Historical Respirable Quartz Exposures of Industrial Sand Workers: 1946–1996

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Background *Besides a clear relationship to silicosis, crystalline silica—quartz—has been associated with lung cancer, nonmalignant renal disease, and auto-immune disease. To study diseases associated with crystalline silica further, NIOSH conducted a cohort mortality study of workers from 18 silica sand plants, which had quarry, crushing, and bagging operations to produce industrial sand. Twelve of these plants also had grinding mills to produce fine silica powder. The historical crystalline silica exposures of workers at these plants were estimated to facilitate exposure–response analyses in the epidemiologic study.*

Methods *NIOSH obtained personal respirable dust measurement records from Mine Safety and Health Administration (MSHA) compliance inspections at all 18 plants and from the archives of seven plants which had collected samples. These samples had been analyzed for quartz content by x-ray diffraction. Although no personal samples were available before 1974, impinger dust measurements were reported for 19 silica sand plants in 1946; these data were converted and used to estimate exposures prior to 1974. Statistical modeling of the samples was used to estimate quartz exposure concentrations for workers in plant–job–year categories from the 1930s when mortality follow-up of the cohort began until 1988 when follow-up stopped.*

Results *Between 1974 and 1996, there were 4,269 respirable dust samples collected at these 18 plants. The geometric mean quartz concentration was 25.9* $\mu g/m^3$ *(GSD = 10.9) with a range from less than 1 to 11,700* $\mu g/m^3$*. Samples below 1* $\mu g/m^3$ *were given a value of 0.5* $\mu g/m^3$*. Over one-third of the samples (37%) exceeded the MSHA permissible exposure limit value for quartz (PEL = 10* mg/m^3*/(%quartz + 2)) and half (51%) of the samples exceeded the NIOSH recommended exposure limit (REL = 50* $\mu g/m^3$*). The samples were collected from workers performing 143 jobs within the 18 plants, but too few samples were collected from many of the jobs to make accurate estimates. Therefore, samples were combined into 10 categories of jobs performing similar tasks or located within the same plant area.*

Conclusions *The quartz concentrations varied significantly by plant, job, and year. Quartz concentrations decreased over time, with measurements collected in the 1970s significantly greater than those collected later. The modeled exposure estimates improve upon duration of employment as an estimate of cumulative exposure and reduce exposure misclassification due to variation in quartz levels between plants, jobs, and over time.* Am. J. Ind. Med. 38:389–398, 2000. *Published 2000 Wiley-Liss, Inc.*†

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INTRODUCTION

Depending on concentration, particle size, and duration of exposure, inhaling crystalline silica can lead either to chest radiograph opacities with little lung function impairment or to a profoundly disabling, fatal disease due to respiratory insufficiency. Mineralogically, silica (silicon dioxide) may appear as amorphous silicates or in crystalline form as quartz, cristobalite, and tridymite [Pough, 1960]. Silicates are only slightly fibrogenic while quartz, cristobalite, and tridymite are more intensely fibrogenic in lung tissue, causing one of the oldest known industrial diseases, silicosis [Seaton, 1975]. Quartz is the most commonly occurring crystalline form of silica and is an important constituent of most gravels and sands.

In addition to silicosis, respirable quartz has been associated with lung cancer [IARC, 1997], nonmalignant renal disease [Calvert et al., 1997], and autoimmune disease [Steenland and Goldsmith, 1995]. The National Institute for Occupational Safety and Health (NIOSH) conducted a cohort mortality study of workers in 18 silica sand plants to evaluate the association between quartz exposure and mortality risk for these diseases [Steenland and Sanderson, 2000]. These plants were selected for study because they were members of a major industrial sand association and had joined a medical surveillance program initiated by the association. This cohort included many of the larger silica sand plants throughout the eastern United States and was expected to represent workers from all 60 silica sand plants in operation at the start of the study. In 1987, the industrial sand industry employed approximately 2,600 workers [Amandus, 1987].

Personal respirable quartz measurements collected between 1974 and 1988 and impinger dust samples collected in 1946 were used to estimate historical quartz exposures in the 18 silica sand plants. The samples were used to estimate quartz exposure concentrations for workers in plant–job–year categories from the 1930s when mortality follow-up of the cohort began until 1988 when follow-up stopped. Since quartz exposure data were available until 1996, we also present the results of measurements beyond the end of cohort follow-up in 1988.

Industrial Sand Process

Industrial silica sand is obtained from a variety of sources from a loose, unconsolidated granular state to hard, highly compacted rocks; the ore form determines how it will be mined. Hard rock mining is usually done in an open pit quarry where holes are drilled into the rock layers, filled with explosives, and detonated to break the rock into movable pieces. Trucks haul the rock to the plant for processing, where rocks are crushed to obtain progressively smaller sizes. Uncompacted sand is collected using dredges, hydraulic pumps, scrapers, or clamshells. If the sand is already granular, crushing is usually not necessary. The crushed and granular sand is screened and sized. The screening and sizing operation may be either a wet or dry process; dry screening typically has higher dust exposures. Often the sand is milled in rotating ball mills to reduce the sand to a fine powder. The final sand products, varying in particle size and quartz content, are bagged or bulk-loaded for shipment.

