Metal and Non-Metal Miners' Exposure to Crystalline Silica, 1998–2002

James L. Weeks, ScD, CIH[1*†] **and Cecile Rose,** MD, MPH[2‡]

Background *Crystalline silica is well known to cause silicosis and other diseases. Exposure is common in the mining industry and consequently, the US Mine Safety and Health Administration (MSHA) evaluates miners' exposure to silica to determine compliance with its exposure limit.*
Methods *MSHA exposure measurements were obtained for the 5-year period from 1998 to 2002 and average exposure was calculated classified by occupation and by mine. Evaluation criteria were whether average values exceeded MSHA's permissible exposure limit or the limit recommended by the National Institute for Occupational Safety and Health (NIOSH), whether there was a risk of exposure to freshly fractured silica, and whether there was a risk of a high rate of exposure to silica.*
Results *Miners in certain jobs are exposed to silica above permissible and recommended exposure limits. Some miners may also be exposed at a high rate or to freshly fractured silica.*
Conclusions *Known dust control methods should be implemented and regular medical surveillance should be provided.* Am. J. Ind. Med. 49: 523–534, 2006. *© 2006 Wiley-Liss, Inc.*

KEY WORDS: silica; exposure; metal miners; mine safety and health administration; air samples

INTRODUCTION

Rock dust has been known as a cause of lung disease in miners and stone workers since the 1st century. Adverse health effects in workers exposed to rock dust were described in more detail in the 16th century [Haeublein, 1982] and the specific cause—crystalline silica—was identified in the 19th century [Rosner and Markowitz, 1991].

Silica is the most common mineral in the earth's crust and consequently, most mining activity generates silica dust. Silica occurs in several different crystalline forms. The most abundant and often the only form that occurs naturally at any particular site is α-quartz. Polymorphs, cristobalite and tridymite, may also be present if there is a history of exposure to intense heat, such as from volcanic activity or from some industrial processes.

Silica is the cause of silicosis. It is usually a chronic fibrotic disease, developing over many years of exposure. It is diagnosed with an occupational history of exposure combined with a chest X-ray taken and interpreted according to standards for evaluating pneumoconiosis developed by the International Labor Organization [ILO, 2002]. Symptoms of shortness of breath and chest tightness develop slowly. Silicosis can also appear as an acute condition following brief (i.e., less than a year) exposure to very high levels. Silica also increases susceptibility to tuberculosis [Wagner, 1997].

[1]Advanced Technologies & Laboratories International, Germantown, Maryland
[2]Occupational Medicine Programs, National Jewish Medical and Research Center, Denver, Colorado
†Senior Scientist
‡Director
Contract grant sponsor: US Department of Health and Human Services; Contract grant number: H37CS00066.
*Correspondence to: James L. Weeks, Senior Scientist, Advanced Technologies & Laboratories International, 20010 Century Blvd., Suite 500, Germantown, MD 20854.
E-mail: jweeks@atlintl.com

Accepted 14 March 2006
DOI 10.1002/ajim.20323. Published online in Wiley InterScience (www.interscience.wiley.com)

AB36-COMM-55-5

The International Agency for Research on Cancer classified silica as a suspected carcinogen in 1987 and as a known carcinogen in 1997 [IARC, 1987, 1997]. The National Toxicology Program classified it as ''anticipated to be a human carcinogen'' in 1997 and as a ''known human carcinogen'' in 2001 [NTP, 1997, 2001]. Some autoimmune disorders (most commonly rheumatoid arthritis) are also associated with exposure to silica [Steenland and Goldsmith, 1995].

As these conditions are often resistant to treatment, disabling, and sometimes fatal, prevention is essential. The principal means of preventing the adverse effects of silica is by reducing or eliminating workers' exposure to respirable silica dust. In mining, exposure can be reduced with altered mining methods, well-designed ventilation, use of water, and other engineering methods. These methods are well known, feasible, and effective for most mining operations [Kissell, 2003].

To reduce exposure among miners, the Mine Safety and Health Administration (MSHA) is mandated to set safe exposure limits, to enforce compliance by inspecting mines, to issue penalties for non-compliance, to mandate exposure controls, and to provide technical assistance. To this end, MSHA takes about 3,000 dust samples per year at metal and non-metal mines in the US. These data were obtained and analyzed to identify jobs and mines at higher risk of disease.

MATERIALS AND METHODS

Data Set

The results of 8-hr full shift personal air samples taken by MSHA and analyzed for silica at metal and non-metal mines in the US for the 5-year period from 1998 to 2002 were obtained. MSHA takes personal breathing zone samples for a full 8-hr shift with a belt-mounted pump operating at 1.7 L per min. A 10-mm Dorr–Oliver cyclone removes non-respirable particles, and the respirable fraction is deposited on a 37-mm diameter poly-vinyl chloride filter. The filter is weighed before and after sampling to determine the respirable mass and the sample is analyzed for silica using X-ray diffraction (NIOSH Method 7500). Only samples with greater than 1% silica by mass are included in these data.

The record for each sample contained, among other variables, the date of the sample, concentration of respirable dust (C, mg/m^3), exposure limit (L, mg/m^3), mine name, owner, and unique identification number, type of mine (underground, surface, or mill), state where mine is located, mine status (active, intermittent, non-producing, or abandoned), and the job name and job code. These data neither include information about mine operators' use of dust controls nor include information about whether miners were using personal protective equipment.

Exposure Limit

MSHA adopted as its exposure limit the threshold limit value (TLV) set by the American Conference of Governmental Industrial Hygienists (ACGIH) in 1973 (30 CFR 56.5001 [surface mines] and 57.5001 [underground mines]). The TLV for respirable dust containing >1% quartz is calculated using the following formula:

$$L = 10/(pQ + 2), \text{ in which}$$

L = exposure limit for respirable dust (mg/m^3) and
pQ = percent quartz in the sample of respirable dust.

This formula is derived by combining the TLV for mixtures, with quartz and the remaining respirable dust as the two ingredients in the mixture. The TLV for quartz is set at 100 μg/m^3 and the TLV for the remaining dust is treated as nuisance particulate at 5 mg/m^3 [Hearl, 1996].

Because of a concern with evaluating the risk of adverse health effects from exposure to silica per se, the MSHA measurements were converted into equivalent concentrations of respirable silica by taking the product of pQ and C to obtain

$$Q = 10(10/L - 2)C, \text{ in which}$$

Q = concentration of respirable quartz (μg/m^3)
C = concentration of respirable dust (mg/m^3).

The remainder of this report is concerned with the value of Q.

