RESPIRABLE DUST AND FREE SILICA VARIATION IN MINE ENVIRONMENTS

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Regulations promulgated and enforced by the Mine Safety and Health Administration (MSHA) require that coal mine operators control respirable mine dust to prescribed concentrations.[5] Specifically, coal mine operators must regularly sample (bimonthly) respirable mine dust (RMD) in working mine sections. MSHA on a less frequent basis (once a year) also samples and evaluates RMD and its free silica (FS) content in working coal mines. Sampling is performed by MSHA and mine operators in order to: 1) establish permissible RMD levels in working mine sections when free silica is present; and 2) demonstrate compliance with permissible exposure limits prescribed in regulations. In non-coal mines the sampling frequency is less well defined.

Since passage of the Coal Mine Safety and Health Act of 1969 and the Mine Safety and Health Act of 1977, enormous resources have been focused on controlling RMD in mines with highly satisfactory results. The vast majority of U.S. coal and non-coal mines consistently meet the appropriate RMD Permissible Exposure Limits (see Formula 1) promulgated by MSHA.[12]

In the past five years, more inspector RMD samples have been analyzed for free silica. This has occurred because the analytical technique MSHA uses for the detection of free silica in coal mine dust has been refined and improved resulting in lower detection limits. The use of the "improved" analytical technique has suggested to many that MSHA has placed increased emphasis on enforcement of the coal mine respirable dust (containing free silica) standard. The standard for respirable dusts containing free silica used in coal mines invokes a "sliding scale" to determine the allowable RMD concentration. For % FS concentrations >5, Formula 1 is used to calculate the permissible RMD concentrations in coal mines.

$$\underset{(\text{for } \%\ \text{FS} > 5)}{\text{RMD, mg/M}^3} = \frac{10}{\%\ \text{FS}} \qquad (1)$$

The purpose of this investigation was to gain insight into the extent of FS variation in RMD samples collected from a sample of U.S. coal and non-coal mines. A second goal of this study was to determine the factors (mining operation variables, etc.) associated with this variation. Specifically, the following questions were addressed:

- How large is the sampling and laboratory error in measurements of respirable mine dust concentration (RMD), free silica (FS) and percent free silica (% FS)?
- Is the sampling and laboratory variability different in personal and machine samples, across occupations or mines?
- Is exposure to RMD and FS systematically different across occupations or mines?
- How large is the temporal variability in RMD, FS and % FS?

Thirteen mines, seven coal and six non-coal mines initially offered opportunities for dust sampling in this study. Of the thirteen mines originally volunteering for the investigation, ten (six coal and four non-coal) provided samples for analysis. Each participating mine was required to collect six air samples per day for five consecutive days. The six daily air samples were divided among five occupations with one miner wearing two samplers (paired sample). A total of 374 personal and area samples were collected in the participating mines during 55 sampling days.

Mine dust technicians from the participating companies were used to collect the air samples. Before these individuals were allowed to take part in the investigation they had to participate in a workshop presented by the study authors. Additionally, each participating mine was subjected to a site visit during the sample collection period to insure that the prescribed techniques for sample collection were being used. After collection all dust samples were forwarded to, and analyzed by an independent, accredited laboratory. Results of laboratory analyses of samples were transmitted to JHU for statistical analyses and interpretation of results.

All samples were collected using Mine Safety and Health Administration (MSHA) prescribed procedures with some minor modifications. The samples were analyzed at two commercial laboratories for respirable dust and free silica using the P7 analysis routine. The onsite dust technician or industrial hygienist responsible for sampling completed a standardized questionnaire. Data from questionnaires were analyzed by JHU investigators, as were the analytical results of dust samples.

LITERATURE REVIEW

The Mine Safety and Health Administration requires that coal mine operators conduct extensive sampling for respirable mine dust and airborne free silica. The goal of this sampling is to measure progress toward achieving promulgated dust standards and thus reduce the occurrence of pulmonary disease among the mining population. MSHA's strategy for controlling exposure to pneumoconiosis-producing dusts employs a sampling scheme which utilizes a worst-case scenario.

Although there is extensive scientific and technical literature which addresses the variability of measured mine dust concentrations resulting from the dust sampling process, few studies have sought to define the variability associated with sampling for respirable dust and its free silica content in mine environments. Factors affecting variability of airborne free silica dust, such as occupation, production rates, equipment operating time, and other mine and production variables have not been examined.

