Appendix 1

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Comprehensive Assessment of Exposures to Elongate Mineral Particles in the Taconite Mining Industry

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Since the 1970s, concerns have been raised about elevated rates of mesothelioma in the vicinity of the taconite mines in the Mesabi Iron Range. However, insufficient quantitative exposure data have hampered investigations of the relationship between cumulative exposures to elongate mineral particles (EMP) in taconite dust and adverse health effects. Specifically, no research on exposure to taconite dust, which includes EMP, has been conducted since 1990. This article describes a comprehensive assessment of present-day exposures to total and amphibole EMP in the taconite mining industry. Similar exposure groups (SEGs) were established to assess present-day exposure levels and buttress the sparse historical data. Personal samples were collected to assess the present-day levels of worker exposures to EMP at six mines in the Mesabi Iron Range. The samples were analyzed using National Institute for Occupational Safety and Health (NIOSH) methods 7400 and 7402. For many SEGs in several mines, the exposure levels of total EMP were higher than the NIOSH Recommended Exposure Limit (REL). However, the total EMP classification includes not only the asbestiform EMP and their non-asbestiform mineral analogs but also other minerals because the NIOSH 7400 cannot differentiate between these. The concentrations of amphibole EMP were well controlled across all mines and were much lower than the concentrations of total EMP, indicating that amphibole EMP are not major components of taconite EMP. The levels are also well below the NIOSH REL of 0.1 EMP cc^{-1}. Two different approaches were used to evaluate the variability of exposure between SEGs, between workers, and within workers. The related constructs of contrast and homogeneity were calculated to characterize the SEGs. Contrast, which is a ratio of between-SEG variability to the sum of between-SEG and between-worker variability, provides an overall measure of whether there are distinctions between the SEGs. Homogeneity, which is the ratio of the within-worker variance component to the sum of the between-worker and within-worker variance components, provides an overall measure of how similar exposures are for workers within an SEG. Using these constructs, it was determined that the SEGs are formed well enough when grouped by mine for both total and amphibole EMP to be used for epidemiological analysis.

Keywords: elongate mineral particles; exposure assessment; exposure variability; fiber measurement; similar exposure groups; taconite

INTRODUCTION

Since the 1970s, concerns about occupational health have intensified in both the taconite mining industry and the communities adjacent to the mines in the Mesabi Iron Range in north-eastern Minnesota (Axten and Foster, 2008; Wilson *et al.*, 2008). Minnesota counties in the vicinity of taconite mining operations have been found to have elevated age-adjusted rates for mesothelioma (Case *et al.*, 2011). The elevated rates challenge conventional understanding because mineralogical data

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suggest that the ore body comprised primarily non-asbestiform cleavage fragments which have not been thought to have high potential for disease (Berry and Gibbs, 2008; Gamble and Gibbs, 2008; Mossman, 2008). For the last three decades, ongoing and unresolved concerns about health risks from taconite mining have been driven, in part, by limited epidemiological assessments and insufficient quantitative exposure data. Concerns about the elevated rates of mesothelioma in the Mesabi mining cohort led to epidemiological investigations evaluating the relationship between cumulative exposures to components of taconite dust and mesothelioma, lung cancer, and non-malignant respiratory disease. However, no research on exposure to taconite dust, which includes elongate mineral particles (EMP), has been conducted since 1990 (Sheehy and McJilton, 1990).

The results presented here are part of a larger epidemiological study assessing the respiratory health effects of exposure to components of taconite dust. This article describes our approach to comprehensively assess present-day exposure levels to total and amphibole EMP in the taconite mining industry. The term 'total EMP' refers to any mineral particle with a minimum aspect ratio of 3:1 that is of inhalable, thoracic, or respirable size, while the term 'amphibole EMP' refers to a subset of double chain silicate minerals (crocidolite, amosite, anthophyllite, tremolite, and actinolite) that can be asbestiform or non-asbestiform (NIOSH, 2011). Asbestiform EMP are likely to be thinner, longer, and more flexible than non-asbestiform EMP, with layers parallel to those from 'native (unprocessed) samples' (Addison and McConnell, 2008). Although the chemical composition of asbestiform and non-asbestiform EMP can be the same, they differ in their 'habit' or morphology (Langer *et al.*, 1979).

The first and most critical step of our exposure assessment involves the classification of workers into similar exposure groups (SEGs). SEGs can be used to efficiently assess exposure levels based on job titles, locations, tasks, and procedures rather than individual workers (Bullock and Ignacio, 2006). Workers who have similar exposure profiles and whose tasks involve similar procedures and materials are grouped together in a single SEG. The success of a grouping strategy depends on the between-group variability, between-worker variability, and within-worker variability. To reduce exposure misclassification errors in subsequent epidemiological studies, it is important that the exposure distributions of SEGs be distinct from each other and homogeneous within (Kromhout and Heederik, 1995). This requires a detailed characterization of between-SEG and within-SEG exposure variability. However, the sparseness of the available historical exposure data precludes such an analysis for taconite workers. A detailed assessment of present-day exposure levels was carried out to understand exposure variability, which enabled the development of better-formed SEGs.

The mineralogy of the Mesabi Iron Range changes from east to west, with the three taconite mining companies owning five operating mines in the western and one in the eastern zone. Amphiboles are mainly detected in the east. Phyllosilicates such as minnesotaite, greenalite, and stilpnomelane, which are not regulated as asbestiform or amphibole EMP, dominate the west (McSwiggen and Morey, 2008; Zanko *et al.*, 2008). The amphiboles in the east are principally of the cummingtonite–grunerite series and include some actinolite (ferroactinolite). Amphiboles and phyllosilicates form two distinct groups of minerals, defined by fundamental differences in their internal crystalline structure. The structure of phyllosilicates is based on sheets of linked silicon tetrahedra. Fibers of phyllosilicate minerals are created when these sheets curl to form tubes. The crystalline structure of amphiboles is based on chains of silicon tetrahedra. The silicate minerals that form EMP have different morphologies in the east; however, the vast majority of the amphiboles are non-asbestiform EMP (Wilson *et al.*, 2008; Zanko *et al.*, 2008). Due to the distinct metamorphic mineralogical characteristics of the eastern versus the western zones, workers in the two zones may potentially be exposed to different types of EMP.

