

Original Article

A Bayesian Approach for Determining the Relationship Between Various Elongate Mineral Particles (EMPs) Definitions

Yuan Shao^{1,2}, Richard F. MacLehose³, Lifeng Lin^{4,5}, Jooyeon Hwang⁵,
Bruce H. Alexander¹, Jeffrey H. Mandel¹ and Gurumurthy Ramachandran^{2,*}

¹Division of Environmental Health Sciences, University of Minnesota, Minneapolis, MN 55455, USA;

²Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD 21205, USA; ³Division of Epidemiology & Community Health, University of Minnesota, Minneapolis, MN 55455, USA; ⁴Department of Statistics, Florida State University, Tallahassee, FL 32306, USA; ⁵Department of Occupational and Environmental Health, Hudson College of Public Health, University of Oklahoma Health Sciences Center, Oklahoma City, OK 73104, USA

*Author to whom correspondence should be addressed. Tel: +1-410-502-0182; e-mail: gramach5@jhu.edu

Submitted 19 October 2019; revised 12 April 2020; editorial decision 17 June 2020; revised version accepted 25 June 2020.

Abstract

A variety of dimensions (lengths and widths) of elongate mineral particles (EMPs) have been proposed as being related to health effects. In this paper, we develop a mathematical approach for deriving numerical conversion factors (CFs) between these EMP exposure metrics and applied it to the Minnesota Taconite Health Worker study which contains 196 different job exposure groups (28 similar exposure groups times 7 taconite mines). This approach comprises four steps: for each group (i) obtain EMP dimension information using ISO-TEM 10312/13794 analysis; (ii) use bivariate lognormal distribution to characterize overall EMP size distribution; (iii) use a Bayesian approach to facilitate the formation of the bivariate lognormal distribution; (iv) derive conversion factors between any pair of EMP definitions. The final CFs allow the creation of job exposure matrices (JEMs) for alternative EMP metrics using existing EMP exposures already characterized according to the National Institute of Occupational Safety and Health (NIOSH)-defined EMP exposure metric (length >5 μm with an aspect ratio ≥ 3.0). The relationships between the NIOSH EMP and other EMP definitions provide the basis of classification of workers into JEMs based on alternate definitions of EMP for epidemiological studies of mesothelioma, lung cancer, and non-malignant respiratory disease.

Keywords: Bayesian approach; bivariate lognormal distribution; elongate mineral particles (EMPs); EMP exposure metrics

Introduction

Since the term ‘fiber’ has been controversial in the context of asbestos (Eastern Research Group, 2003), the National Institute of Occupational Safety and Health (NIOSH) has proposed the use of the term ‘elongate mineral particles’ or EMPs to refer to any mineral particle with a minimum aspect ratio of 3:1 that is of inhalable, thoracic, or respirable size (NIOSH, 2011). In the USA, the current standard analytical method for measuring EMP is *the NIOSH Manual of Analytical Methods (NMAM) 7400: Asbestos and Other Fibers by Phase Contrast Microscopy (PCM)* with its latest update in 2019 (NIOSH, 1989). EMP can be asbestiform or non-asbestiform, and 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 original Occupational Safety and Health Administration (OSHA) regulation defined asbestos only mineralogically without specifying the habit or asbestiform nature. The definition also specified length and aspect ratios that were derived based on measurement reproducibility considerations rather than health relevance (Boulanger *et al.*, 2014). This was the origin of the regulatory definition that a ‘fiber’ should have a length that exceeds 5 μm and an aspect ratio (length:width) that is at least 3:1. However, in many industries including taconite mining and processing, EMPs are created during mechanical processing of the ore (e.g. crushing and fracturing of the mineral) that are referred to as cleavage fragments. These cleavage fragments could meet the regulatory definition of a ‘fiber’ described above, even if they were not naturally occurring and asbestiform in habit.

Non-asbestiform EMPs are mineralogically no different from asbestiform EMPs (Berndt and Brice, 2008), but are morphologically different, with needle-like (acicular) or prismatic crystalline habits (Ilgren, 2004; NIOSH, 2011). NIOSH has explicitly included EMPs from the non-asbestiform analogs of asbestos in its recommended exposure limit. Their rationale for this decision was 3-fold (NIOSH, 2011): (i) the epidemiological evidence from studies where worker populations were exposed to non-asbestiform EMPs (New York talc miners and millers, Homestake gold miners, and taconite miners) was considered inconclusive due to inadequate EMP exposure characterization, not accounting for smoking status, poor reliability of death certificate information, and exposures associated with prior employment; (ii) animal studies showed differential toxicity of asbestiform and non-asbestiform EMP with lower effects of exposure to non-asbestiform EMP and some

evidence that EMP dimensions may be predictors of toxicity; (iii) current analytical methods used for routine analysis of samples, i.e. the NIOSH 7400 phase contrast microscopy (PCM) and NIOSH 7402 transmission electron microscopy (TEM) methods cannot differentiate between asbestiform and non-asbestiform EMP when present in a heterogeneous mixture. This NIOSH definition, regardless of existing criticism targeting its absence of biological evidence (Addison and McConnell, 2008; Berndt and Brice, 2008) and PCM’s inadequacy for differentiating asbestiform from non-asbestiform (Bailey *et al.*, 2003), has become the most commonly used definition of EMP to the extent that other size of EMP are routinely not considered during analysis.

The primary goal of the Minnesota Taconite Work Health Study (TWHs) (University of Minnesota, 2014) was to evaluate whether the elevated mesothelioma rate reported among taconite mining workers in the Mesabi Iron Range in northeastern Minnesota can be attributed to their long-term exposure to the workplace non-asbestiform EMPs. A comprehensive EMP exposure assessment was carried out by collecting all available historical EMP sampling results from different sources (all based on the NIOSH 7400 definition), obtaining more than 1200 new EMP personal samples and analyzing them using the NIOSH 7400 method (Hwang, 2013; Hwang *et al.*, 2013, 2014). A mesothelioma case-control study found that mesothelioma was probably associated with cumulative NIOSH 7400 EMP exposure (RR = 1.10, 95% confidence interval = 0.97–1.24) (Lambert *et al.*, 2016).