The most widely publicized investigation of measured dust concentration variability is a GAO report to Congress.[6] In this report, the GAO indicated that under certain conditions the error associated with respirable mine dust samples could be as great as 50%.

An investigation by the Bureau of Standards studied respirable mine dust sampling and analysis.[8] While focusing specifically on sampling and analysis (gravimetric) for respirable mine dust, each step in the sampling process was examined, e.g. dust weighing, pump flow variation, etc. It was concluded that under tightly controlled conditions with a "well-trained" technician, the average standard deviation associated with the process was ± 0.39 mg/M^3, or 19% (@ the 2 mg/M^3 RMD concentration).

In 1976, NIOSH found that in high risk mine sections (those which had been repeatedly found to be in violation of the 2 mg/M^3 standard) the coefficient of variation for RMD measurements was 91.6%.[9]

In 1980, the National Research Council concluded that uncertainties associated with spatial and temporal variation in RMD estimates from machine mounted samplers precluded this method for estimating personal exposures.[10]

In 1983, a literature review by investigators at the Johns Hopkins School of Hygiene and Public Health concluded that the factors responsible for the variation in RMD had not been quantitated for free silica and estimates of free silica were at least as unreliable as those of RMD.[3] More specifically stated, "Because of the unavailability of data on free silica variation in coal mine respirable dust, the representativeness of a single sample analyzed for free silica can not be assessed." The authors went on to state that the use of a single air sample to determine free silica content of mine environments is meaningless.

Page and Jankowski compared RMD measurements made using a real-time aerosol monitor (RAM-1) and a standard gravimetric sampler at a longwall mining operation.[11] The authors reported ratios of paired RAM-Gravimetric sampler results, expressed as concentrations of RMD ratios of 0.41 to 1.63. The authors attributed this variation to differences in the aerosol cloud being sampled, air flow velocity at the filter face and cyclone orientation.

Burkhart, et al, in a presentation at the American Industrial Hygiene Conference in Dallas, Texas reported data from a limited number of air samples collected from bituminous coal mines in West Virginia.[2] The authors reported %FS concentrations ranging from 2 to 30% in five samples collected on five consecutive days. The samples reported were personal air samples collected on the operator of the continuous mining machine. The source of this variability was not discussed.

Breslin, et al, in a Bureau of Mines Circular reported that for both personal and fixed-point (area) samplers the coefficient of variation for RMD was typically less than 20%.[1]

Kissell, et al, reviewed several factors thought to contribute to RMD and FS variability.[7] The authors, while not specifically evaluating potential contributions to variation from mine sources, concluded that sampler position, geological variation in composition of coal, production factors such as deep or continuous cutting and failure to control known sources such as shuttle car loading, play an important role in RMD and FS sample results.

PAIRED SAMPLE ANALYSIS AND RESULTS

Sampling and laboratory variability for respirable mine dust, free silica and percent free silica were studied using 23 and 20 pairs of dust samples from coal and non-coal mines, respectively. Paired samples were defined for this study as two samples collected on the same occupation for the same time period and located not more than 14 inches apart. For this analysis, the ratios of the RMD and FS parameters were analyzed to determine variability. % FS was analyzed using the differences between the paired values. Figures 1-3 display the cumulative frequency distributions of RMD, FS and % FS, respectively. All three dust parameters exhibit large variability.

Results of this analysis are presented in Table I and are briefly summarized as follows:

Coal Mines

- The respirable mine dust *ratios* (larger to smaller values) exceeded 1.5 in half of the paired samples and 2.5 in 10% of the pairs.
- For free silica, 50% of the pair *ratios* exceeded 1.52; 10% exceeded 5.7.
- For % free silica, the *differences* (larger minus smaller) exceeded 1.3% in half of the pairs and 5.6% in one out of ten.

Non-Coal Mines

- The variability of respirable mine dust was somewhat less in non-coal mines with 50% of the samples having *ratios* greater than 1.13. 10% of samples demonstrated ratios of 6.19. (This was due to a few extreme outlier sample pairs.)

