.5	7.9	−7.9		
120.6	109.9	0.247	4.6	4.7	−4.7		
46.2	51.1	0.278	35.3	35.3	−35.3	26.1	24.0
23.3	25.8	0.282	1.7	1.8	−1.8		
15.8	22.5	0.315	9.4	10.2	−10.2		
50.2	50.1	0.381	6.3	6.5	−6.5		
159.8	167.7	0.390	2.8	3.1	−3.1		
19.4	20.5	0.396	9.5	10.7	−10.7	18.4	16.9
160.6	161.4	0.407	9.4	9.7	−9.7	17.9	16.5
104.3	107.5	0.432	0.8	1.1	−1.1		

(Continued on next page)

TABLE I

Summary of in-cab sample quartz analysis and resultant coefficients of variation (CVs) for percentage of quartz (single sample) calculation *(Continued)*

Single	Combined	Net dust weight,	CV_{package}	Data		Regression[A]	
Average of 3 scans				$+CV_{\text{cab}}$	$-CV_{\text{cab}}$	$+CV_{\text{cab}}$	$+CV_{\text{cab}}$
μg quartz	μg quartz	mg	pct	pct		0.02 mg[B]	0.001 mg[C]
120.2	125.2	0.441	8.0	8.0	−8.0	16.5	15.2
97.6	106.0	0.444	3.6	3.8	−3.8		
88.3	85.6	0.448	2.1	2.4	−2.4		
134.2	143.7	0.458	6.7	6.8	−6.8	15.9	14.7
235.0	227.2	0.499	4.3	4.8	−4.8	14.7	13.5
147.4	150.1	0.636	4.7	4.8	−4.8	11.6	10.7
152.7	153.3	0.725	4.3	4.7	−4.7	10.2	9.4
239.4		0.834	4.6	4.6	−4.6	8.9	8.3
196.1		0.838	3.1	3.2	−3.2	8.9	8.2
343.4	330.7	1.037	5.0	5.4	−5.4	7.3	6.8
278.8	288.3	1.128	4.0	4.7	−4.7	6.8	6.3
492.7		1.219	2.5	2.7	−2.7	6.3	5.9
520.3		1.272	3.0	3.1	−3.1	6.1	5.7
712.5	665.9	1.456	4.4	4.5	−4.5	5.4	5.1
591.9		1.542	3.2	3.5	−3.5	5.2	4.8

[A] Regression values at points which represent the outermost boundary of the error propagation.
[B] Regression values corresponding to a net weight precision of 0.02 mg.
[C] Regression values corresponding to a net weight precision of 0.001 mg.

