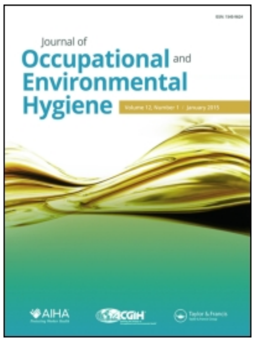

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A comprehensive assessment of exposures to respirable dust and silica in the taconite mining industry

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ABSTRACT

This study assessed the present-day levels (year 2010–2011) of exposure to respirable dust (RD) and respirable silica (RS) in taconite mines and evaluated how the mining process influences exposure concentrations. Personal samples (n = 679) were collected to assess exposure levels of workers to RD and RS at six mines in the Mesabi Iron Range of Minnesota. The RD and RS concentrations were measured using the National Institute for Occupational Safety and Health (NIOSH) 0600 and NIOSH 7500, respectively. Between-mine, between-SEG (similar exposure groups), within-SEG, and within-worker components of variability for RD and RS exposures were estimated using a two- or three-way nested random-effects ANOVA model. The majority of RD concentrations across all mines were below the Mine Safety and Health Administration (MSHA) Permissible Exposure Limit (PEL). The highest concentrations of RD were often observed in either the *Pelletizing* or *Crushing* departments, which are inherently dusty operations. With a few exceptions, the concentrations of RS in the crushing and concentrating processes were higher than those in the other mining processes, as well as higher than the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for RS. The magnetic separation and flotation processes in the concentrating department reduced the levels of RS significantly, and lowered the percentage of quartz in RD in the pelletizing department. There was little variability among the six mines or between the two mineralogically distinct zones for either RD or RS exposures. The between-SEG variability for RS did not differ substantially across most of the mines and was a major component of exposure variance. The within-SEG (or between-worker) variance component was typically the smallest because in many instances one worker from a SEG within a mine was monitored multiple times. Some of these findings were affected by the degree of censoring in each SEG and mine, characteristics of the taconite rock, seasonal effects during sampling, or the tasks assigned to each job in that mine.

KEYWORDS
Exposure assessment; respirable dust; respirable silica (quartz); taconite; variance components

Introduction

The potential relationship between taconite dust exposure and health risks in northeastern Minnesota's Mesabi Iron Range has raised concerns in the taconite mining industry and its surrounding communities. Respirable dust and respirable silica are the most common dust components observed during the taconite mining processes—drilling, crushing, feeding, and transferring. Respirable dust (RD) is the fraction of inhaled dust that can penetrate into the alveolar region of the respiratory tract using a sampler based on the respirable criterion curve with a 50% sampling efficiency for particles with an aerodynamic diameter of 4 µm.[1] Respirable silica (RS), which is a sub-fraction of RD, consists of two mineral forms: crystalline (free silica) and amorphous. The crystalline form has three subgroups: quartz, tridymite, and cristobalite,[2] the most common of which is quartz. In our study, we focused on crystalline quartz.

Exposure to the crystalline forms of silica in industrial settings has long been associated with the development of silicosis, a fibrotic pulmonary disease.[3–8] Although the National Institute for Occupational Safety and Health[9] found that the number of deaths from silicosis has decreased by a factor of 10 from 1968–2007, several

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hundred deaths per year still occur as does the non-lethal lung impairment related to silica exposure. A radiographic study of taconite miners in 1980 found several cases of silicosis but no other significant abnormalities or diseases.[10] Higgins et al.[11] studied the taconite workers in the Reserve Mining Company in the Mesabi Range and found no association between mortality and lifetime exposure to either RD or RS, concluding that the taconite miners did not have an elevated risk of mortality. However, these were small studies with limitations in exposure assessment and disease latency.

Only a few studies have investigated exposure to RD and RS in the taconite mining industry. Sheehy[12] found that RS exposures in the taconite industry often exceeded 0.05 mg/m^3, the NIOSH REL (Recommended Exposure Limit) at that time. Sheehy and McJilton[13] reported that the concentrations of silica-containing dust were above acceptable limits in mines, crushers, and concentrators, but not in pellet plants. The limits referenced included the NIOSH REL at 0.05 mg/m^3 as well as the Permissible Exposure Limit (PEL), set by the Mine Safety and Health Administration (MSHA) for crystalline respirable quartz, which is currently 10 mg/m^3 divided by the percentage of quartz plus 2. Quartz silica concentrations ranged from less than 0.04 to 0.11 mg/m^3, and no tridymite or cristobalite was found in any of the samples.[14] No additional studies of exposure levels to RD and RS in the taconite mining industry have been performed since the 1990s.

Concentrations of RD and RS can vary across taconite processes. In this article, we focus on the taconite open pit mining processes, sub-grouped by department (mining, crushing, concentrating, and pelletizing). In the mining step, the hard taconite rock is broken up by dynamite. Production trucks haul the taconite rocks directly to the crushing plant, where a large amount of dust is generated as the ore is dumped. The rocks are crushed to about 10 cm in diameter in the primary crusher and to smaller sizes in the secondary or tertiary crusher. The size of the crushed ore varies by the type of crusher and mine. The crushing process produces a noticeable amount of dust. Next, in the concentrating department, the crushed ore is mixed with water and ground in rotating mills until it becomes a fine powder. A magnetic separator then removes the waste rock (called "tailings") from the iron-bearing grains of taconite powder (called "concentrate"). Flotation processes separate lighter silica-containing particles from heavier iron-containing particles, which settle out. In the last step, the pelletizing process removes water from the concentrated iron slurry and then mixes the slurry with bentonite clay and/or limestone in large rotating cylinders to make pellets about 1 cm in diameter. The pellets are dried and hardened by heating to 1300°C, and then transported to steel mills.

The goals of this paper are: (i) to assess the present-day exposures to RD and RS in six active mines within the Minnesota taconite mining industry; (ii) to estimate the between-mine, between-SEG (similar exposure group), within-SEG, and within-worker components of variability for RD and RS exposures; and (iii) to evaluate the influence of the taconite mining and processing on exposures to RD and RS. To assess exposure concentrations of these dust components, we conducted personal air sampling across all operating mines in the Mesabi Iron Range. Currently, one mine operates in the eastern zone (Mine A) and five mines in the western zone (Mines B, C, D, E, and F).

Methods

Formation of SEGs

SEGs can be used to efficiently assess exposures using job titles, locations, tasks, and procedures.[15] The process we used to form SEGs has been previously described.[16] Briefly, we created a historical exposure database based on job titles and areas according to tasks and processes from four databases: MSHA, a previous study of the taconite mining industry,[12] industrial hygiene and human resources from the three companies that own the Mesabi Range mines (U.S. Steel, Cliffs Natural Resources, and Arcelor Mittal), and *Job Descriptions and Classifications*.[17] Using information on the tasks and processes related to these job titles, we created a set of 60 SEGs. This list was further condensed to 28 SEGs using the subjective professional judgments of the lead industrial hygienists at the three mining companies. The number of job titles represented in each SEG ranged from 1–19. The final list contained 181 job titles, forming 28 SEGs that we further grouped into seven departments.[16]

Sampling design and data handling

An assessment of personal exposures was conducted across six currently operational mines on the Mesabi Iron Range. The dates for sampling in the mines varied (e.g., Mine A: January–April 2010; Mine B: November 2010–February 2011; Mine C: February–May 2011; Mine D: June 2010; Mine E: July–September 2010; Mine F: October 2010). Prior to the day of sampling, the researchers and representatives from the mining companies discussed workers' schedules and identified potential participants. At the beginning of the work shift on each sampling day, the researchers explained the purpose of the study and presented the potential participants with the consent form approved by the University of Minnesota Institutional Review Board (IRB code: 0901M58041).