Statistical Evaluation

As expected, the frequency distribution of Q is lognormal. (Fig. 1a,b). Arithmetic and geometric means and standard deviations for the dataset were calculated as a whole and as classified by job, mine, and state. The potential for cumulative exposure and risk of disease was calculated using arithmetic means and trends and differences among subsets were calculated using geometric means. To the extent feasible, a comparison of these data with earlier reports by others was initiated. All calculations and graphics were done using Statistica Version 6.1 or by hand.

Evaluation Criteria

Chronic silicosis typically occurs more than 10 years from first exposure and lung cancer typically occurs with a longer period of latency. Both are associated with cumulative exposure, that is, $Exp = \Sigma C_i T_i$, (C_i = average concentration for time interval i and T_i = its duration) and is typically expressed with the units, mg-years/m^3.

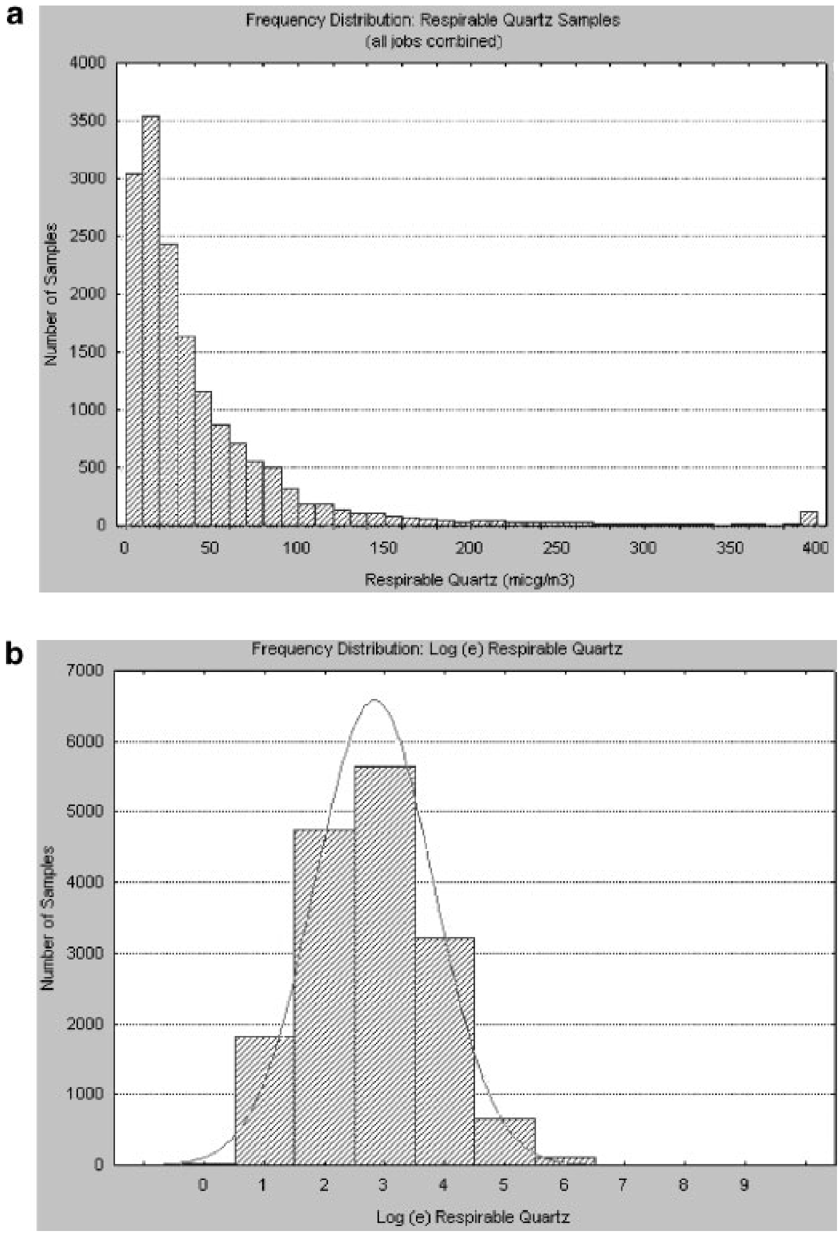

FIGURE 1. **a**: Frequency distribution: concentration of respirable quartz. **b**: Frequency distribution: Log_e (concentration of respirable quartz).

When setting permissible exposure limits, the conventional practice is to assume a working lifetime of 47 years (from age 18 to 65) as the total expected duration of exposure. A time-weighted average exposure limit for a shift is then selected that would reduce risk of disease to an acceptable level. The MSHA permissible exposure limit is roughly equivalent to a TWA limit of 100 μg/m^3 of quartz.

In 1972 and again in 2000, the National Institute for Occupational Safety and Health (NIOSH) recommended an exposure limit for respirable silica of 50 μg/m^3 for a 10-hr work shift as necessary to prevent silicosis [NIOSH, 1972, 2000]. Several risk assessments support this recommendation [Rice and Stayner, 1995; Steenland and Brown, 1995; Finkelstein, 2000; Chen et al., 2001; Rice et al., 2001; Steenland et al., 2001; Mannetje et al., 2002; Park et al., 2002; Attfield and Costello, 2004]. Because it is well supported by available data, it was concluded that an average exposure (over the entire 5-year period considered in these data) greater than 50 μg/m^3 was a risk factor for silicosis and for lung cancer.

A second evaluation criterion arises from the apparent elevated risk of disease associated with a high rate of exposure. The exposure limit above assumes a linear relationship between cumulative exposure and the risk of silicosis. This linear relationship appears to be valid in the absence of episodes of very high exposure. However, with instances of very high exposure, even when average exposure over time is at or below an acceptable exposure limit, the risk of silicosis appears to be higher than a linear model would predict [Smith, 1992; Seixas et al., 1993; Wagner, 1997; Buchanan et al., 2003]. The level (per shift), frequency, and duration of very high exposure at which a departure from linearity occurs have not been estimated.

Nevertheless, as a precautionary consideration, the occurrence of exposure to ''high'' levels is worth noting. Therefore, as a conservative approximation, we suggest that the occurrence of more than 10% of samples for a job exceeding 150 $\mu g/m^3$ constituted a second risk factor.