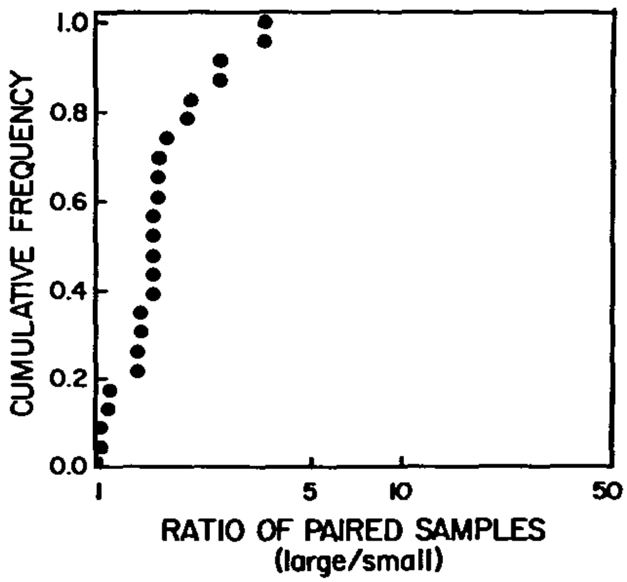


Figure 1. Cumulative distribution of RMD sample pair ratios.

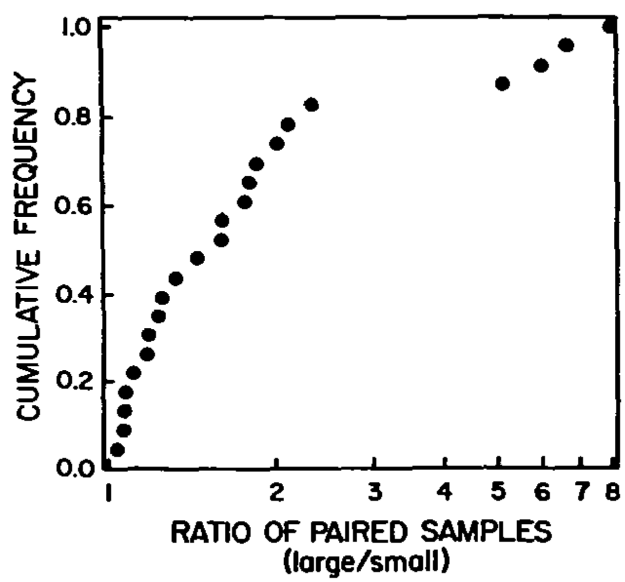


Figure 2. Cumulative distribution of FS sample pair ratios.

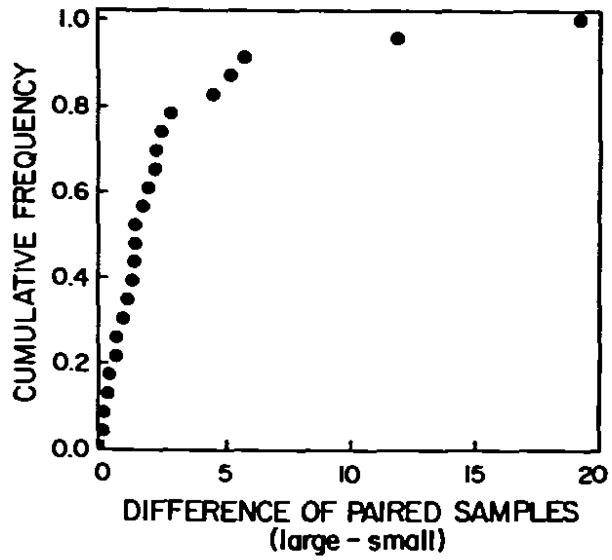


Figure 3. Cumulative distribution of % FS sample pair differences.

- For free silica, 50% of the respirable mine dust sample pair *ratios* exceeded 1.25 and 10% exceeded 2.0.
- The variability of % FS was slightly greater in non-coal mines. The *differences* in 50% of the samples were at least 1.7% free silica; 10% had differences equal to or greater than 7.7% free silica.

EFFECT OF INCREASED NUMBER OF SAMPLES ON VARIABILITY OF DUST PARAMETERS

The use of paired samples to measure variability in RMD, FS and % FS permits the prediction of variability reductions achievable by averaging increased numbers of samples. Figures 4 and 5 demonstrate the improvement in sample variability for the mean value of RMD and % FS. These figures were calculated from all paired samples and reflect the average variability improvement.