To perform a baseline exposure assessment for a job title, the American Industrial Hygiene Association (AIHA) sampling strategy[15] recommends that a minimum of 6, but preferably 8–10, exposure samples per SEG be obtained. Two workers per SEG were selected for personal sampling in the eastern zone; approximately eight workers per SEG were chosen across the five remaining mines in the western zone. Each consenting participant wore a personal air-sampling pump (Apex Pro pump, Casella Inc., Amherst, NH) on his or her waist, with the sampler located in the breathing zone for approximately hr, which accounts for at least 70% of a daily work shift. Personal sampling for each worker was completed during three different work shifts, although not necessarily on consecutive days. One blank sample per sampling day (approximately 14% of the samples) was collected for quality control.

Each sample for RD and RS was obtained using a single filter cassette. We used 5-μm pore size, 37-mm diameter polyvinyl chloride (PVC) membrane filters and 3-piece filter cassettes with a 37-mm aluminum cyclone (SKC Inc., Eighty Four, PA) for sampling. The flow rate for the sampling pump was calibrated at 2.5 L/min.

Analytical methods and limitations

The RD concentration, based on the mass of the respirable dust fraction, was calculated using NIOSH 0600 *Respirable particulates not otherwise regulated gravimetric method*.[18] The RS analysis was performed using NIOSH 7500 *Crystalline silica X-ray diffraction*.[19] These NIOSH methods stipulate that particles collected by the filter not exceed a mass of 2 mg because the collected particles could then block the filter, resulting in a lower airflow rate than that in the calibrated air sample. We excluded three samples that were overloaded with particles and six that exhibited a low sampling volume from further data analysis.

If all of the measurements for a given SEG fell below the limit of detection (LOD), summary statistics such as the arithmetic means (AM), geometric means (GM), and geometric standard (GSD) deviations were reported as "<LOD." If at least one sample for an SEG in a particular mine had measurements above the LOD, then summary statistics were calculated using beta-substitution. Ganser and Hewett[20] and Huynh et al.[21] examined beta-substitution with multiple scenarios using different combinations of number of samples (N), percent LOD, and GSD. Based on simulations, these authors found that the beta-substitution method exhibits better precision than other methods and only a minor bias overall in estimates of the mean. While the beta-substitution method, which replaces each observation $<$ LOD with a value equal to β x LOD, worked well for estimating summary statistics, it failed when all the data for an SEG/mine were $<$ LOD.[21] During the estimation of the variance components (described in the next section), for such cases, each censored value was replaced with a value LOD/2.

Statistical analysis methods

Of the 28 SEGs, 27 were monitored. We were not able to monitor the *Janitor* SEG because all of the janitors currently working in the taconite mining industry are independent contractors. Furthermore, not all 27 SEGs were represented in each mine. For instance, some mines have detailed job titles that correspond to an SEG (e.g., *Boiler technician*), but others have no corresponding jobs or tasks.

For each SEG, we used a simple one-way ANOVA model to determine if there were significant differences between mines. The dependent variables were RD and RS exposure concentrations. The log-transformed estimated exposures Y_{ij} of each mine were expressed as

$$Y_{ij} = \log\left(X_{ij}\right) = \mu_y + \alpha_i + \varepsilon_{ij} \text{ for } i = 1, 2, \ldots, 6, \text{ and } j = 1, 2, \ldots, 12, \quad (1)$$

where X_{ij} = exposure concentration of the i^{th} mine at the j^{th} observation for each SEG, μ_y = overall mean of Y_{ij}, α_i = the i^{th} mine's mean exposure difference from μ_y, and ε_{ij} = random error of the j^{th} observation from the i^{th} mine's mean. Equation (1) assumes that the ε_{ij} are independently and identically distributed with a normal distribution. In addition to the one-way ANOVA, Tukey's Studentized Range test was used for pair-wise comparison of exposures within each mine by SEG to determine homogeneity.

A two-way nested random-effects ANOVA model based on Kromhout et al.[22] and Rappaport et al.[23] was used for estimating between-SEG (BG), within-SEG (WG), and within-worker (WW) variance components using the log-transformed exposure concentrations:

$$Y_{kjl} = \log\left(X_{kjl}\right) = \mu_y + \alpha_k + \beta_{kj} + \varepsilon_{kjl} \text{ for the observations } k = 1, 2, \ldots, 27, \; j = 1, 2, \ldots, 12, \text{ and } l = 1, 2, 3, \quad (2)$$

where X_{kjl} = l^{th} repeated observation of exposure concentration of the j^{th} worker in the k^{th} SEG, μ_y = overall mean of Y_{kjl}, α_k = random deviations of the k^{th} SEG's mean exposure from μ_y, β_{kj} = random deviations of the mean exposure of the j^{th} worker in the k^{th} SEG from $\mu_{y,k}$ (mean exposure of the k^{th} SEG), and ε_{kjl} = random deviations of the l^{th} repeated observation of the j^{th} worker in the k^{th}

SEG from $\mu_{y,k,j}$ (mean exposure of the j^{th} repeated measurements per worker in k^{th} SEG). The random deviations α_k, β_{kj}, and ε_{kjl} are assumed to be normally distributed with zero means and variances σ^2_α, σ^2_β, and σ^2_ε, respectively. These random variables are mutually uncorrelated and estimated as variance components $S_y{}^2{}_{BG}$, $S_y{}^2{}_{WG}$, and $S_y{}^2{}_{WW}$, respectively.

A three-way nested random-effects ANOVA model was used for estimating between-mine (BM), between-SEG (BG), within-SEG (WG), and within-worker (WW) variance components using the log-transformed exposure concentrations:[24]

$$Y_{ikjl} = \log\left(X_{ikjl}\right) = \mu_y + \alpha_i + \beta_{ik} + \gamma_{ikj} + \varepsilon_{ikjl}$$
$$\text{for the observations } i = 1, 2, \ldots, 6,$$
$$k = 1, 2, \ldots, 27,\ j = 1, 2, \ldots, 12,\ \text{and } l = 1, 2, 3, \tag{3}$$

where X_{ikjl} = l^{th} repeated observation of exposure concentration of the j^{th} worker in the k^{th} SEG of the i^{th} mine, μ_y = overall mean of Y_{ikjl}, α_i = random deviations of the i^{th} mine's true exposure from μ_y, β_{ik} = random deviations of the i^{th} mine's k^{th} SEG's mean exposure from $\mu_{y,i}$ (mean exposure of the i^{th} mine), γ_{ikj} = random deviations of the mean exposure of the j^{th} worker for the i^{th} mine's k^{th} SEG from $\mu_{y,i,k}$ (mean exposure of the k^{th} SEG in the i^{th} mine), and ε_{ikjl} = random deviations of the l^{th} repeated observation of the j^{th} worker in the k^{th} SEG for the i^{th} mine from $\mu_{y,i,k,l}$ (mean exposure of the j^{th} worker in k^{th} SEG in the i^{th} mine). The random deviations α_i, β_{ik}, γ_{ikj} and ε_{ikjl} are assumed to be normally distributed with zero means and variances σ^2_α, σ^2_β, σ^2_γ, and σ^2_ε, respectively. These random variables are mutually uncorrelated and estimated as variance components $S_y{}^2{}_{BM}$, $S_y{}^2{}_{BG}$, $S_y{}^2{}_{WG}$, and $S_y{}^2{}_{WW}$, respectively.