Over the years, there have been several EMP definitions proposed based on alternative size ranges (Stanton *et al.*, 1981; Lippmann, 1988; Berman *et al.*, 1995; Berman and Crump, 2003, 2008; Dodson *et al.*, 2003; Eastern Research Group, 2003; Suzuki, *et al.*, 2005; Chatfield, 2008; Dement *et al.*, 2008; Loomis *et al.*, 2010, 2012; NIOSH, 2011). Dodson *et al.* (2003) concluded that asbestos EMPs of all lengths induce pathological responses and cautioned against ignoring EMP $<5 \mu\text{m}$ since they constituted the bulk of EMP exposures. Suzuki *et al.* (2005) concluded that short ($\leq 5 \mu\text{m}$), thin EMP ($\leq 0.25 \mu\text{m}$) were more strongly associated with malignant mesothelioma through analysis of lung and mesothelial tissues in human patients. In contrast, Chatfield (2008) suggested that thin ($0.04 \mu\text{m} \leq \text{width} \leq 0.25 \mu\text{m}$) and long ($20 \leq \text{aspect ratio} \leq 1000$) EMPs are more dangerous. Dement *et al.* (2008) showed using a TEM analysis of chrysotile fibers that all combinations of lengths and widths (lengths ranging from <1.5 to $>40 \mu\text{m}$ and widths ranging from 0.25 to $3.0 \mu\text{m}$) were

highly statistically significant predictors of lung cancer and asbestosis. This reinforced their previous conclusion that since the traditional counting method (NIOSH 7400 PCM and NIOSH 7402 TEM) counts only EMPs $>5 \mu\text{m}$ in length, shorter EMPs are not counted but may contribute substantially to work exposure (Dement *et al.*, 1983). Pott (1987) proposed that for natural fibers and man-made mineral fibers, EMPs $>3 \mu\text{m}$ in length, $<1 \mu\text{m}$ in width, and $>5:1$ aspect ratio, were carcinogenic.

A reanalysis of the 1268 filter samples collected during the TWHS to obtain the sizes of all EMP presents a unique opportunity to more definitively address the various competing hypotheses regarding the health effects of different EMP dimensions. The objectives of this study are 2-fold. First, we propose a new mathematical approach for deriving numerical relationships between several EMP dimension-specific definitions. Second, this approach will be applied to the taconite EMP data so as to derive a set of numerical conversion factors for the Minnesota Taconite Worker Health Study. These factors will allow the creation of job exposure matrices (JEMs) for alternative EMP metrics from our existing NIOSH-EMP JEM (Shao *et al.*, 2019) for future epidemiologic analysis.

Methods

Consistent with previous TWHS publications, all six then active mines were coded as Mine A through Mine F. Hwang *et al.* (2013) grouped all taconite workers job titles into 28 similar exposure groups (SEGs) based on their potential different exposure risks and collected EMP personal samples in all six mines (Table 1). Of the 28 SEGs, 27 SEGs were monitored. The Janitor SEG was not monitored because all janitors in the current taconite mining industry were independent contractors and not employed by the mining companies.

The detailed sampling procedures used to collect EMP samples are described elsewhere (Hwang, 2013;

Hwang *et al.*, 2013). In brief, personal samples were collected on the Iron Range from January 2010 to May 2011. 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. The average sampling time was 6 h, and the sampling rate varied by sample with the overall range of 0.65–0.95 l min^{-1} . EMPs were collected 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. Prior to this study, all personal samples had been analyzed using the NIOSH 7400 PCM method. The overall range of the NIOSH 7400 concentrations among all personal samples was from 0.007 to 2.164 EMP cc^{-1} .

Step 1: obtain single EMP dimension information using ISO-TEM analysis

In this study, all 1268 archived personal samples were analyzed using the ISO 10312 or 13794 TEM methods in an AIHA-accredited laboratory (EMSL Analytical, Inc.). Specifically, each personal sample was first screened by the ISO 10312 TEM method with 15 grid openings. If a particular filter was overloaded, then it would be reanalyzed using the ISO 13794 method but with 10 grid openings. The total filter area needed for this ISO-TEM analysis was about $\frac{1}{4}$ of the original complete filter (complete filter area: 490 mm^2). Under a high-resolution TEM microscope ($\sim \times 20\,000$ magnification), the lengths and widths of all eligible EMP (width (W) $\geq 0.01 \mu\text{m}$, length (L) $\geq 0.3 \mu\text{m}$, aspect ratio, $AR = L/W \geq 3$) were measured and reported. The new method allowed us to observe a much wider range of EMP compared with the traditional NIOSH PCM method.

Step 2: use bivariate lognormal distribution to characterize overall EMP size distribution

EMP size distributions can be described by a bivariate lognormal distribution, in which EMP lengths and widths individually follows a univariate lognormal distribution (Schneider and Holst, 1983; Holst and Schneider, 1985; Schneider *et al.*, 1985; Cheng, 1986; Quinn *et al.*, 2010). The overall distribution of our EMP data is shown in Fig. 1.

Mathematically, a bivariate lognormal distribution can be described by five parameters ($\mu_L, \mu_W, \sigma_L, \sigma_W, \rho$), and its probability density function is expressed as follows:

Table 1. EMP samples used in this paper by mine.

Mine	# of personal EMP samples
Mine A	253
Mine B	198
Mine C	218
Mine D	199
Mine E	270
Mine F	130
Total	1268

$$f(l, w) = \frac{1}{2\pi\sigma_L\sigma_W\sqrt{1-\rho^2}} \exp \left[-\frac{\left(\frac{\ln l - \mu_L}{\sigma_L}\right)^2 + \left(\frac{\ln w - \mu_W}{\sigma_W}\right)^2 - 2\rho\left(\frac{\ln l - \mu_L}{\sigma_L}\right)\left(\frac{\ln w - \mu_W}{\sigma_W}\right)}{2(1-\rho^2)} \right], \tag{1}$$

where $\mu_L, \mu_W, \sigma_L,$ and σ_W are the means and standard deviations of the natural logarithms of L and W , respectively; and ρ is the correlation between $\ln L$ and $\ln W$. An important property of this distribution is that its marginal distributions are lognormal as well. In other words, $\ln L$ and $\ln W$ individually follow a normal distribution (equation (2)).

$$\ln L \sim N(\mu_L, \sigma_L^2); \quad \ln W \sim N(\mu_W, \sigma_W^2) \tag{2}$$

Equivalently, we can get the geometric mean (GM) and the geometric standard deviation (GSD) of L and W using equation (3).