A third risk factor is the potential for exposure to freshly fractured silica. Risk of silicosis (and perhaps lung cancer) may be related to whether respirable dust has been freshly fractured from its parent rock. Several published reports have shown that freshly fractured quartz particles generate free radicals in vitro [Castranova, 1994; Shoemaker et al., 1995; Vallyathan et al., 1997]. Many characteristics of these free radicals, such as their pathogenic potential in vivo, the importance of the mode of fracture (e.g., drilling, crushing, blasting), the activity level related to the percent silica in the parent rock, and others have not been assessed. Nevertheless, and also as a precautionary consideration, we note those circumstances when such exposure is likely. These are situations when miners are present at the time and place that parent rock is being broken and respirable particles generated.

A positive or nil trend in exposure, in combination with any of the first three risk factors, constitutes an additional risk factor for disease. The data set in this report cover only 5 years but even so, there may be some trends in exposure over this relatively short time interval. In addition, data from the same source evaluated earlier by others can also be used to estimate trends. Consequently, trends for the time interval encompassing these data were analyzed. These measurements, to the extent feasible, were compared with those from prior reports.

To summarize, the risk factors we used as criteria to evaluate exposure are:

- Mean exposure (5-year) above 50 $\mu g/m^3$,
- The occurrence of more than 10% of samples above 150 $\mu g/m^3$ for any particular job or mine,
- Potential exposure to freshly fractured quartz, and
- A positive or nil trend in exposure for jobs with other risk factors.

RESULTS

Data Editing

From 1998 to 2000, MSHA took a total of 16,578 measurements for respirable quartz at 4,726 mines operating in every state in the US for at least part of this time period. There were 114 different job codes, 50 states, and 3 types of mines (Strip/Open Pit, Mill/Prep Plant, and Underground).

Of the total, 356 samples from the data set were deleted because they were outside the bounds of possible values. From equation (1) above, the upper and lower limits to the exposure limit for total respirable dust are 3.33 mg/m^3 and 0.098 (rounded to 0.10) mg/m^3, respectively, corresponding to implied concentrations of quartz of less than 1% and greater than 100%. Thirty-three samples had an exposure limit greater than 3.33 and 323 had exposure limits less than 0.10. It was assumed that these values resulted from errors that occurred during data processing. Also deleted were 15 samples from this data set that were analyzed for cristobalite. (Analysis was conducted on the remaining 16,207 samples with >1% quartz (Table I).

Percent Silica

For these dust samples, the percent silica increases with the number of samples, from 1% to 100% (Fig. 2). This distribution differs significantly from the frequency distribution noted in a report jointly prepared by the Bureau of Mines and the Public Health Service [Ankney and Heiman, 1963]. It is reported that 98% of over 20,000 samples from both surface and underground metal mines had less than 40% quartz. This difference may be a consequence of MSHA enforcement policy of sampling more frequently those mines and jobs with greater potential for exposure to quartz. In 1963, the federal government had a significantly weaker enforcement mandate.

TABLE I. Mine Safety and Health Administration Respiratory Quartz Samples Analyzed for Silicon and Exclusions

Types of samples	N
Total number of samples analyzed for SiO_2	16,596
Analyzed for cristobalite	15
Analyzed for tridymite	0
Containing >1% α-quartz	16,581
Samples with values out of bounds	
Exposure limit <0.10	337
Exposure limit >3.33	37
Samples analyzed	16,207

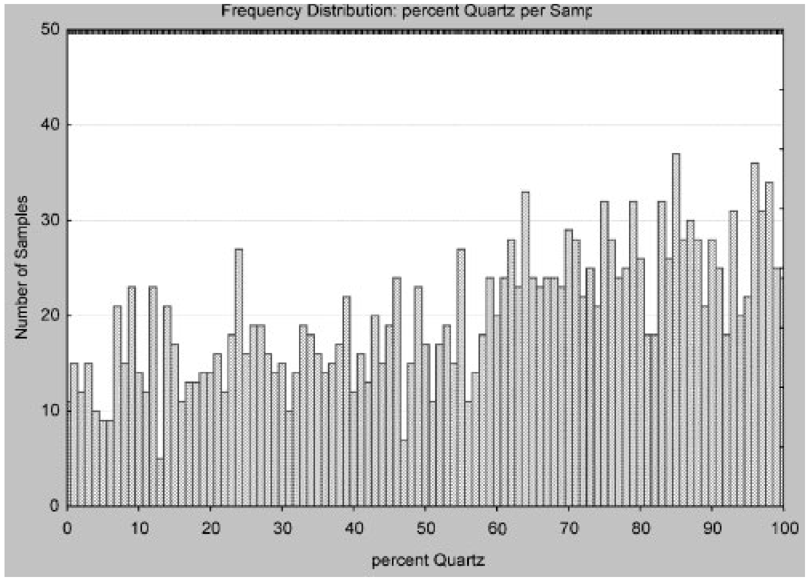

FIGURE 2. Frequency distribution: samples by percent quartz.

Summary Statistics

The grand geometric mean concentration was 27.2 μg/m^3. The geometric mean minus and plus one geometric standard deviation were 10.2 μg/m^3 and 72.4 μg/m^3, respectively. The grand arithmetic mean was 47.2 ± 129.3 μg/m^3 and the grand median 25.9 μg/m^3 (Table II).

Most (85%) samples were taken at strip or open pit mines, 7% were taken at mills or preparation plants, and 8% were taken in underground mines (Table II). The differences in geometric mean did not differ significantly when classified by type of mine. The percent of samples above 150 μg/m^3 ranged from 4.4% at preparation plants and mills to 5.5% in underground mines.

Samples Exceeding Exposure Limits

From among these samples taken together, 11.5% exceeded MSHA's permissible exposure limit as described above and among these, 8.8% exceeded MSHA's citation threshold value (CTV). This is the value above which MSHA issues a citation for non-compliance.[1] More than one out four samples (27.2%) exceeded NIOSH's recommended exposure limit of 50 μg/m^3 (Table III).

TABLE II. Mean and Geometric Mean (GM) Concentration of Respirable Quartz (μg/m^3) by Type of Mine

Type of mine	N	%	Mean	% > 150 μg/m^3	GM
Strip/open pit	13,702	84.5	47.1	4.6	27.1
Preparation plant/mill	1,145	7.1	44.9	4.4	26.7
Underground	1,360	8.4	49.6	5.5	28.6
Total	16,207		47.2	4.6	27.2

Higher proportions of samples exceed exposure limits in specific jobs. For stone polishers and bagging operators, approximately half of samples exceed the NIOSH REL and one out of four exceed the MSHA PEL. For cleanup workers, two out of five samples exceed the REL and one out of five exceed the PEL. For crusher operators and laborers, one out of three samples exceed the REL and one out of seven exceed the PEL (Table IV).