Silica sand has a variety of industrial uses. It is used in sandblasting, foundry molds, fine polishing, glass making, and rubber manufacture (where silica powder is used as a dry lubricant). It is also used as a filler in plastics and paints and as a carrier in cosmetics [Davis, 1996]. Potentially intense quartz exposures have been documented historically in these industries.

METHODS

Historical respirable quartz measurements were sought from a variety of sources to estimate quartz exposures across all jobs within the 18 plants in the industrial sand cohort. NIOSH obtained the greatest number of personal, respirable dust measurement records for these plants from the Mine Safety and Health Administration (MSHA). Industrial hygiene samples had been collected in all 18 plants by MSHA inspectors beginning in 1974 to determine compliance with MSHA exposure standards [NIOSH, 1996]. The data for personal exposure samples included the sampling date, contaminant code, airborne concentration, occupation, permissible exposure limit, percent silica, silica concentration, standard industrial classification, and the mine at which the sample was obtained. This data system is currently maintained by MSHA Technical Support in Denver, Colorado.

Personal respirable quartz measurements were also available from the archives of seven of the 18 plants. These plants had collected respirable quartz samples in the same manner as MSHA to document workers' silica exposures and guide their dust control intervention efforts. These measurements were coded into a computer spreadsheet using the same variable fields as the MSHA data in order to combine the data if they were found to comparably represent workers' exposures.

These samples were collected by having workers wear portable battery-powered pumps drawing air at 1.7 liters per minute (L/min) through cyclone pre-separators followed by dust collection filters. The cyclone pre-separator selectively allowed "respirable" dust—mass median aerodynamic diameter of 3.5 μm—to pass on to the filter [Lippman, 1970; Hearl, 1997]. The filters were weighed to determine the mass of dust collected and those with a mass of at least 0.1 mg were analyzed for quartz content by x-ray diffraction [Watts and Parker, 1995]. The lowest quartz concentrations that could have been measured directly on the samples with this method would have been approximately 20–30 μg per sample or 25 μg/m^3 over an 8-hour work day [NIOSH, 1994].

If the dust mass on the filters was less than 0.1 mg, the reported airborne quartz concentrations were derived by multiplying the dust mass on the filters by the percentage of quartz believed to be in the dust, rather than analyzing the quartz content directly on the filters. The percentage of quartz was estimated by analyzing the quartz content of bulk dust or high-volume air samples. Using this technique, quartz concentrations lower than 25 μg/m^3 were calculated for samples with low dust mass. Quartz concentrations as low as 1 μg/m^3 were reported with sample concentrations lower than 1 μg/m^3 typically reported as zero. In this study, all sample concentrations lower than 1 μg/m^3 were given the value 0.5 μg/m^3, the least biased estimator of concentrations between zero and one [Hornung and Reed, 1990]. Samples greater than 15 mg/m^3 respirable quartz dust were deleted because it was believed these samples were outliers not representative of sand plant environments and were possibly transcription errors [Watts and Parker, 1995]. Only three samples were greater than 15 mg/m^3.

As many jobs within the 18 plants were represented by too few samples, accurate exposure estimates could not be made for these jobs over time. Therefore, samples were combined into 10 broad categories of jobs performing similar tasks or located within the same area of the plant (Table I). These categories were similar to job categories used by other researchers [Hatch et al., 1947; Severns, 1979]. Statistical modeling was used to stratify the samples into plant and time categories and to estimate the quartz concentrations for workers in each plant–job–year category.

No personal respirable quartz measurements were available from MSHA or the companies before 1974. However, researchers with the Industrial Hygiene Foundation of America, Inc. had conducted a cross-sectional dust exposure assessment study of 19 silica sand plants in 1946 [Hatch et al., 1947]. The dust samples in this study were obtained using midget impingers with *n*-propyl alcohol as the collecting fluid. Both breathing zone and general area samples were collected. Where workers were stationed at one position, samples were collected in the breathing zone within a few inches of their noses. In many cases it was necessary to follow workers around a department to obtain representative samples. Where no obvious source of dust was present, the researchers collected general air samples to estimate dust exposures of groups of workers.

The dust particles in alcohol suspension were placed in a Sedgwick Rafter Cell and allowed to settle for 20 min. All particles at or near the bottom of the cell, smaller than 5 μm, were then microscopically counted in five widely spaced locations within the cell. Since the toxic action of crystalline silica particles had been shown to increase progressively with a decrease in size, these small particles were considered to be the most important for evaluating respiratory hazard. The results of these counts were reported as million dust particles per cubic foot of air (mppcf).