All analyses reported here were conducted using SAS version 9.4 (SAS Institute, Cary, NC). The variance components for each model (Equations (2) and (3)) were determined using PROC NESTED. The statistical analyses were conducted for RD and RS. Significance was defined by p-values of 0.05 or lower.

Results

RD and RS concentrations

Table 1 lists the number of personal samples analyzed using both NIOSH 0600 and NIOSH 7500 for each mine. The total number of samples and the number of blanks were 679 and 132, respectively. The blanks did not show any dust or silica above the LOD, so they were not used further in our analyses. Table 1 also shows the percentage of samples that had RD and RS levels below the LOD, as measured by NIOSH 0600 and NIOSH 7500, respectively. Overall, many of the RD samples had levels lower than the LOD across all mines (ranges: 39–74%), and most of the RS samples had levels lower than the LOD (ranges: 50–79%). Table 2 shows the number of observations, minimum (Min), maximum (Max), arithmetic means (AM), geometric means (GM), and geometric standard deviations (GSD) of RD concentrations by SEG in all mines. The highest and lowest GMs were found in Mine A (0.61 mg/m^3 for *Balling drum operator*, 0.001 mg/m^3 for *Rail road*). Most of the GSDs were less than 3, indicating moderate variability. The highest GSD was found for *Rail road* in Mine A, because the *Rail road* SEG had one measured sample (1.2 mg/m^3) that differed significantly from the rest of samples which had levels less than the LOD (< 0.09 mg/m^3). In Mine A, *Office staff* was the only SEG in which all samples had RD concentrations less than the LOD. The other five mines had multiple SEGs (6–12) in which all measurements fell below the LOD.

Table 1. Number of personal samples and percent of samples < limit of detection (LOD) by mine and mineralogical zone.

Zone	Mine	Workers	Number of RD/RS Samples	% <LOD of RD[a]	% <LOD of RS[b]
Eastern	A	56	161	39	50
Western	B	34	101	48	50
	C	38	113	47	56
	D	34	100	69	79
	E	48	139	68	65
	F	22	65	74	72
Total		232	679		

[a]Personal respirable dust (RD) samples analyzed by NIOSH 0600.
[b]Personal respirable silica (RS) samples analyzed by NIOSH 7500.

Similarly, Table 3 summarizes the RS concentration by SEG in all mines. The highest GM (0.13 mg/m^3) was found for *Operating technician* in Mine C, and the highest GSD was found for *Rail road* in Mine A (the same with high GSD of RD). Even if the RD concentration was less than the LOD for a given SEG, the RS concentration did not necessarily fall below the LOD for that same SEG, and vice versa. For instance, all samples for the *Crusher maintenance* SEG in Mine D had RD concentrations less than the LOD, but not all RS concentrations were less than the LOD. For the *Pelletizing operator* SEG in Mine A, all samples had RS concentrations less than the LOD, but not RD.

While mineralogical differences lead to different exposure levels for elongated mineral particles,[16] RD and RS did not differ between the two zones. Although our sampling strategy took into account the two different mineralogical zones, we found no differences between them for most of the SEGs (results are not shown). When (1) was used to explore the differences in RD and RS exposure levels across mines, the p-values by SEG indicated groups for which there was a significant difference between at least

Table 2. Summary statistics of respirable dust for each SEG measured in all mines (Min, Max, AM, and GM unit: mg/m^3).

