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Development of a Model to Aid in Reconstruction of Historical Silica Dust Exposures in the Taconite Industry

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The ability to reconstruct employee exposure histories would be a valuable research tool for the evaluation of occupation as a factor in disease. In many cases, however, historical environmental data are available but have not been used to compute past exposures because of differences in sampling methods. This paper describes a quantitative model to convert historical environmental data (from taconite mine and mill operations) into a form consistent with current sampling methods and results and, therefore, will enable past exposure histories to be used. (Past exposure histories are to be determined in an epidemiological study.) In this study, parallel sampling results from the environmental data base were used to obtain a coefficient for the conversion of impinger-particle counts (old sampling method) to filter-respirable mass sampling results (new sampling method). Parameters in the model were estimated using multiple regression techniques. Results show that a consistent ratio exists between impinger-particle counts and filter-respirable mass concentrations for samples collected at the same locations.

Introduction

This research report presents a model for converting historical environmental measurement data in the taconite industry into a form consistent with current sampling methods and results for silica-containing dusts. The purpose of the model is to provide epidemiologists working on a system of classification of exposures — a step-by-step procedure to interpret historical industrial hygiene data — and to allow the preparation of a matrix of respirable silica dust concentrations over time and by job classification for the taconite mining and processing industry of northern Minnesota.

Epidemiologists, attempting to establish the association between chronic human disease (particularly latent disease) and exposures to occupational health hazards, have had access to either qualitative estimates of worker exposure or no data at all. Most attempts have been limited to defining dose as high, medium, low or exposed/not exposed. What is needed is a means to determine quantitatively workers' past exposures to potential occupational health hazards; epidemiologists then can use this exposure information to evaluate a potential hazard as a risk factor in disease. The need to establish a quantitative relationship between historical impinger sample results and the current respirable mass sampling method is evident from the several studies[1-4] that have attempted to determine such a ratio.

Rice[1] used a ratio of 0.09 mg/m^3 respirable dust to 1 mppcf (million particles per cubic foot) for reconstructing silica dust exposures in the North Carolina dusty trades; Reno and Sutton[2] used 0.09 mg/m^3 respirable dust to 1 mppcf; and Ayer *et al.*[4] used 0.13 mg/m^3 in a study of the granite shed industry.

The model equation developed in this study is used to predict mean respirable dust concentrations for job classifications or sample locations from average area sample impinger concentrations. The respirable dust measurements reported are for total respirable dust. Free silica concentrations usually were determined from bulk samples or high-volume samples. High-volume air samples showed free silica content up to 40% in the total fraction and up to 28% in the fine fraction in Plant A. The fine fraction was the portion of dust that passed through the cyclone. The weight and percent silica then were determined separately for each fraction. A bulk sample taken during a 1983 survey at Plant B showed 22% free silica in the concentrator building.[5]

Since 1925, the impinger has been used by the United States Public Health Service[6,7] for sampling mineral dusts in dusty mines and industries. In 1942, the impinger method[8] was chosen as the standard for environmental studies in dusty industries by the American Conference of Governmental Industrial Hygienists (ACGIH). At the taconite plants on the Minnesota iron range, impinger samples (nearly all midget impinger) were collected from 1956 to 1976.

Records of 10 400 impinger samples were obtained from the companies. In the early to mid 1970s, the filter-respirable mass method replaced the impinger method. In the taconite industry, the major shift to respirable mass sampling occurred in 1974 to 1975. With the impinger sampler, dust particles are collected in solution in a glass impinger flask at 0.1 cubic feet per minute (cfm) for between 10 and 30 min, and the particles are counted with an optical microscope. Impinger results are reported in million particles per cubic foot (mppcf). Filter samplers are used presently for collecting silica dust samples and consist of a filter preceded by the 10-mm cyclone; the battery-powered pump operates at an airflow of 1.7 Lpm. Filter samples are analyzed gravimetrically and are reported as milligrams per cubic meter (mg/m^3) total respirable dust.