To estimate the quartz concentration of the dust particles smaller than 5 μm, airborne dust was collected with the I-H-F sampler which consists of a high volume air pump drawing air through two filters one foot square at 30 cubic feet per minute (849 L/min); the filters were composed of felted layers of salicylic acid crystals [Hatch et al., 1947]. The filters were placed in alcohol to dissolve the acid and the dust was filtered and washed. Samples of settled dust from less accessible areas (rafters) were also collected for size separation and quartz analysis. The dust from either the I-H-F samplers or settled dust was agitated in alcohol to

TABLE I. List of Job Categories and Selected Job Titles Within Those Categories; Industrial Sand Workers

Job category	Selected specific job titles
Quarry	driller, blaster, scraper operator, dredge operator, truck driver, front-end loader, bull dozer operator, quarry laborer
Crushing	primary crusher operator, secondary crusher operator, conveyor belt attendant, transfer line maintenance
Wet process	wash plant operator, flotation operator, washman, drain bin operator, vacuum table operator
Drying	dryer operator, dryer helper, dryer building clean-up, conveyor attendant at dryer
Screening	screen plant operator, screen plant helper, screen plant clean-up, screen plant tester, sizing operator
Milling	mill operator, mill helper, mill clean-up, mill tester, mill foreman, mill mechanic
Bagging	bagger, whole grain sand bagger, ground flour bagger, bagging clean-up, palletizer, forklift operator, speciality sand bagger
Loading	loader, truck loader, rail loader, car cleaner, whole grain sand loader, ground flour loader, front-end loader in loading area
Administration	plant manager, engineer, secretary, clerical, lab tester, lab technician, geologist, watchman
Other	general laborer, maintenance, mechanic, electrician, welder, oiler, dust control maintenance, pipefitter, carpenter, warehouseman

provide a uniform suspension and allowed to settle for 40 min and then the supernatant was withdrawn by suction. This procedure was repeated 8–10 times, reportedly separating the dust into two portions—one less than 5 µm and the other greater. The amount of quartz in the portion of dust less than 5 µm was determined by x-ray diffraction analysis.

Unfortunately, the identity of the 19 plants in the Hatch study were not available; therefore, the impinger measurements could not be directly compared to the plant-specific quartz samples collected since 1974. However, these impinger measurements could provide estimates of the airborne quartz exposures for specific jobs in the silica sand industry in the late 1940s across all plants. The impinger dust measurements in mppcf had to be converted to mass per volume (mg/m^3) to compare them to the respirable quartz measurements collected with a cyclone pre-separator. Based on comparisons of side-by-side impinger and respirable dust cyclone measurements reported by other researchers, the impinger dust count measurements in mppcf were converted to respirable dust mass in mg/m^3 by multiplying them by 0.1 [Ayer et al., 1973; Rice et al., 1984; Sheehy and McJilton, 1987]. These converted values were then multiplied by 1000 and by the average percentage of quartz found in the historical dust mass samples to provide an estimate of the respirable quartz concentration in µg/m^3.

Exposure Standards

Exposure standards for quartz have been developed to prevent respiratory disease; the historical exposure measurements were compared to these criteria. MSHA incorporated the 1973 American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) as the permissible exposure limit (PEL) for respirable mass of mineral dust containing quartz [CFR, 1997]. This standard employs the following formula:

$$\text{PEL} = 10\,\text{mg/m}^3/(\%\ \text{quartz} + 2)$$

where the "% quartz" is the percent-by-weight of quartz in the personal respirable dust sample. The PEL is measured as respirable dust mass, in contrast to the NIOSH recommended exposure limit (REL) of 50 µg/m^3, which is measured as a time-weighted respirable quartz level for up to 10 h day during a 40-hour work week [NIOSH, 1992]. The ACGIH currently recommends a TLV for respirable quartz of 100 µg/m^3 [ACGIH, 1999].

Statistical Analysis

Statistical Analysis System (PC-SAS®) computer software was used for all statistical analyses [SAS, 1996]. Because the distributions of the quartz measurements were right skewed, the measurements were transformed using the natural logarithm. Therefore, geometric means (GM) and geometric standard deviations (GSD) of the measurements were calculated for each plant, job, and year category. Analysis of variance and Student's *t*-test were used to test differences in the mean quartz measurements across various plant, job, and year categories. Analysis of variance using general linear models was used to evaluate the effect of plant, job, and year on quartz concentrations, and to estimate the adjusted quartz exposure levels by the plant, job, and year categories.

RESULTS

A total of 4,269 respirable quartz samples were available for estimating historical exposures in the 18 silica sand plants between 1974 and 1996; 2,975 samples collected by MSHA inspectors and 1,294 samples collected by seven companies. Approximately one-fourth (23.7%) of the samples were recorded to be 1 µg/m^3 or less and 1,585 samples (37%) were less than 25 µg/m^3. The MSHA and company-collected data were combined into a single dataset, since no significant differences were found by analysis of variance ($P = 0.54$) between the quartz measurements collected by MSHA and those collected by the seven companies across plants, jobs, and years. Also, no trend was observed indicating that MSHA measurements were usually either higher or lower than company-collected measurements. The overall geometric mean quartz concentration was 25.9 µg/m^3 (GSD = 10.9) and the highest concentration was 11,700 µg/m^3. Over one-third (37%) of all samples exceeded the MSHA–PEL and one-half (51%) of the samples exceeded the NIOSH–REL.