Concentration by Job

The mean concentration ranged from 271.7 μg/m^3 for continuous miner operators (five samples taken at three mines) to 6.1 μg/m^3. For jobs with 100 or more samples, the mean concentration ranged from 75.5 μg/m^3 (stone polisher/cutter) to 28.4 μg/m^3. More than 10% of samples exceeded 150 μg/m^3 at 14 jobs, five of which had more than 100 samples.

Distribution of values for 17 jobs with more than 100 samples is shown in Figure 3 using a box and whiskers display. This graph shows the median value near the midpoint of the box, the 25th and 75th percentiles at the lower and upper end of the box and the 5th and 95th percentiles at the lower and upper whiskers. Extreme and outlier values—less than the 5th and greater than the 95th percentile values are not shown. Variation is high for all jobs, with values extending

[1] MSHA adopted the CTV to accommodate sampling and analytical error and to ensure a high degree of confidence that actual as opposed to measured exposure exceeded the exposure limit. The CTV is MSHA's threshold for issuing a citation for non-compliance.

TABLE III. Number and Percent of All Samples Exceeding Selected Exposure Limits

Exposure limits	Number	Percent
MSHA PEL (C/L >1.0)	1,867	11.5
MSHA CTV (C/L >1.2)	1,427	8.8
NIOSH REL (C >50 μg/m^3)	4,414	27.2

PEL, permissible exposure limit; C/L, ratio of concentration to exposure limit (TLV); CTV, citation threshold value; REL, recommended exposure limit.

over two orders of magnitude for all but four of these jobs. The median values range from 56 μg/m^3 to 17 μg/m^3; the 75th percentile exceeds 100 μg/m^3 at one job (stone polisher/cutter) and the 95th percentile exceeds 200 μg/m^3 for four jobs (stone polisher/cutter; rotary drill operator; supervisor; and mechanic) and is near this level for one more job (bagging operator).

Risk Factors for Selected Jobs

Three risk factors (mean >50 μg/m^3, >10% of samples >150 μg/m^3, and exposure to freshly fractured quartz) were present for stone polishers/cutters and ball mill operators (Table V). Two risk factors (mean >50 μg/m^3 and exposure to freshly fractured quartz) were present for rotary drill operators and crusher operators. Mean exposure exceeded 50 μg/m^3 for six more jobs and exposure to freshly fractured quartz occurred without other risk factors for one job (drill operator).

The purpose of selecting jobs with more than 100 samples is to focus attention on those jobs that are both numerous and have higher levels of exposure. However, this should not obscure the occurrence of risk factors on less frequently sampled jobs. These jobs are tabulated (in alphabetical order, Table VI) showing the number of samples, the average exposure, the percent of samples greater than 150 μg/m^3, and the likelihood of being exposed to freshly fractured quartz. Similar jobs are grouped together and listed if any job in the category has an average greater than 50 μg/m^3. Such jobs are cutting machine workers, drill operators, jobs listed as "miners," operators of mobile machinery, and sand fillers. The list of drill operators also includes roof bolters and drilling jobs with more than 100 samples. Average concentration of respirable quartz for nearly all drill operators is greater than 50 μg/m^3 and this dust, by the usual proximity of drill operators to the drilling operation, likely also contains freshly fractured quartz. This list of jobs includes several in which rock is cut or broken (continuous miner operator, cutting machine operator or helper, and jackhammer operator). These data should be interpreted with caution because as the number of samples decreases so does the relevance of the measure and the stability of the mean and of the percent of samples greater than 150.

TABLE IV. Number and Percent of Samples Exceeding Exposure Limits for Selected High Exposure Jobs

Job (number of samples)	Number and percent of samples exceeding exposure limits: MSHA EL N	MSHA EL %	MSHA CTV N	MSHA CTV %	NIOSH REL N	NIOSH REL %
Bagging (839)	194	23.1	149	17.8	393	46.8
Crusher operator (2,955)	433	14.7	337	11.4	964	32.6
Laborer bullgang (900)	161	17.9	134	14.9	338	37.6
Cleanup (529)	104	19.7	86	16.3	218	41.2
Stone polisher (364)	91	25.0	67	18.4	208	57.1

Concentration by Job and by Type of Mine; Two-Way ANOVA

A two-way analysis of variance (not shown) of log-transformed values classified by job (with >100 samples) and type of mine showed that the geometric mean concentration varied significantly ($P < 0.001$) by job and by mine. The concentration for specific jobs is somewhat higher at strip and open pit mines than for the same jobs at other types of mines. However, the small *P*-value is more a consequence of the large number of data points than of meaningful differences.

Concentration by Mine

During this 5-year time period, there was only one sample per mine for 69% of all mines and there were fewer than 10 samples per mine for 93% of mines. Such few samples do not provide reliable estimates of exposure for specific mines. The distribution in the number of samples per mine is shown in Figure 4a.

Mine-specific mean and geometric mean values for mines with more than 10 samples show that mean exposure was above 100 μg/m^3 for 2 mines, was between 50 μg/m^3 and 100 μg/m^3 for 29 mines, and was <50 μg/m^3 for the remaining 88 mines. The maximum exposure was greater than 1,000 μg/m^3 for 2 of these mines, it was between 500 μg/m^3 and 1,000 μg/m^3 for 20 mines, was between 100 μg/m^3 and 500 μg/m^3 for 130 mines, and was less than 100 μg/m^3 for the remainder. Examination of job-specific values within mines with very high concentration shows that the high values almost always occurred at jobs listed in Figure 3.