$$\begin{aligned} \text{GM}(L) &= e^{\mu_L}, & \text{GM}(W) &= e^{\mu_W}, \\ \text{GSD}(L) &= e^{\sigma_L}, & \text{GSD}(W) &= e^{\sigma_W} \end{aligned} \tag{3}$$

Step 3: use a Bayesian approach to facilitate the formation of the bivariate lognormal distribution
Our aim is to estimate the distribution of fiber lengths and widths in each mine-SEG combination. Although this study sampled a larger number of EMPs than previous studies, after we separated them by their sampling location, data were not evenly distributed across the SEGs. For example, as shown in Table 2, Mine A-Crusher maintenance

had 844 EMP while no EMPs were found among Mine C-Carpenter. To address this sparsity and provide reasonable estimates for every mine-SEG combination, we fit a Bayesian hierarchical model to the EMP data in order to represent the nested structure of the data. Specifically, our hierarchical model estimated mine-SEG-specific length and widths from the individual EMP dimensional information obtained from Step 1. This model has two levels: mines, and SEGs within each mine (Fig. 2). In the first level, non-informative prior and the overall EMP data of this mine were used to inform the parameters of a bivariate lognormal distribution. The output of the first level becomes the prior for the second level, and this mine-level prior then gets updated with SEG level data. EMP dimensional information are not borrowable across mines (level 1) but are borrowable across SEGs within each mine (level 2). This design would allow SEGs with no EMP information can borrow information from other SEGs within the same mine. If SEG X of Mine A had no EMP data, then its distribution would be the same as the overall distribution of Mine A. We did not assume there was exchangeability between mines because, based on geological information, EMP characteristics could vary substantially by mine location. The complete equations of our model are listed in equations (4)-(8).

For each individual EMP k in the SEG j and the Mine i , we assumed its length L_{ijk} and its width W_{ijk} follow a bivariate lognormal distribution.

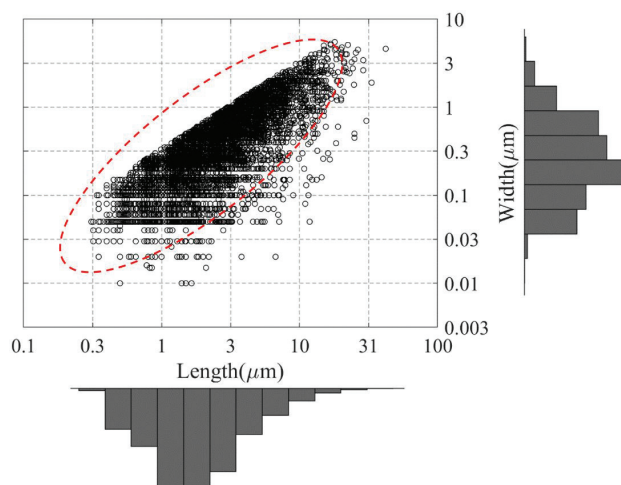


Figure 1. The scatter plot with marginal histograms for all study EMPs reported from ISO-TEM analysis (red eclipse: a bivariate lognormal distribution with the center of (1.78, 0.25 μm)).

Table 2. Summary of statistics (GMs and GSDs for lengths and widths) for the EMPs reported from ISO-TEM analysis in each mine-SEG location (unit of GMs: μm).

Mine/SEG	Mine A				Mine B				Mine C						
	N	GM(L)	GSD(L)	GM(W)	GSD(W)	N	GM(L)	GSD(L)	GM(W)	GSD(W)	N	GM(L)	GSD(L)	GM(W)	GSD(W)
Auto mechanic	55	3.42	1.94	0.52	2.17	60	1.32	1.62	0.14	2.16	9	1.72	1.98	0.14	2.73
Balling drum operator	226	1.79	2.00	0.32	2.29	0	/	/	/	/	55	1.12	1.96	0.15	2.09
Basin operator	0	/	/	/	/	20	1.35	2.37	0.13	3.34	30	1.87	2.09	0.23	2.31
Boiler technician	0	/	/	/	/	0	/	/	/	/	22	1.42	2.43	0.20	2.94
Carpenter	0	/	/	/	/	21	1.97	2.62	0.20	1.95	0	/	/	/	/
Concentrator maintenance	435	2.14	2.13	0.28	2.61	175	1.23	1.83	0.11	2.00	28	0.94	1.80	0.16	1.63
Concentrator operator	497	2.43	2.18	0.36	2.50	312	1.10	1.77	0.10	2.07	111	1.31	1.92	0.15	1.98
Control room operator	147	2.09	2.07	0.25	2.74	5	3.54	1.64	0.50	3.07	23	1.24	2.03	0.16	2.40
Crusher maintenance	844	2.54	2.13	0.45	2.36	135	1.37	2.06	0.14	2.75	162	0.94	1.94	0.13	1.96
Crusher operator	723	2.55	2.08	0.42	2.29	79	1.99	1.95	0.27	2.38	101	1.97	2.00	0.27	2.38
Dock man	68	1.59	2.17	0.17	2.73	8	1.57	2.82	0.11	1.85	61	1.15	1.94	0.15	2.24
Electrician	434	2.18	2.20	0.36	2.70	43	1.76	2.21	0.19	2.99	67	2.21	2.01	0.26	2.09
Furnace operator	149	1.72	1.96	0.31	2.17	0	/	/	/	/	118	0.81	1.82	0.11	1.86
Lab analyst	833	2.17	2.08	0.33	2.33	108	1.10	1.95	0.11	2.36	40	1.33	2.24	0.15	3.14
Lubricate technician	174	2.75	2.29	0.43	2.74	0	/	/	/	/	347	1.10	2.01	0.14	1.99
Maintenance technician	32	2.56	2.18	0.39	2.91	40	1.58	1.75	0.21	2.13	26	2.00	1.96	0.24	1.96
Mining operator 1	167	2.63	2.03	0.47	2.28	39	1.07	1.78	0.11	2.25	14	1.66	1.71	0.25	1.84
Mining operator 2	255	2.55	2.07	0.42	2.32	92	1.65	1.92	0.18	2.64	15	2.11	1.98	0.30	2.58
Office staff	5	2.13	2.04	0.26	3.57	43	1.13	1.91	0.10	2.36	0	/	/	/	/
Operating technician	99	1.89	2.51	0.29	3.17	0	/	/	/	/	124	1.12	2.23	0.15	2.10
Pelletizing maintenance	90	2.13	2.27	0.30	2.55	27	1.32	2.08	0.14	2.26	91	1.06	2.01	0.15	2.22
Pelletizing operator	241	1.71	1.86	0.26	2.24	17	1.42	2.23	0.16	2.57	33	0.92	1.76	0.13	1.73
Pipefitter/plumber	0	/	/	/	/	0	/	/	/	/	70	1.73	2.14	0.19	2.47
Rail road	121	2.60	2.50	0.39	3.08	0	/	/	/	/	0	/	/	/	/
Repairman	0	/	/	/	/	117	1.22	1.82	0.11	2.16	0	/	/	/	/
Supervisor	554	2.40	2.01	0.41	2.56	7	1.00	1.98	0.15	2.95	6	1.23	1.99	0.12	2.06
Warehouse technician	16	4.16	1.92	0.65	2.00	19	1.32	2.18	0.20	2.68	4	1.28	2.05	0.17	4.01
Total	6165	2.30	2.13	0.36	2.51	1367	1.30	1.95	0.13	2.41	1557	1.22	2.10	0.16	2.19