Summary statistics of the personal respirable quartz measurements collected between 1974 and 1996 are presented by plant in Table II. The plants are presented in order of increasing adjusted geometric mean dust concentration; the geometric means were adjusted by job category and year. The number of samples collected, geometric means, and maximum quartz concentrations varied dramatically across the plants. These data indicate that silica sand workers have historically encountered overexposure to quartz. Even among those plants with relatively low geometric mean quartz concentrations, a portion of the samples exceeded the PEL; in only one plant (4A)—represented by 38 samples—did none of the samples exceed the PEL.

Summary statistics of the personal respirable quartz measurements collected between 1974 and 1996 are presented by job category in Table III. Geometric means and standard deviations of the quartz concentrations were adjusted by plant and year. Screening and bagging jobs tended to have the greatest quartz exposures; approximately one-half of the samples from these two job categories exceeded the PEL. Milling, bagging, and loading jobs encoun-

TABLE II. Personal Respirable Quartz Measurements by Plant: 1974–1996; Industrial Sand Workers

Plant	# Samples	Adjusted GM (GSD)[a] μg/m³	Unadjusted GM (GSD)[a] μg/m³	Maximum μg/m³	% > PEL[a]	% > REL[a]
1 A	60	1.4 (8.4)	1.2 (5.8)	180	5	5
2 A	29	2.4 (8.2)	2.5 (7.5)	112	3	7
3 A	338	8.5 (9.7)	12.2 (9.4)	2,610	22	31
4 A	38	8.9 (8.3)	5.2 (5.3)	57.5	0	3
5 A	93	10.6 (8.3)	16.4 (13.7)	608	33	46
6 A	318	11.2 (9.3)	15.6 (12.6)	1,240	31	46
7 B	207	14.7 (8.8)	17.7 (10.8)	2,090	28	45
8 B	157	15.4 (9.2)	30.1 (9.8)	11,700	41	55
9 B	777	15.6 (11.7)	29.6 (12.9)	5,570	44	55
10 C	307	18.2 (9.5)	21.0 (12.1)	2,900	36	47
11 C	197	18.3 (8.8)	14.1 (14.0)	3,820	28	40
12 C	57	18.7 (8.7)	29.6 (5.0)	208	21	44
13 C	322	22.5 (9.7)	35.6 (6.6)	3,620	34	52
14 C	175	24.9 (8.9)	54.6 (7.6)	5,380	43	67
15 D	340	30.5 (9.3)	46.0 (7.2)	2,410	41	61
16 D	292	31.9 (9.0)	45.0 (7.9)	1,760	46	65
17 D	294	32.7 (9.1)	64.1 (8.7)	2,200	53	64
18 D	268	41.5 (9.7)	31.0 (10.1)	2,610	38	53

[a]GM, geometric mean; GSD, geometric standard deviation adjusted by job category and year; PEL, MSHA permissible exposure limit = 10/(%quartz+2 mg/m³) respirable mass; REL, NIOSH recommended exposure limit = 50 μg/m³ respirable quartz.
The letter codes—A, B, C, and D—indicate which plants were grouped together to create the historical quartz exposure estimates for the epidemiological study.

TABLE III. Personal Respirable Quartz Measurements by Job Category: 1974–1996; Industrial Sand Workers

Job category	# Samples	Adjusted GM (GSD)[a] μg/m³	Unadjusted GM (GSD)[a] μg/m³	Maximum μg/m³	Average % quartz (SD)	% > PEL[a]	% > REL[a]
Quarry	680	5.5 (9.8)	9.6 (9.3)	2,610	15 (18)	18	27
Crushing	282	9.9 (9.6)	17.1 (11.1)	1,470	23 (23)	28	42
Wet process	280	9.0 (9.1)	17.7 (11.0)	2,940	24 (25)	30	43
Drying	42	18.9 (9.7)	30.6 (8.7)	3,620	23 (19)	36	54
Screening	163	45.5 (9.2)	44.6 (9.6)	5,380	25 (19)	47	66
Milling	392	20.0 (9.8)	30.2 (10.6)	1,430	31 (25)	41	58
Bagging	1,142	39.8 (15.2)	60.2 (9.9)	11,700	37 (26)	54	69
Loading	252	20.9 (9.2)	28.5 (9.8)	1,220	29 (26)	41	54
Administration	97	3.3 (8.6)	3.5 (6.6)	49	8 (11)	1	1
Other	554	13.7 (10.4)	21.3 (10.2)	2,610	22 (22)	30	46
Overall	4,269		25.9 (10.9)	11,700	26 (24)	37	51

[a]GM, geometric mean; GSD, geometric standard deviation adjusted by plant and year; PEL, MSHA permissible exposure limit = 10/(%quartz+2 mg/m³) respirable mass; REL, NIOSH recommended exposure limit = 50 μg/m³ respirable quartz.

tered dusts with the greatest percentage of quartz. Quarry and administration jobs had the lowest quartz exposures.