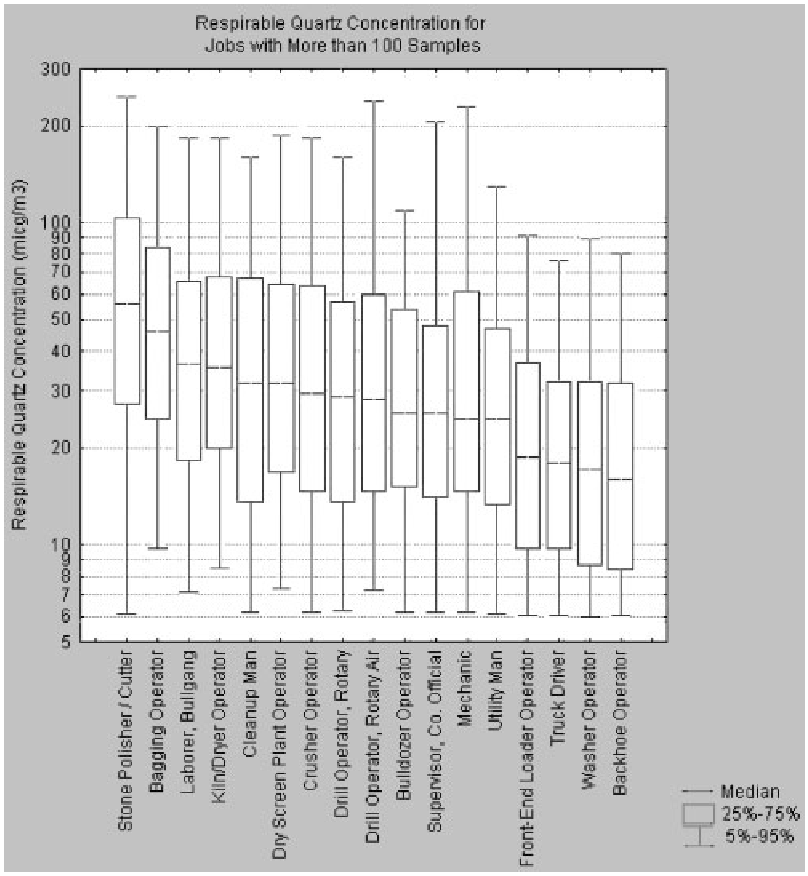

FIGURE 3. Concentration of respirable quartz by occupation (more than 100 samples).

There are a large number of mines with high mean concentration but few samples (Fig. 4b). A small number of samples at mines with very high levels of exposure is not consistent with a policy of taking more samples at mines where exposure is elevated. There were 191 samples that exceeded MSHA's CTV and were the only samples at these mines during the time interval of these data. This suggests there were no follow-up inspections at these mines although there could have been other types of follow-up. It is conceivable that these samples were taken towards the end of the 5-year time interval and that follow-up inspections occurred after the end of this interval and therefore were not included in this data set. These inspections, however, occurred throughout this time interval and were not concentrated at the end.

TABLE V. Jobs With >100 Samples and ≥1 Risk Factors; Metal and Non-Metal Miners

Jobs	Mean >50 μg/m^3	Percent of samples >150 μg/m^3	Exposure to freshly fractured quartz
1. Stone polisher/cutter	75.5	10.7	•
2. Ball mill operator	69.8	11.6	•
3. Drill operator, rotary	55.9	3.8	•
4. Crusher operator	54.7	6.3	•
5. Cleanup man	70.6	9.3	
6. Bagging operator	69.4	9.0	
7. Lab technician	63.7	6.3	
8. Laborer, bullgang	61.9	7.3	
9. Truck loader	55.0	8.4	
10. Mechanic	54.4	5.1	
11. Kiln/dryer operator	52.9	5.0	
12. Drill operator, rotary air	55.9	8.1	•

Concentration by State

The mean concentration of respirable silica by state (all mines combined) ranges from 84.8 μg/m^3 to 9.1 μg/m^3. The mean value exceeds 50 μg/m^3 in 15 states. Five of the 10 states with the highest mean concentration are Rocky Mountain States, Nevada, Utah, Montana, Colorado, and Idaho.

A two-way ANOVA of log-transformed values for mountain states and type of mine showed significant differences between states, by type of mine, along with significant interaction. The highest geometric mean concentration occurred for underground mines, particularly

TABLE VI. Jobs With <100 Samples and ≥1 Risk Factors; Metal and Non-Metal Miners

Job	Number of samples	Average	Percent of samples >150 μg/m^3	Exposure to freshly fractured quartz
Belt cleaner	63	61.0	7.9	
Cont. miner operator	5	271.7	60.0	•
Cutting machine				
Helper	9	95.5	11.1	•
Operator	27	68.7	7.4	
Drill workers				
Diamond	13	47.0	0.0	•
Helper	24	54.1	12.5	•
Jackleg/stopper	26	69.7	15.4	•
Churn	1	22.1	0.0	•
Jet piercing	11	63.4	9.1	•
Jumbo percussion	43	41.0	2.3	•
Rotary	290	45.3	3.8	•
Rotary air	248	55.9	8.1	•
Wagon drill operator	6	94.2	16.7	•
Roof bolter, rock	21	53.0	0.0	•
Roof bolter, mounted	14	28.7	6.9	•
Ground control, timber	3	148.6	33.3	
Hand loader	4	51.2	0.0	
Hydrating plant oper.	8	106.4	12.5	
Jackhammer operator	34	88.6	20.6	•
Mason	6	71.6	0.0	
Miners				
Drift	23	64.3	4.4	•
Raise	2	98.9	50.0	•
Stope	10	53.1	0.0	•
Mobile machine oper.				
Mucking machine oper.	13	91.9	23.1	
Scoop-tram operator	25	63.2	8.0	
Shuttle car operator (diesel)	2	67.4	0.0	
Shuttle car operator (electric)	3	10.6	0.0	
Skip dumper	15	59.5	6.7	
Nipper, supply man	2	75.6	0.0	
Oiler, greaser	77	57.9	6.5	
Pelletizer operator	61	55.0	13.1	•
Sampler, dust	38	61.6	7.9	
Sand filler				
Dry	6	63.9	16.7	
Wet	4	11.9	0.0	

in Nevada, Utah, and Idaho. Levels are generally higher in Nevada and Utah and lower in New Mexico and Arizona.

Trend Analysis

For the data set as a whole there is no discernable trend by simple linear regression of log-transformed data on the date of the sample. Although the very large number of samples produced results with $P < 0.05$, the adjusted value of R^2 was only 0.004. Similarly, there was no trend for selected jobs (bagging, stone polishing, crusher operator, cleanup, and laborer).

These data were compared with prior measurements by other investigators. As it was not possible to match jobs exactly, comparisons should be interpreted with caution. Published reports of prior exposure to silica among metal and non-metal miners show higher geometric mean exposure for bagging operators, lower levels for workers in crushing or

