RESPIRATORY DISEASES AND EXPOSURES TO TACONITE DUST COMPONENTS

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Dedications

To my late aunt (my mom's eldest sister) who did not wait to see my PhD graduation and forever left me in 2017. I miss you so much. Although you had been suffering from paraplegic since early childhood, you were the Helen Keller of my family. You were always optimistic to the life, and never yielded to any life difficulties. We had been living together since I was six, and you had become my another parent in my heart. You had been protecting me when I was a kid, and I never ever felt lonely even when my parents were out of town for months. I wish I could have earned enough money to take you to see the best doctor in the world, I am not smart enough to make that happen.

Table of Contents

List of Tables

List of Figures

Chapter 1 :

Introduction

Taconite mining in Minnesota and Taconite Workers Health Study (TWHS)

Low-grade taconite ore in Michigan and Minnesota is the primary source of iron for the iron and steel industry in the United States (Hubbell, Heller and Yang, 2001). In 2016, mines in these two states shipped 98% of the usable iron ore products in the US with an estimated value of $3.4 billion (National Minerals Information Center, 2017). Minnesota mines contributes about 76% of the production, and had 4514 employees in 2014 that did not include professional or clerical workers at mines, pelletizing plants, and maintenance shops or research lab workers (U.S. Geological Survey, 2014). Minnesota's taconite mining industry began in the 1950s in northeastern Minnesota along the Mesabi Iron Range after the depletion of hematite reserves (Berndt & Brice, 2008). The mining and processing of the taconite ores include four main steps – mining, crushing, concentrating and pelletizing, that increase the iron content from 15-30% in the ore to as high as 65% in the final product (US EPA, 2012). This process however generates a significant amount of dust that can result in workers' potential exposures to mixtures of respirable dust (containing iron, silica, and other chemicals) and Elongate Mineral Particles (EMP). The respirable dust here refers as the fraction of inhaled airborne particles that can penetrate beyond the terminal bronchioles into the gas-exchange region of the lungs. Its D_{50}, aerodynamic particle diameter corresponding to 50% sampling efficiency, is 4 µm.

Health concerns were initially expressed in the 1970s when increasing number of lung disease cases began to be reported in counties in proximity to where taconite was mined (Axten and Foster, 2008; Wilson *et al.*, 2008). However, follow-up occupational studies demonstrated little evidence of elevated disease rates among workers (Clark *et al.*, 1980;

Higgins *et al.*, 1983; Cooper, Wong and Graebner, 1988; Cooper *et al.*, 1992). In 1983, a cohort that included 68,737 individuals who had ever worked in the mining industry in northeastern Minnesota between the 1930s and the end of 1982 was enumerated through the Mineral Resources Health Assessment Program (MRHAP) with the support of the Iron Range Resources and Rehabilitation Board (IRRRB) and the cooperation of the seven mining companies then in operation (MDH, 1985). In 1997, this cohort was matched with cancer information from the Minnesota Cancer Surveillance System (MCSS) and subsequent reports in 2003 and 2007 showed a 2.9-fold increase in the rate of mesothelioma in the iron mining industry workers when compared to the rest of Minnesota (MDH 2003, 2007). These findings challenged conventional understanding since mineralogical data suggest that the ore body involves almost exclusively non-asbestiform EMP (McSwiggen & Morey, 2008; Zanko et al., 2008), that had not been thought to have high potential for disease (Gamble & Gibbs, 2008; Berry & Gibbs, 2008; Mossman, 2008).

Concerns about the potential excess rates of mesothelioma in this cohort led the Minnesota State Legislature in 2008 to fund the Taconite Workers Health Study (TWHS) to evaluate mesothelioma, lung cancer, and non-malignant respiratory disease (University of Minnesota, 2014). Since then, studies on exposure assessment for present-day exposure to respirable dust (RD), respirable silica (RS) and EMP (Hwang *et al.*, 2013, 2014, 2017), mortality (Allen *et al.*, 2014; Mandel, Ramachandran and Alexander, 2016), cancer incidence (Allen et al., 2015), lung cancer case-control (Allen et al., 2015), mesothelioma case-control (Lambert *et al.*, 2016) and pulmonary function tests (Odo *et al.*, 2013) have been reported. These studies report the following broad conclusions: (1)

Taconite workers have an increased risk for mesothelioma, lung, laryngeal, stomach, and bladder cancers. (2) Taconite workers may be at increased risk for mortality from lung cancer, mesothelioma, and cardiovascular disease (specifically, hypertensive heart disease and ischemic heart disease). (3) Mesothelioma was associated with the number of years employed in the taconite industry (RR=1.03, 95% CI 1.00 - 1.06), and cumulative EMP exposure (RR=1.10, 95% CI 0.97 –1.24) as defined by the National Institute for Occupational Safety and Health (NIOSH) EMP 7400 method. (4) Lung cancer case-control study suggests that the estimated taconite mining exposures do not increase the risk of developing lung cancer.

New NIOSH-funded study

As part of a new NIOSH-funded research grant (2014), we re-analyzed all 1269 archived EMP personal samples, that were collected in the original TWHS from all six active mines (five in the western and one in the eastern zone of the Mesabi Iron Range), using the more advanced ISO TEM 10312/13794 analytical methods. These methods, compared to the traditional NIOSH 7400/7402 methods can detect EMP with a wider size range and report the length and width information for each of every identified EMP. The new detailed EMP information, in conjunction with existing study cohorts assembled in the original TWHS made the test of the following research hypotheses possible: (1) long-term on-site exposure to non-asbestiform EMP contributes to the development of mesothelioma and lung cancer observed in the taconite mines. (2) the selection of different EMP exposure metrics will impact the disease risk estimated from epidemiological studies.

Beside the new EMP ISO-TEM results, all existing historical industrial hygiene measurements assembled in the original TWHS study were further processed and cleaned. The previous mesothelioma cohort was updated in 2015 based on the Minnesota Cancer Surveillance System (MCSS), and 23 new in-state cases and 1 out of state case were identified.

Asbestos and Elongated Mineral Particles (EMP)

Legislatively, the term “asbestos fiber” refers to a set of six naturally occurring fibrous minerals regulated by the OSHA in 1970s. These minerals include the serpentine mineral - chrysotile, and the five amphibole minerals - actinolite, amosite, anthophyllite, crocidolite, and tremolite (IARC 2012). The definition also specified length and aspect ratios that were derived from measurement reproducibility considerations rather than health relevance. 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 (OSHA 1979). Asbestos fibers have been being heavily researched in the past 40 years, and there is general consensus that all types of asbestos cause lung cancer, mesothelioma, cancer of the larynx and ovary, and asbestosis (fibrosis of the lungs) (ICOH, 2013; Collegium Ramazzini, 2016; WHO, 2016).

The term “elongated mineral particles” or EMP, which refer to any mineral particle with a minimum aspect ratio of 3:1 that is of inhalable, thoracic, or respirable size (NIOSH, 2011), is a broader concept. Theoretically, this concept can be further divided into two sub-groups based on mineral habit: asbestiform EMP and non-asbestiform EMP; and the OSHA-specific fibers discussed above belong to the asbestiform EMP. However in practice, traditional analytical methods (Phase Contrast Microscopy (PCM) and Transmission Electron Microscopy (TEM)) cannot explicitly distinguish asbestiform EMP from their non-asbestiform analogues when present in a heterogeneous mixture and it is especially true for amphibole EMP (ISO 1995; ISO 1999; NIOSH 1994). For this reason, some research groups statistically analyzed the potential dimension differences between prepared asbestiform amphibole EMP and non-asbestiform amphibole EMP samples, and proposed dimension-based criteria (Chatfield, 2008; Van Orden *et al.*, 2009) in an attempt to solve this differentiation problem. Unfortunately, these criteria might not work well in practice (Harper, 2008; Harper *et al.*, 2008, 2012).

Furthermore, non-asbestiform EMP, based on their origins, can be further divided into naturally occurring EMP and cleavage fragments. Cleavage fragments by definition are the structures that are created via comminution, whether deliberate during crushing or grinding, or incidental in usage (Ilgren, 2004). Although taconite ore itself may not contain many natural occurring EMP, taconite mining processes (e.g. crushing) could create significant numbers of cleavage fragments, that end up creating a dusty non-asbestiform EMP environment.

Because of the difficulty of distinguishing non-asbestiform EMP from other EMP, the relationship between non-asbestiform EMP and adverse health effects is not understood well (NIOSH, 2011). Adverse health effects examined in some epidemiology studies have been linked to non-asbestiform EMP, in gold and talc mining studies, where non-asbestiform EMP exposures also exist. *The NIOSH Roadmap* (NIOSH, 2011) *clearly* *identifies the taconite miners of northeastern Minnesota as a population that should be studied further with detailed exposure characterization.*

EMP dimensions and health risks

EMP dimension affects penetration and deposition in different regions of the lung. Macrophages cannot remove particles from the lung when the EMP length is longer than the macrophage diameter, and the lung cannot function when the thinner EMP deposit in the deeper alveoli region of the lung (Baron, 2003).

However, the question of how the dimensions of the asbestiform EMP are related to carcinogenic lung disease development has been controversial. Stanton et al. (1981) hypothesized that carcinogenicity of EMP is related to dimension and durability and less with mineral type and ascribed carcinogenicity to EMP with a length > 8 µm and a diameter < 0.25 µm. Subsequently, Lippmann (1988) suggested that lung cancer was associated with associated with asbestos EMP longer than 10 µm with a diameter > 0.15 µm, while mesothelioma was associated with asbestos EMP longer than 5 µm with a diameter < 0.1µm. A series of analyses by Berman et al. (1995, 2003, 2008) consistently suggested that it is likely that length categories with minimum cut points substantially longer than 10 µm contribute most heavily to both asbestos-induced lung cancer and mesothelioma. Loomis et al. (2010, 2012) also found that the occurrence of lung cancer is associated most strongly with exposure to long thin asbestos fibres (5-10 µm long and <0.25 µm in diameter) in workers at asbestos textile mills in North Carolina and South Carolina, USA. A panel of experts convened by ATSDR (Eastern Research Group, 2003) concluded that there is a weight of evidence that asbestos and synthetic vitreous fibers (SVFs) shorter than 5 μm are unlikely to cause cancer in humans.

Other researchers have argued against ruling out the effect of short fibers. Dodson et al. (2003) concluded that asbestos EMP of all lengths induce pathological responses and cautioned against ignoring EMP < 5 μm since they constituted the bulk of EMP exposures. Suzuki et al. (2005) concluded that short (≤5 μm), thin EMP (≤0.25 μm) were more strongly associated with malignant mesothelioma through analysis of lung and mesothelial tissues in human patients. Dement et al. (2008) showed using a TEM analysis of chrysotile fibers that all combinations of lengths and widths (lengths ranging from <1.5 μm to > 40 μm and widths ranging from 0.25 - 3.0 μm 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 EMP > 5 μm in length, shorter EMP are not counted, but may contribute substantially to work exposure (Dement *et al.*, 1983). Pott (1987) proposed that for natural fibers and manmade mineral fibers (MMMF), EMP >3 μm in length, <1 μm in width, and >5:1 aspect ratio were carcinogenic.

The above discussion highlights the following – (1) the lack of well-defined studies regarding the health effects of non-asbestiform EMP, and (2) the lack of agreement on the appropriate threshold dimensions of EMP that are health-relevant.

Research objectives

The primary research question addressed in this work is whether long-term on-site exposure to non-asbestiform EMP contributes to the development of mesothelioma and lung cancer observed in the taconite mines. If so, which EMP exposure metric (what size range of the study EMP) is most associated with the mesothelioma cases among taconite worker population. This question could not be well answered in previous TWHS study due to the limitations of the data available at that time.

Specific aim 1

To reconstruct the historical respirable silica (RS) and respirable dust (RD) exposures of workers in Minnesota taconite industry from 1955-2010 by developing job-exposure matrices (JEM) that uses 9,128 RS and 19,408 RD industrial hygiene monitoring data. The result of this study is a JEM by mine, department, and year for RD and RS that will form the basis for future epidemiological studies.