*Statistics were not available for the groups with less than three reported EMPs.

$$\left(\ln L_{ijk}, \ln W_{ijk} \right)^T \sim \text{Bivariate } N \left(\left(\alpha_{L,ij}, \alpha_{W,ij} \right)^T, \begin{pmatrix} \sigma_{L,i}^2 & \sigma_{LW,i} \\ \sigma_{LW,i} & \sigma_{W,i}^2 \end{pmatrix} \right); \quad (4)$$

where $\alpha_{L,ij}$ and $\alpha_{W,ij}$ are the i th mine and j th SEG-specific mean fiber ln-length and ln-width, respectively. We further assumed that those mine and seg-specific means are normally distributed about common mine-specific mean lengths, $\mu_{L,i}$ with a common variance of τ_L^2 , and widths, $\mu_{W,i}$ with a common variance of τ_W^2 . It is a random-effect model.

$$\alpha_{L,ij} \sim N(\mu_{L,i}, \tau_L^2); \quad \alpha_{W,ij} \sim N(\mu_{W,i}, \tau_W^2). \quad (5)$$

Non-informative priors ($N(0,1000)$ and Inverse Gamma(.1,.1)) are placed on each of these mine-specific dimensions (MacLehose *et al.*, 2007).

$$\mu_{L,i} \sim N(0, 1000); \quad \mu_{W,i} \sim N(0, 1000); \quad (6)$$

$$\tau_L^2 \sim \text{Inverse Gamma}(.1, .1); \quad \tau_W^2 \sim \text{Inverse Gamma}(.1, .1). \quad (7)$$

Within each Mine i , all SEGs uses the same variance-covariance matrix $\begin{pmatrix} \sigma_{L,i}^2 & \sigma_{LW,i} \\ \sigma_{LW,i} & \sigma_{W,i}^2 \end{pmatrix}$. This matrix follows an inverse Wishart distribution.

$$\begin{pmatrix} \sigma_{L,i}^2 & \sigma_{LW,i} \\ \sigma_{LW,i} & \sigma_{W,i}^2 \end{pmatrix} \sim \text{Inverse Wishart} \left(\begin{pmatrix} 10 \\ 01 \end{pmatrix}, 2 \right). \quad (8)$$

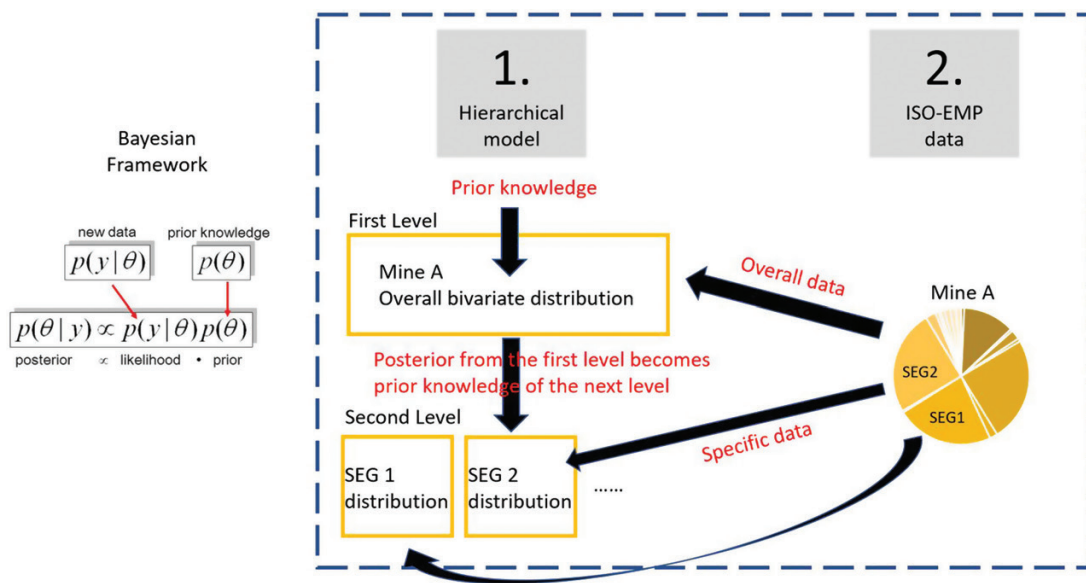


Figure 2. Schematic representation of Bayesian hierarchical model.

Table 3. EMP definitions considered in this study.

#	EMP definitions	Width (µm)	Length (µm)	Aspect ratio (AR)
1	ISO-TEM EMP (1995, 1999)	≥0.01 ^a	≥0.3 ^b	≥3 ^c
2	NIOSH EMP (1994)	≥0.25 ^d	>5	≥3
3	Chatfield EMP (2008)	0.04–1.5	NA	20–1000
4	Suzuki EMP (2005)	≤0.25	≤5	NA
5	Cleavage fragments (2008)	NA	NA	<20

^aThe minimum reported diameter in our study.

^bThe minimum reported length in our study. The method default value was 0.5 µm.

^cThe actual AR used in our study. The method default AR was 5:1.

^dEMP less than approximately 0.25 µm in diameter will not be detected by PCM.