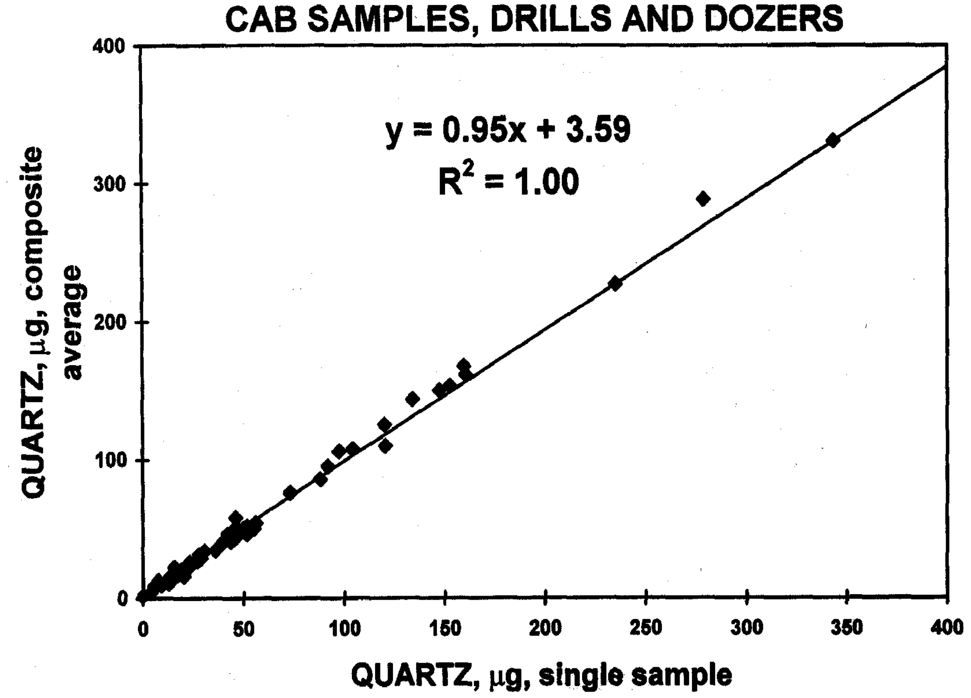

FIGURE 1

P7 quartz analysis comparison of a single sample versus a composite of three remaining samples in the sampling package, 0 to 350 μg quartz.

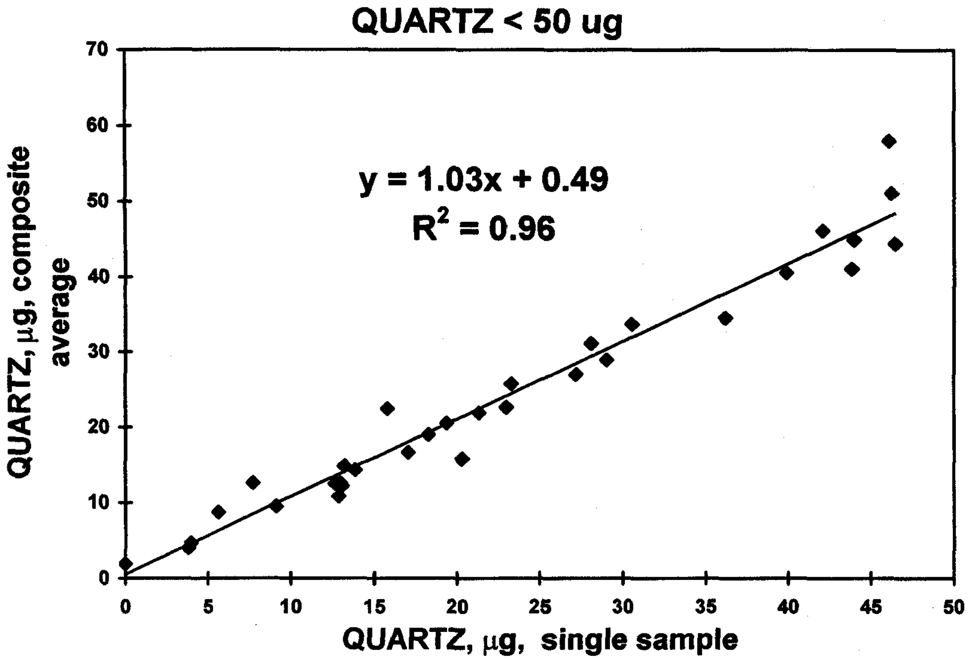

FIGURE 2
P7 quartz analysis comparison of a single sample versus a composite of three remaining samples in the sampling package, 0 to 50 μg quartz.