The geometric mean respirable quartz measurements by year, adjusted for plant and job category, are presented in Figure 1. This figure shows that respirable quartz levels have fallen dramatically since 1974. The average quartz exposure in 1974—based on only 44 samples—was 100 μg/m³, dropping steadily until 1985 when the average annual quartz exposure was 16 μg/m³. The annual geometric mean quartz exposure has remained below 20 μg/m³ since 1982

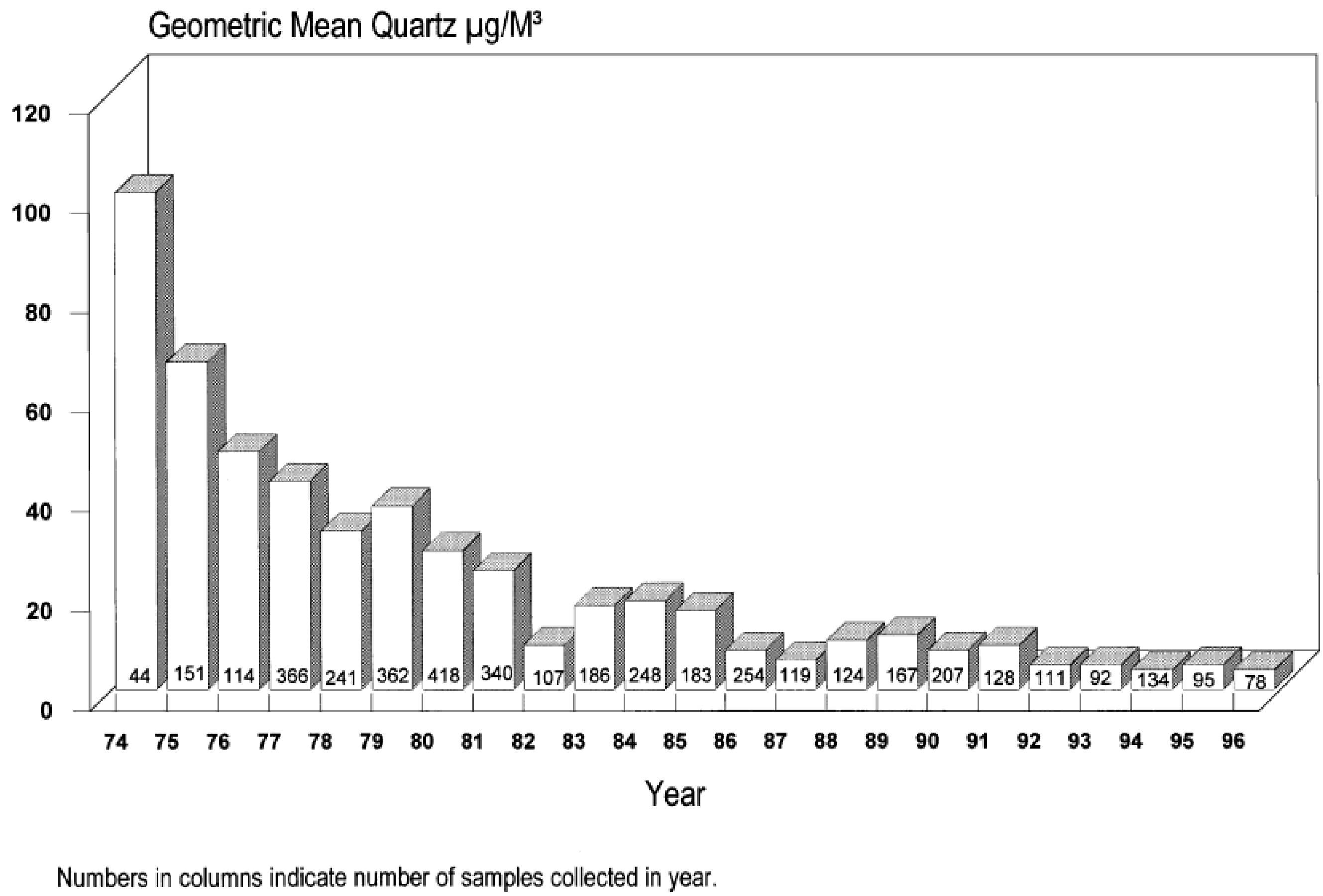

FIGURE 1. Geometric mean respirable quartz concentrations by year: 1974–1996 adjusted by plant and job categories; industrial sand workers.

and has remained below 10 µg/m^3 since 1990. Mining regulations were strengthened in 1977 with the passage of the Federal Mine Safety and Health Act. These measurements indicate that quartz exposures were already falling before 1977 in the silica sand industry, and continued to decrease after 1977. The data also indicate that quartz exposures dropped further after 1981 and 1991. They have been fairly stable since 1992, averaging about 5 µg/m^3. The quartz exposure levels appeared to increase somewhat in 1988 after MSHA changed the analytical standard for quartz analysis (Minusil V) to more accurately analyze for quartz and conform to international methodology [Watts and Parker, 1995].

Summary statistics of the personal respirable quartz measurements collected between 1974 and 1996 are presented by year category in Table IV. These data show that silica sand workers have historically had increased risk of overexposures to quartz. Over 40% of the personal respirable samples were not in compliance with the quartz standard between 1974 and 1984 and 57% exceeded the NIOSH—REL during these years. However, the proportion of samples exceeding respirable quartz criteria has been steadily declining since the early 1970s. These measurements may be compared to a NIOSH study of crushed stone workers conducted between 1979 and 1982 at limestone, granite, and traprock mines in which only 14% of the respirable quartz samples exceeded the MSHA–PEL and 25% exceeded the NIOSH–REL [Kullman et al., 1995].