The goals of this article are (i) to assess the present-day levels of exposure to EMP in the taconite industry across the two mineralogical zones, (ii) to estimate the between-SEG, between-worker, and within-worker components of variability in EMP exposures, (iii) to use the components of variability to assess whether the SEG are distinct from each other and relatively homogeneous within, and (iv) to evaluate the impact of variability on the exposure estimates for the SEGs that will be used in the epidemiological studies. We also examined whether SEGs developed for total EMP are valid for amphibole EMP and if the same set of SEGs can be used for workers in the mineralogically distinct eastern and western zones of the Mesabi Iron Range.

METHODS

Formation of SEGs

For this study, we derived job titles from four sources: (i) records maintained by the Mine Safety and Health Administration that listed approximately 190 job titles; (ii) information from a previous University of Minnesota study by Sheehy (1986) that listed 140 job titles; (iii) industrial hygiene and human resources databases maintained by the three companies currently operating mines in the Mesabi Iron Range (U.S. Steel, Cliffs Natural Resources, Arcelor Mittal), which listed approximately 150 job titles; and (iv) *Job Descriptions and Classifications* published by the Reserve Mining Company (1974), which contained 142 job titles. 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 to 19. The final list contained 181 job titles, forming 28 SEGs that we further grouped into 7 departments. Due to the distinct mineralogical characteristics of the eastern versus the western zones, the SEGs for the eastern and western zones were considered separately.

Sampling design and data handing

Personal exposure assessment was conducted across all operating mines in both zones of the Mesabi Iron Range, beginning in January 2010 and ending in May 2011. The purpose of the personal sampling was to assess the present-day levels of worker exposures to EMP in the taconite mining industry. The researchers and representatives from each of the three mining companies discussed workers' schedules to identify potential participants prior to the day of sampling. At the beginning of the work shift on each sampling day, the researchers explained the purpose of the study to the potential participants and presented them with the consent form approved by the University of Minnesota Institutional Review Board (IRB code: 0901M58041).

To perform a baseline exposure profile for a job title, the American Industrial Hygiene Association sampling strategy by Bullock and Ignacio (2006) recommends a minimum of six data points per SEG and recommends 8–10. Two workers per SEG were selected for personal EMP sampling in the eastern zone and each worker was sampled during three different shifts. In the western zone, approximately eight workers per SEG were chosen, with each worker being sampled on three different shifts. For the SEGs in the western zone, the eight workers were drawn from five different mines. This design allows the estimation of between- and within-SEG, between- and within-mine, between- and within-zone, and within-worker variance components.

Each consenting participant wore a personal air-sampling pump (Apex Pro pump, Casella Inc., Amherst, NH, USA) on his or her waist, with the sampler located in the breathing zone, for approximately 6 h during the work shift. Six hours accounts for at least 70% of a daily work shift. Personal sampling for each worker was completed during three different work shifts, though not necessarily on consecutive days.

EMP sampling was conducted using a mixed cellulose ester membrane filter, 25 mm in diameter with 0.8 µm pores. The filter was placed in a polycarbonate membrane cassette with a conductive extension cowl of 50 mm. The flow rate for the EMP sampling pump was set at the lowest available flow rate per pump to avoid overloading the filter (range 0.65–0.95 l min^{-1}). As a further precaution against overloading, the polycarbonate membrane cassettes usually were changed at the end of about the first 3 h of sampling. Overall, 18 samples were excluded because they either were overloaded particles or had damaged filter. Exceptions were made if the participants had a conflict in their work schedule or the researchers decided not to change the cassettes due to lower expected particle exposure levels for some samples (e.g. warehouse technician, office staff).

Analytical methods and limitations

The personal filter samples were analyzed by phase contrast microscopy (PCM) using National Institute for Occupational Safety and Health (NIOSH) method 7400 (NIOSH, 1994a), which identifies all EMP longer than 5 µm with an aspect ratio ≥3.0 (Counting Rules A). While this method can be used to count the number of EMP, it cannot differentiate between asbestiform and non-asbestiform EMP. While it is commonly stated that NIOSH 7400 cannot identify EMP with a width less than 0.25 µm (NIOSH, 1994a), this depends on the refractive index of the EMP (NIOSH, 2011). If the refractive index does not differ from the substrate material or the counting medium, the resolution is low, and vice versa (Kenny and Rood, 1987). Rooker *et al.* (1982) have shown that under proper calibration and use of appropriate mounting media, EMP with widths of 0.15 µm were measured using PCM. Kenny and Rood (1987) measured widths of 0.125 µm under PCM.

In contrast, the NIOSH method 7402 by transmission electron microscopy (TEM; NIOSH, 1994b) is used to identify EMP that meet the PCM counting criteria. This method includes expanded characterization of elemental composition with energy dispersive X-ray analysis and crystalline structure by selected area electron diffraction. Therefore, it can identify EMP that are amphiboles or chrysotile. While laboratories typically claim to distinguish between asbestiform and non-asbestiform EMP using TEM, a more conservative assessment is that this method can identify amphibole versus non-amphibole EMP (in addition to chrysotile EMP), especially in the heterogeneous mixture of particles found in the taconite industry in Minnesota.

As indicated previously, two samples per work shift were collected for most participants on three different days. The results from the two samples were combined to calculate a single time-weighted average concentration for the shift for each participant. While all personal EMP samples were analyzed using NIOSH 7400, at least one sample per worker was randomly chosen to be analyzed using NIOSH 7402. Thus, while all of the filter samples underwent analysis using NIOSH 7400, ~18% of the samples underwent additional analysis using NIOSH 7402. For the NIOSH 7402 analysis, samples were analyzed by indirect preparation, which included suspension in solution, sonication, and re-filtration. For all personal samples, we used only one-fourth or half of the filter depending on the analysis methods chosen, and the remaining three-forth or half has been archived at the University of Minnesota.