Step 4: EMP size-based definitions

The five EMP definitions considered in this study are listed in Table 3. The (i) ISO-TEM EMP has the widest size range and can help us to see a nearly complete picture of the total EMP population; (ii) the NIOSH EMP and (iii) the Chatfield EMP refer to long and thin fibers; (iv) the Suzuki EMP refer to short fibers; (v) the Cleavage fragments are created by mechanical processes in mining, and should be less

biologically potent than the naturally occurring fibers (Ilgren, 2004; Gamble and Gibbs, 2008; Harper *et al.*, 2008).

Fig. 3 shows the regions of the hypothetical overall EMP bivariate lognormal distribution that correspond to each definition (non-gridded area). The volume under each region is proportional to the number of EMP according to that particular EMP definition.

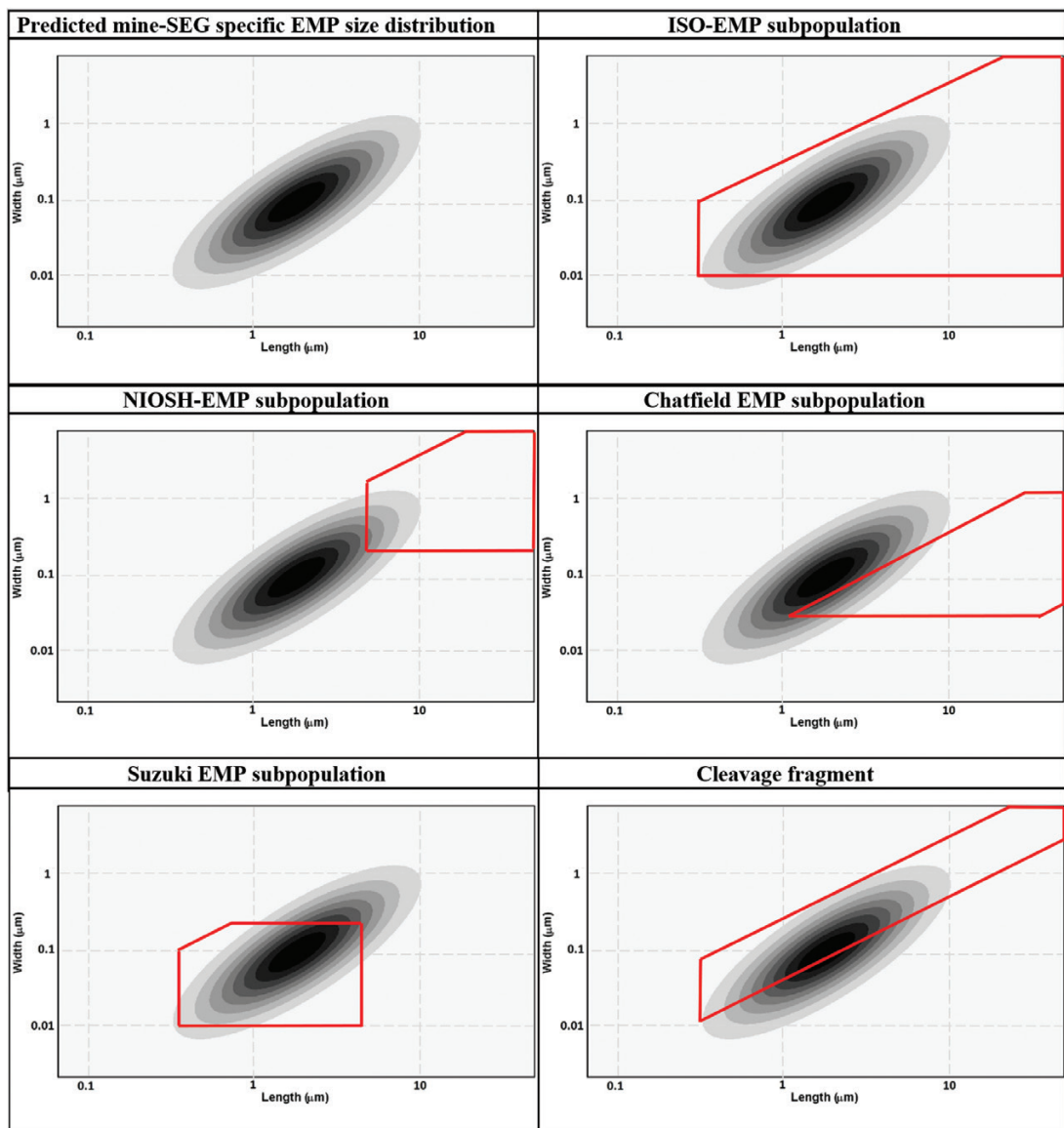


Figure 3. Specific region within the overall EMP size distribution corresponding to each EMP definition (area within red box).

Table 4. Summary of statistics (GMs and GSDs for lengths and widths) for the EMPs reported from ISO-TEM analysis in each mine-SEG location (unit of GMs: μm).

Mine/SEG	Mine D			Mine E			Mine F					
	N	GM(L)	GSD(L)	N	GM(L)	GSD(L)	N	GM(L)	GSD(L)	N	GM(L)	GSD(L)
Auto mechanic	7	1.72	1.93	16	1.70	2.28	13	1.07	1.70	13	1.07	1.70
Balling drum operator	57	1.46	2.18	78	1.37	1.97	36	0.97	1.80	36	0.97	1.80
Basin operator	2	/	/	11	2.41	2.54	0	/	/	0	/	/
Boiler technician	0	/	/	48	0.81	2.96	0	/	/	0	/	/
Carpenter	9	2.53	1.94	29	1.87	1.98	0	/	/	0	/	/
Concentrator maintenance	50	1.53	1.90	77	1.57	2.09	38	1.53	2.10	38	1.53	2.10
Concentrator operator	34	1.44	1.78	71	2.17	1.95	9	3.24	2.44	9	3.24	2.44
Control room operator	1	/	/	16	0.94	1.72	13	1.29	2.50	13	1.29	2.50
Crusher maintenance	46	1.23	2.02	51	2.21	1.93	16	3.73	1.98	16	3.73	1.98
Crusher operator	26	1.37	1.86	35	1.96	1.93	120	1.29	1.95	120	1.29	1.95
Dock man	21	1.40	2.25	17	1.91	2.01	9	1.56	2.56	9	1.56	2.56
Electrician	12	1.21	1.94	105	1.87	1.68	12	1.54	1.90	12	1.54	1.90
Furnace operator	29	1.11	1.88	13	1.54	2.25	13	0.89	1.74	13	0.89	1.74
Lab analyst	28	1.12	2.03	1	/	/	17	1.26	1.90	17	1.26	1.90
Lubricate technician	0	/	/	0	/	/	36	1.44	1.83	36	1.44	1.83
Maintenance technician	1	/	/	8	0.89	1.41	23	1.27	1.84	23	1.27	1.84
Mining operator 1	45	1.09	1.81	15	1.15	2.29	101	1.24	1.77	101	1.24	1.77
Mining operator 2	113	1.37	2.02	29	1.39	1.98	8	1.15	1.81	8	1.15	1.81
Office staff	5	1.84	1.25	9	0.90	2.60	0	/	/	0	/	/
Operating technician	0	/	/	0	/	/	0	/	/	0	/	/
Pelletizing maintenance	27	1.62	2.14	8	1.84	1.34	17	1.09	1.80	17	1.09	1.80
Pelletizing operator	63	1.43	2.19	44	1.06	2.13	97	0.94	2.07	97	0.94	2.07
Pipefitter/plumber	0	/	/	44	1.12	1.78	0	/	/	0	/	/
Rail road	0	/	/	0	/	/	0	/	/	0	/	/
Repairman	0	/	/	54	1.28	1.77	29	1.06	2.01	29	1.06	2.01
Supervisor	5	1.38	1.64	71	1.16	2.00	3	/	/	3	/	/
Warehouse technician	0	/	/	4	1.92	1.13	13	1.12	1.74	13	1.12	1.74
Total	581	1.37	2.03	854	1.48	2.11	623	1.24	2.03	623	1.24	2.03