Specific aim 2

To reconstruct the historical NIOSH EMP exposures of workers in Minnesota taconite industry from 1955-2010 based on 751 historical and 1285 present-day EMP measurements, and some time-trend information learned from specific aim1 using two different reconstruction strategies. The result of this study is two strategy-specific NIOSH-EMP based JEMs. These two JEMs will form the basis for future epidemiological studies.

Specific aim 3

A variety of dimensions (lengths and widths) of elongate mineral particles (EMP) have been proposed as being related to health effects such as mesothelioma and lung cancer. The goal of third study is to develop a mathematical approach for deriving numerical conversion factors (CFs) between these exposure metrics. These CFs will allow us to develop dimensional-specific EMP JEMs based on existing NIOSH-EMP based JEM developed in specific aim 2.

Specific aim 4

An excess of mesothelioma has been observed in iron ore miners in Northeastern Minnesota. Mining and processing of taconite iron ore generate exposures that include elongate mineral particles (EMP). As an update of the 2010 Minnesota mesothelioma study that evaluated the association between mesothelioma, employment and EMP exposures from taconite mining, the goal of this study is to re-evaluate this association for the EMP of different size ranges using the updated study cohort and new dimension-specific EMP JEMs developed in specific aim 3.

Organization of the dissertation

The dissertation has a total of six main chapters. The first chapter includes a brief history of Minnesota iron mining industry, mining related health concerns, and the resulting Minnesota Taconite Worker Health Study (TWHS) conducted from 2008 to 2013. It summarizes the main findings of this previous study and the new research directions after this study. The primary research hypotheses and four associated specific aims are described. Chapter 2 describes the exposure reconstruction process for historical respirable silica (RS) and respirable dust (RD) exposures of workers in Minnesota taconite industry from 1955-2010 in specific aim 1. This chapter also discusses how the historical dust exposure changed over time in each mine-department combination. Chapter 3 addresses specific aim 2, and describes how the historical EMP exposure levels are predicted using EMP data and the time-trends obtained from specific aim 1. Chapter 4 describes the mathematical modeling approach for deriving numerical conversion factors (CFs) between EMP of different size ranges. This chapter also discusses how these CFs are important in the development of alternative dimension-specific EMP JEMs starting from the existing NIOSH-EMP based JEM developed in specific aim 2. This work addresses specific aim 3. Chapter 5 describes a mesothelioma case-control study conducted using an updated study cohort and new dimension-specific EMP JEMs developed in specific aim 3. The chapter addresses specific aim 4 and provides answers to the primary research question of this dissertation. In the last chapter, I summarize the overall conclusion and propose some future research directions. The research roadmap diagram is listed in Figure 1-1.

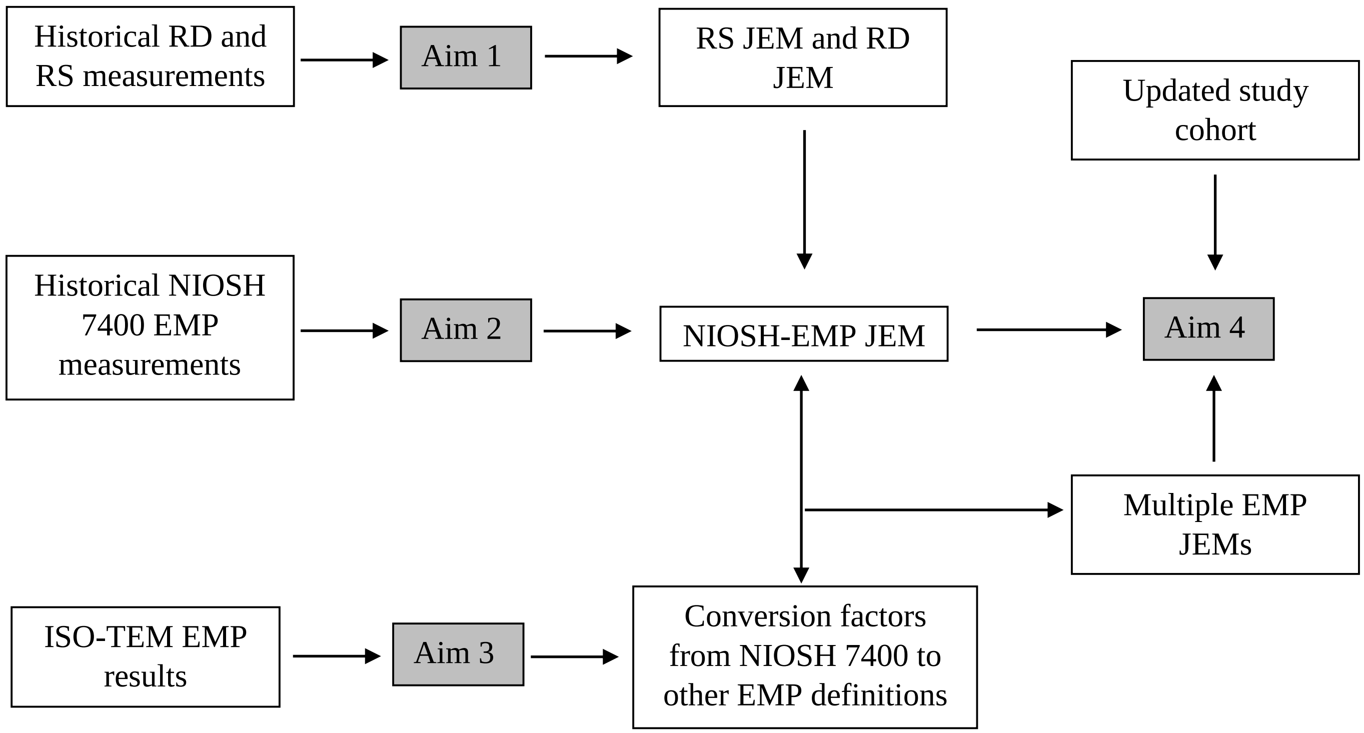

FIGURE 1-1 The overall research roadmap in the dissertation

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Chapter 2 :

Reconstructing Historical Exposures to Respirable Dust and Respirable Silica in the Taconite Mining Industry for 1955–2010

OUTLINE

Objective: As part of ongoing epidemiological studies of Minnesota taconite mining workers for assessing the association between exposure to taconite dusts and the development of respiratory diseases, the goal of our study is to reconstruct the historical respirable silica (RS) and respirable dust (RD) exposures of workers in Minnesota taconite industry from 1955-2010 by developing a job exposure matrix (JEM) that uses 9,128 RS and 19,408 RD industrial hygiene monitoring data.

Methods: Historical RS and RD data were obtained for seven taconite mines (ArcelorMittal, Hibbtac, Keetac, LTV, Minntac, Northshore and Utac) from three sources: (1) the Mine Safety and Health Administration (MSHA) has online database records for all inspection results since 1978 for 13 MSHA Mine IDs with 4,303 RD monitoring records; (2) the mining companies' internal monitoring reports contain 14,417 RD records, most of which date from the late 1970s. Only one mine has records dating back to 1956; (3) a University of Minnesota study in 2010 collected 688 pairs of RS and RD measurements covering six active mines. In the historical dataset, about 20% of the measurements (prior to 1975) were in the now-defunct count unit of millions of particles per cubic foot (mppcf). We converted these to mass concentration using the OSHA-recommended conversion factor of 1 mppcf = 0.1 mg/m^3. Unlike RD data that can be directly obtained from industrial hygiene reports, historical RS data have to be calculated using RD and percent silica information, and 8,840 RS data were calculated using this method. Zero values (1721 RD records and 1161 RS records) were replaced with one half of the limit of detection (LOD) value of current NIOSH analytical methods for the RD and the RS (0.06 and 0.006 mg/m^3 for RD and RS respectively). After data treatment, the data were grouped into seven mines and then into eight departments (Concentrating, Crushing, Janitor, Mining, Office/control room, Pelletizing, Shop (mobile), Shop (stationary)). Within each department, we applied a two-level random-intercept model which assumes that the natural log of Y (RD or RS concentration) changes over time at a constant rate.

Results: The overall predicted historical mean RD exposure was between 0.05 and 0.56 mg/m3. High RD values were located in one/multiple of the following departments: Crushing, Concentrating, Pelletizing and Shop (mobile). The overall predicted historical mean RS exposures was between 0.00 and 0.10 mg/m3. High RD values were located only in either Crushing or Shop (mobile). The annual change rates for the historical RD and RS exposures were between -3.3% to 3.2%. The silica percentage in the dust varied by location with the highest value of 29.3% in ArcelorMittal Crushing and the lowest one of 2.1% in Hibbtac Pelletizing.

Conclusion: In this study, we conducted a careful aggregation of available historical monitoring data for RD and RS from multiple sources, after processing and cleaning the data so that they were in consistent units. There are sufficient monitoring data for exposure reconstruction as a function of time at the mine/department level, but not at smaller levels of resolution, e.g., similar exposure groups within departments. The result of this study is a JEM by mine, department, and year for RD and RS that will form the basis for future epidemiological studies.

INTRODUCTION

Minnesota's taconite mining industry began in the 1950s in northeastern Minnesota along the Mesabi Iron Range after the depletion of hematite reserves (Berndt and Brice, 2008). The mining and processing of the taconite ores include four main steps – mining, crushing, concentrating and pelletizing, that increase the iron content from 15-30% in the ore to as high as 65% in the final product (Hubbell, Heller and Yang, 2001; US EPA, 2012). This process, however, generates significant amount of hazardous dusts that can result in worker exposure to mixtures of respirable dust containing iron, silica, and other materials. Health concerns about Minnesota taconite workers led the Minnesota State Legislature in 2008 to fund the Taconite Workers Health Study (TWHS) to evaluate mesothelioma, lung cancer, and non-malignant respiratory disease (NMRD) (University of Minnesota, 2014).

Several studies, including the TWHS, have reported on exposures in the taconite industry (Sheehy, 1986; Sheehy and McJilton, 1987; Axten and Foster, 2008; Wilson *et al.*, 2008; Zanko, Niles and Oreskovich, 2008; Hwang, 2013; Hwang *et al.*, 2013, 2014). The TWHS study includes one inactive and six active taconite mines. All workers job titles have been grouped into 28 similar exposure groups (SEG) within eight departments. The earliest taconite mine in the study was opened in 1955, and the latest one was opened in late 1970s. The oldest onsite industrial hygiene (IH) measurements date from 1956 and the longest continuous records are from 1956 to 2010, a 55-year span.

The current study presents the reconstruction of the historical exposures of workers and the creation of the job exposure matrix (JEM) in the taconite industry in Minnesota for respirable silica (RS), and respirable dust (RD) using available historical industrial hygiene (IH) measurements.

To develop JEMs for multiple dust components in a study, there are several strategies. The first approach (Føreland *et al.*, 2008; Fayerweather *et al.*, 2011; Gao *et al.*, 2000; Zhuang, Hearl, Odencrantz, W. Chen, *et al.*, 2001; Tu *et al.*, 2005; Leal *et al.*, 2012) is to construct the JEM for a particular component independent of other dust components. Specifically, the RS JEM would be constructed using only RS IH data, and the RD JEM would rely only on RD IH data. This method, because different JEMs rely on data from different sources, statistically, has a greater probability of avoiding "multiple-collinearity" issues in multivariable epidemiologic studies. But because this method treats each agent separately, the quality of one JEM could be better than the other due to the different IH data quality of the two agents. Additionally, the two JEMs may not necessarily be consistent with each other. For example, in some extreme cases, a predicted RS concentration could be higher than its corresponding RD concentration due to poor data quality. To prevent these drawbacks, another approach has been used sometimes (Zhuang *et al.*, 2001; Føreland *et al.*, 2012) that first develops a "parent" JEM for one agent, typically the one with the best data quality. Conversion factors are derived between other exposure agents to the parent agent usually based on side-by-side measures, and these factors are then applied to the parent JEM to develop "child" JEMs. The drawback of this strategy, however, is these JEMs are likely to be highly correlated.

To improve upon these two strategies, a new approach is proposed here for reconstructing RS and RD exposures in this study. This new approach uses both RS and RD data into consideration during the reconstruction process, without assuming that they are independent of each other within a sampling location. Rather, they carry some similar characteristics resulting from their common sampling location. For example, they may share the same time trend due to the same dust-control practices being implemented in a given location. We define a categorical dummy variable – **Agent** and assume this variable has two levels – RS and RD, then we can use a general regression-based model to analyze the similarities at the individual data level as well as the differences between the two agents. We expect that this model will provide one RS JEM and one RD JEM that are statistically uncorrelated, yet share common information.