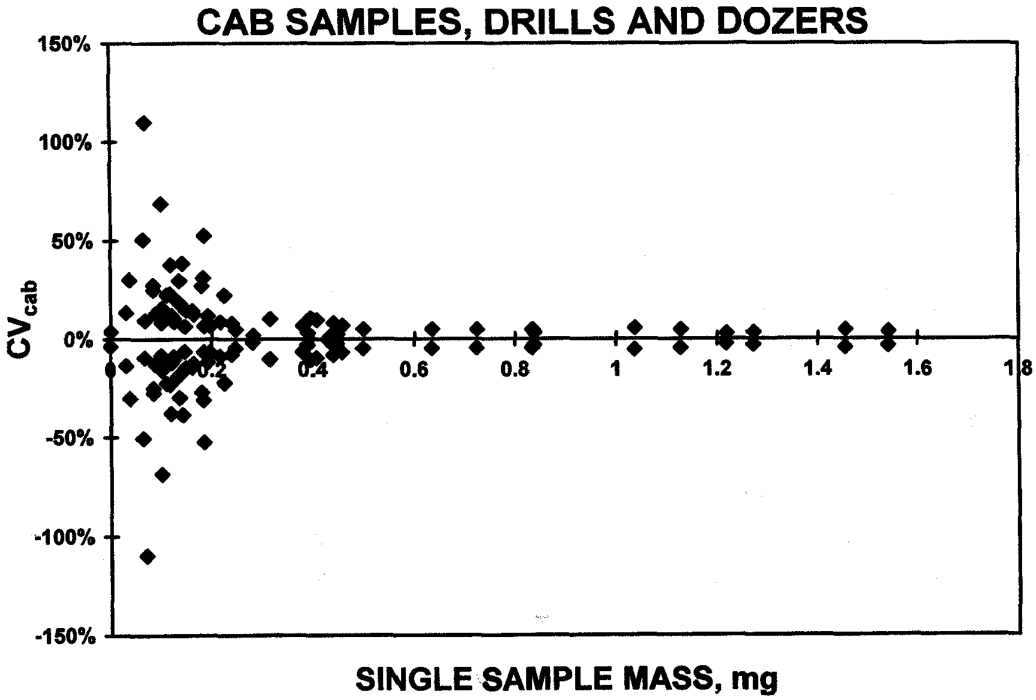

FIGURE 3
Coefficient of variation (*CV*) versus single sample respirable dust mass, all sampler packages for drill and dozer cabs.

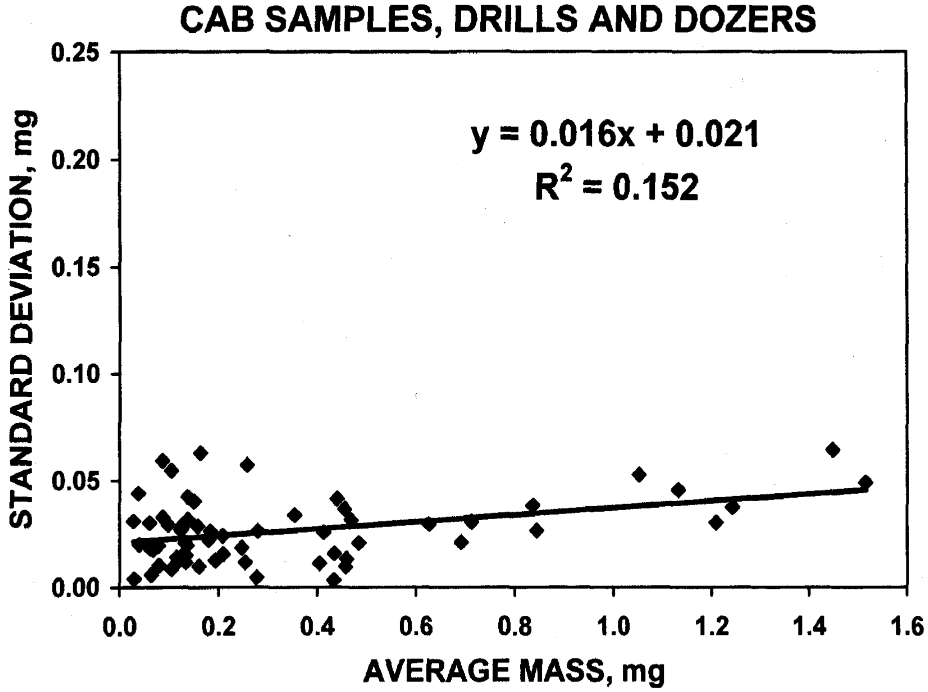

FIGURE 4
Standard deviation versus average sampler package dust mass, all sampler packages for drill and dozer cabs.