In creating the historical exposure matrix for epidemiologic analysis, too few samples were available to estimate quartz exposures for each plant–job category ($n = 180$) for every year between 1974 and 1988. Therefore, the 18 plants were reduced to four categories (Plants 1–6; Plants 7–9; Plants 10–14; and Plants 15–18) and the years grouped into three categories (1974–1979; 1980–1984; and 1985–1988) for a total of 120 plant–job–year categories.

Combining the 18 plants into four categories was accomplished by comparing the least-squares geometric mean quartz concentrations (adjusted by job and year) of the plants and grouping those plants with very similar means. The least significant difference test was used to guide grouping of the plants. Divisions between the plant groups

TABLE IV. Personal Respirable Quartz Measurements by Year Category: 1974–1996; Industrial Sand Workers

Years	# Samples	GM (GSD)[a] μg/m³	% > PEL[a]	% > REL[a]
1974–1979	1278	51.2 (10.5)	42	57
1980–1984	1299	25.6 (10.2)	44	57
1985–1988	680	11.6 (9.5)	30	45
1989–1996	1012	7.5 (9.1)	24	38

[a]GM, geometric mean; GSD, geometric standard deviation adjusted by plant and job category; PEL, MSHA permissible exposure limit = 10/(%quartz+2 mg/m³) respirable mass; REL, NIOSH recommended exposure limit = 50 μg/m³ respirable quartz.

attempted to maximize the similarity of the geometric mean quartz concentrations of plants within a group, while maximizing the difference between groups. The geometric mean quartz concentrations for plants within a category were more closely related than plant concentrations outside their category. The geometric mean quartz concentrations of the four plant categories were significantly different from each other. The letter codes in Table II indicate which plants were grouped together.

The same approach was used to combine the years into three time categories. The yearly least-squares geometric mean quartz concentrations (adjusted by plant and job) were compared and years with very similar means were grouped. The least significant difference test was also used to guide grouping of the years.

The adjusted geometric mean quartz concentrations for the plants were usually lower than the unadjusted mean because, in general, more measurements were collected during the early years when quartz exposures were higher and greater weighting was given these high-early samples when unadjusted mean exposures were calculated. The adjusted means were used for decision making, because these means were less influenced by dramatically differing numbers of samples across the plant–job–year categories.

A statistical model was used to predict the quartz exposure estimates from 1974 to 1988 for the 120 plant–job–year categories (four plant, ten job, and three year categories). The independent variable terms in the model were categorical (plant, job, and year) and were highly significant ($P < 0.001$). The square of the regression coefficient for this model was $r^2 = 0.21$. All two-way interaction terms between the independent variables were also statistically significant; however, they were not included in the model to predict quartz exposure estimates because some plant–job–year cells contained few or no samples and including the interaction terms often led to either unreasonably high or low exposure estimates in these cells.

Since no personal respirable dust samples had been collected before 1974, quartz exposures before this year were estimated using impinger dust measurements which had been collected by researchers in 1946 [Hatch et al., 1947]. Table V presents a summary of the impinger samples collected during this study grouped into eight of the 10 job categories of 1974–1996 data. No impinger measurements were available for the ‘‘other’’ and ‘‘administrative’’ job categories. Impinger samples collected across all job categories (overall) in 1946 were used to estimate exposures for the ‘‘other’’ job category. The measurements across all job categories were selected for the ‘‘other’’ job category because—as shown in Table III—the geometric mean of the ‘‘other’’ job category was similar to the overall geometric

TABLE V. Reported Means of Impinger Measurements for Respirable Dust by Job Category: 1946; Industrial Sand Workers

Job category[a]	# Sample means	Mean ranges mppcf	Mean of means mppcf	Median of means mppcf	Median quartz concentration μg/m³
Quarry	7	0.6–16	4.9	1.6	26
Crushing	12	1.5–15	4.8	2.9	70
Wet process	23	0.3–4.7	1.3	1.1	29
Drying	19	0.7–100	9.0	2.8	67
Screening	18	1.0–175	69.9	23	529
Milling	23	0.5–77	11.1	2.3	76
Bagging	8	5–60	19.8	16.5	644
Loading	15	0.5–350	55.2	8.0	256
Overall[a]	125	0.3–350	22.3	2.8	78

mppcf, millions of dust particles per cubic foot.
[a]*Note:* No measurements were available for the Administrative and Other job categories.

mean of the 1974–1996 measurement data. The "administrative" job category was given the value of approximately one-fifth the overall median of the impinger measurements across all job categories in 1946 because—as shown in Table III—the measurements collected between 1974 and 1996 indicated that administrative jobs were considerably lower than other silica sand jobs.

As the identities of the plants where the impinger samples were taken were not known, these samples could not be used to directly estimate quartz exposures for the 18 plants in the cohort study. Instead, an indirect plant adjustment was made to estimate quartz exposures for the years 1946 through 1974 using the following steps.