METHODS

Background

The TWHS study comprises seven taconite mines (ArcelorMittal, Hibbtac, Keetac, LTV, Minntac, Northshore and Utac) and Hwang et al. (2013) grouped all taconite workers job titles into 28 similar exposure groups (SEG) within eight departments. Ideally, exposure assessment would be conducted at the SEG level, but given poor coverage of the raw data at this level, we chose to develop the JEMs at the more aggregate department level. For each of the seven taconite mines, workers were sorted into eight departments (Concentrating, Crushing, Janitor, Mining, Office/control room, Pelletizing, Shop (mobile) and Shop (stationary)), leading to 56 mine-department combinations in the study.

As we can see in Table 2-1, taconite mines started operating in different years with the earliest one in 1955 and the latest in 1977 (Sheehy, 1986). As of the year 2010 when the onsite investigation of the THWS study was conducted (Hwang *et al.*, 2013), six mines including the oldest one were still in operation, whose life spans ranged from a minimum of 34 years (1977-2010) to 56 years (1955-2010).

TABLE 2-1 Profile of taconite mines in the study

#	Taconite Mine	Year Opened	Status (as of 2010)	IH Measurement Coverage
1	ArcelorMittal	1977	Active	1978-2010
2	Hibbtac	1974	Active	1976-2010
3	Keetac	1967	Active	1971-2010
4	LTV	1957	Closed in 2001	1978-2000
5	Minntac	1967	Active	1979-2010
6	Northshore	1955	Active	1956-2010
7	Utac	1964	Active	1978-2010

* Mining Companies: http://www.taconite.org/mining-industry/mines;

Historical RS and RD data collection and supplementary IH sampling

Historical RS and RD data were obtained for seven taconite mines from two sources: (1) the Mine Safety and Health Administration (MSHA) has online records for all inspection results since 1978 for 13 MSHA Mine IDs with 4,303 RD monitoring records with their occupational exposure limits (OELs) (enabling calculation of RS concentrations); (2) the mining companies' internal monitoring reports contain 14,417 RD records, each of which has concentration and corresponding OEL information;

To supplement existing historical measurements, the University of Minnesota in 2010 collected additional 688 pairs of RS and RD 6-hr-long personal sample measurements covering six active mines. These RD and RS samples were analyzed using NIOSH 0600

(NIOSH, 1998) and NIOSH 7500 (NIOSH, 2003) respectively.

For each data record, we collected the following information: concentration, sampling year, sampling agent, personal/area sample and sampling location. We were aware of the potential difference in sampling purpose between area samples and personal samples. But as we can see in Table 2-2, in the early operation years of taconite mines, there was no personal sample available. Area samples, although may not be health-related, might successfully fill this year gap if properly used. They would help us better understand the occupational exposure levels of the early-years in taconite mines. We, in the following modelling step, introduced a categorical variable (0 for personal sample, 1 for area sample) to adjust for the potential systematic difference in numerical value between these two sample types.

TABLE 2-2 Numbers of RS and RD data by sample type and year period

RD	Year					
	1950s	1960s	1970s	1980s	1990s	2000-2010
Personal sample	0	0	1926	3850	2356	4244
Area sample	867	1882	2714	1037	295	209
RS	Year					
	1950s	1960s	1970s	1980s	1990s	2000-2010
Personal sample	0	0	1451	3031	1272	1464
Area sample	0	0	480	1035	268	126

It is also worth noticing that in the mining industry, the MSHA, unlike the Occupational Safety and Health Administration (OSHA), does not regulate RD directly, but instead regulates the respirable dust containing silica using a case-varying OEL (MSHA, 1989). The value of this OEL, as shown in Eqs.1 and 2, is a function of the silica mass percentage (% silica) in the dust sample being analyzed. Thus a "pure" silica sample

(100% silica) will have an OEL of 0.1 mg/m3 or 2.5 mppcf. But if the respirable dust contains no silica, the equations produce an OEL of 5 mg/m3 or 50 mppcf.

$$OEL\ \left(\frac{mg}{m^3}\right) = 10\ \left(\frac{mg}{m^3}\right)/(2 + \%\ silica)$$

(Eq.1)

$$OEL\ (mppcf) = 250\ (mppcf)/(5 + \%\ silica)$$

(Eq.2)

Given this OEL equation, we can calculate % silica and then use Eq.3 to calculate RS concentration values from the original RD values. In this manner, an additional 8,840 RS data were calculated.

$$RS\ concentration\ (\frac{mg}{m^3}\ or\ mppcf) = RD\ concentration\ (\frac{mg}{m^3} or\ mppcf)\ \times \%\ silica$$

(Eq.3)

The data cleaning process included: data completeness check, unit conversion and zero value replacement. The data cleaning was performed using SAS statistical software (version 9.3, SAS Institute, Cary, North Carolina, United States). There were a total of 76 RD records and 56 RS records removed using this process due to the incomplete information. About 20% of the measurements (prior to 1975) are in the now-defunct count unit of millions of particles per cubic foot (mppcf). We converted these to mass concentrations using the OSHA-recommended conversion factor of 1 mppcf = 0.1 mg/m3 (Occupational Safety and Health Administration, 2017). Since we don't have the lab results for historical data, censored values and zero values (1721 RD records and 1161 RS records) were replaced with one half of the limit of detection (LOD) value of current NIOSH analytical methods for the RD and the RS depending on the agent. The LOD of NIOSH 7500 is about 0.075 mg/m^3 (for a minimum detectable dust mass of 0.03 mg and maximum collected air of 400 L) and that of NIOSH 0600 is about 0.005 mg/m3 (for a minimum detectable silica mass of 0.005 mg, and maximum collected air of 1000 L) (NIOSH, 1998, 2003). After the data cleaning procedures, a total of 9,072 RS data and 19,332 RD data were available for subsequent modelling. Each data record is associated with six variables (concentration, year, personal sample or area sample, RD or RS, department, and mine).

Statistical model

The varying-intercept model (see Eq. 4), a simple type of the multilevel modeling family was used in the study. This model assumes that within each mine-department combination, the predicted ln(RS) and ln(RD) lines with Year (variation on RS and RD with Year) share the same slope, but with a varying intercept determined by the grouping variable AGENT. This model also adjusted for the sample type variance. In other words, we can think of multilevel modeling as a regression that includes a categorical input variable representing group membership (Gelman and Hill, 2007).

Level 1: $Ln\ (\boldsymbol{Conc}|\boldsymbol{Mine},\boldsymbol{Dept})_{ij} = \beta_{00} + \beta_{10}\boldsymbol{Year} + \beta_{20}\boldsymbol{Type} + \varepsilon_{ij}$

Level 2: $\beta_{00} = \gamma_{00} + \gamma_{01}\boldsymbol{Agent}$

(Eq.4)

Where: Conc| Mine, Dept is the predicted mean exposure value in mg/m^3 for a given mine-department combination; Year is the sampling year; Type is the sample type (0 = Personal sample, 1 =Area sample); Agent is the targeted agent (0 = RD, 1 for RS).

The default value for valuable "Type" is 0, meaning that the final model outputs will be focused on personal samples.

The advantage of this model is its model parameters are very interpretable and very helpful for the historical exposure reconstruction. The physical meanings of these parameters are list as follows:

For a given mine-department exposure location:

$$Annual\ exposure\ change\ rate = \frac{\boldsymbol{Conc}|(\boldsymbol{Year} = n + 1)}{\boldsymbol{Conc}|(\boldsymbol{Year} = n)} = e^{\beta_{10}}$$

(Eq.5)

$$Silica\ percent\ in\ the\ dust: \frac{\boldsymbol{Conc}|(\boldsymbol{Agent} = 1)}{\boldsymbol{Conc}|(\boldsymbol{Agent} = 0)} = e^{\gamma_{01}}$$

(Eq.6)

For the locations that had insufficient data, we borrowed other mine's data or aggregated data as model inputs for their reconstructions. Besides the actual 7 mines and 8 departments for each mine, we further created an ‘all 7 mines’ column and an ‘all 8 departments’ row for potential reconstruction needs. Specifically, we borrowed “Northshore” mine data for exposure reconstruction in mine “LTV”, and aggregated data across all departments within a mine (data in the ‘all 8 departments’ row) for “Janitor” exposure reconstruction. “Office/ control room” departments relied on aggregating data across all departments within a mine to estimate the time-trend, and their exposure magnitudes were determined by their present-day measurements.

The model was implemented using the MATLAB “fitlm” function (MATLAB version R2014b, the MathWorks, Inc., Natick, Massachusetts, United States). The mean response values were estimated using the “predict” function with option “Simultaneous”. The 95% confidence intervals for the mean response values were estimated using the “yci” option.

All model outputs (GMs: geometric means and GSDs: geometric standard deviations) were finally used to calculated their corresponding arithmetic means using the conversion equation shown in Eq.7.

$$AM = GM \times \exp(\frac{1}{2}\log^2(GSD))$$

(Eq.7)

The final product of this study will be a RD JEM and a RS JEM. Each of them will be a data table in which we can find an arithmetic mean exposure level in mg/m3 for each year-department- mine combination. These JEMs, when linked to specific taconite workers' working history, will allow us to calculate the cumulative exposure for the study population in future epidemiologic studies.

RESULTS & DISCUSSION

There are a total of 9,128 RS data and 19,408 RD data across all mines and departments as summarized in Table 2-3. The distribution of the samples, to some extent, reflects overall IH sampling priorities in the taconite industry. Most of IH samples were collected in the four main taconite processes – mining, crushing, concentrating and pelletizing. In contrast, there are no data available for any of the Office/control room departments in the seven mines. Meanwhile, the LTV mine has no any present-day measurements due to its shutting down in 2001.

TABLE 2-3 Numbers of historical (H) and present-day (P) RD and RS measurements

RD																
Mine-Department	ArcelorMittal		Hibbtac		Keetac		LTV		Minntac		Northshore		Utac		All 7 mines	
Year	***H***	***P***	***H***	***P***	***H***	***P***	***H***	***P***	***H***	***P***	***H***	***P***	***H***	***P***	***H***	***P***
Mining	197	6	635	15	274	20	145	0	391	18	620	20	405	12	2667	91
Crushing	172	6	3127	12	156	9	101	0	446	12	2573	29	250	18	6825	86
Concentrating	62	6	2462	12	413	12	31	0	297	12	375	18	37	9	3677	69
Pelletizing	161	15	1271	18	362	26	111	0	271	29	1805	33	161	30	4142	151
Shop (mobile)	35	15	178	27	52	15	45	0	198	42	152	27	82	27	742	153
Shop (stationary)	39	9	12	12	16	12	29	0	22	15	88	24	72	12	278	84
Office/control room	1	9	0	6	0	6	0	0	3	12	1	15	0	6	5	54
Janitor	20	0	101	0	48	0	25	0	55	0	43	0	64	0	356	0
All 8 departments	687	66	7786	102	1321	100	487	0	1683	140	5657	166	1071	114	18692	688
RS																
Mining	71	6	468	15	222	20	65	0	147	18	84	20	216	12	1273	91
Crushing	119	6	1989	12	87	9	65	0	401	12	200	29	179	18	3040	86
Concentrating	46	6	844	12	218	12	26	0	225	12	21	18	29	9	1409	69
Pelletizing	99	15	1096	18	210	26	46	0	115	29	200	33	107	30	1873	151
Shop (mobile)	23	15	121	27	44	15	18	0	131	42	36	27	55	27	428	153
Shop (stationary)	15	9	5	12	15	12	16	0	16	15	15	24	55	12	137	84
Office/control room	1	9	0	6	0	6	0	0	0	12	0	15	0	6	1	54
Janitor	20	0	78	0	42	0	17	0	41	0	33	0	47	0	278	0
All 8 departments	394	66	4601	102	838	100	253	0	1076	140	589	166	688	114	8439	688

Model outputs

Personal exposure histories were reconstructed for each of the 56 mine-department combinations. The nine ArcelorMittal plots and nine LTV plots are shown in Figure 2-1 and 2-2 as example results of the exposure reconstruction. Plots for the other five mines can be found in the Supplementary Materials.