Data Description and Results

Analysis of Side-by-Side Impinger Dust Count and Filter-Respirable Mass Samples

Side-by-side impinger dust count area samples and filter-respirable mass area samples were collected at two taconite plants. Impinger samples were collected at an airflow of 2.8 Lpm or 0.1 cfm and reported in million particles per cubic foot (mppcf). Impinger samples were all area samples and did not include any personal samples. Respirable mass filter samples were taken at an airflow of 1.7 Lpm and reported as mg/m^3 total respirable dust. At each plant, paired (side-by-side) samples were collected by mining company personnel at the following locations: coarse crusher, ore tunnels, primary concentrator and pellet plants. One pair of samples was collected in the open pit. Particle-size distribution results obtained with the Royco 218 optical particle counter showed about the same particle-size distribution for these production areas in a taconite plant.[5]

The paired sample data were analyzed for the following: 1) to determine a ratio between mean filter-respirable mass mean concentrations and mean impinger dust concentrations and the precision of the ratio; 2) to develop a linear model of the form $Y_i = B_o + B_1 X_i + E_i$, where Y_i = mean filter-respirable mass concentration (mg/m^3) at sample location 'i', B_o = intercept, B_1 = model parameter for relating impinger dust count concentrations to respirable mass concentrations, and X_i = average impinger dust count concentration in mppcf at sample location 'i', and E_i is an error term; 3) to compare the ratios between the taconite plants; and 4) to compare the degree of correlation between impinger and filter samples placed side-by-side with the correlation between fixed filter samples and traverse impinger samples. (Traverse samples were taken by moving the sampler through the area during sampling.)

At Plant A, 23 paired samples were taken during a four-week period in September and October 1974, and 13 paired samples were taken at Plant B during a two-week period in August 1974. Samples in both data sets were collected at fixed locations with side-by-side sampling by company industrial hygiene personnel to determine a ratio between the two sampling methods. Because the new standard for allowable silica dust levels would be based on the filter sampling method, the company wanted to know the quantitative ratio between the two methods to determine if the company would be in compliance with the new method. During sampling, the impinger and filter samples were placed right next to each other. One impinger sample was collected for each filter sample. The impingers were short-term samples of 20 to 30 min and the filter samples were 4 to 6 hr duration. The possibility exists that short-term samples do not account for temporal variations in dust concentrations, but in the taconite plants, a sufficient number of samples were taken to account for temporal variations in dust concentrations as well as differences in the sample duration for the two sampling methods.

The results of the statistical analysis of Data Sets 1 (Plant A) and 2 (Plant B) are presented in Table I. The ratio of respirable mass sample concentrations to impinger dust concentrations averaged 0.102 mg/m^3 to 1 mppcf and was nearly identical for these data sets. The standard error of the ratio was about 0.01 for Data Sets 1 and 2 and only 0.006 for the combined data sets. The correlation coefficients of the two data sets individually and combined are highly significant ($p < 0.0001$). The correlation coefficient for the 36 pairs of data was 0.86. Correlation coefficients as large as those for Data Sets 1 and 2 and for the combined data sets indicate a positive linear relationship between impinger and filter-respirable mass samples.

TABLE I
Correlation of Paired Impinger and Filter Respirable Mass Area Samples

	Data Set(s) 1	Data Set(s) 2	
Taconite Plant Sampled	A	B	Total (A & B)
Industrial Hygienist	Company	Company	Company
Pairs of Samples	23	13	36
Statistics			
Ratio^A Mean	0.102	0.101	0.102
Standard Error	0.007	0.0095	0.0056
Correlation Coefficient	0.87	0.94	0.86
Significance of Correlation Coefficient	0.0001	0.0001	0.0001
General Linear Model			
R-square	0.75	0.87	0.73
F-value	63.0	77.0	93.0
Significance of F	0.0001	0.0001	0.0001
Slope (B_1)	0.084	0.18	0.123
Intercept (B_o)	0.08	−0.41	−0.14
Significance of Intercept	0.40	0.055	0.25

^A Ratio = respirable mass concentration (mg/m^3) to impinger dust count concentration (mppcf).

The paired samples also were analyzed using the general linear model $Y_i = B_o + B_1 X_i$. The R-squared value (equal to the square of the correlation coefficient) shows the variability of the data that can be attributed to the model. The R-squared value for the two data sets combined is 0.73. The model intercept is not statistically different than zero for Data Set 1 and for the combined data sets, but the intercept for Data Set 2 is barely not significant ($p = 0.055$). The slope of the model for Data Set 2 did not differ significantly from the slope of Data Set 1. Data Sets 1 and 2 combined, plotted in Figure 1, had a slope of 0.12.