First, for the years 1974–1979, the ratios of the geometric means of the plant–job-specific respirable quartz measurements to the geometric means of the 10 job-specific respirable quartz measurements were calculated for each of the four plant categories. This ratio was multiplied by the median quartz level of the 1946 job-specific measurements (in μg/m^3) to estimate the predicted plant effect on job exposures. This adjustment assumes that the differences in concentrations across the four plant categories remained relatively constant between 1946 and 1974. The medians of the 1946 job-specific estimates were chosen because they most represent the geometric means of these measurements, which is consistent with using the geometric means of the later measurements.

Second, to adjust for exposure changes between 1946 and 1974, exposure estimates were incrementally changed each year in a linear fashion. Exposures may have actually fluctuated up and down during these years. On the other hand, the 1946 study commissioned by the silica sand industry probably indicated concern about silicosis risk among employees, possibly leading to process changes or environmental controls to reduce workers' exposures. Therefore, exposures more likely changed in a stepwise fashion across the various plants as controls were implemented. However, the specific points in time when dust control measures may have been instituted at the various plants remains unknown. Therefore, changing the quartz levels at a linear rate was assumed to be the least biased estimator of quartz exposure changes over time. However, the yearly rate of change varied by job category depending of the absolute difference between the 1946 median quartz exposure estimate and the 1974–1977 geometric mean. Figure 2 provides a graph of the predicted quartz exposure estimates of bagging workers in the four plant categories for the years 1946–1988.

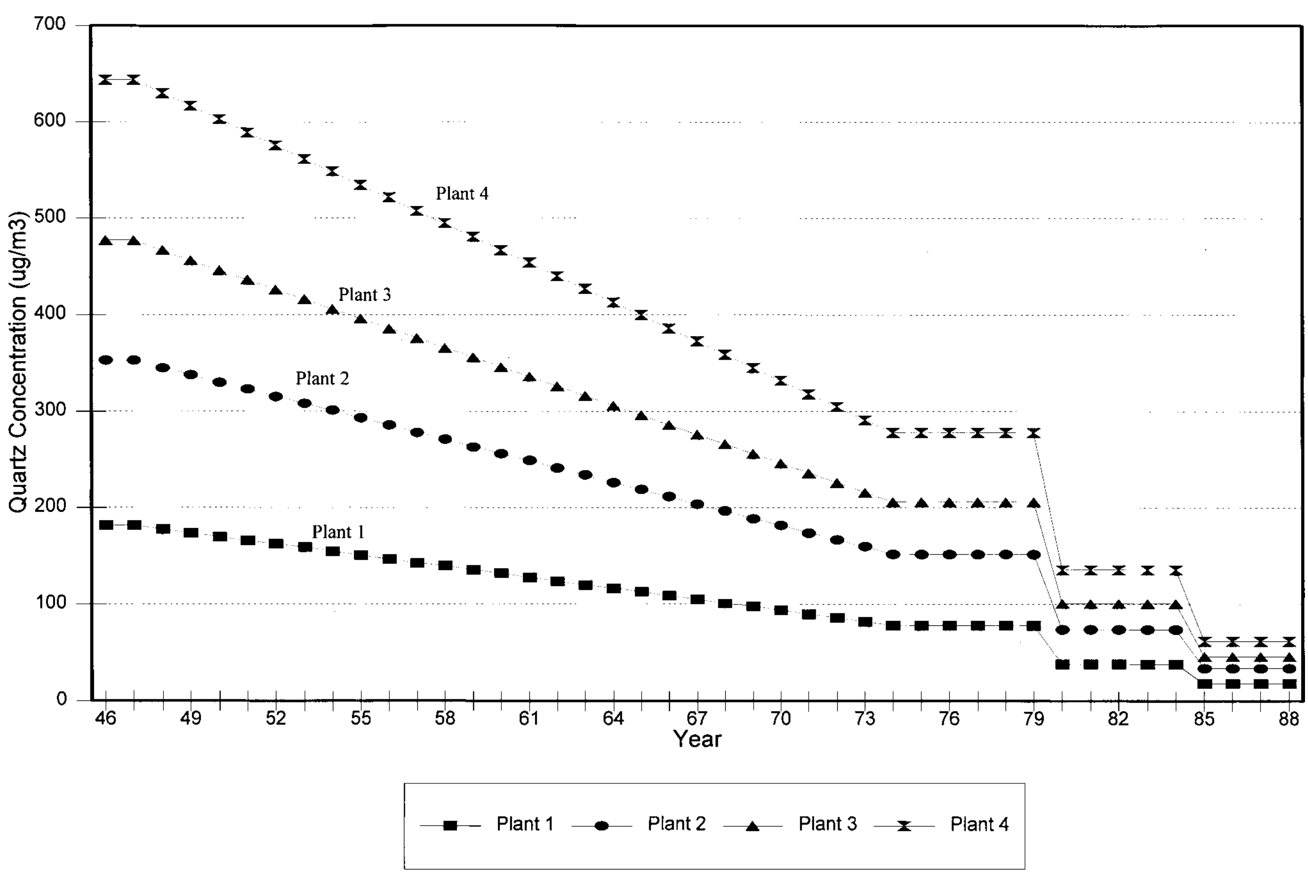

FIGURE 2. Predicted respirable quartz exposures for bagging workers by four plant categories: 1946–1988; industrial sand workers.