Generally speaking, the intercept-varying model fits the data very well over the reconstruction time periods. These reconstruction year periods are the same as the actual mine operation periods. Under the natural log scale (y-axis), the RD prediction line parallels its paired RS line but with a different intercept, and the slope of these lines was determined by the overall data. The underlining assumption here is that the silica percentage in airborne taconite dust in each location does not change over time. The assumption appears to be reasonable, given the good model fit as well as our understanding of taconite mining process.

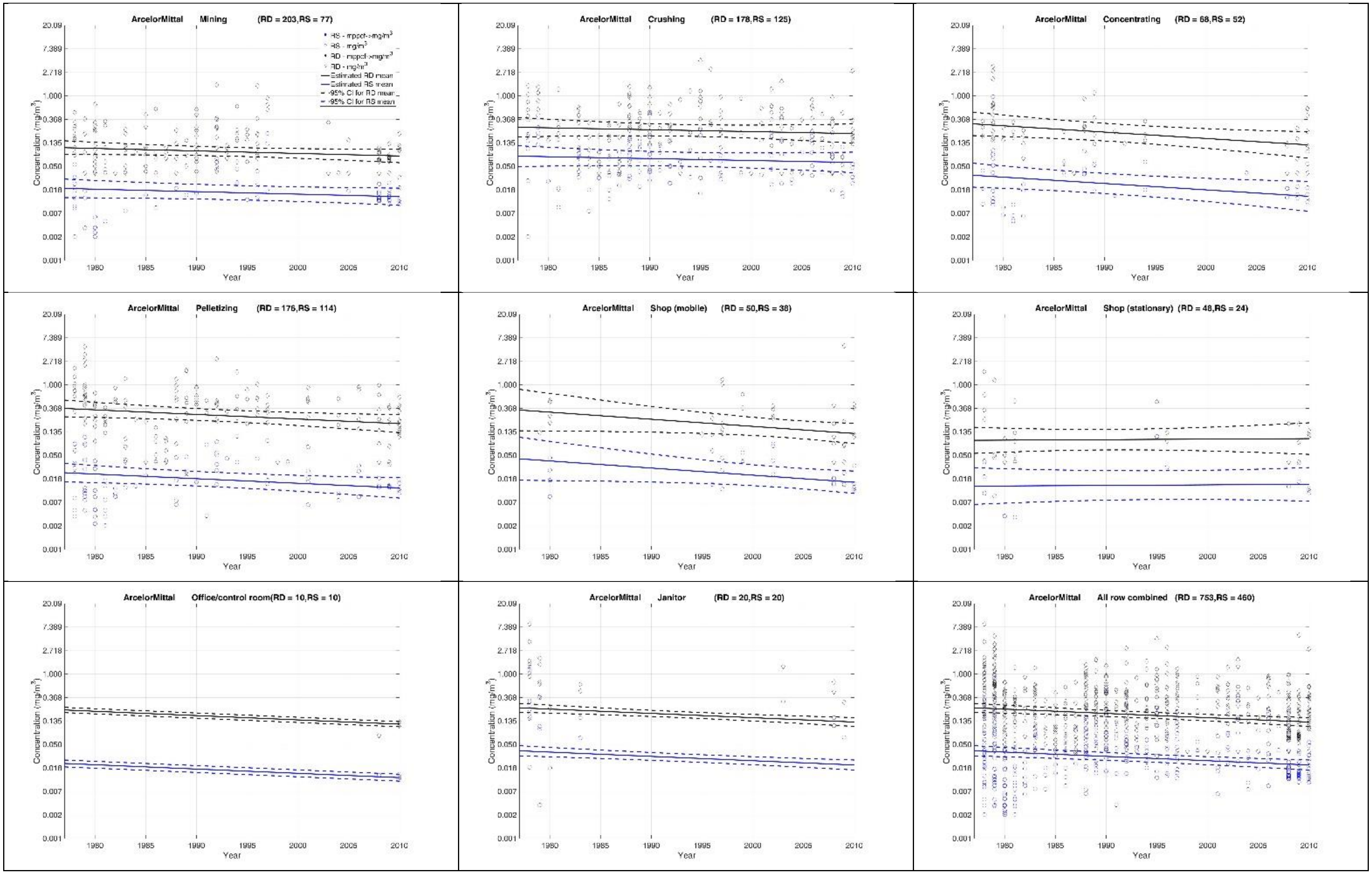


FIGURE 2-1 Model fitting for each ArcelorMittal department

Several mines had no early measurement records in their first 10 more years (Table 2-1), and that the LTV mine has the greatest data gap. We don’t have any of its early-year (1957-1977) exposure information and we did not have opportunity to conduct present-day measurement as we did for all other six mines in 2010, since LTV shut down in 2001. To model its historical exposure, we chose to borrow Northshore mine data given their geological proximity. These TLV prediction lines, as shown in Figure 2-2, also fit well with this mine’s original historical data.

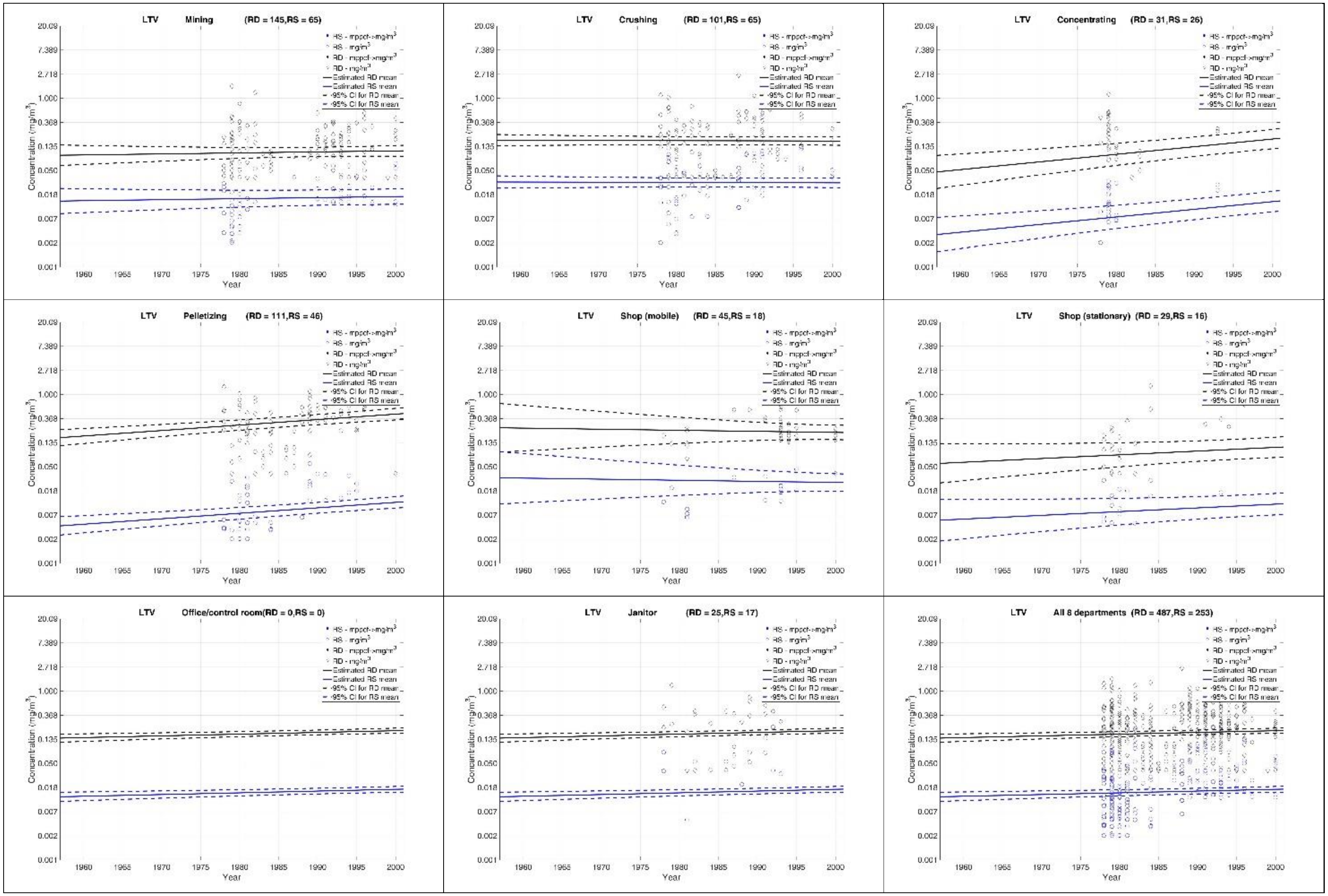


FIGURE 2-2 Model fitting for each LTV department

Predicted annual avenged exposure level change rate by exposure location

Exposure reconstructions in many industries have typically shown trends of decreasing levels over time that have been attributed to increased exposure controls as well as more stringent occupational regulations over time (Coble, Lees and Matanoski, 2001; Zhuang *et al.*, 2001; Creely *et al.*, 2007).

However, this is not true in this study. Table 2-4 lists the time trends in the RS and RD exposure for all mine-department locations. In the study, the location-specific predicted annual change rates vary by location, but all within a narrow range of -3.3% to 3.2%. These low values indicate that the exposure changes over the entire mine history were small in the taconite mining industry. In other words, a mine's first-year dust exposure value is at most 4 times higher ($1.03^{50} = 4.4$) or one fifth ($0.97^{50} = 0.22$) of its last-year's value in a 50-year period. Among the 56 mine-department locations, 33 locations show a decreasing or flat RS and RD trend with a maximum rate of decrease of 3.3% per year; 23 locations show a trend with a maximum annual increase rate of 3.2%. We however did not find any patterns in these trends. Exposures showed decreasing trends in 7 of 8 ArcelorMittal departments whereas Northshore only had two exposure decreasing departments. As for departmental trends across mines, we did not find any pattern in the four main departments. But it is noted that the values in all 8 Shop (mobile) departments were negative. For overall time-trend for each mine, 3 mines shown an increasing trend and 4 mines shown a decreasing trend. The overall time-trend in this study was -0.2%, which suggested that the overall historical dust exposure in the entire taconite industry may had been decreasing but at a very low rate.

TABLE 2-4 Location-specific averaged annual exposure level change rate

Mine-Department	ArcelorMittal	Hibbtac	Keetac	LTV	Minntac	Northshore	Utac	All 7 mines
Mining	-1.1%	-0.1%	-1.8%	0.4%	-0.6%	0.4%	1.0%	-0.4%
Crushing	-0.8%	-2.5%	-3.3%	-0.1%	2.3%	-0.1%	2.2%	-0.7%
Concentrating	-2.7%	1.6%	-2.9%	3.2%	2.2%	3.2%	0.0%	2.0%
Pelletizing	-2.0%	0.9%	-1.5%	2.3%	-0.3%	2.3%	0.1%	0.2%
Shop (mobile)	-3.0%	-2.1%	-0.3%	-0.4%	-2.5%	-0.4%	-1.4%	-1.0%
Shop (stationary)	0.2%	1.1%	1.2%	1.5%	0.3%	1.5%	-2.6%	-0.2%
Office/control room	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%
Janitor	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%
All 8 departments	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%

Predicted silica mass percentages in different exposure locations

In Table 2-5, we can see that the percent silica changes as the ore moves from mining, via crushing, concentrating to the final pelletizing; and these changes seems to follow a similar pattern across the mines: within each mine, the silica percentage increases from mining to crushing, reduces from crushing to concentrating; and reduces further to its lowest level from concentrating to pelletizing. This general trend shows the impact of different taconite processes on the silica percentage in airborne dust: during the crushing process, silica which is originally in the ore is released into the air as the taconite ore is crushed to small pieces; during the concentrating process, airborne dust and silica levels are reduced due to the wet process that removes the slag containing much of the non-iron silica material. In the final pelletizing process, 1-10% limestone (CaCO3) is usually added into the product, some of which may be dispersed into the air. As a result, these airborne CaCO3 particles will dilute the original silica percentage in the airborne dust.