The achievement of a standard deviation of 0.2 (mg/m^3) for respirable mine dust in coal and non-coal mines would require eight sample pairs. (Figure 4) In both coal and non-coal mines, a standard deviation of 1.5% free silica can be achieved with six sample pairs. (Figure 5)

Table I
Selected Cumulative Percentages of Coal and Hardrock Mine Dust Parameters

	Coal Mine			Hardrock Mine		
	RMD	FS	%FS	RMD	FS	%FS
	(ratio)		(diff.)	(ratio)		(diff.)
50 percentile	1.50	1.52	1.31	1.13	1.25	1.67
80 percentile	1.96	2.20	3.47	1.25	1.60	5.05
90 percentile	2.50	5.72	5.58	1.50	2.00	7.69
95 percentile	3.33	6.56	10.98	6.19	2.67	9.21
100 percentile	3.50	8.00	19.23	13.00	3.00	18.06

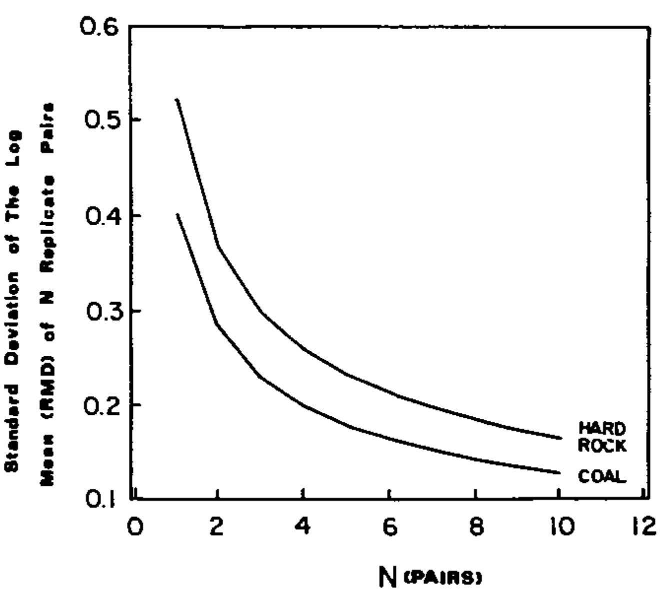


Figure 4. The effect of increased sample pairs on the variability of RMD estimates.

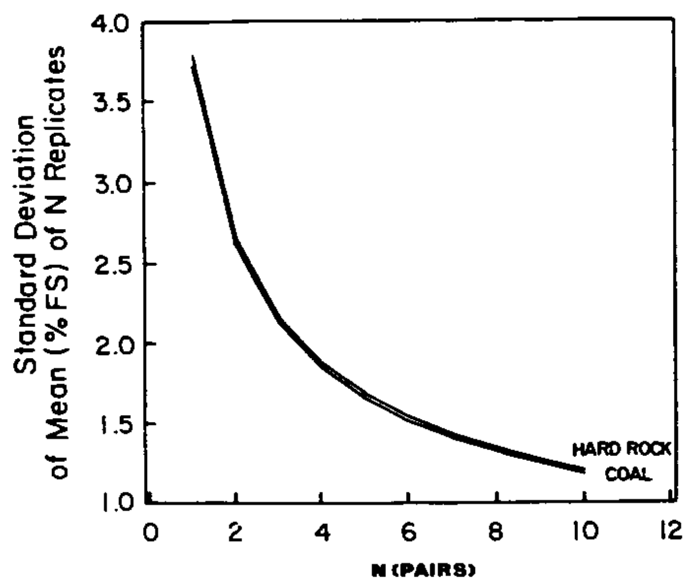


Figure 5. The effect of increased sample pairs on the variability of % FS estimates.

CONTRIBUTION OF STUDY PARAMETERS TO VARIATION

Linear regression analysis was used to determine the contribution to sample variability associated with study variables, i.e. production rate, sampler location, etc. The results demonstrate that for:

Coal Mines

- Sampler location was an important contribution to the demonstrated variability. Machine-mounted samples showed an improvement in variability for all measured parameters. The improvement in variability for machine-mounted samples when compared with personal samples was 40%, 20% and 5% for RMD, FS and % FS, respectively. The improvement in % free silica variability associated with machine mounted samples was not statistically significant.
- Sample variability for respirable mine dust, free silica, and % free silica did not appear to be related to occupational category.
- Respirable mine dust exposure variability across mines was greater than within mine variability for occupation categories. Respirable mine dust, free silica and % free

silica are more dependent on production and/or dust control within the mine than on occupational category. Exposure to free silica demonstrated a consistent pattern, regardless of the respirable mine dust concentration in the mine. Roof bolters were exposed to respirable mine dust levels containing 2–3% more free silica than continuous miner or standard shuttle car operators, and approximately 5% more free silica than center or offside shuttle car operators.