Analysis of Other Paired Filter and Impinger Samples

The ratio between filter-respirable mass concentrations and mean impinger dust concentrations was further evaluated by including 44 additional pairs of impinger and filter samples in the analysis. These 44 samples were collected in the same general plant areas but on different dates. Unlike the paired data (in Data Sets 1 and 2), the additional sample pairs were not taken expressly for the purpose of correlating sampling methods, but were taken at the same location and on the

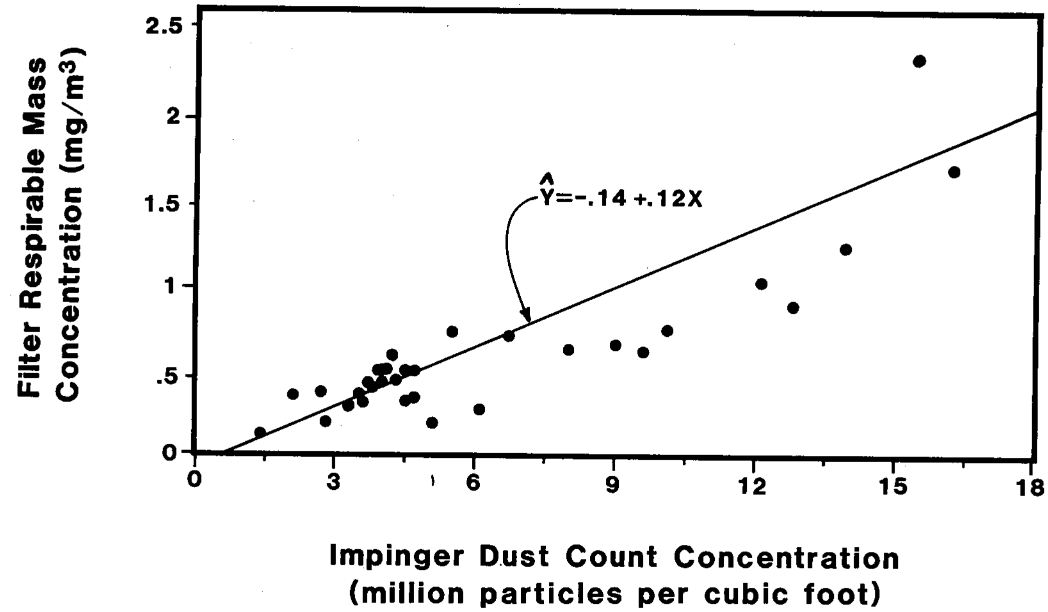

Figure 1 — Paired impinger and filter samples from Data Sets 1 and 2.

same date, and the impinger sample period of about 15 to 40 min was within the filter sample period of 4 to 6 hr. The 44 pairs were analyzed statistically in three Data Sets: 3, 4, and 5. Data Set 3 consisted of paired samples taken at Plant B by company personnel and included a few traverse impinger samples. Samples in Data Sets 4 and 5 were taken by an industrial hygiene engineering consultant at Plants B and A, respectively. Most of these impinger samples were traverse samples while the respirable mass samples were at fixed locations. Moving the impingers while sampling was expected to increase the variability of the ratio between impinger and filter sample results; thus, compared to Data Sets 1 and 2, the correlation of Data Sets 4 and 5 should be much weaker.

As shown in Table II, the correlation coefficients for Data Sets 4 and 5 are much lower than for Data Sets 1 and 2. Correlation coefficients calculated for Data Sets 4 and 5, however, are still significant at the 5% level. The correlation coefficient for Data Set 3 was highly significant.

The average ratios for Data Sets 4 and 5 of 0.094 and 0.092, respectively, were not significantly different from each other, and neither ratio was significantly different from the average ratio for Data Sets 1 and 2 based on overlapping confidence intervals. The ratio for Data Set 3 (0.139), however, was significantly different (p = 0.003) from the average ratio for Data Sets 1 and 2 (0.102). General linear model results give significant F values for Data Sets 3, 4 and 5, but

TABLE II
Statistics for Paired Impinger and Filter Area Sample Results (Arithmetic Scale)