The measured silica percentage values from the dust samples taken in each study location was summarized in Table 2-7 of the supplementary material. To quickly check whether the predicted values listed in Table 2-5 could be comparable with their corresponding actual measurements in the four main process departments, we created a predicted vs. measured plot shown in Figure 2-3. The slope of 0.92 and R^2 of 0.64 suggested a good one-on-one correspondence.

TABLE 2-5 Summary of model estimated RS/RD ratio by location

Mine-Department	ArcelorMittal	Hibbtac	Keetac	LTV	Minntac	Northshore	Utac	All 7 mines
Mining	17.7%	4.4%	12.7%	15.0%	15.6%	15.0%	11.3%	9.7%
Crushing	29.3%	8.4%	19.2%	17.6%	23.1%	17.6%	15.7%	13.0%
Concentrating	11.3%	5.0%	14.4%	7.5%	16.5%	7.5%	8.3%	7.5%
Pelletizing	6.5%	2.1%	8.7%	2.6%	5.9%	2.6%	5.4%	3.3%
Shop (mobile)	12.6%	11.1%	11.6%	12.6%	14.0%	12.6%	10.5%	12.0%
Shop (stationary)	14.3%	12.1%	7.1%	9.5%	7.1%	9.5%	11.5%	10.3%
Office/control room	10.9%	10.0%	10.0%	9.7%	11.7%	9.7%	10.0%	10.4%
Janitor	16.0%	5.5%	11.5%	8.8%	16.2%	8.8%	10.7%	8.2%
All 8 departments	16.0%	5.5%	11.5%	8.8%	16.2%	8.8%	10.7%	8.2%

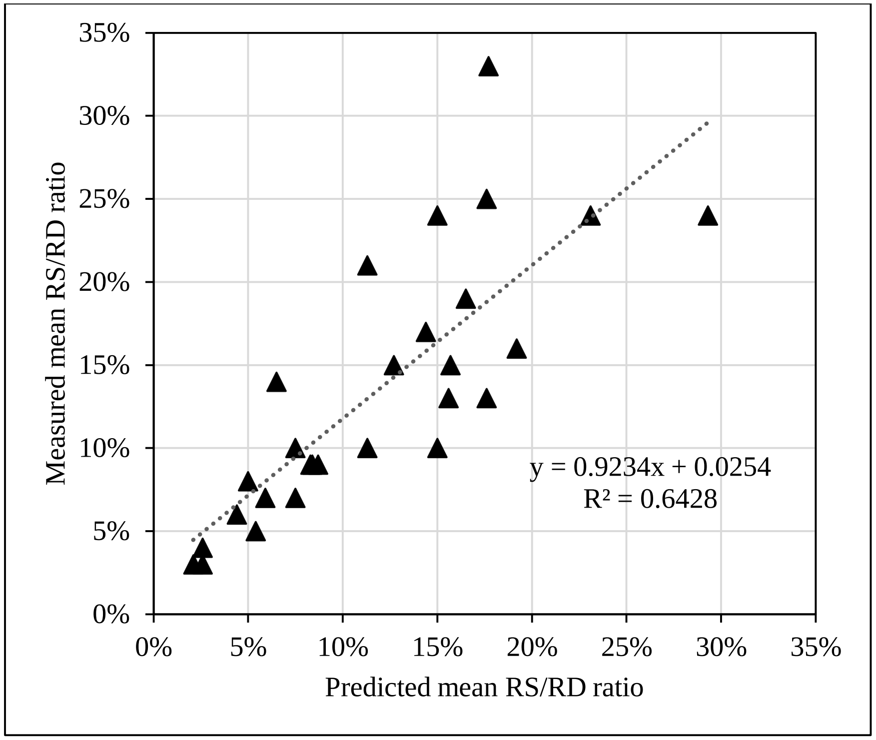


FIGURE 2-3 Predicted vs. measured silica percentages

Predicted arithmetic mean of RS and RD exposure by exposure location

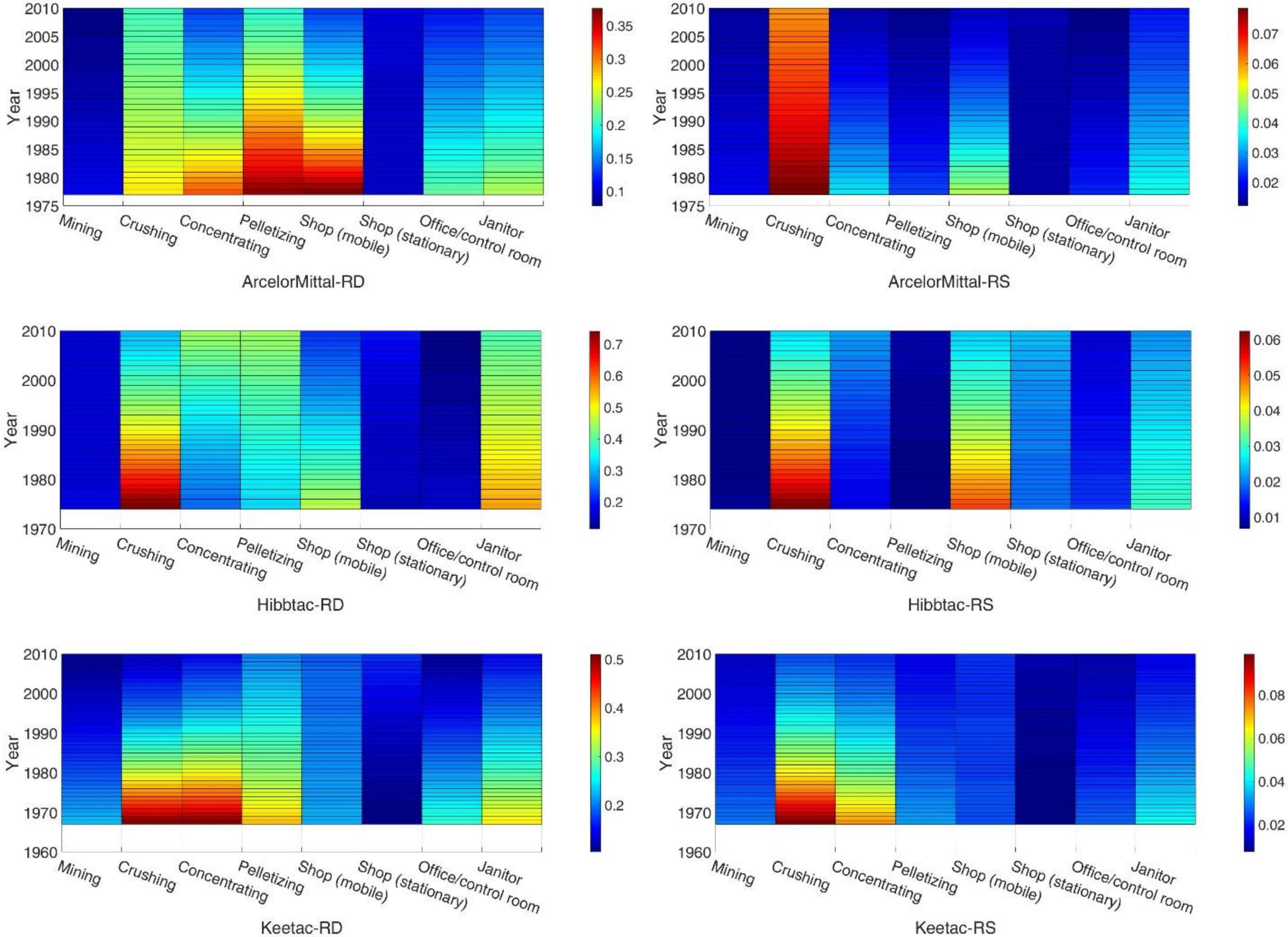
As suggested by other researchers (Rice *et al.*, 1984; Seixas, Robins and Moulton, 1988; Rappaport, 1991; Crump, 1998; Verma *et al.*, 2011), the arithmetic mean (AM), instead of geometric mean (GM), is a more appropriate exposure metric in creating a job-exposure matrix (JEM) for future health studies. The range of AM results of the study were listed in Table 2-6.

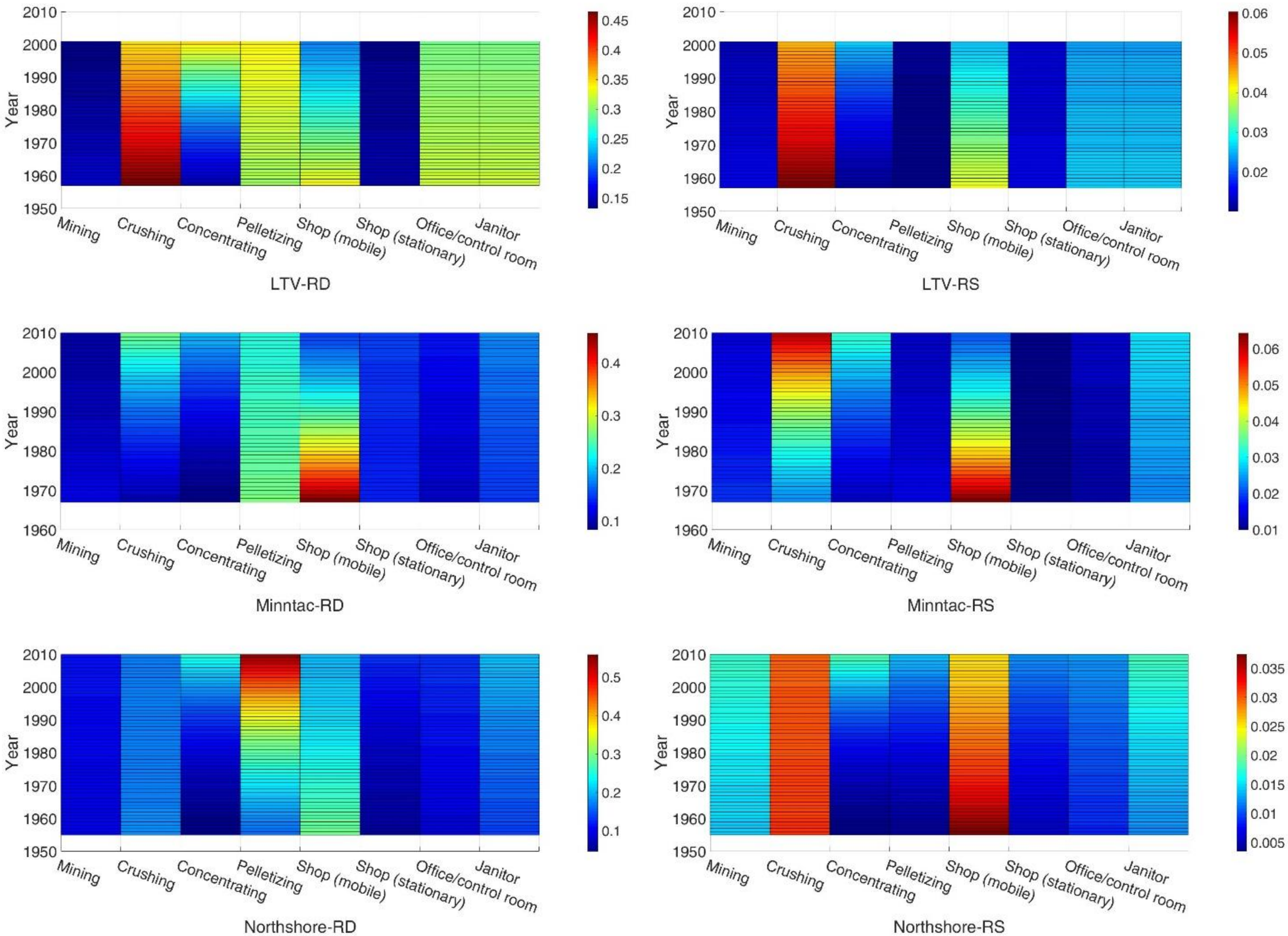
TABLE 2-6 First-year and last-year AMs of RD and RS exposure levels in each study location (mg/m3)