Non-Coal Mines

Regression analysis of non-coal mine results could not be performed because of differences in mining methods employed by participants. These differences did not permit comparison of data between mines.

COMPARISONS OF EXPOSURES BY OCCUPATION

The analytical results of all dust samples were used to address the question of whether dust (RMD, FS and % FS) exposure differs across occupations within a mine, and whether there are differences in dust exposure within occupations across mines.

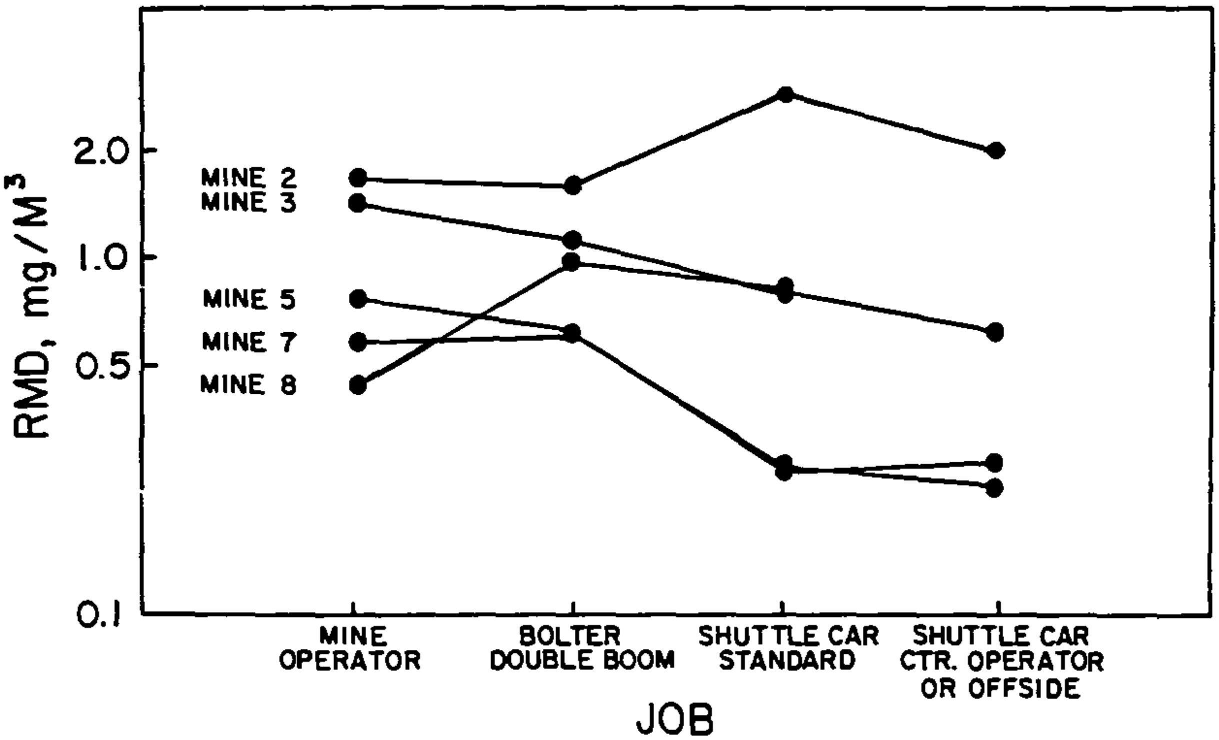
Because only coal mines have uniform job descriptions we have focused our analysis on coal mines. The geometric mean exposure and geometric standard deviation by occupation for coal mines are presented in Table II. Figures 6-8 display the mean exposures for the three variables RMD, FS, and % FS by job classification: mine operator, bolter (double boom), shuttle car operator-standard and shuttle car operator-center