		A						B						C						D						E						F						
Department	SEG	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	P-value
Mining	Basin operator	.[c]	.	.	.	.	.	6	LOD[d]	LOD	LOD	LOD	LOD	6	<0.11	0.28	0.10	0.07	2.87	3	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	NA
	Mining operator 1	6	<0.08	0.84	0.17	0.03	7.56	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	NA
	Mining operator 2	9	<0.08	0.26	0.11	0.09	1.88	3	<0.11	0.17	0.25	0.18	3.10	3	LOD	LOD	LOD	LOD	LOD	11	<0.10	0.21	0.03	0.01	4.57	6	<0.10	0.25	0.10	0.07	2.87	3	LOD	LOD	LOD	LOD	LOD	**<0.0001**
	Rail road	5	<0.09	1.2	0.24	0.001	34.0	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	NA
Crushing	Crusher maintenance	11	<0.07	0.72	0.36	0.27	2.17	6	<0.11	0.15	0.15	0.15	1.44	6	0.13	0.96	0.36	0.28	2.18	6	LOD	LOD	LOD	LOD	LOD	6	<0.11	0.45	0.23	0.17	2.43	2	0.15	0.18	0.16	0.16	1.14	0.4649
	Crusher operator	11	<0.07	0.77	0.29	0.22	2.35	5	0.22	1.70	0.53	0.36	2.74	5	<0.11	0.17	0.12	0.12	1.33	3	LOD	LOD	LOD	LOD	LOD	6	<0.11	0.73	0.27	0.18	2.85	3	0.17	0.24	0.20	0.20	1.19	0.4094
	Operating technician	5	0.17	0.28	0.23	0.22	1.20	.	.	.	.	.	.	6	0.31	1.20	0.64	0.56	1.74	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**0.0064**
Concentrating	Concentrator maintenance	6	<0.11	1.40	0.46	0.21	4.05	6	<0.11	0.30	0.18	0.17	1.53	3	0.19	0.35	0.26	0.25	1.36	6	<0.11	0.27	0.06	0.02	5.01	6	<0.10	0.22	0.10	0.08	2.18	3	<0.11	0.57	0.28	0.17	3.44	**0.0114**
	Concentrator operator	10	<0.11	0.21	0.12	0.11	1.48	6	<0.11	0.33	0.20	0.18	1.60	6	<0.11	0.20	0.16	0.15	1.48	6	LOD	LOD	LOD	LOD	LOD	6	<0.11	0.40	0.17	0.11	2.82	3	LOD	LOD	LOD	LOD	LOD	0.3372
Pelletizing	Balling drum operator	9	0.26	1.80	0.73	0.61	1.88	.	.	.	.	.	.	6	<0.16	0.31	0.22	0.21	1.38	6	0.14	0.51	0.31	0.28	1.54	6	0.13	0.34	0.26	0.25	1.49	3	<0.12	0.41	0.21	0.16	2.53	**0.0039**
	Dock man	6	<0.12	0.56	0.33	0.26	2.18	6	<0.11	0.68	0.26	0.17	2.81	6	LOD	LOD	LOD	LOD	LOD	2	<0.10	1.10	0.55	0.06	20.5	5	<0.11	0.31	0.07	0.03	5.59	3	LOD	LOD	LOD	LOD	LOD	0.8902
	Furnace operator	6	0.22	0.81	0.57	0.51	1.62	.	.	.	.	.	.	9	<0.17	1.40	0.54	0.43	2.09	6	<0.11	0.25	0.16	0.14	1.71	6	<0.12	0.96	0.27	0.18	2.76	3	<0.11	0.21	0.10	0.08	2.73	0.5199
	Pelletizing maintenance	6	0.25	1.10	0.68	0.59	1.76	6	<0.11	0.30	0.18	0.17	1.59	6	0.17	0.40	0.25	0.24	1.37	6	<0.13	1.20	0.32	0.19	3.10	6	<0.11	0.33	0.17	0.15	1.85	3	<0.11	0.13	0.12	0.12	1.36	0.1340
	Pelletizing operator	5	0.22	0.5	0.34	0.32	1.48	6	0.15	0.72	0.39	0.33	1.91	3	0.15	0.27	0.21	0.20	1.34	6	0.22	0.43	0.30	0.28	1.36	6	<0.12	0.35	0.20	0.18	1.75	3	0.22	0.59	0.38	0.35	1.65	0.0913
Shop(mobile)[a]	Boiler technician	.	.	.	.	.	.	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	6	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	NA
	Carpenter	.	.	.	.	.	.	3	<0.11	0.23	0.10	0.07	3.27	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	6	<0.12	0.55	0.19	0.12	3.13	.	.	.	.	.	.	0.6080
	Electrician	6	<0.11	0.25	0.12	0.11	1.78	6	LOD	LOD	LOD	LOD	LOD	6	<0.10	0.34	0.13	0.10	2.32	6	<0.12	0.33	0.20	0.17	1.95	6	<0.12	0.14	0.09	0.09	1.36	3	LOD	LOD	LOD	LOD	LOD	0.4564
	Lubricate technician	6	<0.11	0.17	0.06	0.05	2.32	.	.	.	.	.	.	9	<0.11	0.32	0.19	0.17	1.64	.	.	.	.	.	.	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	**0.0014**
	Maintenance technician	6	<0.11	0.53	0.22	0.16	2.45	9	<0.11	1.30	0.23	0.10	4.16	3	LOD	LOD	LOD	LOD	LOD	3	<0.12	0.28	0.19	0.16	2.17	5	<0.11	2.30	0.47	0.05	12.20	3	<0.12	0.43	0.28	0.19	3.11	0.2048
	Pipefitter/Plumber	.	.	.	.	.	.	.	.	.	.	.	.	3	<0.11	0.14	0.12	0.12	1.30	.	.	.	.	.	.	6	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	NA
	Repairman	.	.	.	.	.	.	6	<0.11	0.28	0.20	0.18	1.54	.	.	.	.	.	.	.	.	.	.	.	.	6	<0.11	0.31	0.06	0.02	6.31	3	LOD	LOD	LOD	LOD	LOD	0.3374
	Supervisor	9	<0.07	0.2	0.06	0.04	2.54	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.08	0.15	0.05	0.03	2.97	3	LOD	LOD	LOD	LOD	LOD	0.5056
Shop (stationary)[b]	Auto mechanic	6	<0.10	0.29	0.14	0.10	2.50	6	<0.12	0.38	0.15	0.10	4.16	6	<0.11	0.15	0.10	0.09	1.45	3	<0.12	0.19	0.12	0.10	2.02	6	<0.10	0.12	0.08	0.08	1.42	3	<0.11	0.14	0.10	0.09	1.53	0.7433
	Lab analyst	12	<0.08	0.25	0.12	0.11	1.50	3	<0.11	0.32	0.26	0.18	1.54	3	LOD	LOD	LOD	LOD	LOD	6	<0.12	0.12	0.12	0.12	1.04	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	**0.0200**
	Warehouse technician	6	<0.08	0.19	0.04	0.02	4.36	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.11	0.12	0.11	0.10	1.19	3	LOD	LOD	LOD	LOD	LOD	**0.0049**
Office/Control room	Control room operator	9	<0.10	0.37	0.07	0.03	4.47	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	NA
	Office staff	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.11	0.33	0.06	0.02	6.96	3	LOD	LOD	LOD	LOD	LOD	NA

[a]Shop (mobile) refers to those SEGs whose work is more likely done in multiple places in the plants.
[b]Shop (stationary) refers to those SEGs whose work is more likely done in a single workplace.
[c]I. indicates no measurement.
[d]LOD indicates all samples containing below LOD.
[e]Numbers in **boldface** indicate statistically significant differences among mines ($P<0.05$).

Table 3. Summary statistics of respirable silica for each SEG measured in all mines (Min, Max, AM, and GM unit: mg/m^3).