determined as

$$S_{(\text{spatial}+\text{cyclone})} = (S^2_{\text{limit}} - S^2_{\text{weighing}})^{1/2}$$
$$S_{(\text{spatial}+\text{cyclone})} = (0.072^2 - 0.028^2)^{1/2} = 0.066 \text{ mg} \quad [7]$$

Using the value of 0.066 mg as an estimate of the remaining variability, it is possible to re-plot the regression data as a function of any desired weighing precision. Figure 5 shows the limit values of the boundary data points with two regressions for comparison. Whether the weighing precision is 0.020 mg or an extreme value of 0.001 mg, Figure 5 and Table II show that the summed dust mass spatial variability and cyclone variation, even within an enclosed cab environment, is the dominant factor.

Figure 5 shows two data points represented by open diamonds. These points are a result of one filter weight (#2 of the group of four in each of the two sampling packages) being significantly different. However, no legitimate reason was documented to allow for the elimination of these points from the analysis. The arrow tips indicate where the data points would be located if the filter weight in question from each package were in conformity with the other filter weights in their respective sampler packages. Note, however, that movement of these points would not affect the analysis appreciably. In fact, a re-run of the regression changed the two curves by an almost imperceptible amount.

This study did not directly determine the cyclone variability. However, an estimated value previously reported can be used to estimate by difference the dust mass spatial variability component. Previous studies(13,14) have reported CV_{cyclone} to be 5 percent and 2 percent, respectively. Bartley et al.(13) present the most recent data on intercyclone variability. However, their stated CV_{cyclone} of 5 percent in the evaluation was based on particle count penetration of the cyclones at a fixed non-dust aerosol concentration. Therefore, the relationship of CV_{cyclone} with concentration is not known. Using their more conservative value of 5 percent for the CV_{cyclone}, a single point evaluation of the standard deviation is 0.025 mg at 0.5 mg dust mass. Substituting this value into Eq. 7 results in the equation

$$S^2_{\text{spatial}} + S^2_{\text{cyclone}} = (0.066)^2$$
$$S^2_{\text{spatial}} + (0.025 \text{ mg})^2 = (0.066)^2 \quad [8]$$
$$S_{\text{spatial}} = (0.062) \text{ mg}$$

indicating that the cyclone variability is a negligible contribution in comparison to the dust mass spatial variability.

Procedure B

Table III lists 107 valid samples obtained at outside locations around eight different drills. CV_{outside} was calculated in the same manner as in procedure A, with the exception that CV_{P7} was set to the fixed value of 2.2 percent, as determined by extensive replication in procedure A. The results are plotted in Figure 6. Since every dust sample of each sampler package was analyzed