Table 1 lists the number of personal samples analyzed using both NIOSH 7400 and NIOSH 7402 for each mine and zone. In addition, one blank sample per sampling day was obtained for NIOSH 7400 quality control for a total of 243. Further, one blank sample per NIOSH 7402 sampling day was obtained for quality control for a total of 66. Table 1 also shows the percentage of samples with EMP levels that fell below the limit of detection (LOD), as measured by NIOSH 7400 and NIOSH 7402. Overall, many of the samples had levels less than the LOD, especially the NIOSH 7402 samples in the western zone. If all the measurements for a given SEG were below the LOD, summary statistics such as the arithmetic and geometric means (GM) and geometric standard deviations (GSD) were not reported. If at least one sample for an SEG in a particular mine was above the LOD, then summary statistics were calculated by assuming that censored data were represented by one half of the LOD.

Only three chrysotile asbestiform EMP (0.24% of all EMP samples) were identified by the NIOSH 7402 analysis. These were excluded from our analyses, leaving only amphibole—specifically cummingtonite–grunerite and actinolite—and non-amphibole EMP in our data set. Using the NIOSH 7400 and 7402 results, average concentrations of EMP identified as total and amphibole for each SEG in each mine were calculated. This estimate was then applied to all of the NIOSH 7400 samples for that SEG in that mine to obtain personal exposure levels to NIOSH 7402 amphibole EMP when the samples had at least one value above LOD for that SEG.

Table 1. Number of personal samples and percent of samples less than LOD by mine and mineralogical zone.

Zone	Mine	Workers	Samples analyzed by PCM[a]	% <LOD by PCM	Samples analyzed by TEM[b]	% <LOD by TEM
Eastern	A	56	266	7.1	102	68.6
Western	B	34	197	68.5	34	100.0
	C	38	218	53.2	36	100.0
	D	34	203	37.0	34	100.0
	E	48	267	20.6	47	100.0
	F	22	129	48.8	22	100.0
Total		232	1298	—	275	—

[a]Personal samples analyzed by NIOSH 7400 PCM, counting all EMP with length >5 µm and aspect ratio >3.0.
[b]Personal samples analyzed by NIOSH 7402 TEM, counting only amosite, non-amosite and chrysotile EMP with length >5 µm and aspect ratio >3.0.

$$C_{ij}(\text{NIOSH 7402, amphibole EMP}) = C_{ij}(\text{NIOSH 7400, total EMP}) \times \frac{\overline{C_i}(\text{NIOSH 7402, amphibole EMP})}{\overline{C_i}(\text{NIOSH 7400, total EMP})} \quad (1)$$

for C, concentration (particles per cubic centimeter); $\overline{C}$, average concentration (particles per cubic centimeter); i, SEG in a mine; j, observation.

Statistical analysis methods

Of the 28 SEGs, 27 SEGs were monitored. We were not able to monitor the Janitor SEG because all janitors in the current taconite mining industry are independent contractors and not employed by the mining companies. A *t*-test was used to determine which SEGs differed between the two zones for each EMP classification (Table 2). Of the 27 SEGs, 21 were present in both zones for statistical evaluations. To ensure that at least one of the 27 SEGs is different from the others and that the exposures within each SEG are homogeneous, two different approaches were used to evaluate the variability of exposure between SEGs, between workers, and within workers.

One-way analysis of variation. We used a simple one-way analysis of variation (ANOVA) model to compare the log-transformed estimated exposures Y_{ij} of each SEG.

$$Y_{ij} = \log(X_{ij}) = \mu_y + \alpha_i + \varepsilon_{ij} \text{ for } i = 1, 2, \ldots, 27, \text{ and } j = 1, 2, \ldots, 24 \quad (2)$$

where X_{ij} = exposure concentration of the ith SEG at the jth observation for each SEG, μ_y = overall mean of Y_{ij}, α_i = random deviation of the ith SEG's true exposure from μ_y, and ε_{ij} = random deviation of the jth observation from the ith SEG's true exposure. Equation (2) assumes that the ε_{ij} is independently and identically distributed with a normal distribution. This model was used to determine if the differences between the SEGs were statistically significant. A pairwise comparison of the SEGs was used to identify which SEGs were significantly different from each other.

Contrast and homogeneity. Kromhout and Heederik (1995) proposed a two-way nested random-effects ANOVA model for estimating between-SEG, between-worker, and within-worker variance components using the log-transformed exposure concentrations. The variance components were constructed using PROC NESTED with a nested structure of data set as follows:

$$Y_{ikn} = \log(X_{ikn}) = \mu_y + \alpha_{ik} + \beta_{ikn} + \varepsilon_{ikn} \text{ for the observations } i = 1, 2, \ldots, 27, k = 1, 2, \ldots, 4; \text{ and } n = 1, 2, \ldots, 6 \quad (3)$$

where X_{ikn}, nth observation of exposure concentration for the kth worker of the ith SEG; μ_y, overall mean of Y_{ikn}; α_i, random deviations of the ith SEG's true exposure from μ_y; β_{ik}, random deviations of the ith SEG's kth worker's true exposure from $\mu_{y,i}$ (mean exposure of the ith SEG); and ε_{ikn}, random deviations of the nth observation for the ith SEG's kth worker from $\mu_{y,ik}$ (mean exposure of the kth worker in the ith SEG). The random deviations (α_i, β_{ik}, and ε_{ikn}) are assumed to be normally distributed with zero means and variances (σ^2_α, σ^2_β, and σ^2_ε, respectively). These variances are mutually uncorrelated and estimated as variance components ($S^2_{y\mathrm{BG}}$, $S^2_{y\mathrm{BW}}$, and $S^2_{y\mathrm{WW}}$, respectively).