Table II

Results of Air Sampling Analyses by Occupation and Mine for Coal Mines

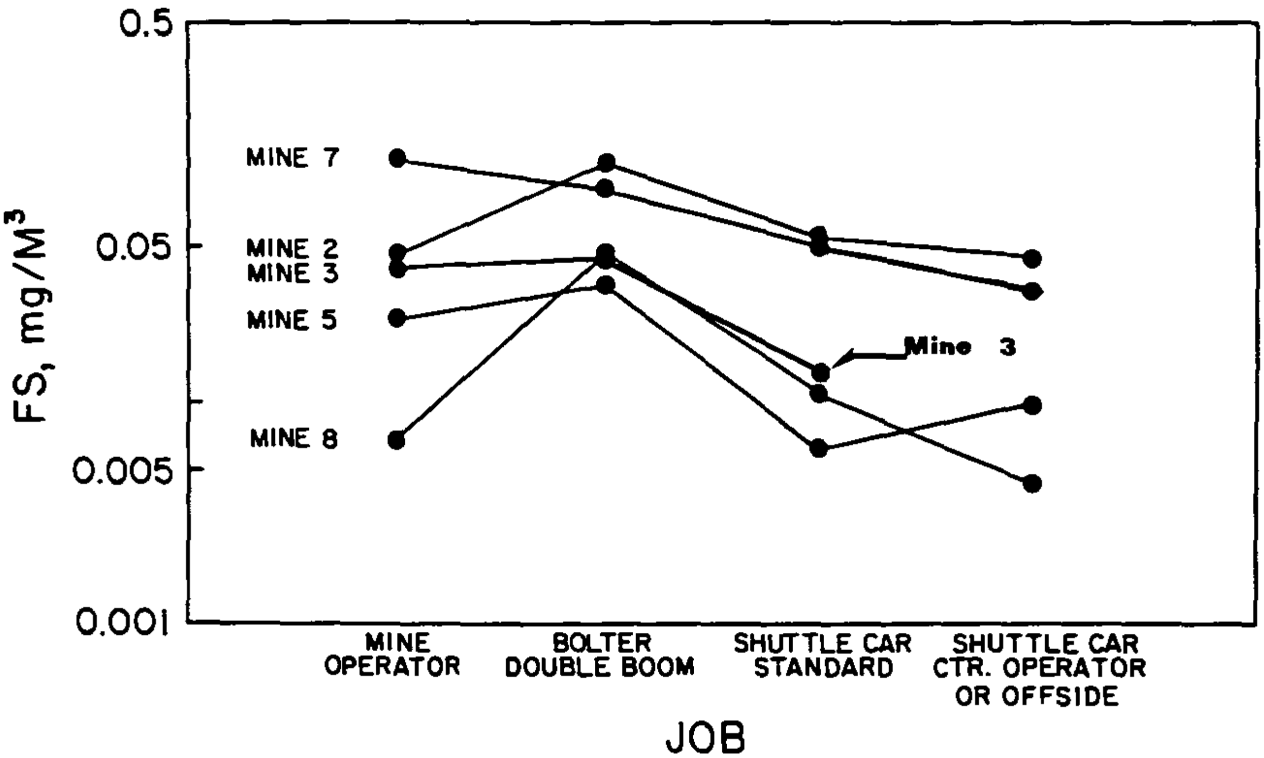
Mine ID	N	Occupation Code[1]	RMD (GM[2], mg/M^3)	G.S.D.[3]	FS (GM[2], mg/M^3)	G.S.D.[3]	%FS (Mean)	S[4]
2	8	1	1.67	1.58	0.045	1.41	2.95	1.45
	15	3	1.61	1.31	0.117	3.13	7.66	2.08
	6	4	2.52	1.86	0.054	2.97	1.93	0.89
	8	6	1.97	3.98	0.044	1.45	2.92	0.88
3	7	1	1.42	2.03	0.039	5.90	3.73	1.88
	12	3	1.12	1.74	0.048	1.69	6.41	3.15
	11	4	0.80	1.76	0.017	2.45	2.78	2.34
5	8	1	0.767	1.60	0.023	2.03	4.05	2.84
	12	3	0.620	1.09	0.033	2.03	5.56	1.34
	3	4	0.252	1.92	0.006	1.32	2.83	1.59
	9	6	0.268	2.36	0.010	1.77	4.42	3.82
7	7	1	0.580	2.46	0.121	3.11	27.7	25.7
	15	3	0.612	2.13	0.090	3.39	23.1	18.7
	5	4	0.261	1.44	0.050	1.48	21.5	12.1
	5	6	0.267	2.39	0.030	4.56	14.9	8.81
8	5	1	0.474	1.38	0.010	1.83	2.24	0.917
	12	3	0.975	1.98	0.047	1.85	5.04	1.59
	6	4	0.824	2.30	0.011	3.71	2.00	2.06
10	10	31	1.07	1.70	0.014	2.30	1.96	2.19
	10	32	1.21	1.49	0.36	2.55	4.34	3.68
	4	34	1.09	4.22	0.016	1.52	7.92	12.8