RD																
Mine-Department	ArcelorMittal		Hibbtac		Keetac		LTV		Minntac		Northshore		Utac		All 7 mines	
Year	***1977***	***2010***	***1974***	***2010***	***1967***	***2010***	***1957***	***2001***	***1967***	***2010***	***1955***	***2010***	***1964***	***2010***	***1955***	***2010***
Mining	0.11	0.08	0.18	0.17	0.23	0.11	0.10	0.11	0.12	0.09	0.10	0.12	0.12	0.19	0.16	0.13
Crushing	0.27	0.20	0.74	0.30	0.51	0.13	0.18	0.17	0.10	0.27	0.18	0.17	0.16	0.44	0.47	0.32
Concentrating	0.31	0.13	0.25	0.45	0.51	0.20	0.05	0.19	0.08	0.20	0.05	0.26	0.26	0.23	0.14	0.42
Pelletizing	0.37	0.19	0.32	0.44	0.38	0.20	0.17	0.45	0.27	0.23	0.16	0.56	0.26	0.27	0.31	0.35
Shop (mobile)	0.38	0.13	0.46	0.22	0.22	0.19	0.29	0.21	0.46	0.15	0.29	0.20	0.37	0.19	0.34	0.19
Shop (stationary)	0.10	0.11	0.15	0.20	0.10	0.17	0.06	0.09	0.14	0.15	0.06	0.13	0.35	0.11	0.15	0.14
Office/control room	0.22	0.12	0.16	0.12	0.27	0.11	0.14	0.19	0.11	0.13	0.09	0.14	0.08	0.11	0.14	0.12
Janitor	0.24	0.13	0.56	0.39	0.36	0.15	0.14	0.19	0.15	0.18	0.14	0.21	0.17	0.25	0.32	0.29
All 8 departments	0.24	0.13	0.56	0.39	0.36	0.15	0.14	0.19	0.15	0.12	0.14	0.21	0.17	0.25	0.32	0.29
RS																
Mining	0.02	0.01	0.01	0.01	0.03	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.02	0.02	0.01
Crushing	0.08	0.06	0.06	0.02	0.10	0.02	0.03	0.03	0.02	0.06	0.03	0.03	0.03	0.07	0.06	0.04
Concentrating	0.04	0.01	0.01	0.02	0.07	0.02	0.00	0.02	0.01	0.03	0.00	0.02	0.02	0.02	0.01	0.03
Pelletizing	0.02	0.01	0.01	0.01	0.03	0.02	0.00	0.01	0.02	0.01	0.00	0.01	0.01	0.01	0.01	0.01
Shop (mobile)	0.05	0.02	0.05	0.02	0.03	0.02	0.04	0.03	0.06	0.02	0.04	0.03	0.04	0.02	0.04	0.02
Shop (stationary)	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04	0.02	0.02	0.01
Office/control room	0.02	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Janitor	0.04	0.02	0.03	0.02	0.04	0.02	0.01	0.02	0.02	0.03	0.01	0.02	0.02	0.03	0.03	0.02
All 8 departments	0.04	0.02	0.03	0.02	0.04	0.02	0.01	0.02	0.02	0.03	0.01	0.02	0.02	0.03	0.03	0.02

For historical RD mean exposures, their overall range was in between 0.05 and 0.56 mg/m3. This range reflected large exposure variations across study locations, but it also suggested that the historical mean dust exposures in the taconite mining history might not be as dusty as what we used to think considering the OSHA 8-hour Time Weight Averaged (TWA) limit for RD of 5 mg/m^3. To visually check within-mine exposure variation, we created independent color plot for each mine (Figure 2-4). Within each mine, the highest exposure value was colored in red and the lowest value was colored in blue. Each mine had its own color map scale. As we can see, within each mine, the red bar usually appeared in either Crushing, Concentrating, Pelletizing or Shop (mobile). In terms of temporal pattern within each mine, most high exposure values were located in the early mine years.

For historical RS exposures, its overall range of AMs was in between 0.00 and 0.10 mg/m3. This range also reflected large exposure variations across study locations. Within each mine (see Figure 2-4), its highest RS exposure department was also varied by mine, but the red bars were occurred only in either Crushing or Shop (mobile). It is a little bit different than what we found in RD exposures. In terms of temporal pattern within each mine, unlike RD exposures, high RS exposure values could be located in early years or late years depending on mines.


Year
Mining
Crushing
Concentrating
Pelletizing
Shop (mobile)
Shop (stationary)
Office/control room
Janitor
ArcelorMittal-RD
ArcelorMittal-RS
Hibbtac-RD
Hibbtac-RS
Keetac-RD
Keetac-RS


Year
Mining
Crushing
Concentrating
Pelletizing
Shop (mobile)
Shop (stationary)
Office/control room
Janitor
LTV-RD
LTV-RS
Minntac-RD
Minntac-RS
Northshore-RD
Northshore-RS

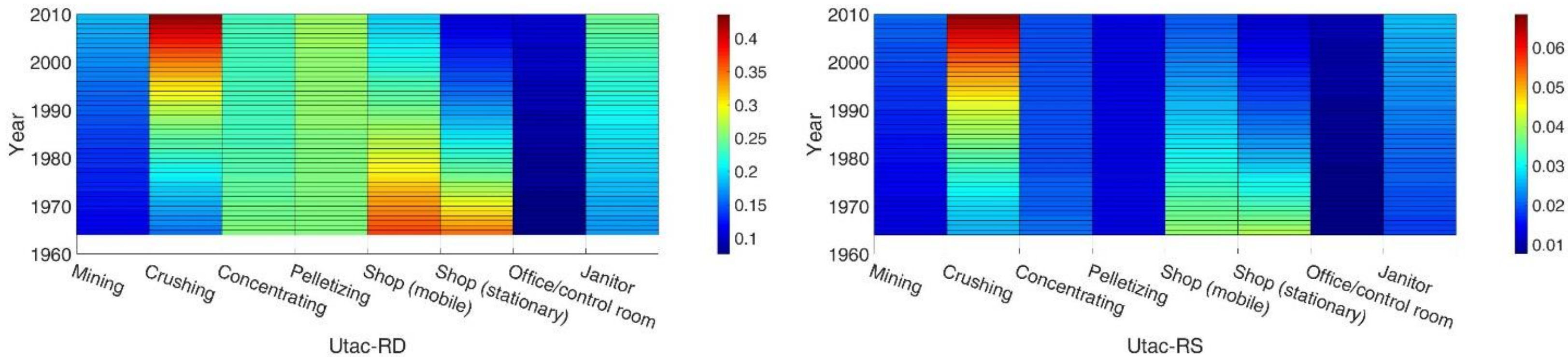


FIGURE 2-4 Within mine variation in exposure value for historical RS and RD exposures

Limitations

Exposure reconstruction relies on historical IH measurements, and the year gap between the JEM's expected time coverage and actual data coverage is a limitation of the study. This gap varies by mines, with the maximum value of 14 years in Utac. This large year gap may result in big uncertainties in model outputs, which in turn could introduce big uncertainties of dose calculation in future epidemiologic study and thus lead to an insignificant epidemiologic conclusion.

CONCLUSION

In this study, we conducted a careful aggregation of available historical monitoring data for RD and RS from multiple sources, and processed and cleaned up the data so that they are in consistent units. There are sufficient monitoring data for exposure reconstruction as a function of time at the mine/department level. The result of this study is a JEM by mine, department, and year for RD and RS that will form the basis for future epidemiological studies.

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DISCLAIMER

The authors declare that there are no conflicts of interest relating to the material in relation to this article.