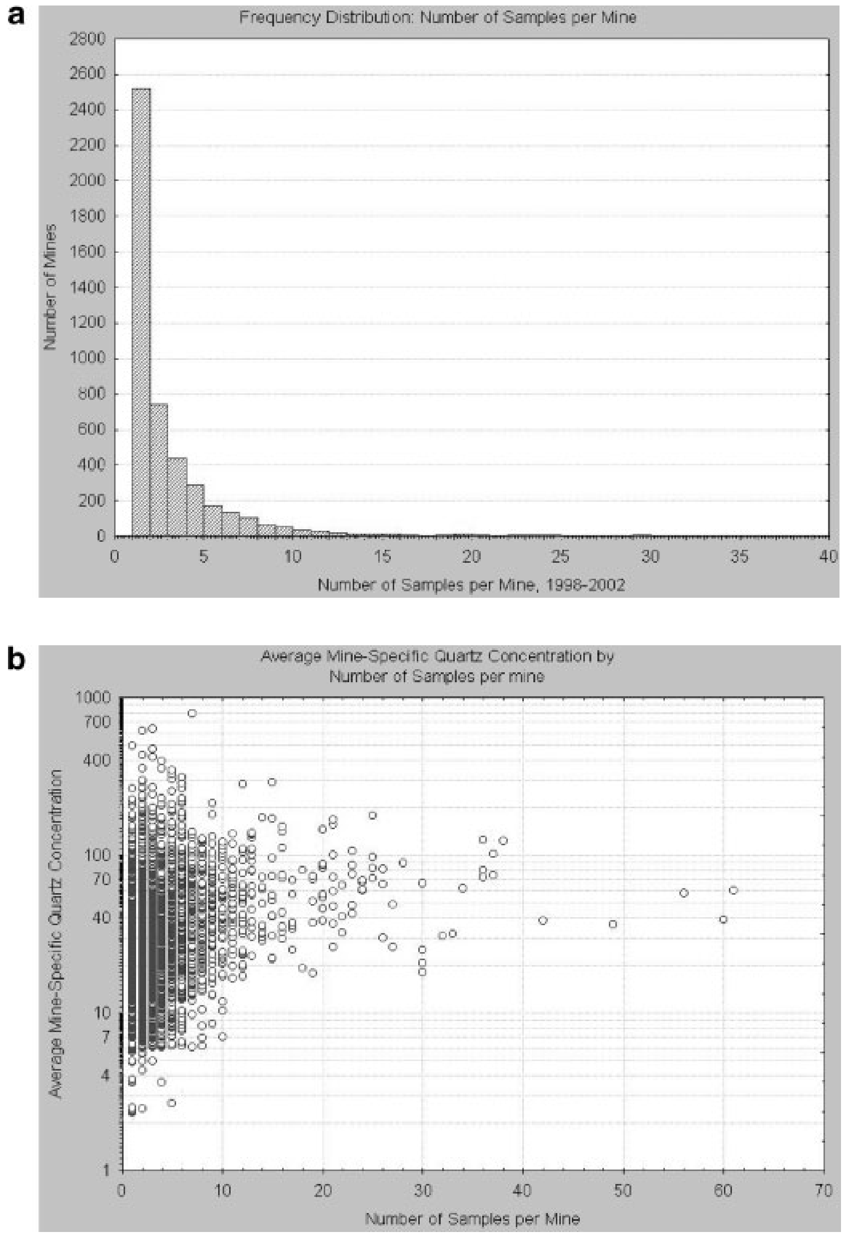

FIGURE 4. **a**: Frequency distribution: number of samples per mine. **b**: Respirable quartz concentration by number of samples per mine.

mill operations, and approximately the same level for other jobs (Table VII). As part of a risk assessment of silicosis among gold miners in the US, Steenland and Brown [1995] evaluated miners' exposure from 1940 to 1965. They reported a median level of 50 μ/m^3 with 150 μg/m^3 for workers hired before 1930. Steenland and Sanderson [2001], in a study of lung cancer among industrial sand workers, evaluated over 4,000 samples collected from 1974 to 1995 and reported, as in the study of gold miners, a median exposure level of 50 μg/m^3. Separately, these same authors provided additional information for the same population and reported a geometric mean of 25.9 μg/m^3, with some exposure measurements as high as 11,700 μg/m^3 [Sanderson et al., 2000]. (The grand geometric mean in the present data is 27.2 μg/m^3.) More than a third of samples exceeded the MSHA exposure limit and about half exceeded the NIOSH REL. In the present data analysis, 11.5% of samples exceeded MSHA's exposure limit and 27.2% exceeded the REL, suggesting substantial improvement.

Kullman et al. [1995] reported on exposure to crushed stone operations from 1979 to 1982. They reported that one in seven samples exceeded the MSHA permissible exposure limit (i.e., the 1973 TLV) and one in four exceeded the NIOSH recommended limit of 50 μg/m^3. Mill operators and

TABLE VII. Comparison of Geometric Mean Exposure: Industrial Sand Workers, 1974–1995 (Steenland and Sanderson [2001]) Versus All Metal and Non-Metal Miners, 1998–2002

		Geometric mean		
Job	**N**	**1974–1995**	**1998–2002**	**N**
Quarry	680	9.6		
Crushing	282	17.1	31.4	2,955
Wet process	280	17.7		
Drying	427	30.6	32.5	238
Screening	163	44.6		
Milling	392	30.2	38.0*	155
Bagging	1,142	60.2	44.6	836
Loading	252	28.5		

Number of samples and geometric mean (μg/m^3).
*Ball mill operator, 1998–2002.

mill laborers consistently had the highest and most frequent overexposure to silica. In our data analysis, one of seven (14.7%) samples of crusher operators exceeded MSHA's exposure limit and one of three (32.6%) exceeded the REL, suggesting an increase in exposure for this job. In our data, stone polishers consistently had the highest level of exposure; we had no job comparable to mill operators or laborers.

For three out of four jobs, the geometric mean is higher in the more recent period and for one job (bagging), recent exposure measurements are lower by a third. In the 1974–1995 period, the geometric mean for bagging operator was 60.2 μg/m^3 but this had been reduced to 44.6 μg/m^3 by 1998–2002.

Watts et al. [1989] analyzed nearly 12,000 samples taken at all metal and non-metal mines from 1974 to 1981. Data were obtained from the same source as these data, that is, they were taken by MSHA and its predecessor agencies for compliance purposes. Results were compared to the 1973 TLV for silica. Over this time period, they found significant decline in the percent of samples greater than the MSHA exposure limit, from 46% in 1974 to as low as 14% in 1979. There were significant differences between jobs and types of mines.

For baggers, Watts et al. [1989] found that 39.8% of samples exceeded the exposure limit, as did 21.9% of laborers' samples, 18.5% of crushing machine operators, and 19.4% of samples for rotary drill operators for the period 1978–1981. Higher levels were reported for the period 1974–1977, prior to the creation of MSHA.

For the period considered in this report, 25% of samples taken for stone-cutters, 23% of those for bagging, 20% of samples for cleanup workers, 17% of samples for general laborers, and 15% of samples taken at crushing jobs exceeded the exposure limit. For drill operators, 15.7% of samples for rotary (air) drill operators exceeded the exposure limit as did

TABLE VIII. Comparison of Exposure Measurements With Metal and Non-Metal Miners, 1978–1981 Versus 1998–2002

	Percent of samples > TLV	
Job	**1978–1981**	**1998–2002**
Bagging	39.8	23.1
Laborer, bullgang	21.9	17.9
Stone crushing	18.5	14.7
Rotary drill operators	19.4	15.7*
		11.0**
Total (all jobs)	15.1	11.5

*Rotary (air) drills.
**Rotary drills.