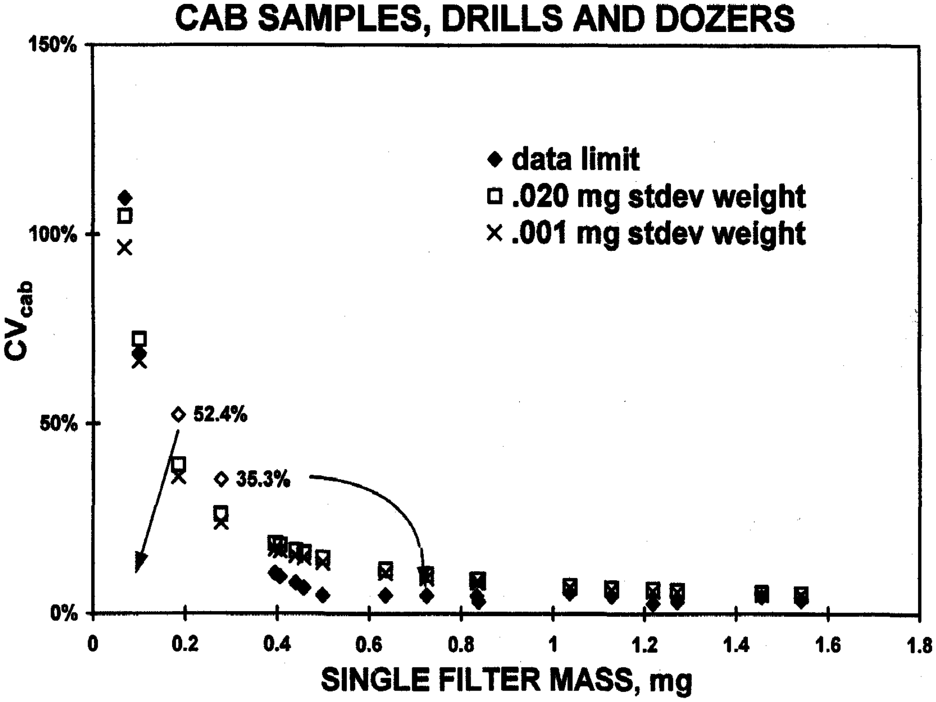

FIGURE 5

Maximum coefficient of variation (CV) versus single sample respirable dust mass, all sampler packages for drill and dozer cabs. Regression values shown, represented by open squares and Xs, indicate sensitivity analysis for weighing precision.

for quartz, each filter mass gain from each sampler package could be considered as a measurement of the airborne dust and was compared to the CV_{outside} for that package. Therefore, the other filter mass gains (from samplers 1, 3, and 4) in each package are entered as data points in Figure 6. Figure 6 shows values of CV_{outside} as large as 50 percent were obtained for sample dust masses up to nearly 3.5 mg. It appears that, with respect to the NIOSH Accuracy Criterion, much less certainty can be placed on quartz percentage determinations based on outside samples when dust mass spatial variability is included in the analysis.

TABLE II

Values of S resulting from single weighing S values of .020 and .001 mg

	S, mg
Single weight	0.020
S_{weighing}	0.0283
S_{total}	0.0723
$S_{\text{spatial+cyclone}}$ (by difference)	0.0665
Single weight	0.0010
S_{weighing}	0.0014
$S_{\text{spatial+cyclone}}$ (by difference)	0.0665
S_{total}	0.0665

DISCUSSION

Procedure A represents what is perhaps a dust sampling condition that is as near to ideal as can be expected in a mining environment. Within the cab environment, air currents are low velocity (compared with the outside ambient conditions). However, dust mass spatial variability can be expected due to air movement created by the cab air system and movement of the operator himself.

In comparison to the results of procedure A, the increased data scatter obtained in procedure B strongly suggests that the ambient environment variability has a significant effect on the sampler package CVs. The effects of wind velocity and orientation on cyclone performance have previously been documented. Cecala et al.[15] concluded that, depending on cyclone orientation, the cyclone could either over- or under-sample by approximately 40 percent at 2000 ft/min (23 mph) ambient air velocities. Clearly, wind speeds on a surface coal mine bench can gust to this value, if not exceed it. Organiscak et al.[16] observed that cyclone pairs oriented with inlets pointed into the wind (parallel) averaged 14.07 mg/m^3, and 9.38 mg/m^3 with inlets perpendicular to the wind. The average CVs for parallel and perpendicular orientation pairs were 20 and 15 percent, respectively. It is reasonable to suggest that outside samples at surface coal mines under these conditions are susceptible to significant airborne dust mass spatial variability. Although there were no known sampling malfunctions for the data above 1.00 mg that

TABLE III

Summary of outside samples and resultant coefficients of variation (*CV*s), assuming 2.2 percent *CV* for P7 analysis of each sample