*Statistics were not available for the groups with less than three reported EMPs.

Table 5. The numerical conversion factors (NIOSH EMP to Chatfield EMP).

Mine/SEG	Mine A	Mine B	Mine C	Mine D	Mine E	Mine F
Auto mechanic	0.03	0.73	2.31	0.82	0.34	0.93
Balling drum operator	0.03	0.74	0.24	1.85	0.40	0.47
Basin operator	0.05	0.93	0.21	0.26	0.09	0.84
Boiler technician	0.05	0.74	0.16	0.56	0.46	0.84
Carpenter	0.05	0.64	0.27	0.32	0.10	0.84
Concentrator maintenance	0.11	1.63	0.09	1.06	0.34	0.53
Concentrator operator	0.05	1.72	0.40	0.66	0.13	0.66
Control room operator	0.16	0.40	0.25	0.57	0.24	1.20
Crusher maintenance	0.02	0.77	0.28	0.45	0.06	0.40
Crusher operator	0.03	0.15	0.09	0.18	0.10	0.90
Dock man	0.30	1.90	0.29	0.80	0.09	0.63
Electrician	0.03	0.52	0.19	1.34	0.12	0.44
Furnace operator	0.03	0.74	0.42	1.55	0.54	0.55
Lab analyst	0.05	1.35	0.51	0.76	0.24	1.81
Lubricate technician	0.03	0.74	0.34	0.57	0.21	1.19
Maintenance technician	0.04	0.29	0.20	0.58	0.41	0.94
Mining operator 1	0.02	0.96	0.11	0.34	0.31	1.43
Mining operator 2	0.03	0.53	0.11	0.35	0.05	0.57
Office staff	0.09	1.71	0.27	0.09	0.21	0.84
Operating technician	0.06	0.74	0.26	0.56	0.21	0.83
Pelletizing maintenance	0.08	0.83	0.18	0.45	0.16	1.31
Pelletizing operator	0.07	0.64	0.28	1.32	0.17	1.04
Pipefitter/plumber	0.05	0.74	0.34	0.56	0.64	0.84
Rail road	0.05	0.74	0.27	0.56	0.21	0.84
Repairman	0.05	1.88	0.27	0.57	0.33	2.23
Supervisor	0.02	0.30	0.67	0.16	0.39	0.70
Warehouse technician	0.04	0.23	0.25	0.56	0.20	0.68

Step 5: deriving conversion factors between any two EMP definitions

The final mine- and SEG-specific conversion factor between any two EMP definitions is the ratio of the proportion of the density under the area of the fitted bivariate distribution for the definitions in Step 4. For example, if for a given mine/SEG combination, 3% of the EMP density falls under the NIOSH EMP area, and 60% of the total population falls under the Suzuki EMP area, then the conversion factor between the NIOSH EMP and the Suzuki EMP is 1:20. Thus, if a sample NIOSH 7400 result is 1 EMP cc⁻¹ for example, then the corresponding Suzuki EMP concentration will be 20 EMP cc⁻¹.

Software used

In this study, the EMP length and width ISO-TEM result were stored and sorted using SAS statistical software (version 9.4, SAS Institute, Cary, NC, USA). The Bayesian modeling in Step 3 was implemented in R with the Bayesian Graphical Models using MCMC 'rjags' package (R version 3.4.1, rjags version 4–6). The R-code

is provided in [Supplementary Materials](#), available at *Annals of Work Exposures and Health* online. Steps 4 and 5 were implemented in MATLAB (MATLAB version R2014b, the MathWorks, Inc., Natick, MA, USA).

Results and discussion

Measured EMP by SEG

The ISO-TEM analysis of the 1268 EMP personal samples resulted in a total of 11 147 eligible ISO-TEM EMPs. We sorted these EMPs by mine and SEG, and the number of available EMP in each of the 162 mine–SEG combinations (6 mines by 27 SEGs) is listed in [Tables 2](#) and [4](#). As we can see, the overall range of the EMP with size information in each combination was between 0 (no EMPs) and 844 EMPs. As many as 32 combinations (20%) had no EMPs with size information, and there were an additional 23 combinations with fewer than 10 EMPs. [Tables 2](#) and [4](#) also present GM and GSDs for the length and width of the EMPs within each mine–SEG combination. These statistics varied by mine–SEG

Table 6. The numerical conversion factors (NIOSH EMP to Suzuki EMP).