1. 1 - Continuous Mine Operator, 3 - Roof Bolter, 4 - Shuttle Car Operator (Standard), and Shuttle Car Operator (center and off-side).
2. GM - Geometric Mean
3. GSD - Geometric Standard Deviation.
4. S - Standard



RMD Associated with Selected Jobs in Coal Mines, Expressed as Geometric Means (mg/M^3).

Figure 6. Comparison of measured geometric mean exposures by occupation for RMD.



Free Silica Associated with Selected Jobs in Coal Mines, Expressed as Geometric Means (mg/M^3).

Figure 7. Comparison of measured geometric mean exposures by occupation for FS.

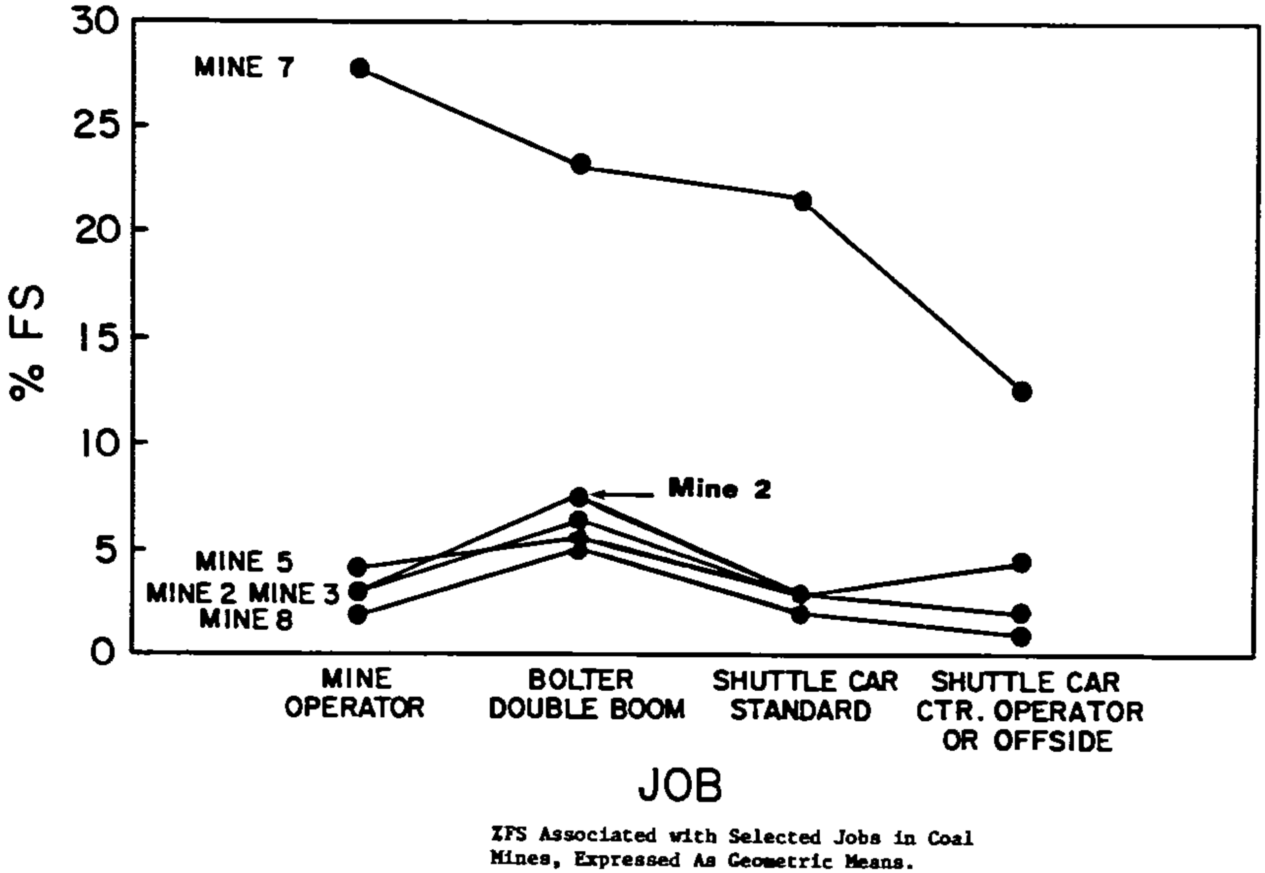


Figure 8. Comparison of measured geometric mean exposures by occupation for % FS.

or off side for coal mines (Mines 2, 3, 5, 7 and 8). Figures 6-8 demonstrate that dust exposure variability across mines is greater than the variability associated with occupations within a mine. RMD, FS and % FS levels are more dependent on the production and/or control of dust within the mine than on occupation.

% FS is more consistent than RMD or FS across all mines except mine 7 where the occupation-specific % FS averages range from 15 to 20% FS over the four occupations. This is three to four times as high as in the other mines. The occupational exposure to free silica does have a consistent pattern regardless of RMD concentrations in a mine. Bolters are exposed on average to RMD containing 2 to 3% more free silica than continuous miner and standard shuttle car operators, and about 5% more than center or offside shuttle car operators who are exposed to the lowest % FS.

TEMPORAL COMPONENT OF VARIATION

The results of the previous sections have been used in combination with the published precision of our laboratory procedures to characterize the contributions to variability in dust parameters of: laboratory analysis; sampling; time; occupation and mines. The analytical lab component is the variance among repeated lab analyses for the same sample. The sum of the laboratory and sampling variances for this investigation was estimated from the paired samples study. The sum of all components as well as the contributions of occupation and mine have been estimated by ANOVA. By combining the results for the ANOVA and the paired sample analysis the variability over time for a given occupation and mine can be estimated.

Table III summarizes the contributions to variability from each source for RMD, FS and % FS for coal mines in absolute units and as a percent of total.