Net dust weight, mg	Average mg	Standard deviation mg	Standard error mg	$CV_{package}$ pct	$+CV_{outside}$ For pct quartz pct	$-CV_{outside}$ For pct quartz pct
0.182						
0.509	0.346	0.23	0.16	66.9	67.0	−67.0
0.156						
0.286	0.221	0.09	0.06	41.6	41.7	−41.7
0.458						
0.432	0.445	0.02	0.01	4.1	4.7	−4.7
0.354						
0.350	0.352	0.00	0.00	0.8	2.4	−2.4
0.517						
0.414	0.466	0.07	0.05	15.6	15.8	−15.8
0.418						
0.420	0.419	0.00	0.00	0.3	2.3	−2.3
1.572						
1.766	1.669	0.14	0.10	8.2	8.5	−8.5
1.122						
1.302	1.212	0.13	0.09	10.5	10.7	−10.7
0.333						
0.313	0.323	0.01	0.01	4.4	4.9	−4.9
0.474						
0.382	0.428	0.07	0.05	15.2	15.4	−15.4
0.602						
0.459	0.531	0.10	0.07	19.1	19.2	−19.2
0.579						
0.390	0.485	0.13	0.09	27.6	27.7	−27.7
0.321						
0.407	0.364	0.06	0.04	16.7	16.9	−16.9
0.502						
0.418	0.460	0.06	0.04	12.9	13.1	−13.1
0.574						
0.996	0.785	0.30	0.21	38.0	38.1	−38.1
0.295						
0.207	0.251	0.06	0.04	24.8	24.9	−24.9
0.237						
0.225	0.231	0.01	0.01	3.7	4.3	−4.3
0.199						
0.228	0.213	0.02	0.01	9.6	9.9	−9.9
2.533						
2.294	2.414	0.17	0.12	7.0	7.4	−7.4
3.269						
1.622	2.446	1.16	0.82	47.6	47.7	−47.7
0.714						
0.687						
0.780	0.727	0.05	0.03	6.6	7.0	−7.0
3.376						
4.214						

(*Continued on next page*)

TABLE III
Summary of outside samples and resultant coefficients of variation (*CVs*), assuming 2.2 percent *CV* for P7 analysis of each sample *(Continued)*

					$+CV_{outside}$	$-CV_{outside}$
Net dust weight, mg	Average mg	Standard deviation mg	Standard error mg	$CV_{package}$ pct	For pct quartz pct	
3.671	3.754	0.43	0.25	11.3	11.5	−11.5
0.790						
0.954						
0.756						
0.871	0.843	0.09	0.04	10.5	10.7	−10.7
0.987						
1.067						
0.960						
0.912	0.982	0.06	0.03	6.6	7.0	−7.0
0.842						
0.828						
0.817						
0.752	0.810	0.04	0.02	4.9	5.4	−5.4
2.078						
1.964						
2.061						
2.137	2.060	0.07	0.04	3.5	4.1	−4.1
0.638						
0.664						
1.117						
0.550	0.742	0.25	0.13	34.3	34.4	−34.4
1.007						
1.017						
1.073	1.032	0.04	0.02	3.4	4.1	−4.1
1.212						
1.306						
1.343						
1.230	1.273	0.06	0.03	4.9	5.4	−5.4
1.668						
1.563						
1.516						
1.497	1.561	0.08	0.04	4.9	5.4	−5.4
2.483						
2.600						
2.533						
2.536	2.538	0.05	0.02	1.9	2.9	−2.9
1.638						
1.730						
1.722						
1.840	1.733	0.08	0.04	4.8	5.3	−5.3
0.045						
0.042						
0.027	0.038	0.01	0.00	25.4	25.5	−25.5
0.066						
0.069						
0.056						

(*Continued on next page*)

TABLE III
Summary of outside samples and resultant coefficients of variation (*CV*s), assuming 2.2 percent *CV* for P7 analysis of each sample *(Continued)*

Net dust weight, mg	Average mg	Standard deviation mg	Standard error mg	CV_{package} pct	$+CV_{\text{outside}}$ For pct quartz pct	$-CV_{\text{outside}}$ For pct quartz pct
0.073	0.066	0.01	0.00	11.0	11.2	−11.2
0.132						
0.136						
0.135						
0.117	0.130	0.01	0.00	6.8	7.2	−7.2
0.187						
0.152						
0.138	0.159	0.03	0.01	15.9	16.0	−16.0
0.086						
0.086						
0.099						
0.099	0.093	0.01	0.00	8.1	8.4	−8.4
0.354						
0.357						
0.351						
0.365	0.357	0.01	0.00	1.7	2.8	−2.8