	Data Set							
	1	2	3	4	5	All	1, 5	2, 3, 4
Plant	A	B	B	B	A	A & B	A	B
No. of Pairs	23	13	12	15	17	80	40	40
Ratio[A] Mean	0.102	0.101	0.139	0.094	0.092	0.104	0.098	0.110
Standard Error	0.007	0.0095	0.010	0.017	0.015	0.0055	0.0074	0.0082
Correlation Coefficient	0.87	0.94	0.84	0.54	0.54	0.81	0.84	0.85
Significance of Correlation	0.0001	0.0001	0.0006	0.0371	0.0253	0.0001	0.0001	0.0001
Proc GLM[9]								
CV	40%	52%	26%	52%	58%	58%	46%	55%
R-square	0.75	0.87	0.71	0.29	0.29	0.65	0.70	0.72
F-value	63.0	77.0	24.0	5.4	6.2	147.0	90.0	96.0
Slope (B_1)	0.084	0.18	0.11	0.05	0.03	0.11	0.081	0.15
Intercept (B_0)	-	−0.41	-	-	+0.19	-	-	−0.23
Significance of Intercept	0.40	0.055	0.33	0.25	0.014	0.29	0.52	0.06

[A]Ratio = respirable mass concentration (mg/m³)/impinger dust count concentration (mppcf).

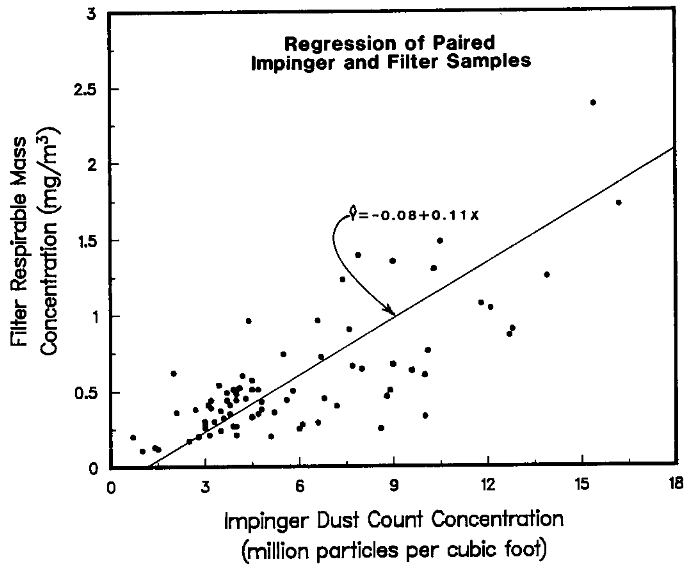

Figure 2 — Respirable mass filter concentrations and impinger dust count concentrations for all five data sets plotted on an arithmetic scale.

the F values for Data Sets 4 and 5 are much less than for Data Sets 1 and 2. The intercepts for Data Sets 3 and 4 were not significantly different than zero; only the intercept for Data Set 5 was significantly different than zero (p = 0.014).

The paired data also were analyzed to determine if differences existed between taconite plants, and these results are shown in Table II. Data Sets 2, 3 and 4 were taken at Plant B and Data Sets 1 and 5 at Plant A. Forty pairs were collected at each plant. The ratios of respirable mass to impinger dust count concentration for Plants A and B data were not statistically different from each other based on a t-test. The correlation coefficients, R-squared values and F values for both plants were nearly equal.

Combining all five data sets resulted in 80 pairs of filter-respirable mass and impinger dust samples. The mean ratio of filter sample concentrations to impinger concentrations for all 80 pairs was 0.104, which is equivalent to the ratio for the closely matched 36 pairs (Sets 1 and 2). The correlation coefficient (0.81) and R-squared value (0.65) were slightly smaller for all 80 pairs than the correlation coefficient (0.86) and R-squared value (0.73) for the 36 matched pairs. The intercept of the model for all 80 pairs was not statistically different than zero. The respirable mass filter concentrations and the impinger dust count concentrations for all five data sets are plotted on an arithmetic scale in Figure 2.

Company personnel in 1974 conducted one additional environmental survey at Plant B to compare sampling methods; the results are shown in Table III. One impinger and three filter samples were hung on a wire next to each other. The three filter samples were taken for 360 min while the impinger sample was collected for 20 min and then, after 20 min, was replaced with a second impinger sample. Nine impinger samples were collected for 20 min each for a total of 180 min of sampling over the 360 min period. A second identical test was repeated a week later. The ratio for the combined results averaged 0.089, which was not statistically different from the ratio detailed above.