		A						B						C						D						E						F						
Department	SEG	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	N	Min	Max	AM	GM	GSD	P-values
Mining	Basin operator	.[c]	.	.	.	.	.	6	LOD[d]	LOD	LOD	LOD	LOD	6	<0.01	0.07	0.02	0.004	7.09	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.02	0.01	0.01	1.79	.	.	.	.	.	.	0.5069
	Mining operator 1	6	<0.01	0.27	0.05	0.01	9.09	6	LOD	LOD	LOD	LOD	LOD	3	<0.01	0.01	0.01	0.01	1.47	6	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.01	0.01	0.01	1.40	3	<0.01	0.03	0.01	0.01	2.35	0.9591
	Mining operator 2	9	<0.01	0.02	0.01	0.01	1.35	3	0.02	0.16	0.12	0.07	2.52	3	<0.01	0.03	0.01	0.01	2.28	11	<0.01	0.06	0.01	0.0001	22.51	6	<0.01	0.02	0.01	0.01	1.65	3	LOD	LOD	LOD	LOD	LOD	**<0.0001**
	Rail road	5	<0.01	0.17	0.03	0.0001	46.2	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	NA
Crushing	Crusher maintenance	11	<0.01	0.12	0.06	0.03	3.08	6	<0.01	0.02	0.03	0.03	2.37	6	0.02	0.05	0.04	0.02	1.26	6	<0.01	0.04	0.01	0.01	4.52	6	0.02	0.05	0.04	0.04	1.29	2	0.02	0.03	0.14	0.06	4.48	**0.0162**
	Crusher operator	11	0.01	0.26	0.24	0.08	4.16	5	0.03	0.26	0.09	0.06	1.45	5	<0.02	0.05	0.04	0.02	1.43	3	LOD	LOD	LOD	LOD	LOD	6	0.01	0.08	0.05	0.03	1.92	3	0.05	0.06	0.05	0.05	1.09	0.2019
	Operating technician	5	0.03	0.06	0.05	0.04	1.21	.	.	.	.	.	.	6	0.09	0.28	0.15	0.13	1.59	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	**0.0007**
Concentrating	Concentrator maintenance	6	<0.01	0.03	0.02	0.02	1.56	6	<0.01	0.08	0.04	0.03	2.37	3	0.02	0.03	0.02	0.02	1.26	6	<0.01	0.03	0.01	0.01	2.22	6	<0.01	0.02	0.02	0.02	1.28	3	<0.01	0.06	0.03	0.02	3.33	0.2899
	Concentrator operator	10	<0.01	0.02	0.01	0.01	1.75	6	0.03	0.09	0.07	0.06	1.45	6	<0.01	0.04	0.02	0.02	1.43	6	<0.01	0.02	0.01	0.01	1.58	6	0.01	0.08	0.07	0.03	2.17	3	0.01	0.02	0.02	0.02	1.25	**<0.0001**
Pelletizing	Balling drum operator	9	<0.01	0.02	0.01	0.01	1.60	.	.	.	.	.	.	6	<0.01	0.02	0.01	0.01	1.42	6	<0.01	0.02	0.01	0.01	1.36	6	<0.01	0.02	0.01	0.01	1.81	3	LOD	LOD	LOD	LOD	LOD	0.0678
	Dock man	6	<0.01	0.02	0.01	0.01	2.63	6	<0.01	0.02	0.01	0.01	1.41	6	LOD	LOD	LOD	LOD	LOD	2	<0.01	0.03	0.01	0.01	4.13	5	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	0.0988
	Furnace operator	6	<0.01	0.02	0.01	0.01	2.56	.	.	.	0.01	.	.	9	<0.01	0.08	0.02	0.01	4.21	6	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	0.6179
	Pelletizing maintenance	6	<0.01	0.02	0.01	0.003	4.11	6	<0.01	0.02	0.01	0.01	1.27	6	<0.01	0.02	0.01	0.01	1.48	6	<0.01	0.03	0.01	0.003	5.24	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	**0.0026**
	Pelletizing operator	5	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.02	0.02	0.01	1.47	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.02	0.01	0.01	1.58	6	<0.01	0.02	0.01	0.004	3.26	3	LOD	LOD	LOD	LOD	LOD	**0.0101**
Shop(mobile)[a]	Boiler technician	.	.	.	.	.	.	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	6	<0.01	0.01	0.01	0.01	1.41	.	.	.	.	.	.	NA
	Carpenter	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	.	.	.	.	.	.	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.08	0.03	0.02	4.79	.	.	.	.	.	.	NA
	Electrician	6	<0.01	0.05	0.02	0.01	2.18	6	<0.01	0.02	0.01	0.01	1.55	6	<0.01	0.02	0.01	0.01	1.64	6	<0.01	0.06	0.02	0.01	2.91	6	<0.01	0.02	0.01	0.01	1.70	3	LOD	LOD	LOD	LOD	LOD	0.9125
	Lubricate technician	6	<0.01	0.03	0.01	0.01	1.83	.	.	.	.	.	.	9	<0.01	0.05	0.02	0.02	1.67	.	.	.	.	.	.	.	.	.	.	.	.	3	<0.01	0.02	0.01	0.01	1.71	**0.0395**
	Maintenance technician	6	LOD	LOD	0.01	LOD	LOD	9	<0.01	0.03	0.01	0.01	2.00	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	5	LOD	LOD	LOD	LOD	LOD	3	<0.01	0.03	0.01	0.01	2.09	0.3845
	Pipefitter/Plumber	.	.	.	.	.	.	.	.	.	.	.	.	3	<0.01	0.02	0.01	0.01	3.06	.	.	.	.	.	.	6	<0.01	0.04	0.01	0.01	2.31	.	.	.	.	.	.	0.4462
	Repairman	.	.	.	.	.	.	6	0.03	0.06	0.05	0.05	1.33	.	.	.	.	.	.	.	.	.	.	.	.	6	<0.01	0.03	0.01	0.01	1.78	3	<0.01	0.01	0.01	0.01	1.16	**<0.0001**
	Supervisor	9	<0.01	0.09	0.02	0.01	3.09	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.00	0.02	0.01	0.01	3.10	3	LOD	LOD	LOD	LOD	LOD	0.1973
Shop (stationary)[b]	Auto mechanic	6	<0.01	0.02	0.01	0.01	2.15	6	<0.01	0.05	0.02	0.01	3.73	6	LOD	LOD	LOD	LOD	LOD	3	<0.01	0.02	0.01	0.01	2.34	6	<0.01	0.03	0.01	0.005	4.45	3	LOD	LOD	LOD	LOD	LOD	0.5109
	Lab analyst	12	<0.01	0.02	0.01	0.01	1.51	3	0.02	0.08	0.04	0.03	2.46	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.02	0.01	0.01	1.80	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	**0.0011**
	Warehouse technician	6	<0.01	0.02	0.01	0.01	1.97	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.02	0.01	0.01	1.46	3	LOD	LOD	LOD	LOD	LOD	0.3913
Office/Control room	Control room operator	9	<0.01	0.02	0.01	0.004	3.10	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.01	0.01	0.01	1.58	0.1593
	Office staff	6	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	3	LOD	LOD	LOD	LOD	LOD	6	<0.01	0.05	0.01	0.001	11.31	3	LOD	LOD	LOD	LOD	LOD	NA

[a]Shop (mobile) refers to those SEGs whose work is more likely done in multiple places in the plants.
[b]Shop (stationary) refers to those SEGs whose work is more likely done in a single workplace.
[c]indicates no measurement.
[d]LOD indicates all samples containing below LOD.
[e]Numbers in **boldface** indicate statistically significant differences among mines ($P<0.05$).