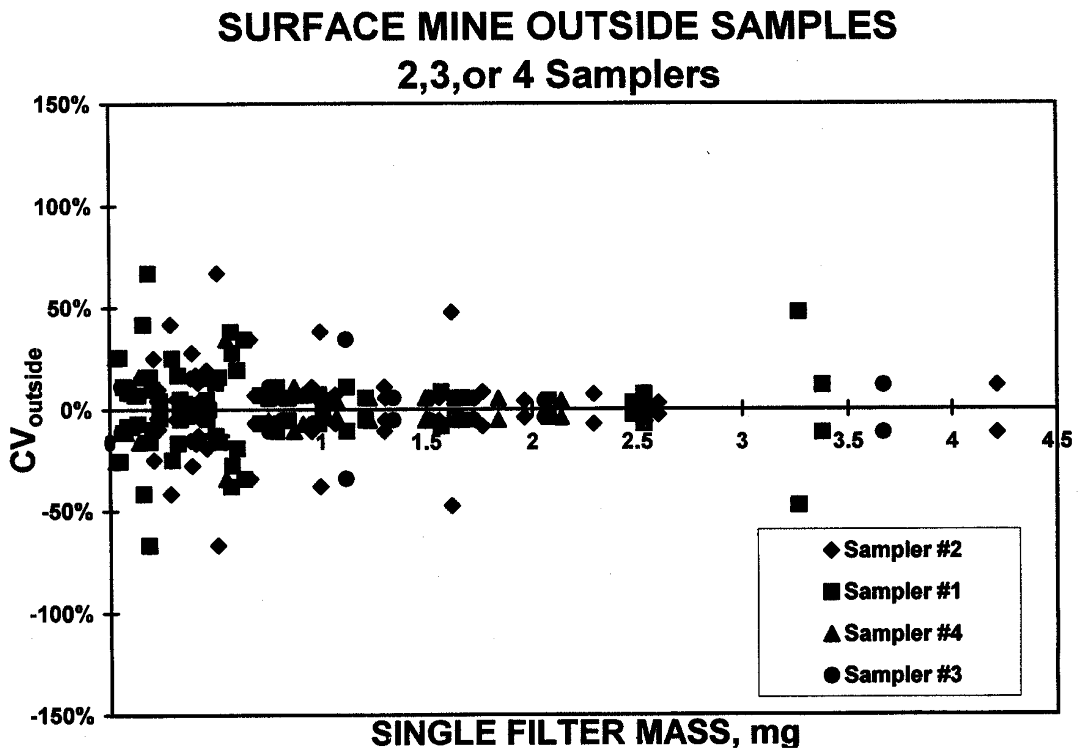

FIGURE 6
Coefficient of variation (*CV*) versus single sample respirable dust mass, all outside drill sampler packages.

appear to be outliers in Figure 5, it is entirely possible that these high values of CV_{outside} could be due to exceptionally windy conditions on those sampling days.

CONCLUSIONS

The results of this study show that, for samples collected within the environment of an enclosed cab, 1) the P7 method may be precise and linear with quartz mass loadings as low as approximately 5 μg of quartz, 2) the environmental dust mass spatial variability, even within an enclosed cab environment, is the dominant factor of variability in propagation of error in estimating the percentage of quartz of the obtained dust samples for weighing precision values up to at least 0.02 mg. In addition, samples collected at various locations exterior to the drill cab showed increased data scatter in the measured *CV*s at these outside locations in comparison to the inside cab samples. This strongly suggests that the ambient dust mass spatial variability, likely due to wind velocity and orientation effects, has a significant effect on the propagation of error in estimating the percentage of quartz of the outside dust samples.

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