According to Kromhout and Heederik (1995), contrast (ε) is a ratio of between-SEG variability to the sum of between-SEG and between-worker (i.e. within SEG) variability and provides an overall measure of whether there are distinctions between the SEGs and is given as follows:

$$\text{Contrast}(\varepsilon) = \frac{S^2_{y\mathrm{BG}}}{S^2_{y\mathrm{BG}} + S^2_{y\mathrm{BW}}} \quad (4)$$

When the between-SEG variance component ($S^2_{y\mathrm{BG}}$) approaches 0, the contrast value approaches 0, indicating that the SEGs are similar and not distinct from each other. When the between-worker variance component within the SEG ($S^2_{y\mathrm{BW}}$) approaches 0, the contrast value approaches 1, indicating that between-SEG variability are dominant and implying that at least one SEG is distinct from the others.

Analogously, we can define homogeneity (η) to provide an overall measure of how similar the exposures are for workers within an SEG. It is defined as the ratio of the within-worker variance component to the sum of the between-worker and within-worker variance components, and is given as follows:

Table 2. Arithmetic mean (particles per cubic centimeter) in each zone and *t*-test results (*P* value) by EMP classification for each SEG.

Department	SEG	Total EMP (particles cm^{-3})			Amphibole EMP (particles cm^{-3})		
		East	West	*P* value	East	West	*P* value
Mining	Basin operator	—	0.053	—	—	<LOD	—
	Mining operator 1	**0.065**	**0.015**	**<0.0001**	<LOD	<LOD	NA
	Mining operator 2	**0.097**	**0.031**	**0.0016**	0.004	<LOD	NA
	Rail road	0.072	—	—	<LOD	—	—
Crushing	Crusher maintenance	**0.194**	**0.044**	**<0.0001**	0.026	<LOD	NA
	Crusher operator	**0.193**	**0.038**	**<0.0001**	0.030	<LOD	NA
	Operating technician	**0.341**	**0.014**	**<0.0001**	0.110	<LOD	NA
Concentrating	Concentrator maintenance	**0.207**	**0.058**	**<0.0001**	0.030	<LOD	NA
	Concentrator operator	**0.176**	**0.023**	**<0.0001**	0.024	<LOD	NA
Pelletizing	Balling drum operator	0.050	0.077	0.9371	0.010	<LOD	NA
	Dock man	**0.206**	**0.085**	**0.0014**	0.020	<LOD	NA
	Furnace operator	**0.066**	**0.040**	**0.0141**	0.015	<LOD	NA
	Pelletizing maintenance	0.067	0.073	0.0852	<LOD	<LOD	NA
	Pelletizing operator	0.109	0.095	0.1739	0.014	<LOD	NA
Shop (mobile)[a]	Boiler technician	—	0.041	—	—	<LOD	—
	Carpenter	—	0.064	—	—	<LOD	—
	Electrician	**0.309**	**0.077**	**<0.0001**	0.063	<LOD	NA
	Lubricate technician	**0.145**	**0.033**	**0.0006**	0.016	<LOD	NA
	Maintenance technician	0.043	0.031	0.0919	<LOD	<LOD	NA
	Pipefitter/Plumber	—	0.048	—	—	<LOD	—
	Repairman	—	0.064	—	—	<LOD	—
	Supervisor	0.064	0.045	0.3246	0.012	<LOD	NA
Shop (stationary)[b]	Auto mechanic	**0.118**	**0.023**	**<0.0001**	<LOD	<LOD	NA
	Lab analyst	**0.114**	**0.030**	**<0.0001**	<LOD	<LOD	NA
	Warehouse technician	0.018	0.041	0.3243	0.004	<LOD	NA
Office/control room	Control room operator	0.021	0.017	0.5269	<LOD	<LOD	NA
	Office staff	0.009	0.016	0.0546	<LOD	<LOD	NA

Numbers in **boldface** indicate statistically significant differences between eastern and western zone ($P < 0.05$).
<LOD, samples containing LOD; NA, data containing LOD in either one of two zones.
[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.

$$\text{Homogeneity } (\eta) = \frac{S^2_{y\text{WW}}}{S^2_{y\text{BW}} + S^2_{y\text{WW}}} \quad (5)$$

When the within-worker variance component ($S^2_{y\text{WW}}$) is small compared with the between-worker variability, homogeneity approaches 0, indicating that the exposures of the workers within each SEG are heterogeneous. When the between-worker variance component ($S^2_{y\text{BW}}$) is small, homogeneity approaches 1.

The statistical analyses were conducted for total and amphibole EMP. Significance was defined by *P* values of 0.05 or lower. All analyses reported here were conducted using SAS version 9.3 (SAS Institute, Cary, NC, USA).

RESULTS

The results of *t*-tests used to determine the differences between the zones by SEG are shown in Table 2. When a SEG was not present in both zones, the *P* value could not be calculated. Sixty-two percent (13 of 21) of the SEGs were significantly different between the zones for total EMP. For the amphibole EMP exposures in the western zone, all the data were less than the LOD. Additionally, eight SEGs in the eastern zone contained all data less than the LOD. Therefore, we did not test for differences between two zones for amphibole EMP. Both the total and amphibole EMP classifications had substantially different arithmetic mean exposures between the two zones. Only four SEGs (balling drum operator, pelletizing maintenance, warehouse technician, and office staff) were found to have higher total EMP exposures in the western zone, but none of these four were significantly different between the two zones ($P > 0.05$).

Total and amphibole EMP concentrations

The box plots in Fig. 1 show the total EMP concentrations by SEG across all mines. The concentration of total EMP in mine A tended to be higher than in the mines in the western zone. For most of the SEGs in the various mines, the arithmetic mean (the *X* in the box plot) was greater than the median (the middle line in the box plot), indicating a non-normal, skewed distribution.