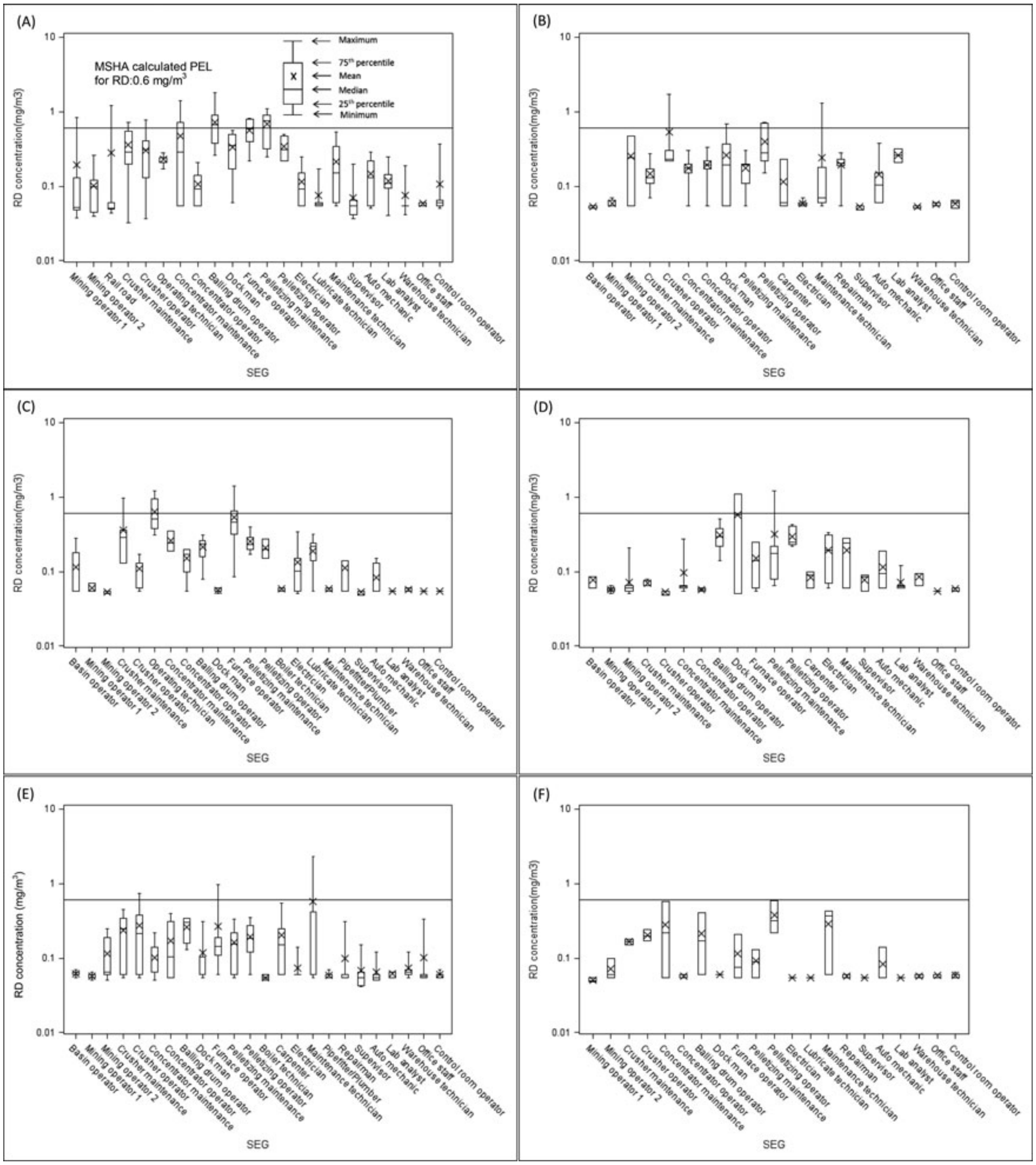

Figure 1. Box plots for respirable dust for each SEG in all mines (the horizontal line indicates the MSHA calculated PEL for RD = 0.6 mg/m^3).

two of the mines (see Tables 2 and 3, respectively). Seven SEGs had at least two mines with significantly different means for RD (p-values: <0.05). And nine SEGs had at least two mines with significantly different means for RS. We did not calculate p-values when no mines or only one mine had concentrations above the LOD.

The distributions of RD and RS concentrations are illustrated by box-plots in Figures 1 and 2, respectively. We calculated MSHA PEL using the formula 10/(% quartz+2) based on the average of percent quartz (15%) across the taconite mining industry (0.6 mg/m^3, a line in Figure 1). The majority of the samples (95% or 643 out of 679) had levels below the PEL. We also compared each sample individually to the PEL calculated using the percent quartz measured for that sample. Almost all samples (97.5%, 662 out of 679) had levels below this PEL. For the samples with levels above the PEL, the RD concentration was up to three times higher than the PEL using either calculation. With a few exceptions, the RD concentrations in the milling processes (crushing, concentration, and pelletizing) tended to be higher than those in the non-milling processes (mining, shop, and office/control room). For many of the SEGs, the box-plot displays almost non-existent variability (e.g., *Basin operator* SEG in Mine B in Figure 1) because the minimum and maximum values for the SEG were

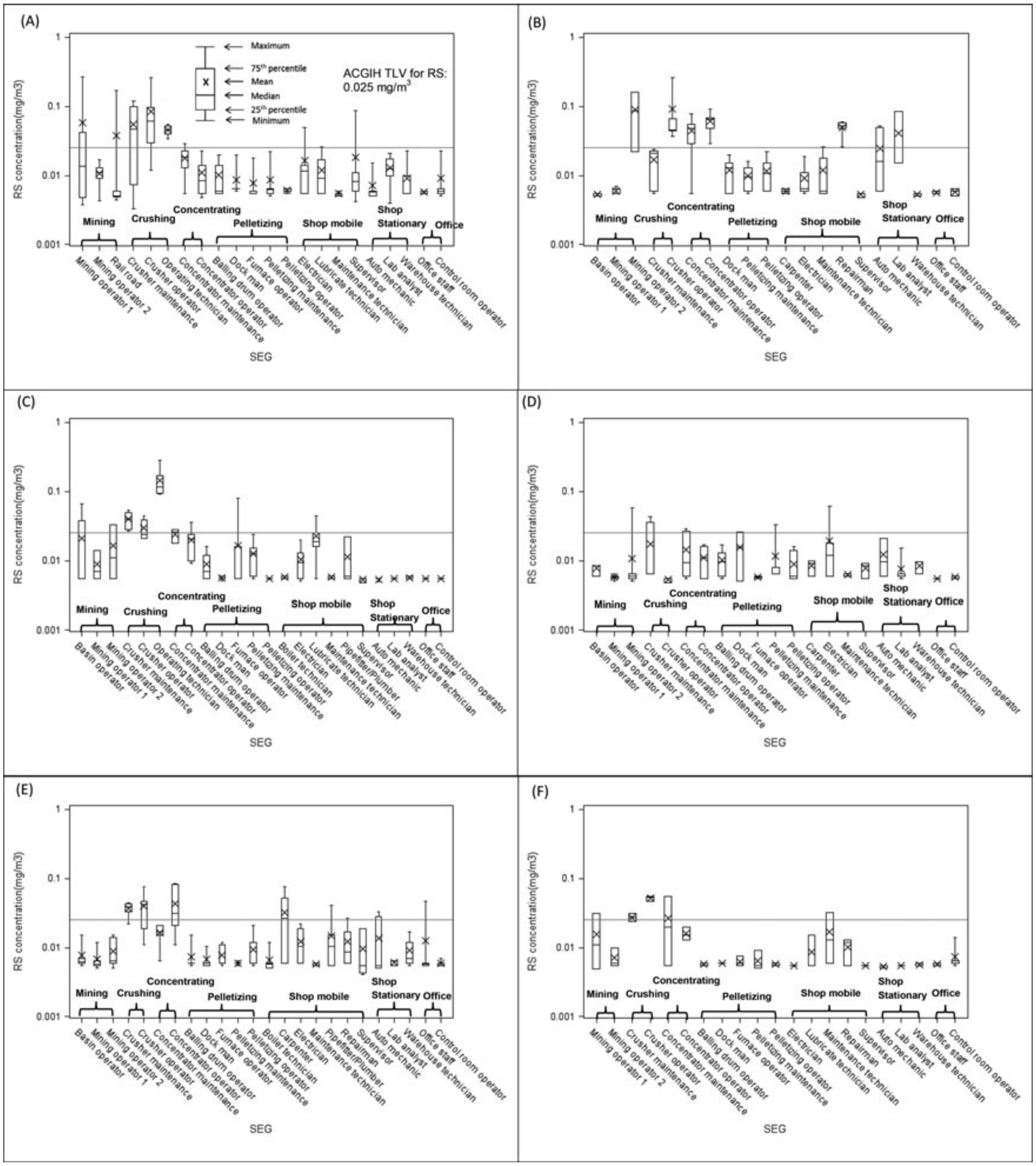

Figure 2. Box plots for respirable silica for each SEG in all mines (the horizontal line indicates the ACGIH TLV for RS = 0.025 mg/m^3).

similar or equal and because most of the samples had concentrations less than the LOD (Table 2). With a few exceptions in Mines B and D, the concentraitons of RS in the crushing and/or concentration processes were higher than the ACGIH TLV for RS (0.025 mg/m^3), as well as higher than those measured in the rest of the taconite processes.