Mine/SEG	Mine A	Mine B	Mine C	Mine D	Mine E	Mine F
Auto mechanic	0.93	14.14	9.99	9.03	7.01	16.29
Balling drum operator	3.26	12.79	16.25	10.92	10.08	21.54
Basin operator	1.99	13.37	6.31	10.11	5.36	12.64
Boiler technician	1.98	12.88	10.10	10.83	28.34	12.63
Carpenter	1.99	7.31	11.63	6.51	5.66	12.60
Concentrator maintenance	2.68	18.75	20.12	9.39	7.53	8.84
Concentrator operator	1.76	25.75	12.35	10.14	3.70	5.18
Control room operator	2.92	6.81	12.72	12.31	14.86	13.07
Crusher maintenance	1.30	13.05	27.46	13.20	3.61	3.01
Crusher operator	1.37	4.69	4.16	10.70	5.03	13.19
Dock man	4.93	11.17	15.64	10.60	6.12	10.52
Electrician	2.10	7.68	3.87	12.08	4.76	10.12
Furnace operator	3.46	12.84	40.03	15.79	7.82	20.91
Lab analyst	2.28	23.91	11.99	15.04	7.45	14.21
Lubricate technician	1.26	12.82	18.88	10.85	8.52	11.11
Maintenance technician	1.66	9.11	5.85	8.23	12.11	13.42
Mining operator 1	1.23	21.84	8.47	16.68	11.24	15.63
Mining operator 2	1.41	8.26	6.13	10.42	9.31	14.40
Office staff	2.11	20.34	11.65	10.61	13.12	12.64
Operating technician	3.03	12.84	17.08	10.84	8.55	12.61
Pelletizing maintenance	2.47	13.96	18.53	8.40	7.19	16.90
Pelletizing operator	4.11	12.33	22.78	10.92	15.64	28.50
Pipefitter/plumber	1.99	12.84	6.75	10.84	14.43	12.63
Rail road	1.52	12.81	11.64	10.85	8.55	12.62
Repairman	1.99	19.43	11.65	10.83	11.29	20.37
Supervisor	1.57	18.37	12.14	12.14	14.27	9.81
Warehouse technician	1.01	13.44	11.85	10.87	7.52	15.37

combination with a range of 0.56–9.50 μm for GM(L); 1.00–3.53 for GSD(L); 0.05–1.50 μm for GM(W); 1.00–5.48 for GSD(W), supporting our hypothesis that the lengths and widths of EMPs from each can be described as bivariate lognormal distributions.

Conversion factors from NIOSH 7400 to alternative EMP metrics

The goal of this study was to derive numerical conversion factors between various EMP definitions that will allow us to create alternative JEMs based on EMP metrics other than the NIOSH-EMP JEM for future epidemiologic analyses. Three tables (see [Tables 5–7](#)) of conversion factors were derived for converting from the NIOSH EMP to Chatfield EMP, the Suzuki EMP, and the Chatfield non-asbestiform, respectively.

The median (IQR) of the conversion factors to ‘Chatfield EMP’, ‘Suzuki EMP’, and ‘Cleavage fragments’ from the ‘NIOSH EMP’ were 0.37 [0.16–0.74], 10.85 [6.13–13.19], and 15.13 [10.28–18.12], respectively.

The interpretation of these values is that if we observed 100 NIOSH EMP using PCM on a filter, there would have been, on average, around 37 Chatfield EMPs, 1085 Suzuki EMPs, and 1513 Cleavage fragments existing on that filter as well. In other words, NIOSH 7400 method reports a small portion of total EMPs collected on a sampling filter. The majority of taconite EMPs are short Suzuki EMPs and Cleavage fragments NIOSH EMPs are a very small fraction of the overall EMP population, and the long and thin Chatfield EMPs are even rarer than the NIOSH EMP in taconite mines.

Comparison between lab results and model predictions for each EMP definition

The Bayesian hierarchical model relies on several important assumptions: the bivariate lognormal distribution can well describe the overall EMP size distribution for each mine–SEG combination, and a common variance/covariance structure across all SEGs in a mine. To examine the soundness of our approach, we compared

Table 7. The numerical conversion factors (NIOSH EMP to Cleavage fragment).

Mine/SEG	Mine A	Mine B	Mine C	Mine D	Mine E	Mine F
Auto mechanic	3.42	18.58	9.56	11.66	10.61	22.04
Balling drum operator	7.87	16.84	23.10	11.23	14.31	31.62
Basin operator	5.28	16.87	10.35	15.55	10.13	17.67
Boiler technician	5.28	16.95	15.94	14.82	36.24	17.66
Carpenter	5.29	10.28	17.00	10.33	10.38	17.64
Concentrator maintenance	5.84	21.06	30.34	11.39	11.33	13.94
Concentrator operator	4.80	28.73	17.10	13.56	7.17	8.18
Control room operator	5.87	10.55	18.54	16.64	21.46	16.90
Crusher maintenance	4.49	17.05	36.44	18.34	7.74	5.84
Crusher operator	4.47	8.97	8.29	17.01	9.48	18.16
Dock man	8.08	11.75	21.87	13.63	11.22	15.78
Electrician	5.72	11.24	7.11	13.79	8.84	16.26
Furnace operator	8.25	16.92	50.00	17.45	10.84	30.17
Lab analyst	5.76	27.84	16.13	19.17	11.76	16.46
Lubricate technician	4.10	16.89	25.53	14.84	13.42	14.44
Maintenance technician	4.74	14.31	9.84	11.48	16.79	18.32
Mining operator 1	4.37	26.89	14.28	23.47	16.27	19.34
Mining operator 2	4.51	11.95	11.02	15.39	16.60	21.33
Office staff	5.07	22.63	17.02	18.10	19.47	17.71
Operating technician	6.90	16.91	23.94	14.83	13.46	17.69
Pelletizing maintenance	5.74	17.97	26.55	12.20	11.99	21.33
Pelletizing operator	8.52	16.66	30.78	12.51	23.22	36.89
Pipefitter/plumber	5.29	16.91	10.27	14.83	18.56	17.67
Rail road	4.43	16.87	16.99	14.86	13.44	17.67
Repairman	5.28	21.13	17.01	14.81	16.24	22.59
Supervisor	4.90	26.47	15.66	19.22	19.63	14.49
Warehouse technician	3.56	20.68	17.40	14.87	12.17	22.06

the actual and the predicted definition-specific EMP counts across all study mine–SEG combination. In other words, we were comparing what we saw from our sample to what we derived from the population we built based on our sample. Using Mine A—Auto mechanic as an example, Table 2 indicates that there are 55 single EMPs observed in this location. Among them, 14 belong to NIOSH EMPs, 11 belong to Suzuki EMPs, 3 belong to Chatfield EMPs, and 52 belong to Cleavage fragments. These actual counts observed in the sample can be compared with predicted values using the above approach. In this particular case, if there were 55 ISO-TEM EMPs, based on the specific EMP size distribution of this location, we would expect to see 15.9 NIOSH EMPs, 14.8 Suzuki EMPs, 0.55 Chatfield EMPs, and 54.4 Cleavage fragments. The complete observed versus predicted counts comparisons are demonstrated in the four plots of Fig. 4.