11.0% of samples for rotary drill operators (Table VIII). Reduction in exposure for drill operators may result from dust control regulations promulgated by MSHA [1994]. There was a significant reduction in exposure for drill operators at coal mines followed this rule [Weeks, 2002].

These comparisons (Table VIII) show substantial reduction in the number of samples above the exposure limit for baggers, laborers, and drill operators and modest reduction for stone crushing workers.

DISCUSSION

In this investigation, exposures measured from over 16,000 individual samples taken over a 5-year period were analyzed. These samples were taken by MSHA for compliance purposes and, for that reason, jobs with higher exposure are overrepresented. This likely skews findings to create an upward bias compared to a representative sample of all miners' exposure. In contrast, a downward bias for compliance sampling has been demonstrated in analysis of sampling for respirable dust in coal mines [Seixas et al., 1990; Weeks, 2003]. Despite these sources of bias, our analysis provides insight into on-going exposure risks faced by metal/non-metal miners as well as needs for primary prevention by reducing exposure.

There were significant differences in risk factors for exposure to respirable silica among jobs. There were 11 jobs with more than 100 samples for which the mean exposure exceeds 50 μg/m^3. For two of these jobs (stone cutting and polishing and ball mill operator), more than 10% of samples exceeded 150 μg/m^3, suggesting that workers are occasionally exposed to very high levels. These workers are also likely exposed to freshly fractured quartz, further increasing their risk for occupational lung disease.

Exposure was also excessive for many jobs with fewer than 100 samples. Nearly all drilling jobs and jobs involving cutting or breaking rock had average exposure above 50 μg/m^3 combined with the potential for exposure to freshly fractured quartz. Average quartz concentration for operators of mobile equipment also exceeded 50 μg/m^3.

Few samples were taken for most mines, making it difficult to make a reliable estimate of mine-specific exposure. For mines with 10 or more samples, mean exposure exceeded 100 μg/m^3 for a small number of mines and exceeded 50 μg/m^3 at more. In most instances, one of the high exposure jobs listed in Table V accounted for the elevated mean exposure for the mine.

Trends in exposure were mixed. For the 5-year time period during which these samples were taken, there was no change in the geometric mean concentration for any job, even those with high exposure. For workers in bagging operations, the geometric mean and the percent of samples greater than MSHA's exposure limit were both lower than they were during earlier time periods. For workers in stone crushing operations, the more recent geometric mean was higher but the percent of samples higher than the exposure limit was lower than it was for earlier measurements. For milling machine operators, the geometric mean was higher than for earlier time periods and the percent of samples greater than the exposure limit was lower for laborers and drill operators. Thus, the best documented progress in reducing exposure appears to be for bagging operations but even with this job, nearly half the samples exceeded the REL.

Our data suggest that further primary preventive efforts designed to reduce exposure need to be targeted to specific jobs in the metal/non-metal mining industry. Feasible and effective engineering controls for dust in mining operations are available [Burgess et al., 1989; Kissell, 2003]. Dust controls for surface drilling operations are effective [Cecala et al., 2005; Weeks, 2002] and have been mandatory since 1994 (30 CFR 58.620). Dust controls for bag-filling, one of the jobs with historically high exposure levels, have been well known since at least 1964 and bagging machines currently available have local exhaust ventilation hoods as an integral part [Burgess, 1995]. Dust controls for transfer of bulk materials from conveyor belts have been available since at least 1972 [ACGIH, 1978; Burgess et al., 1989]. Local exhaust ventilation for stone cutting operations has been available since 1974.

Given these findings of on-going silica exposure in the mining industry, we expect cases of silicosis and other silica-related diseases will continue to occur decades from now. These are entirely preventable. Harmful effects are significant, irreversible, and well known. Preventive measures are feasible and effective and should be implemented. Workers in high-risk job categories should be provided with medical surveillance program focused on early detection and management of silica-related illnesses. Workers with signs of silica-related disease should have their individual exposure reduced and monitored to diminish the risk of disease progression.

Recommendations

Greater efforts are needed to implement dust controls to reduce exposure for high-risk jobs. Jobs with the potential for episodes of ''high'' exposure should be identified along with conditions that result in these episodes and controls developed specifically to reduce the frequency of such exposure. It is critical that miners' exposure to freshly fractured silica should be reduced and that further research is needed to evaluate exposure and effects for freshly fractured silica. Medical surveillance of miners is recommended. Additional job-specific and mine-specific analysis would be useful for high-risk jobs. Information about exposure such as contained in this report should be distributed throughout the industry.

ACKNOWLEDGMENTS

The assistance and cooperation in obtaining and interpreting these data by Robert Haney, Ed Miller, and Andrew Gero at MSHA's Technical Support Center and of Carol Jones, former Chief of the Metal and Non-Metal Health Division of MSHA are greatly appreciated.

REFERENCES

ACGIH. 1978. Industrial ventilation. A manual of recommended practice. 15th edn. Cincinnati, OH: American Conference of Governmental Industrial Hygienists.

Ankney MJ, Heimann H. 1963. Silicosis in the metal mining industry. A revaluation, 1958–1961. Bureau of Mines and Public Health Service. Public Health Services Publication No. 1076. Washington, DC: US Government Printing Office.

Attfield MD, Costello J. 2004. Quantitative exposure-response for silica dust and lung cancer in Vermont granite workers. Am J Ind Med 45:129–138.

Buchanan D, Miller BG, Soutar CA. 2003. Quantitative relations between exposure to respirable quartz and risk of silicosis. Occ Env Med 60:159–164.

Burgess WA. 1995. Recognition of health hazards in industry. A review of materials and processes. 2nd edn. New York: John Wiley & Sons, Inc.

Burgess WA, Ellenbecker MJ, Treitman RD. 1989. Ventilation for control of the work environment. New York: John A. Wiley & Sons, Inc.

Castranova V. 1994. Generation of oxygen radicals and mechanisms of injury prevention. Env Health Persp 102(Suppl 10):65–68.

Cecala AB, Organiscak JA, Zimmer JA, Heitbrink WA, Moyer ES, Schmitz M, Ahrenholtz E, Coppock CC, Andrews EH. 2005. Reducing enclosed cab drill operator's respirable dust exposure with effective filtration and pressurization techniques. J Occ Env Hyg 2:54–63.