Comparison of SEG variance components

Table 4 shows the between-mine (S^2_{BM}), between-SEG (S^2_{BG}), within-SEG (S^2_{WG}) (that can also be considered as between-worker), and within-worker (S^2_{WW}) variance components for RD and RS by mine, as well as the percentage of the total variance (the sum of the components) contributed by each component. Equation (2) was used to calculate the values of S^2_{BG}, S^2_{WG}, and S^2_{WW}, which were also expressed as percentages of the total variance (assuming that total variance was the sum of only the between-SEG, within-SEG, and within-worker components). Equation 3 was used to calculate the values of S^2_{BM}, S^2_{BG}, S^2_{WG}, S^2_{WW}, which were also expressed as percentages of the total variance (assuming that total variance was the sum of all four components). The between-mine variance was a small portion of the total variance for both RD and RS (3.4% and 2.2%, respectively). While the p-values in Tables 2 and 3 indicate that there were differences between at least two

Table 4. Between-mine (BM), between-SEG (BG), within-SEG (WG), and within-worker (WW) variance components across mine and by mine for respirable dust (RD) and respirable silica (RS).

Classification	Mine	Subject	Sample	Total[b]	BM		BG		WG		WW	
				S^2_{TOTAL}	S^2_{BM}	%	S^2_{BG}	%	S^2_{WG}	%	S^2_{WG}	%
RD	All[a]	232	679	0.144	0.005	3.395	0.051	35.466	0.025	17.084	0.064	44.055
	All	232	679	0.143			0.055	38.503	0.025	17.184	0.064	44.313
	A	56	161	0.199			0.091	45.579	0.007	3.658	0.101	50.764
	B	34	101	0.133			0.032	23.735	0.046	34.261	0.056	42.004
	C	38	113	0.149			0.082	54.735	0.028	19.102	0.039	26.163
	D	34	100	0.109			0.052	47.384	0.000	0.000	0.057	52.616
	E	48	139	0.115			0.011	9.286	0.043	37.666	0.061	53.048
	F	22	65	0.106			0.063	59.661	0.000	0.000	0.043	40.339
RS	All[a]	232	679	0.147	0.003	2.156	0.065	44.065	0.014	9.158	0.066	44.620
	All	232	679	0.147			0.068	46.022	0.014	9.192	0.066	44.786
	A	56	161	0.200			0.077	38.660	0.000	0.000	0.123	61.340
	B	34	101	0.202			0.131	64.805	0.008	3.870	0.063	31.325
	C	38	113	0.177			0.105	59.105	0.026	14.799	0.046	26.097
	D	34	100	0.071			0.000	0.000	0.018	25.506	0.053	74.494
	E	48	139	0.114			0.034	30.187	0.038	33.150	0.042	36.664
	F	22	65	0.097			0.062	63.765	0.000	0.000	0.035	36.236

[a]This variance components include between-mine (BM).
[b]Total variance components (S^2_{TOTAL}) are sum of partitioned BM, between-SEG (BG), within-SEG (WG), and within-worker (WW) variance components.

mines for a given SEG, Table 4 shows that the between-mine component of the overall variability is small relative to the other three variability components. Overall, Mine A had the highest S^2_{TOTAL} (0.199) for RD, a finding that is consistent with the number of large GSDs (>3) for several SEGs (see Table 2). Mines A and D had the high S^2_{TOTAL} (0.200 and 0.202) for RS, a similarly consistent finding given the number of SEGs with large GSDs (see Table 3). Another factor that could affect this is the degree of censoring. When a considerable percentage of measurements are below the LOD, the variances are expected to be underestimated due to the high level of censoring. We observe that this is generally true (but not always) when we compare the S^2_{TOTAL} (Table 4) with the % of below LOD (Table 1) by mine. For instance, mine A had the lowest percentage of values below the LOD and the highest S^2_{TOTAL} for RD and RS, while mine F had the highest percentage of values below the LOD and the lowest S^2_{TOTAL} for RD. The pattern generally held for both RD and RS. If we re-calculated the variances using only the non-censored measurements, this pattern is not observed, suggesting that the censoring plays a role in the estimates of variance.

Comparison of percent of quartz by department

The department, a grouping variable that can be utilized as an alternative to SEG, was used to compare the correlation of RD and RS as well as percent of quartz. After excluding all samples with values less than the LOD for both RD and RS, we calculated the coefficient of determination (R^2) between RD and RS concentrations by department across all mines (Figure 3). The value of R^2 decreased substantially from 0.51 in the *Crushing* department to 0.02 in the *Concentrating* department. With the exception of the *Concentrating* department, the RD and RS concentrations in all departments had a significant positive relationship (p-value <0.05). The low correlation found in the *Concentrating* department indicating that the RS concentrations are independent of the RD concentrations, is likely due to the concentrating processes removing the silica. To calculate the fraction of silica in the respirable dust in each department, we divided the RS concentration (mg/m^3) by the RD concentration (mg/m^3). Our results indicate that the mean percentage of quartz was approximately 15% across all departments except *Pelletizing*, where the percentage dropped considerably to 5% (see Figure 4).

Discussion

Levels of RD and RS

Overall, the highest average concentrations of RD were found in Mine A. Mine F had the lowest average concentration of RD, 0.116 mg/m^3, which is more than 2 times lower than the average of 0.252 mg/m^3 in Mine A. While the differences in processes between these two mines were not significant, Mines A and F are unique in that working environment. By way of example, Mine A is the only mine that does not have a union, which could possibly correlate to a lesser degree of health and safety training and a more dusty environment. Mine F was the smallest in terms of production capacity (smaller by a factor of two than the next smaller mine).

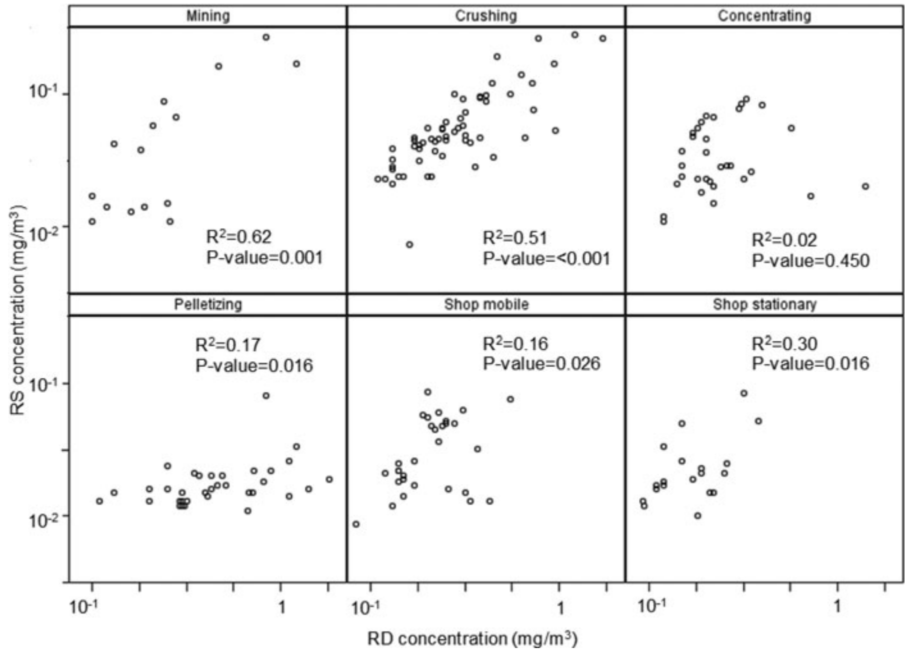

Figure 3. Coefficient of determination (R^2) between respirable dust and respirable silica by department across all mines.