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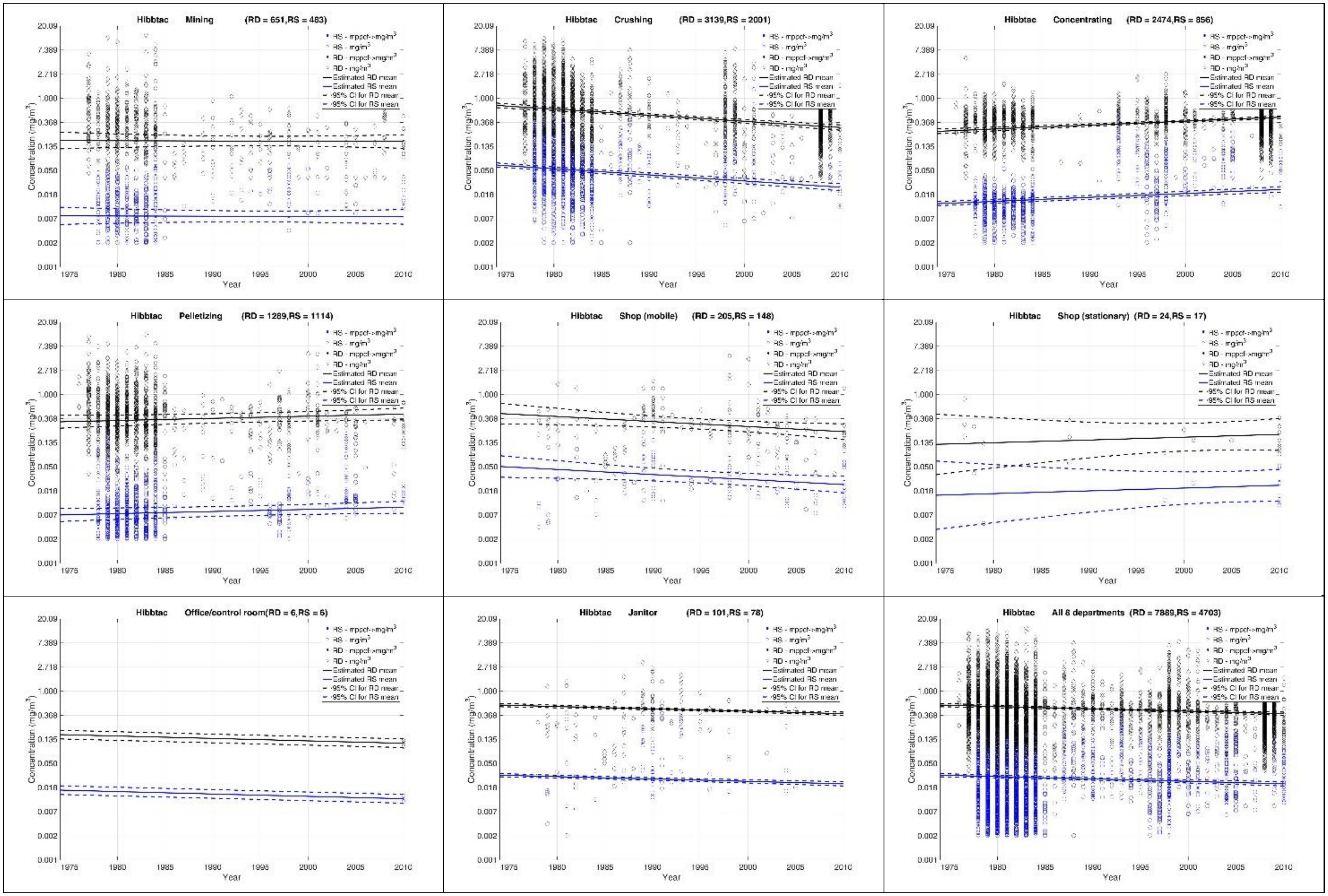
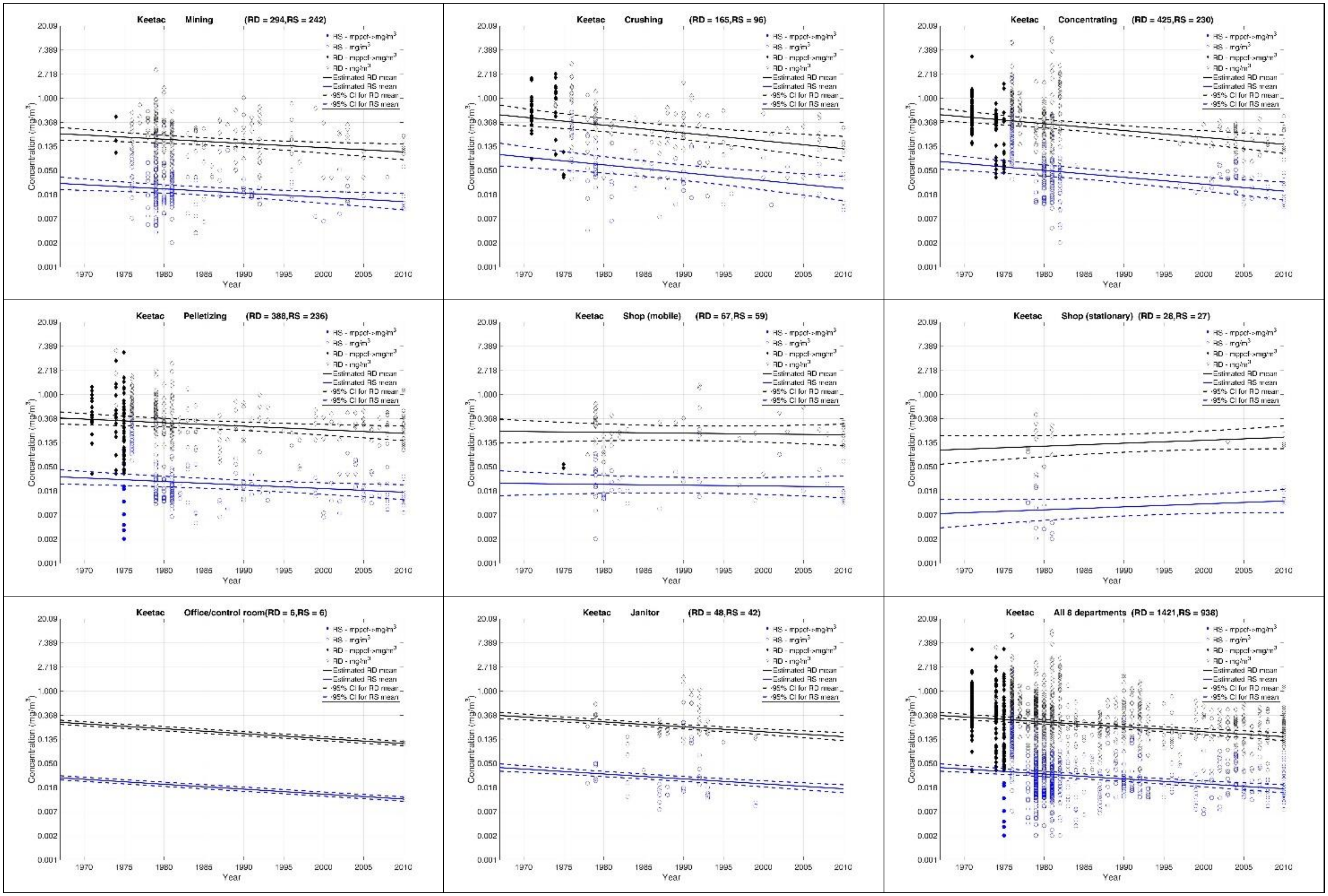
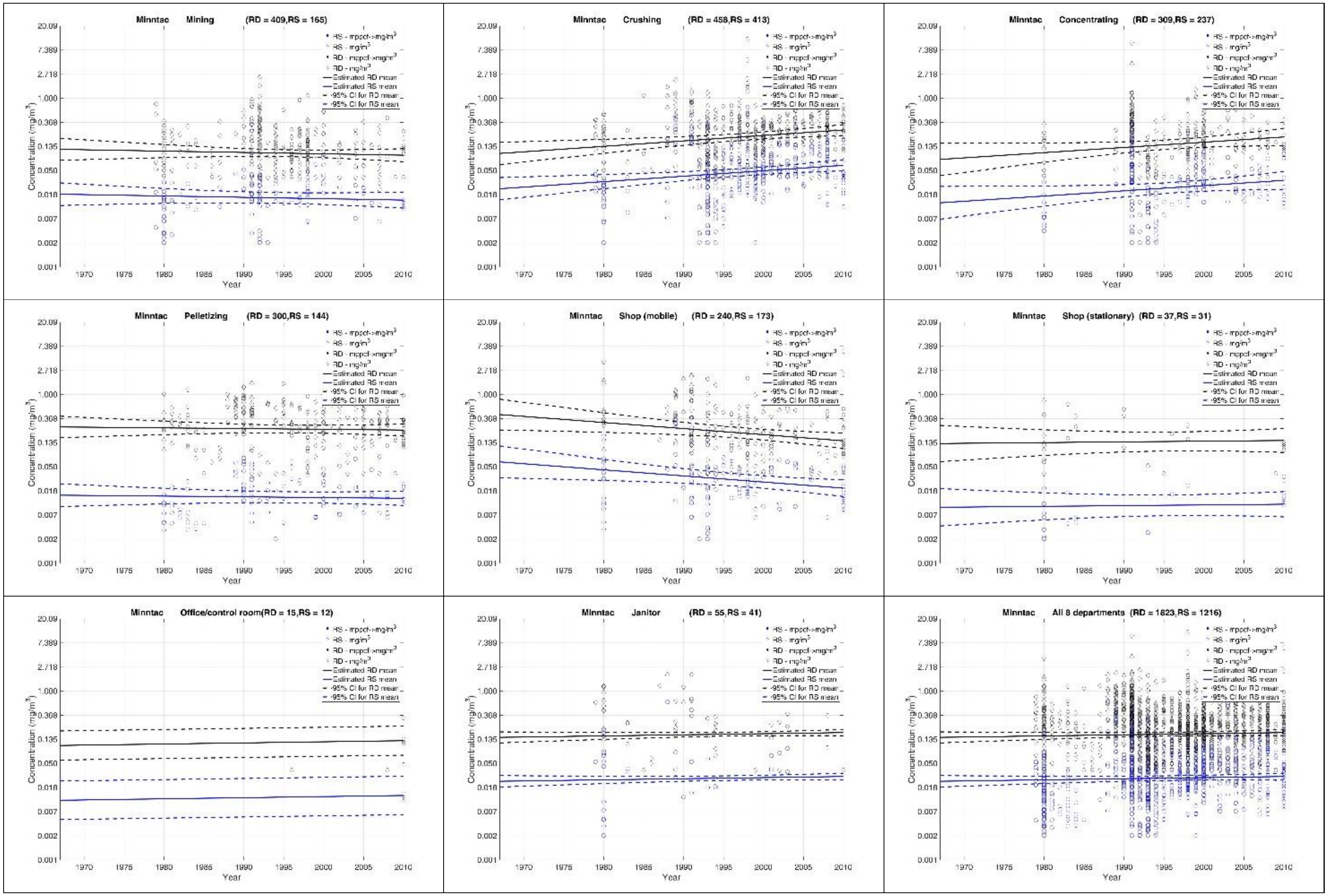
SUPPLIMENTAL MATERIALS

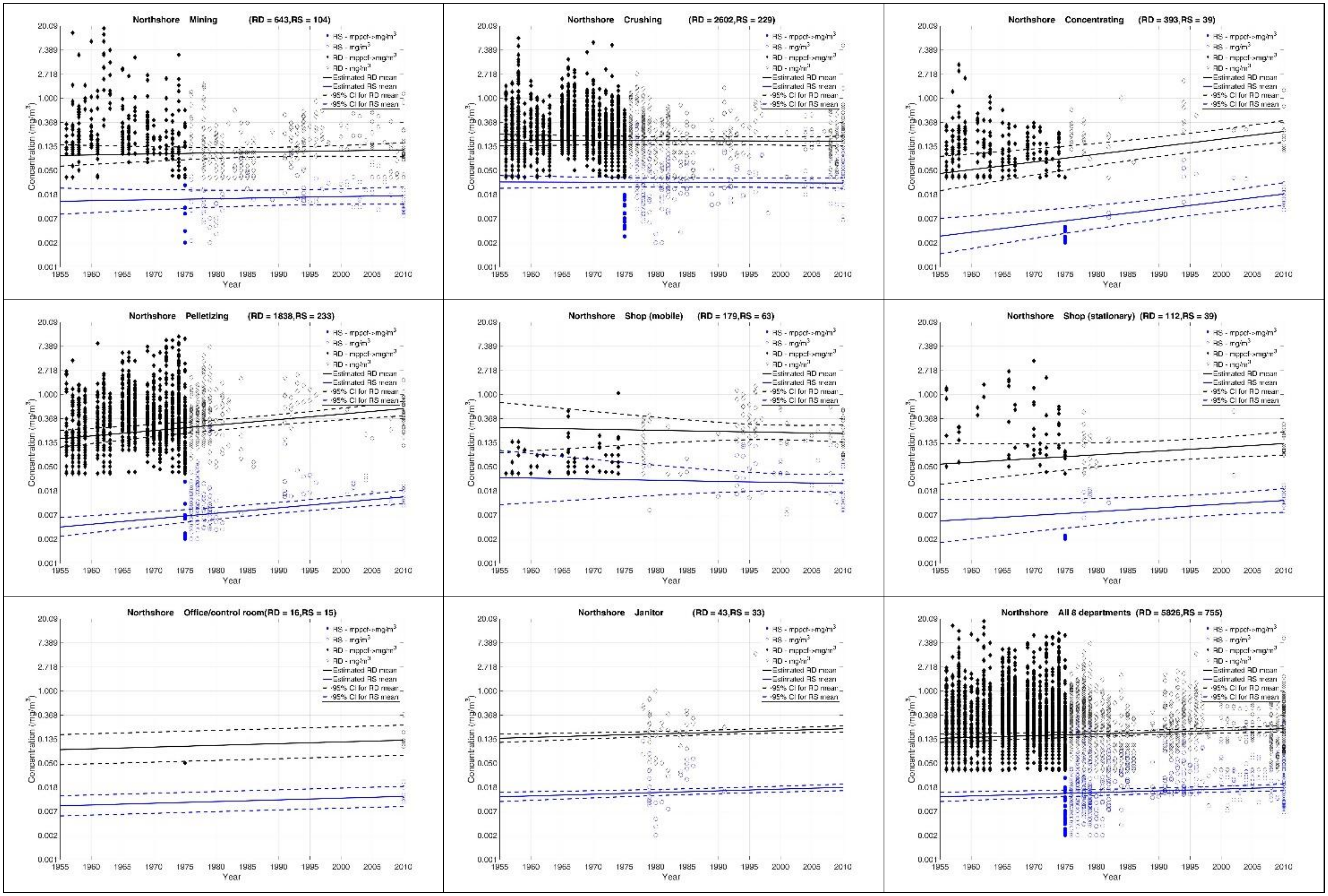
TABLE 2-7 Summary of measured silica percentage in dust samples by location