For NIOSH 7400, Suzuki EMP, and Cleavage fragments cases, their predicted and actual values were

highly consistent. We did not see a strong linear line in the Chatfield EMP plot. One possible reason could be this type of EMP is much rarer in the taconite mines than the other three EMP types, and very few EMPs were available to form a bivariate lognormal distribution for Chatfield EMP. From Fig. 4, we can also see that most of taconite mine related EMPs are neither the traditional regulated NIOSH fibers (median 6% with IQR 5–9%) nor the long Chatfield EMP (median 2% with IQR 1–4%). Rather, a majority of the EMP collected in the taconite mines are the short Suzuki EMP (median 67% with IQR 58–70%) and/or the Cleavage fragments (median 97% with IQR 94–99%).

Improvements from the previous study

A previous study conducted by Hwang *et al.* (2014) had developed conversion factors, but had several drawbacks: (i) it had small EMP samples: size information was obtained for only 2791 single EMP from the ISO-TEM analysis of 92 area samples; (ii) it was not a

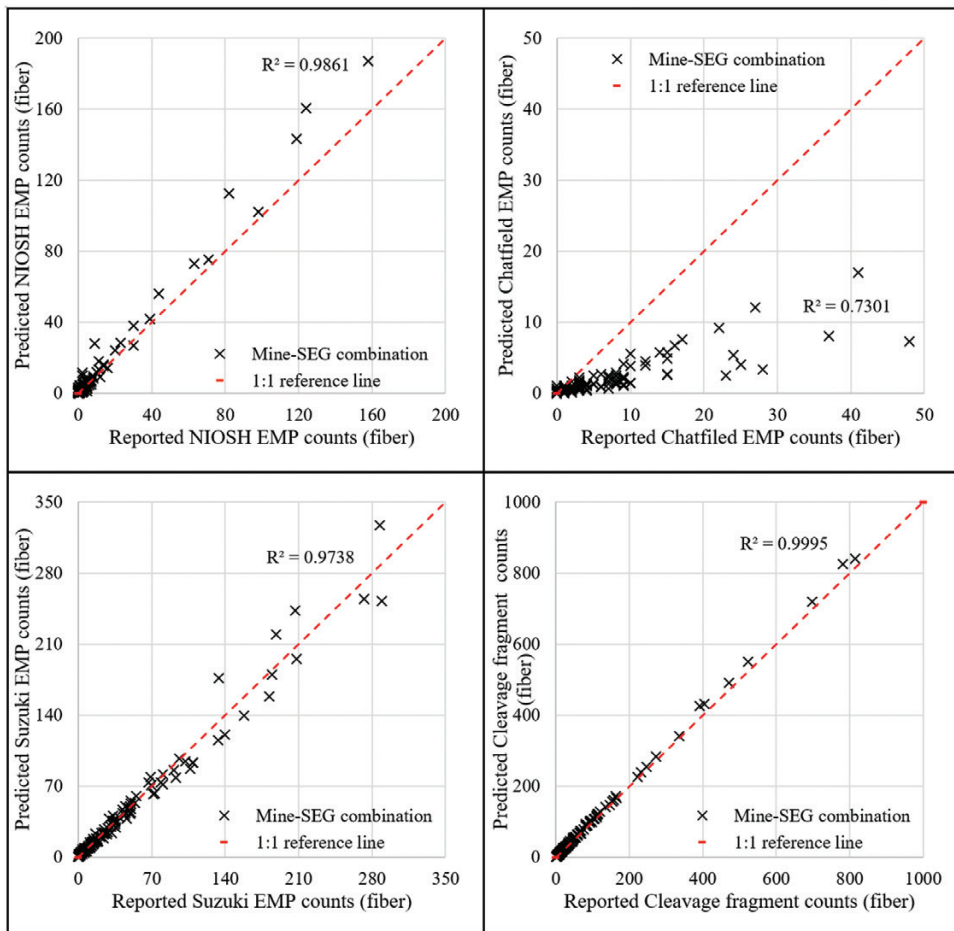


Figure 4. Actual and predicted definition-specific EMP counts given the total actual ISO-TEM EMP counts reported in each mine/SEG combination.

Table 8. The Pearson correlation (r) between different EMP definitions.

Pearson correlation (r)	NIOSH EMP	Chatfield EMP	Suzuki EMP	Cleavage fragment
NIOSH EMP	1			
Chatfield EMP	-0.29	1		
Suzuki EMP	-0.93	0.54	1	
Cleavage fragment	0.34	0.99	-0.59	1

probability-based method, and the conversion factors were derived based on actual sample results, and many locations had zero EMP count. As a result, the derived conversion factors had a high correlation between the NIOSH EMP JEM and other developed JEMs. Lambert *et al.* in 2015 reported that the JEMs, which were developed using the previous conversion factors, were highly correlated. One motivation of conducting this study was to improve upon the study by [Hwang *et al.* \(2014\)](#).

This study addresses the above limitations by developing a model-based Bayesian approach. It creates probability density plots for each location based on a bivariate lognormal distribution for 11 147 EMPs. The new conversion factors vary by location. The correlation between different EMP definitions varies as well (see [Table 8](#)), reflecting the natural association between these EMP definitions.

Conclusion

The Bayesian approach applied to the parameters of the bivariate lognormal distribution allows us to create an overall EMP size distribution for each of the mine-SEG combinations using EMP dimensional information. This method provides more robust estimates compared with estimates based on limited personal measurements. The mathematical relationships between the NIOSH EMP and other EMP definitions using the new ISO-TEM results provide the basis of classification of workers into JEMs based on alternate definitions of EMP for epidemiologic studies of mesothelioma, lung cancer, and nonmalignant respiratory disease. This approach is generalizable for any future research that study EMP size distribution.

Supplementary Data

Supplementary data are available at *Annals of Work Exposures and Health* online.

Funding

This research was supported by an award number 1R01OH010418-01A1 from the National Institute for Occupational Safety and Health. We would also like to thank the State of Minnesota for funding the Taconite Workers Health Study.

Conflict of interest

The authors declare that they have no conflict of interest.

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