Table 3 shows the GM and GSD of total EMP concentration by SEG in all mines. Table 4 summarizes the amphibole EMP concentration by SEG in the eastern zone (mine A). Since all amphibole EMP concentrations are less than the LOD in the western zone, we do not present the GM and GSD estimates. The GM for each SEG in mine A was markedly less for amphibole EMP than for total EMP.

The measured amphibole EMP concentrations by SEG across all mines are illustrated using scatter plots in Fig. 2. Figure 2 shows that, with a few exceptions in mine A, the concentrations of amphibole EMP were lower than the NIOSH Recommended Exposure Limit (REL) of 0.1 particles cm^{-3} for EMP by roughly an order of magnitude.

Comparison of EMP exposure differences

To explore the EMP exposure differences between the SEGs, a pairwise comparison of the SEGs within each mine was performed. The logarithms of the estimated EMP exposures were used in a simple one-way ANOVA model. In each mine, at least two of the SEG means were significantly different for total EMP ($P < 0.0005$).

Comparison of SEG variance components

Table 5 shows the between-SEG (S^2_{BG}), between-worker (S^2_{BW}), and within-worker (S^2_{WW}) variance components as absolute values and as percentage of total variance (sum of the three components), as well as the contrast (ε) and homogeneity (η) values for total EMP by mine in both geologic zones.

DISCUSSION

The available historical data on exposure of workers to taconite EMP are sparse and typically based on NIOSH 7400. They are insufficient for assessing exposure variability in any detail. Our detailed measurements allow for a study of the components of variance of exposure, that in turn, allows the creation of well-formed SEGs and reducing the likelihood of exposure misclassification (Nieuwenhuijsen, 1997; Ramachandran, 2005). Moreover, this analysis identifies notable heterogeneity of exposure to total EMP in the taconite mining industry.

Levels of total and amphibole EMP

This is the first study to report on the concentrations of total and amphibole EMP in the taconite mining industry. Overall, higher concentrations of total EMP were found in mine A, including the highest exposure of 2.2 particles cm^{-3}, ~ 22 times greater than the REL (0.1 particles cm^{-3}) for EMP. The lowest concentration of total EMP was found in mine F, and the total EMP exposure concentrations for all SEGs in this mine were lower than the NIOSH REL. The concentrations of amphibole EMP were much less than the concentrations of total EMP, indicating that amphibole EMP are not major components of taconite EMP. In general, the amphibole EMP concentrations were lower than the NIOSH REL, except for a few SEGs in mine A. Three individual measurements exceeded the NIOSH REL of the amphibole EMP.

Comparison of eastern and western zones

Overall, the exposure levels were higher in the eastern zone than in the western zone. The differences in the exposure levels support the idea of considering the SEGs in the eastern and western zones separately for the larger epidemiology study, and are consistent with the geological differences between the zones. For both total and amphibole EMP categories, the SEG with the highest exposure level in the eastern zone was operating technician (Table 2). In the western zone, the pelletizing operator was the SEG with the highest exposure levels for total EMP (Table 2). More than half of the SEGs had significantly different levels of total EMP exposures between the eastern and western