For RMD the total variance across the 157 samples was 0.76. The analysis contributes 1%; sampling contributes 20%; variability over time for the same occupation and mine contributes 33%; while variability across mines/occupations added the largest fraction, 46%. The relative contributions for free silica are similar to those for RMD. For % FS, analysis again contributed little to variability although the specific amount could not be determined from the literature. The sampling and analysis together contributed 35% to the total variation; temporal variability was approximately 30% of the total; while variation from mines/occupations was 36%.

GENERAL CONCLUSIONS

- Occupation and mine, sampler position, laboratory analysis and repeated sampling time contributions to sample variance were estimated based on the paired sample results and published values for variance associated with

Table III

Decomposition of Variance for RMD, FS and % FS by Components: (1) Occupation and Mine; (2) Time; (3) Sampling; and (4) Laboratory for Coal Mine Data

	RMD		FS		%FS	
Source	Variance	% of Total	Variance	% of Total	Variance	% of Total
Occupation and Mine	.35	46	.76	49	2.8	36
Time	.25	33	.42	27	2.3	29
Sampling	.15	20	.38	24	2.7	35
Laboratory	.01	1	.01	0		
Total	.76	100	1.57	100	7.8	100

laboratory analysis and air sampling techniques. The largest contributions to variance arose from sampling across mines and occupations, which accounted for 46% of the variability associated with respirable mine dust samples.

- The second important contributor to variance was the temporal variability of dust levels in mines, accounting for approximately 33% of total variability.

In summary, this investigation demonstrates that the largest contribution to variability results from sampling across mines.

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Proceedings of the VIIth International Pneumoconioses Conference — *Part* **II**
Transactions de la VIIe Conférence Internationale sur les Pneumoconioses — *Tome* **II**
Transaciones de la VIIa Conferencia Internacional sobre las Neumoconiosis — *Parte* **II**

NIOSH - ILO

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Pittsburgh, Pennsylvania, USA—August 23-26, 1988
Pittsburgh, Pennsylvanie, Etats-Unis—23-26 août 1988
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November 1990

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DHHS (NIOSH) Publication No. 90-108 Part II