Chen W, Zhuang Z, Attfield MD, Chen BT, Gao P, Harrison JC, Fu C, Chen JQ, Wallace WE. 2001. Exposure to silica and silicosis among tin miners in China: Exposure-response analyses and risk assessment. Occ Env Med 58:31–37.

Finkelstein MM. 2000. Silica, silicosis, and lung cancer: A risk assessment. Am J Ind Med 38:8–18.

Haeublein HG. 1982. Early studies of miners and smelters. Am J Ind Med 3:357–358.

Hearl FJ. 1996. Mixture formula justified. Am Ind Hyg Assoc J 57:574–575.

International Agency for Research on Cancer. 1987. Monographs on carcinogenic risk of chemicals. Silica and some silicates, Vol. 42. Lyon, France: World Health Organization.

International Agency for Research on Cancer. 1997. Monographs on carcinogenic risk of chemicals. Silica, some silicates, coal dust and para-aramid fibrils. Vol. 8. Lyon, France: World Health Organization.

International Labor Organization. 2002. Guidelines for the use of the ILO classification of radiographs of pneumoconioses, Revised Ed. Occup Saf Health Series 22:1–43.

Kissell FN. 2003. Handbook for dust control in mining. Publication No. 2003-147. 2003. Pittsburgh, PA: Centers for Disease Control, National Institute for Occupational Safety and Health. Information Circular 9465.

Kullman GJ, Greife AL, Costello J, Hearl FJ. 1995. Occupational exposures to fibers and quartz at 19 crushed stone mining and milling operations. Am J Ind Med 27:641–660.

Mannetje A, Steenland K, Attfield M, Boffetta P, Checkoway H, DeKlerk N, Koskela RS. 2002. Exposure-response analysis and risk assessment for silica and silicosis mortality in a pooled analysis of six cohorts. Occ Env Med 59:723–728.

Mine Safety and Health Administration. 1994. Air quality: Health standards for abrasive blasting and drill dust Control; Final rule. 30 CFR 58.620. 59 Fed Reg: 8318-28.

National Institute for Occupational Safety and Health. 1974. Criteria for a recommended standard: Occupational exposure to crystalline silica. Washington, DC: DHHS(NIOSH) Publication No. 75–120. 1974.

National Institute for Occupational Safety and Health. 2002. NIOSH Hazard Review. Health effects of occupational exposure to respirable crystalline silica. 2002. Publication No. 2002-129. Washington, DC: National Institute for Occupational Safety and Health.

National Toxicology Program. 1997. Sixth annual report on carcinogens. National Institute for Environmental Health Sciences.

National Toxicology Program. 2001. Ninth annual report on carcinogens. National Institute for Environmental Health Sciences.

Park R, Rice F, Stayner L, Smith R, Gilbert S, Checkoway H. 2002. Exposure to crystalline silica, silicosis, and lung disease other than cancer in diatomaceous earth industry workers: A quantitative risk assessment. Occ Env Med 59:36–43.

Rice FL, Stayner LT. 1995. Assessment of silicosis risk for occupational exposure to crystalline silica. Scand J Work Environ Health 21(Suppl 2):87–90.

Rice FL, Park R, Stayner L, Smith R, Gilbert S, Checkoway H. 2001. Crystalline silica exposure and lung cancer mortality in diatomaceous earth industry workers: A quantitative risk assessment. Occ Env Med 58:38–45.

Rosner D, Markowitz G. 1991. Deadly dust. The politics of occupational disease in twentieth century America. Princeton, NJ: Princeton University Press. p 31–38.

Sanderson WT, Steenland K, Deddens JA. 2000. Historical respirable quartz exposures of industrial sand workers: 1946–1996. Am J Ind Med 38:389–398.

Seixas NS, Robins TG, Rice CH, Moulton LH. 1990. Assessment of potential biases in the application of MSHA respirable coal minedust data to an epidemiologic study. Am Ind Hyg Assoc J 51:534–540.

Seixas NS, Robins TG, Becker M. 1993. A novel approach to the characterization of cumulative exposure for the study of chronic occupational disease. Am J Epidemiol 137:463–471.

Shoemaker DA, Pretty JR, Ramsey DM, McLaurin JL, Khan A, Teass AW, Castranova V, Pailes WH, Dalal NS, Miles PR. 1995. Particle activity and in vivo pulmonary response to freshly milled and aged alpha-quartz. Scand J Work Environ Health 21(Suppl 2):15–18.

Shoemaker DA, Ramsey DM, Pretty JR, McLaurin JL. 1995. Freshly fractured quartz inhalation leads to enhanced lung injury and inflammation. Potential role of free radicals. Am J Respir Crit Care Med 152:1003–1009.

Smith TJ. 1992. Occupational exposure and dose over time: Limitations of cumulative exposure. Am J Ind Med 21:35–51.

Steenland K, Brown D. 1995. Silicosis among gold miners: Exposure—Response analyses and risk assessment. Am J Public Health 85:1372–1377.

Steenland K, Goldsmith DF. 1995. Silica exposure and autoimmune diseases. Am J Indus Med 28:603–608.

Steenland K, Sanderson W. 2001. Lung cancer among industrial sand workers exposed to crystalline silica. Am J Epidemiol 153:695–703.

Steenland K, Mannetje A, Boffetta P, Stayner L, Attfield M, Chen J, Dosemeci M, DeKlerk N, Hnizdo E, Koskela R, Checkoway H. 2001. Pooled exposure-response analyses and risk assessment for lung cancer in 10 cohorts of silica-exposed workers: An IARC multicentre study. Cancer Causes Control 12:773–784.

Vallyathan V, Leonard S, Kuppusamy P, Pack D, Chzhan M, Sanders SP, Zweir JL. 1997. Oxidative stress in silicosis: Evidence for the enhanced clearance of free radicals from whole lungs. Mol Cell Biochem 168: 125–132.

Wagner GR. Asbestosis and silicosis. 1997. Lancet 349:1311–1315.

Watts WF, Parker DR, Johnson RL, Jensen KL. 1989. Analysis of data on respirable quartz dust samples collected in metal and nonmetal mines and mills. IC 8967.

Weeks JL. 2002. Reducing exposure to quartz at surface coal mines. Third International Symposium on silica, silicosis, cancer and other diseases. Santa Margherita Liguria, Italy.

Weeks JL. 2003. The fox guarding the chicken coop: Monitoring exposure to respirable coal mine dust, 1969–2000. Am J Public Health 93:1236–1244.