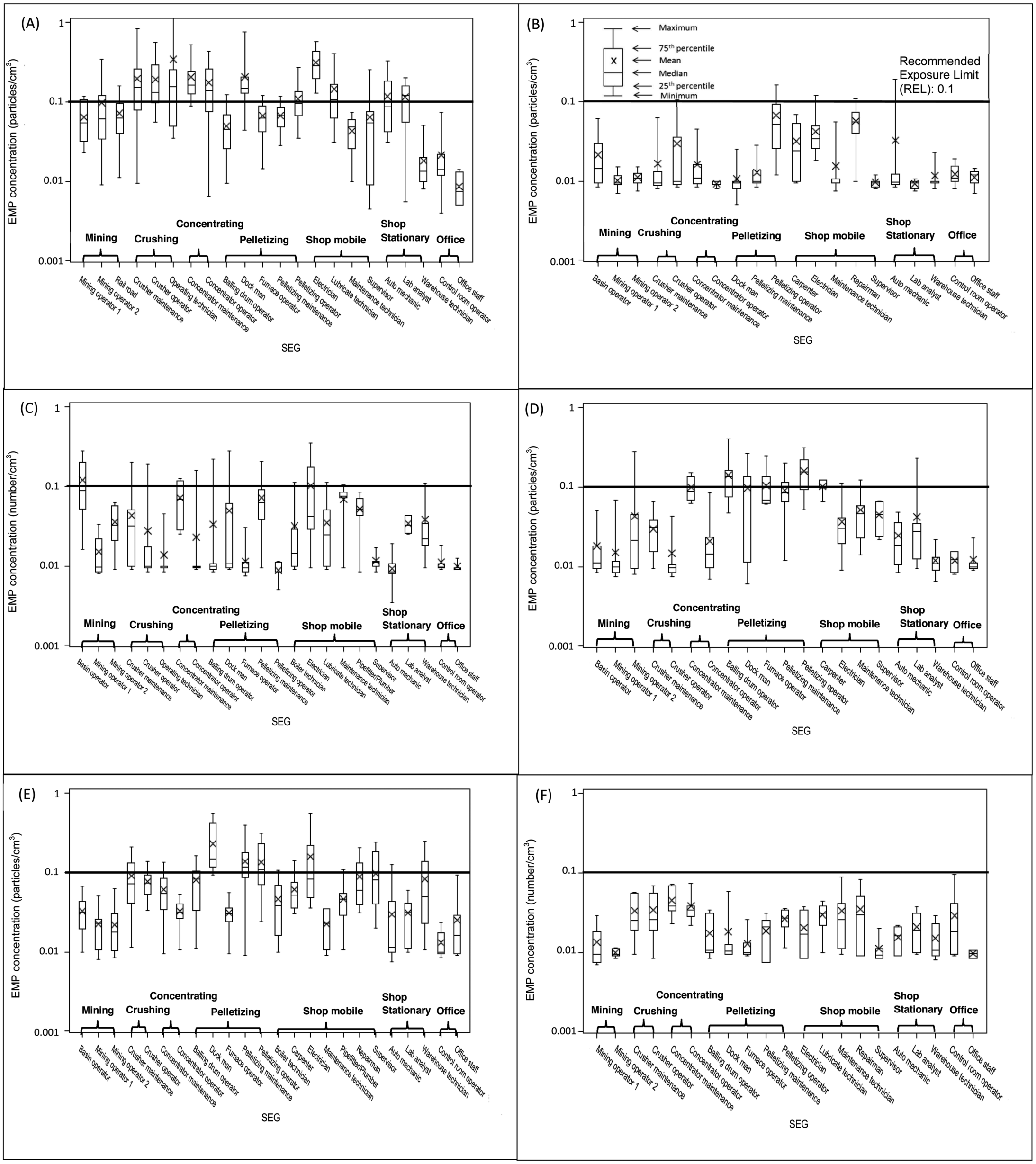

Fig. 1. Box plot of total EMP for each SEG in mines A–F (the horizontal line indicates the NIOSH REL for EMP = 0.1 particles cm^{-3}).

zones. This analysis provides empirical evidence that the geological differences between the two zones are reflected in EMP exposures.

The highest concentration in each mine was observed not only in departments directly involved in the mining process (mining, crushing, concentrating, and pelletizing departments) but also in the Shop (mobile) department, suggesting that the non-mining process may be similarly affected. The employees in the Shop (mobile) department work at various places in the mine, rather than at specific workstations. Therefore, the characteristics of the exposure levels for this department can be similar to those found in the mining process, and these SEGs potentially can have high exposure levels.

When the amphibole EMP concentrations are subtracted from the total EMP concentrations in the eastern zone, there remains a substantial excess

Table 3. Summary statistics of total EMP for each SEG measured in A–F mines (GM unit: particles per cubic centimeter).

Department	SEG	A		B		C		D		E		F	
		GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD	GM	GSD
Mining	Basin operator	—	—	0.017	1.96	0.089	2.40	0.014	1.94	0.028	1.88	—	—
	Mining operator 1	0.054	1.96	0.010	1.25	0.013	1.80	0.012	1.81	0.019	1.78	0.012	1.76
	Mining operator 2	0.057	3.14	0.011	1.27	0.030	2.04	0.025	2.73	0.018	1.95	0.010	1.14
	Rail road	0.054	2.53	—	—	—	—	—	—	—	—	—	—
Crushing	Crusher maintenance	0.131	2.70	0.013	1.95	0.026	2.68	0.025	1.85	0.068	2.29	0.027	2.13
	Crusher operator	0.157	1.95	0.018	2.66	0.015	2.43	0.012	1.91	0.071	1.51	0.027	2.13
	Operating technician	0.140	3.53	—	—	0.012	1.67	—	—	—	—	—	—
Concentrating	Concentrator maintenance	0.180	1.71	0.013	1.77	0.060	2.01	0.093	1.42	0.048	2.16	0.042	1.57
	Concentrator operator	0.116	3.06	0.009	1.08	0.013	2.27	0.016	2.07	0.029	1.69	0.035	1.50
Pelletizing	Balling drum operator	0.042	1.90	—	—	0.015	2.79	0.119	1.77	0.063	2.23	0.015	1.86
	Dock man	0.155	2.12	0.010	1.48	0.024	3.28	0.049	4.48	0.187	1.88	0.014	2.04
	Furnace operator	0.056	1.94	—	—	0.010	1.45	0.091	1.65	0.028	1.64	0.012	1.49
	Pelletizing maintenance	0.061	1.56	0.012	1.45	0.057	2.14	0.077	2.00	0.103	2.57	0.016	1.98
	Pelletizing operator	0.094	1.77	0.050	2.32	0.009	1.39	0.140	1.72	0.104	2.21	0.024	1.52
Shop (mobile)[a]	Boiler technician	—	—	—	—	0.020	2.63	—	—	0.034	2.39	—	—
	Carpenter	—	—	0.023	2.50	—	—	0.100	1.26	0.054	1.65	—	—
	Electrician	0.279	1.62	0.036	1.71	0.057	3.06	0.029	2.04	0.104	2.51	0.017	2.06
	Lubricate technician	0.104	2.43	—	—	0.025	2.40	—	—	—	—	0.026	1.72
	Maintenance technician	0.036	2.04	0.012	1.80	0.054	2.66	0.041	2.15	0.019	1.85	0.025	2.32
	Pipefitter/Plumber	—	—	—	—	0.042	2.28	—	—	0.039	1.91	—	—
	Repairman	—	—	0.050	1.85	—	—	—	—	0.070	2.07	0.023	2.81
	Supervisor	0.034	3.70	0.010	1.17	0.011	1.29	0.041	1.64	0.073	2.22	0.011	1.39
Shop (stationary)[b]	Auto mechanic	0.086	2.34	0.015	2.85	0.009	1.48	0.020	2.12	0.019	2.49	0.015	1.49
	Lab analyst	0.093	2.23	0.009	1.14	0.033	1.28	0.026	2.41	0.025	2.06	0.018	1.91
	Warehouse technician	0.015	1.82	0.011	1.46	0.027	2.48	0.011	1.51	0.053	2.86	0.013	1.71
Office/control room	Control room operator	0.008	1.65	0.011	1.34	0.010	1.13	0.011	1.42	0.018	2.15	0.010	1.10
	Office staff	0.016	2.18	0.012	1.37	0.011	1.29	0.012	1.36	0.012	1.45	0.021	2.35

[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.

of non-amphibole EMP concentration. This is significantly higher than the non-amphibole EMP concentration in the western zone for most SEGs. It is possible that this difference in non-amphibole oncentrations between the zones is related to the mineralogy. As described earlier, there are distinct metamorphic mineralogical differences between the zones. Phyllosilicates are prevalent in the western zone, while amphiboles are prevalent in the eastern zone. However, an analysis of how mineralogy affects the non-amphibole EMP concentration is beyond scope of this study.