Since some cohort members were employed before 1946 and no dust exposure measurements were available before this date, exposures for years pre-1946 were assumed to be the same as exposures in 1946. No information was available indicating industry changes which may have resulted in exposure increases or decreases before 1946.

Interestingly, the quartz concentrations were found to change little between 1946 and the 1970s for quarry, wet process, drying, and milling workers. This was not surprising for quarry and wet process jobs, because they had the lowest exposures in 1946. Therefore, there was less incentive to reduce exposures for workers in these jobs. But it is unknown why drying and milling job exposures, which were some of the higher quartz exposures in 1946, were not shown to decrease over 30 years. Possibly quartz exposures did decrease over time for these jobs, but the decrease was just not reflected by historical sampling. Or, perhaps dust control was not implemented for these jobs at these particular plants to the extent that it was for bagging, loading, and screening jobs.

DISCUSSION

The measurements available to estimate historical quartz exposures in the silica sand industry from 1974 to 1996 show a clear plant effect, with some plants having considerably greater exposure levels than others. The measurements also show a clear job effect with workers in some jobs clearly having a greater chance of respirable quartz exposures than workers in other jobs. The surveys conducted by Hatch in 1946 indicated that significant exposure variability among jobs and plants was evident in the 1940s as well. Therefore, the workers' quartz exposures depended upon which plants they were employed and which jobs they held. And, finally, quartz exposures have generally been decreasing over time. However, this decrease was probably not linear. Data collected since 1974 indicates the decrease may have been logarithmic or quadratic. In fact, the decrease in exposure levels probably occurred in a stepwise fashion for plants and departments as dust controls were introduced.

The decreasing pattern (rate of decrease) was probably not the same across all plants and jobs. Quartz exposures probably decreased rather rapidly for specific jobs at certain plants, while they decreased less rapidly for the same jobs in other plants. Also, the quartz exposures probably did not decrease at the same rate for all jobs within the same plant. Perhaps a more realistic characterization of the change in plant and job exposures over time would be distinct decreases in exposure over relatively short time periods in response to dust control measures and work practice changes implemented by the companies. The exposure pattern would then reflect a descending staircase with steps of varying height and width, differing for each plant and job. Unfortunately, appropriate information as to when changes were made and how they affected quartz exposures was not available to determine when exposures specifically decreased for each job within each plant.

Although our dataset contains a relatively large number of personal, respirable quartz samples, they were not sufficient to make predictions on quartz exposures for each of the 18 individual plants and all 143 jobs which were reported in the work history records of workers in the plants. Therefore, the 18 plants were collapsed into four major categories and 143 jobs into 10 major categories. Exposure estimates for each job grouping and plant grouping certainly suffered some misclassification, because exposures for all plants within the same category and exposures for jobs within the same category were probably not homogenous.

The greatest limitation of these data to predict workers' exposures was the relative lack of data before 1974. The only dust measurements available in the silica sand industry before this date were collected in 1946 with impingers and had to be converted to approximate measurements collected with respirable dust cyclones. These measurements only gave a general idea of what conditions were like in the 1940s. And, since it was not reported from which plants these measurements came, they could not be directly related to the dust levels encountered in the plants in the cohort study. Also, the linear trend which was used to estimate exposure between 1946 and 1974 may not provide a realistic estimate of how exposures truly changed over time.

The MSHA, and to a certain extent the company-collected, quartz exposure measurements may be biased in certain respects [Watts and Parker, 1995]. Compliance sampling targeted workers who were expected to be at greatest risk of overexposure. Therefore, statistical assumptions of randomness, homogenous variance, and normality may not apply and the measurements may not be representative of industrywide sand plant exposures. Also, the change in the analytical standard for quartz in April 1988 altered the relative quantitative values for the quartz measurements pre- and post-1988.

The limitations of the available data and of the assumptions used to create the retrospective exposure matrix clearly reduced the ability of the matrix to accurately predict the true respirable quartz exposures workers would have encountered over time in the various jobs within the 18 plants. However, the limitations were similar to those encountered in any attempt to estimate historical exposures. Indeed, the number of samples in this database and the years over which the samples were collected were superior to what has been available for retrospective cohort mortality studies of other toxic materials. Despite the recognized limitations, use of existing data to estimate exposures quantitatively certainly represents an improvement over other alternatives typically used in epidemiologic analyses—the use of simple duration of exposure as a surrogate for cumulative exposure, regardless of time period, plant, or job. Simply using duration of employment as a surrogate estimate for exposure assumes that tenure at any plant, in any job, during any time period was the same, which was definitely not supported by the data.

Therefore, the efforts utilized in this study should reduce exposure misclassification due to variation in quartz levels among plants, jobs, and over time. Perhaps in the future, as MSHA and companies continue to collect exposure measurements in industrial sand and other industries where respirable quartz exposure occurs, we will be better able to explore the exposure–response relationship between quartz and various diseases.

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