We compared the RD exposure concentrations to the MSHA PEL for RD. No single RD exposure concentration was higher than the PEL in Mine F. The highest individual exposure level of 2.30 mg/m^3 was found in the *Maintainence technician* SEG in Mine E. Overall, between-mine differences for the RD across all SEGs were almost nonexistent ($S^2{}_{BM} = 0.005$).

All mines had some SEGs with values above the ACGIH TLV for RS (0.025 mg/m^3). Across all SEGs, Mine B had the highest average concentration of RS (0.025 mg/m^3), while Mine D had the lowest (0.010 mg/m^3). As we can see in Figure 1, the highest concentrations of RD were often observed in either the *Pelletizing* or *Crushing* departments, which are inherently dusty operations. The highest concentrations of RS were consistently observed in the *Crushing* department (Figure 2), but not in the *Pelletizing* department. Even though the silica is part of the ore during the crushing process, it is removed before the pelletizing step. Sheehy[12]

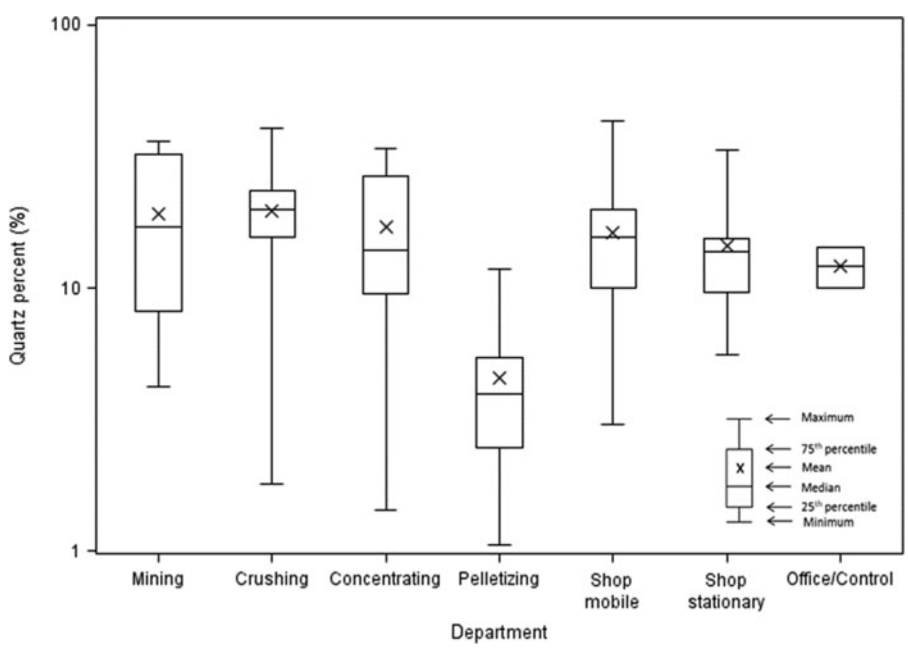

Figure 4. Percent of quartz in respirable dust samples by department.

found that the greatest potential for overexposure to RS occurred in the mining (drill operator), crushing (crusher helper), and concentrating (primary attendant, concentrator laborer) departments; these departments correspond to the *Mining operator 1*, *Crusher operator*, *Concentrator operator* SEGs, respectively, in our study. However, it was unclear whether the specific job tasks performed by the concentrator laborer occurred before or after the magnetic separation processes.

Between-mine variability by process

The taconite mining and milling processes are very similar in all mines. Thus, the levels of exposure to RD and RS during these processes display only a few significant differences by SEG for most of the mines. The between-mine component of variance is the smallest (Table 4). Because most mining jobs in the pit are performed in a cab (e.g., driller, truck driver, shovel operator), the level of exposure to RD and RS depends primarily upon the ventilation system in the operating equipment. Although there are no major differences between mines for these jobs, there are differences between the types of equipment used for each job. For instance, the ventilation filters must be checked more often in some vehicles (e.g., bulldozer or grader) than others (e.g., truck or loader). Also, some small vehicles do not have a ventilation system.

Inside the taconite plants, the conveyance of rocks through the crusher is, in general, a dry process that generates significant RD and RS in all mines. A small fraction of the crushed rock is mixed with water and ground to a powder-like substance in the rod and ball mills. After this milling process, the amount of RD and RS is reduced because the process is wet.

Between-SEG, within-SEG, and within-worker variability

When only the between-SEG (S^2_{BG}), within-SEG (S^2_{WG}), and within-worker (S^2_{WW}) variance components were considered together, instead of all components S^2_{BG}, S^2_{WG}, S^2_{WW}, and the between-mine (S^2_{BM}), the S^2_{BG} variance was slightly larger because it encompassed S^2_{BM} variance as well. The S^2_{BG} for RS did not differ much across mines. However, a small S^2_{BG} for RD was observed in Mine E (0.011), nearly eight times smaller than that for Mine A (0.091). The within-SEG variability was considerably smaller than between-SEG and within-worker variability because in many instances, there was only one worker per SEG in a mine who was sampled multiple times. Many of the SEGs had a relatively consistent level of RS exposure, especially between the departments in Mine D (Figure 2). However, the RS levels in the *Crushing* department varied minimally in Mine D, while the levels in the *Crushing* department in the other mines varied much more. In contrast, the levels of RS in all other departments varied less across mines. All of the RD concentrations for the *Crushing* department in Mine D fell below the LOD because the crusher operator works in a relatively clean crusher control operating room at this mine. The work environment of the crusher operator is different in Mine A, where the crusher operators are more exposed to the work done in the nearby crusher building.

Mine D is located at the end of the western zone of the Mesabi Iron Range and is the farthest mine from Mine A. Therefore, the characteristics of the taconite rock in Mine D and Mine A differ the most among the six mines. Moving from Mine D to Mine A across the Iron Range, the taconite rock changes from soft to hard. Thus, Mine D only needs a primary crusher for the much softer taconite rock, whereas Mine A needs both a primary and secondary crusher. Thus, differing taconite characteristics might contribute to lower RS concentrations in the mining process in Mine D. In addition, sampling was conducted in Mine D in June 2010, which had 21 rainy days,[25] a factor that may have contributed to lower RD and RS concentrations by droplet suppression. Because the more than half of the SEGs (12 out of 21) had RD levels less than LOD, the significantly smaller S^2_{BG} was found in Mine F (Table 4).

Conclusions

In the Minnesota taconite mining operations, respirable dust (RD) and respirable silica (RS) levels show little variation between the two mineralogically distinct zones. The majority of RD concentrations across all mines were below the MSHA PEL, whereas the concentrations of RS were often greater than the ACGIH TLV for RS in all mines. The highest concentrations of RS were generally found in the *Crushing* departments for all mines. The processes in the *Concentrating* department may have reduced the levels of RS significantly, as well as lowered the percentage of quartz in RD in the *Pelletizing* department. There was little variability between the six mines for either RD or RS exposures because the taconite mining and milling processes are similar across all mines. The small fraction of between-mine variability also supported the idea that the differences between the mines are minimal. The between-SEG variability for RS was more substantial and did not differ much among mines. However, smaller between-SEG variability for RD was observed in Mine F. Some of these findings were affected by the percentage of <LOD samples in each SEG and mine, characteristics of

the taconite rock, seasonal effects during sampling, or the tasks assigned to each job in that mine.

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