Analysis of between-SEG and between-worker variabilities

The SEGs formed for this analysis identify workers with similar exposures; however, the exposures to EMP do not vary across all SEGs an only certain SEGs contribute significantly to variance. The between-SEG variance component was higher than the between-worker variance component in the eastern zone. Therefore, at least one of the SEGs is significantly different from the other SEGs in the eastern zone. However, the others may still not be distinguishable. Within the western zone, the between-SEG variance component was highest in mine D and the between-worker variance component was highest in mine F for total EMP.

Much higher contrast was observed in the eastern zone (0.740) than in the western zone (0.130). Since the western zone included five different mines, each SEG included exposures from five different mines, leading to higher between-worker (or within-SEG) variability, which in turn led to lower contrast. In particular, the between-SEG variance component was low in

Table 4. Summary statistics of amphibole EMP for each SEG measured in eastern zone (GM unit: particles per cubic centimeter).

Department	SEG	GM	GSD
Mining	Basin operator	—	—
	Mining operator 1	<LOD	<LOD
	Mining operator 2	0.003	2.62
	Rail road	<LOD	<LOD
Crushing	Crusher maintenance	0.019	2.11
	Crusher operator	0.023	2.07
	Operating technician	0.037	4.02
Concentrating	Concentrator maintenance	0.025	1.96
	Concentrator operator	0.015	3.11
Pelletizing	Balling drum operator	0.009	1.71
	Dock man	0.014	2.18
	Furnace operator	0.013	2.01
	Pelletizing maintenance	<LOD	<LOD
	Pelletizing operator	0.012	1.66
Shop (mobile)[a]	Boiler technician	—	—
	Carpenter	—	—
	Electrician	0.041	2.95
	Lubricate technician	0.012	2.27
	Maintenance technician	<LOD	<LOD
	Pipefitter/Plumber	—	—
	Repairman	—	—
	Supervisor	0.007	3.26
Shop (stationary)[b]	Auto mechanic	<LOD	<LOD
	Lab analyst	<LOD	<LOD
	Warehouse technician	0.004	1.60
Office/ Control room	Control room operator	<LOD	<LOD
	Office staff	<LOD	<LOD

[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.

the western zone except mine D for total EMP. Across the five mines in the western zone, there was a wide range of contrast values (0.000–0.865 for total EMP). Contrast was zero in mine F for total EMP (Table 5). However, the smallest number of subjects was monitored and the fewest number of samples were taken at mine F. The variability for each SEG in mine F was also the least (GSD range: 1.10–2.81 for total EMP), as shown in Table 3. Interestingly, the percentage of the between-worker variance component was ~8% in mine D in the western zone, which led to high contrast regardless of the value of the between-SEG variance component.

The between-worker variance is the only component that affects both contrast and homogeneity. A smaller value for the between-worker variance component leads to higher contrast and homogeneity of the SEG and thus increases the ability to identify exposure differences between the SEGs. The between-worker variance component was lower in the eastern than in the western zone, a finding consistent with the lower contrast in the western zone.

The pattern of total EMP concentrations between-SEGs in each mine and the range of total EMP concentrations between-workers as displayed in the individual box plots were consistent with S^2_{BG} and S^2_{BW}, respectively (Fig. 1). For example, for total EMP, the pronounced fluctuation in the pattern of EMP concentrations between-SEGs in mine D is reflected in the highest S^2_{BG}, as shown in Fig. 1 and Table 5. Likewise, the stable pattern of EMP concentrations between-SEGs found in the mine F is reflected in the lowest S^2_{BG} for that mine.

Analysis of within-worker variability

Within-worker variability was higher in the eastern zone than the western. Although taconite