The paired sample data also were statistically analyzed using a $\log_e$ transformation. The results for the five individual data sets, the combined Data Sets 1 and 2 and all five data sets combined on the arithmetic scale and the $\log_e$ transformed scale are compared in Table IV. The correlation coefficient and the significance of correlation coefficient for the 36 matched pairs (Data Sets 1 and 2) are the same whether using the arithmetic analysis or the $\log_e$ transformed analysis. For example, the correlation coefficient on the arithmetic scale was 0.86 compared to a correlation coefficient of 0.88 for the $\log_e$ transformed data. The F-values from the general linear model were not very different: 93 on the arithmetic scale and 119 on the $\log_e$ scale. The correlation coefficients on both scales were nearly identical for the entire set of 80 pairs, and among the individual data sets there were only small differences in the correlation coefficients between the arithmetic and the $\log_e$ analysis.

Conclusions

The ratio of respirable mass concentrations to impinger dust count concentrations determined from 36 pairs of samples collected experimentally was 0.102 mg/m^3 to 1 mppcf. The

TABLE III
Results of Side-by-Side Sequential Short-Term Impinger Samples with Long-Term Filter Samples

Test Run	Date	Time	Location	No. of Samples: Impinger[A]	No. of Samples: Filter	Ratio Filter to Impinger	Standard Error	Mean Filter Concentration mg/m^3
1	8/29/74	0855 to 1455	on wire in primary concentrator	9	3	0.093		0.74
2	9/04/74	0855 to 1455	on 7th level concentrator	9	3	0.085		0.56
Total				18	6	0.089	0.004	

[A]Each impinger sample was on 20 min and off 20 min and totalled 180 min; three filter samples were operated in parallel for 360 min.

TABLE IV
Arithmetic vs. Log-transformed Statistical Results for Paired Impinger and Filter Area Samples

Data Set	Plant	No. of Pairs	Correlation Coefficient		Significance of Correlation Coefficient		F-value	
			Arith.	Log	Arith.	Log	Arith.	Log
1	A	23	0.87	0.81	0.0001	0.0001	63	40
2	B	13	0.94	0.96	0.0001	0.0001	77	131
3	B	12	0.84	0.90	0.0006	0.0001	24	41
4	B	15	0.54	0.55	0.0371	0.0340	5.4	5.6
5	A	17	0.54	0.66	0.0253	0.0039	6.2	11.6
1 & 2	A/B	36	0.86	0.88	0.0001	0.0001	93	119
All	A/B	80	0.81	0.80	0.0001	0.0001	147	120

correlation coefficient for this ratio was high for environmental data, 0.87. A linear model for the same data showed a slope of 0.12 mg/m^3/mppcf and an intercept of −0.14 with the intercept not statistically different than zero. Because the intercept was not statistically different from zero — and for simplicity — only the simple ratio was used in subsequent analysis to convert impinger dust count mean concentrations to respirable mass mean concentrations.

A further analysis of 80 pairs of data, which included the 36 pairs of samples obtained in side-by-side tests and 44 pairs of impinger and respirable mass samples taken at the same time for exposure monitoring, showed the ratio of respirable mass concentrations to impinger dust count concentrations to be 0.104 mg/m^3 to 1 mppcf.

This ratio is nearly identical to the ratio determined for the 36 pairs taken in side-by-side tests and supports the conclusion to use the ratio of 0.10 mg/m^3 to 1 mppcf as the conversion factor for exposures at these companies.

The ratio developed in this study is not designed to convert individual impinger dust concentrations to respirable mass concentrations. This is due in part to the sampling time where the impinger measurement is less than 1 hr and the filter samples are full shift; however, with a number of samples, the difference in sampling time should average out statistically.

The results from this study are consistent with findings in the literature such as Rice *et al.*[1] and Sutton *et al.*[2] Rice used a conversion factor of 0.09 mg of respirable dust per cubic meter to 1 mppcf in his study of silica exposure in dusty trades. Sutton also used 0.09 mg/m^3 respirable dust to 1 mppcf as the conversion factor in a study of the granite sheds. The nearly identical conversion factor of 0.10 mg/m^3 for the taconite industry found in this study indicates uniformity among many mineral and mining processes. Thus, the results from this study may have applications to many other studies.

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