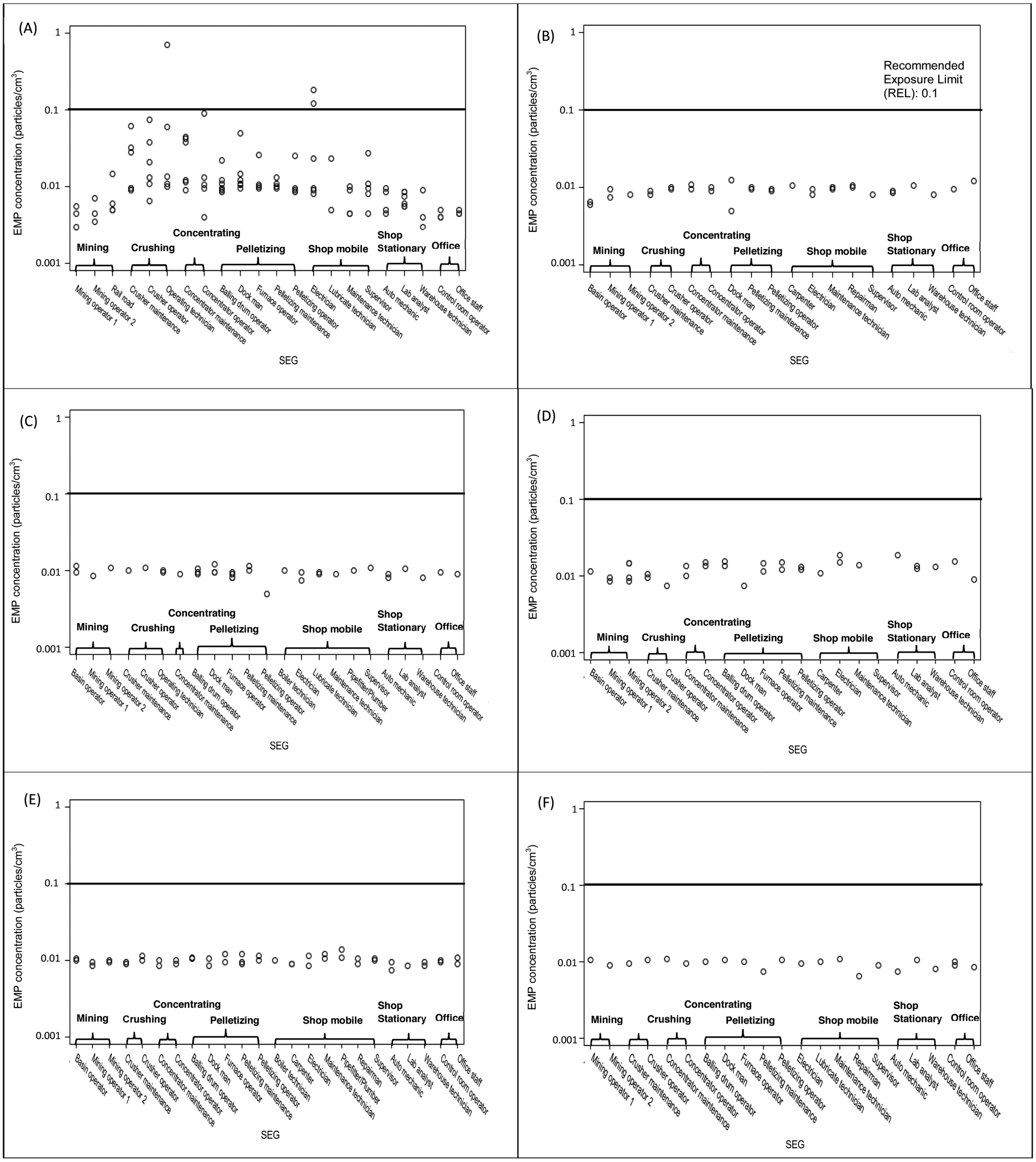

Fig. 2. Scatter plot of amphibole EMP for each SEG in mines A–F (the horizontal line indicates the NIOSH REL for EMP = 0.1 particles cm^{-3}).

processes are similar across all mines currently, the responsibilities for similar job classifications varied slightly between the mines due to the presence or absence of unionization, number of employees, and management. For instance, the workers at mine A, the sole mine in the eastern zone, are non-unionized, and the tasks performed by workers with the same job titles vary more depending on the work shift. Censored data, or values less than the LOD, also impact estimated within-worker variability. A higher percentage of values below the LOD were observed in the western zone, which led to the lower estimated within-worker variability.

The highest S^2_{WW} was observed in mine D and the lowest in mine B for total EMP. Overall, S^2_{WW} was

Table 5. Between-SEGs, between-worker, and within-worker variance components by mine and zone for total EMP.

Zone	Mine	Subject	Sample	BG		BW		WW		ε	η
				S^2_{BG}	%	S^2_{BW}	%	S^2_{WW}	%		
East	A	56	266	0.097	39.65	0.034	13.91	0.113	46.44	0.740	0.77
West	All	176	1014	0.021	8.69	0.142	58.24	0.081	33.07	0.130	0.36
	B	34	197	0.041	33.85	0.020	16.70	0.060	49.45	0.670	0.75
	C	38	218	0.038	19.17	0.076	37.76	0.086	43.07	0.337	0.53
	D	34	203	0.120	53.24	0.019	8.30	0.087	38.46	0.865	0.82
	E	48	267	0.054	28.85	0.069	36.80	0.065	34.36	0.439	0.48
	F	22	129	0.000[a]	0.00	0.204	76.39	0.063	23.61	0.000[a]	0.24

ε, contrast; η, homogeneity.
[a]Assuming that the use of the PROC NESTED model is appropriate, the negative variance components were treated as zero.

the dominant variance component compared to S^2_{BG} and S^2_{BW}, for total EMP for all mines except mines D and F. This finding indicates that the workers' daily tasks are the main source of variability rather than environmental influences. Higher homogeneity was found in the eastern zone than in the western.

Optimality of SEGs

Our results suggest that, in the eastern zone, the SEGs that we defined are formed well enough for total EMP. The pairwise comparison of SEGs between the two zones indicates that 62% of the SEGs had significantly different levels for total EMP. However, for the amphibole EMP, the *P* value for each SEG was not comparable due to LOD presented in either one or both zones. Specifically, the western zone had lower values for contrast and homogeneity than the eastern zone. The primary reason we have low contrast between-SEGs in the western zone is that all amphibole EMP exposure levels in the western zone were below the LOD.

As described earlier, department is a grouping variable that can be used as an alternative to SEG. Therefore, we also evaluated the variance components at the departmental level. However, the contrast and homogeneity values were lower than those calculated for the original SEGs. This finding reconfirmed that the original SEGs were as good as, if not better than, other possible grouping schemes that we considered and represent an appropriate level of analysis.

CONCLUSIONS

For many SEGs in several mines, the exposure levels of total EMP were higher than the REL for EMP. However, the total EMP classification does not necessarily refer to regulated asbestiform EMP because the NIOSH 7400 cannot differentiate between asbestiform and non-asbestiform EMP. The concentrations of amphibole EMP were well controlled across all mines and were much lower than the concentrations of total EMP, indicating that amphibole EMP are not major components of taconite EMP. Overall, we found that the variability of each SEG across mines was small for both total and amphibole EMP. Theoretically, the variability in the eastern zone should have been lower than the western as it consists of only one mine as opposed to five. However, due to the low concentration of EMP (often below LOD), we found lower variability in the western zone. When we compared zones, higher values for contrast and homogeneity were observed in the eastern zone. While low contrast and homogeneity was observed for the western zone taken as a whole, higher values were observed when these parameters were calculated for each mine. We conclude that the SEGs that we defined are appropriate for use in an epidemiological study when grouped by mine for total EMP.

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