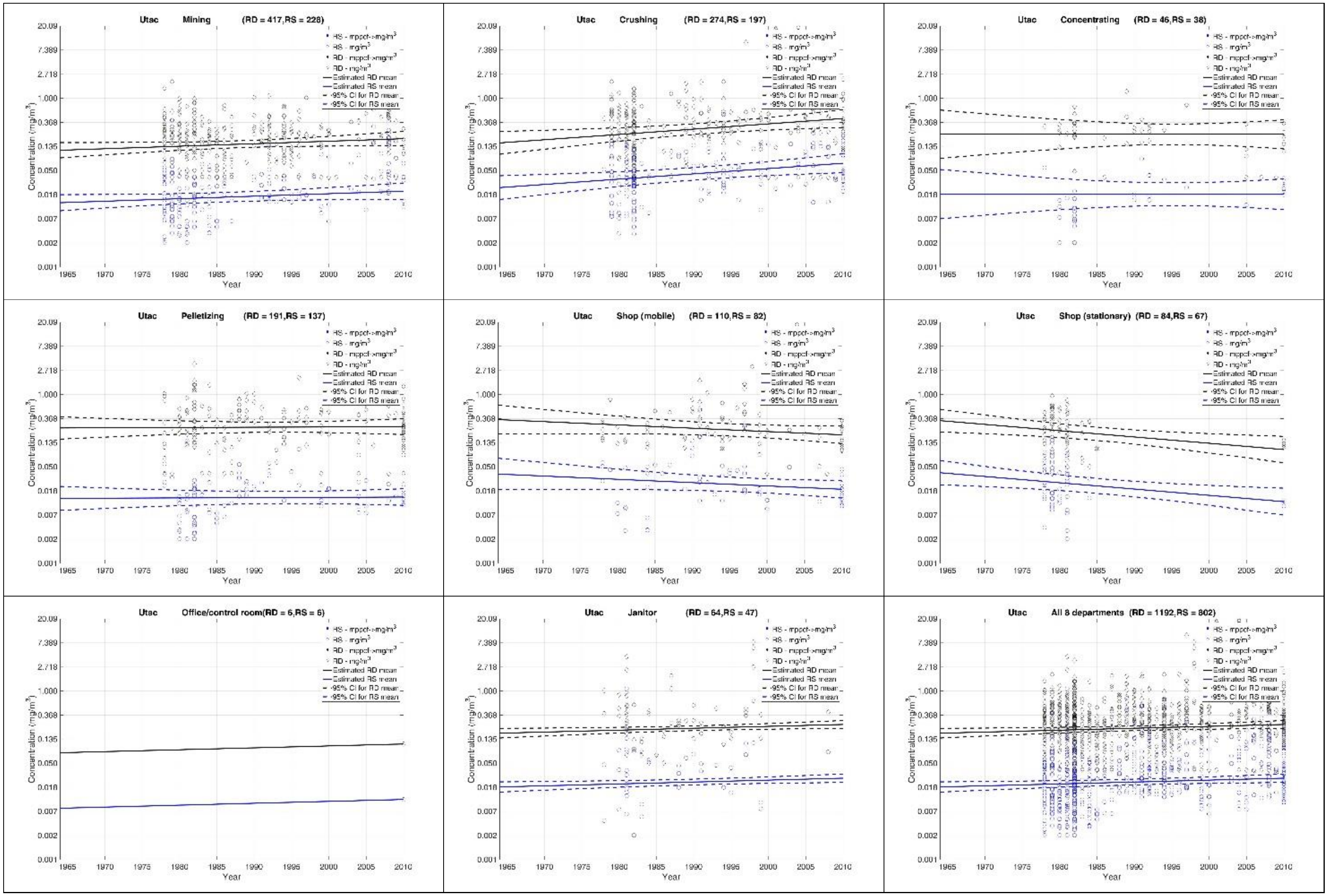
Mine-Department		ArcelorMittal	Hibbtac	Keetac	LTV	Minntac	Northshore	Utac
Mining	N	101	484	244	65	165	122	228
	Mean	33%	6%	15%	10%	13%	24%	10%
	SD	37%	9%	13%	9%	11%	32%	9%
Crushing	N	134	2001	96	65	414	257	197
	Mean	24%	9%	16%	13%	24%	25%	15%
	SD	20%	4%	8%	7%	12%	27%	9%
Concentrating	N	58	856	231	26	237	39	38
	Mean	21%	8%	17%	7%	19%	10%	9%
	SD	28%	9%	12%	5%	14%	4%	8%
Pelletizing	N	125	1114	236	46	145	233	137
	Mean	14%	3%	9%	3%	7%	4%	5%
	SD	27%	3%	8%	3%	9%	3%	5%
Shop (mobile)	N	45	148	59	18	173	63	82
	Mean	24%	12%	13%	6%	15%	12%	11%
	SD	32%	7%	12%	4%	11%	7%	7%
Shop (stationary)	N	27	18	27	16	31	39	67
	Mean	20%	18%	9%	9%	9%	10%	13%
	SD	29%	21%	6%	9%	6%	7%	10%
Office/control room	N	10	6	6	0	12	15	6
	Mean	11%	10%	10%	/	10%	10%	10%
	SD	3%	0%	0%	/	1%	3%	0%
Janitor	N	20	78	42	17	41	33	47
	Mean	17%	13%	10%	15%	15%	11%	14%
	SD	8%	8%	6%	7%	9%	6%	8%


Hibbtac Mining (RD = 651,RS = 483)
Hibbtac Crushing (RD = 3139,RS = 2001)
Hibbtac Concentrating (RD = 2474,RS = 856)
Hibbtac Pelletizing (RD = 1289,RS = 1114)
Hibbtac Shop (mobile) (RD = 205,RS = 148)
Hibbtac Shop (stationary) (RD = 24,RS = 17)
Hibbtac Office/control room(RD = 6,RS = 6)
Hibbtac Janitor (RD = 101,RS = 78)
Hibbtac All 8 departments (RD = 7889,RS = 4703)
RS - mppcf->mg/m3
RS - mg/m3
RD - mppcf->mg/m3
RD - mg/m3
Estimated RD mean
Estimated RS mean
95% CI for RD mean
95% CI for RS mean
Concentration (mg/m3)
Year


Keetac Mining (RD = 294,RS = 242)
Keetac Crushing (RD = 165,RS = 96)
Keetac Concentrating (RD = 425,RS = 230)
Keetac Pelletizing (RD = 388,RS = 236)
Keetac Shop (mobile) (RD = 67,RS = 59)
Keetac Shop (stationary) (RD = 28,RS = 27)
Keetac Office/control room(RD = 6,RS = 6)
Keetac Janitor (RD = 48,RS = 42)
Keetac All 8 departments (RD = 1421,RS = 938)
RS - mppcf->mg/m3
RS - mg/m3
RD - mppcf->mg/m3
RD - mg/m3
Estimated RD mean
Estimated RS mean
95% CI for RD mean
95% CI for RS mean
Concentration (mg/m3)
Year


Minntac Mining (RD = 409,RS = 165)
Minntac Crushing (RD = 458,RS = 413)
Minntac Concentrating (RD = 309,RS = 237)
Minntac Pelletizing (RD = 300,RS = 144)
Minntac Shop (mobile) (RD = 240,RS = 173)
Minntac Shop (stationary) (RD = 37,RS = 31)
Minntac Office/control room(RD = 15,RS = 12)
Minntac Janitor (RD = 55,RS = 41)
Minntac All 8 departments (RD = 1823,RS = 1216)
Concentration (mg/m³)
Year


Northshore Mining (RD = 643,RS = 104)
Northshore Crushing (RD = 2602,RS = 229)
Northshore Concentrating (RD = 393,RS = 39)
Northshore Pelletizing (RD = 1838,RS = 233)
Northshore Shop (mobile) (RD = 179,RS = 63)
Northshore Shop (stationary) (RD = 112,RS = 39)
Northshore Office/control room(RD = 16,RS = 15)
Northshore Janitor (RD = 43,RS = 33)
Northshore All 8 departments (RD = 5826,RS = 755)
RS - mppcf->mg/m3
RS - mg/m3
RD - mppcf->mg/m3
RD - mg/m3
Estimated RD mean
Estimated RS mean
95% CI for RD mean
95% CI for RS mean
Concentration (mg/m3)
Year
20.09
7.389
2.718
1.000
0.368
0.135
0.050
0.018
0.007
0.002
0.001
1955 1960 1965 1970 1975 1980 1985 1990 1995 2000 2005 2010


Utac Mining (RD = 417,RS = 228)
Utac Crushing (RD = 274,RS = 197)
Utac Concentrating (RD = 46,RS = 38)
Utac Pelletizing (RD = 191,RS = 137)
Utac Shop (mobile) (RD = 110,RS = 82)
Utac Shop (stationary) (RD = 84,RS = 67)
Utac Office/control room(RD = 6,RS = 6)
Utac Janitor (RD = 64,RS = 47)
Utac All 8 departments (RD = 1192,RS = 802)
RS - mppcf->mg/m3
RS - mg/m3
RD - mppcf->mg/m3
RD - mg/m3
Estimated RD mean
Estimated RS mean
95% CI for RD mean
95% CI for RS mean
Concentration (mg/m3)
20.09
7.389
2.718
1.000
0.368
0.135
0.050
0.018
0.007
0.002
0.001
Year
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010

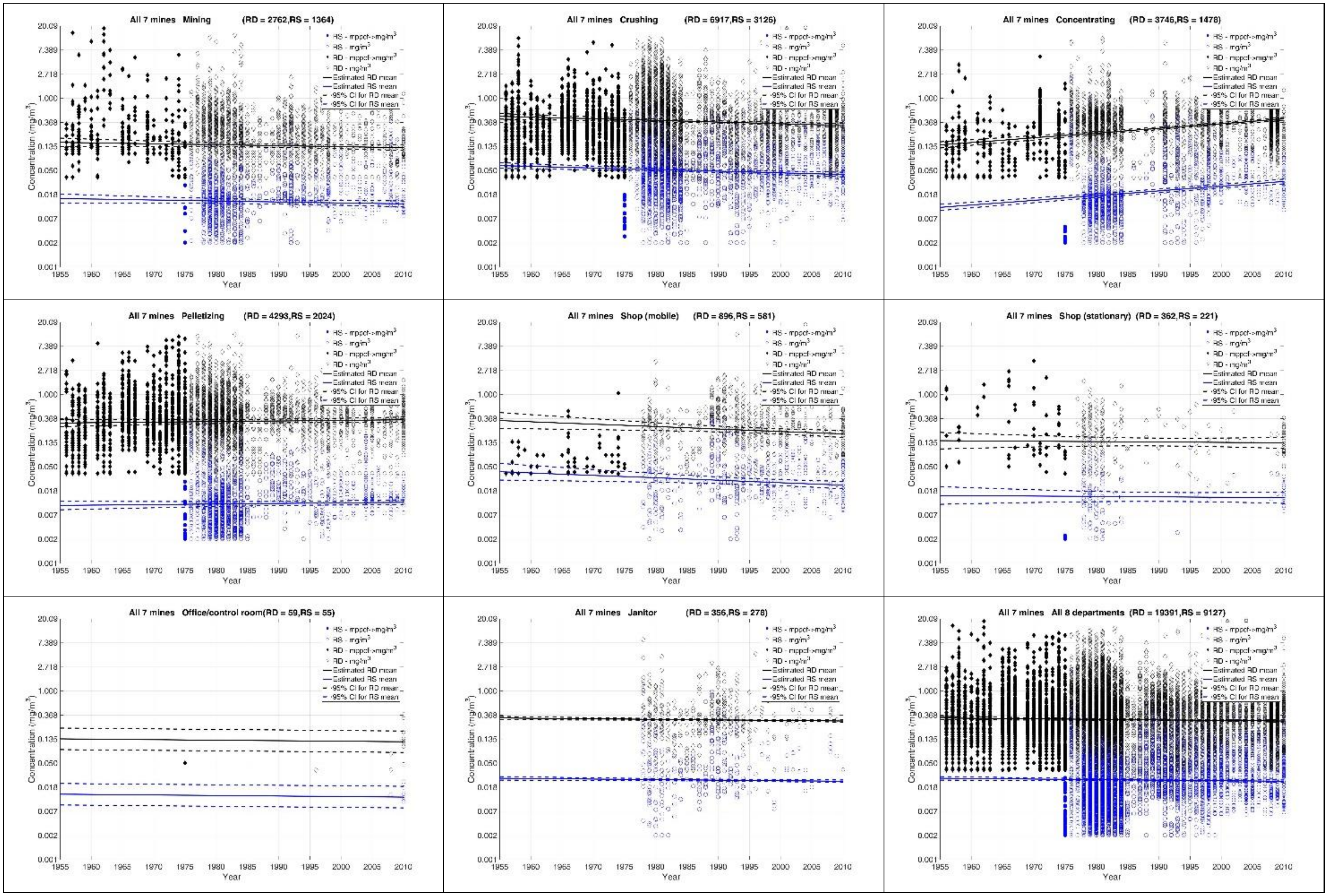


FIGURE 2-5 Predicted GMs of RS and RD with their 95% CIs for each study location

Chapter 3 :

Reconstructing Historical Exposures to Elongate Mineral Particles (EMP) in the Taconite Mining Industry for 1955–2010

OUTLINE

Objective: As part of ongoing epidemiological studies of Minnesota taconite mining workers for assessing the association between exposure to taconite dusts and the development of respiratory diseases, the goal of this study is to reconstruct the Elongate Mineral Particle (EMP) exposures of workers in Minnesota taconite industry from 1955-2010.

Methods: Historical NIOSH-7400 EMP personal exposure data were extracted from two sources: (1) the Mine Safety and Health Administration (MSHA) online database records for all inspection results since 1978 with 655 EMP monitoring records from 1978 to 2010 under 13 MSHA Mine IDs associated with this study; and (2) the mining companies' internal monitoring reports contain 96 personal EMP exposure records with the earliest record in 1983. Present-day NIOSH-7400 EMP personal exposures were measured for the workers in different jobs in all active mines in 2010 by obtaining 1285 personal samples. Measurement values of zero were replaced with a fixed value of 0.001 EMP/cm^3, which is one-half of the average LODs of the present-day measurements. After data treatment, all data were grouped into seven mines and then into eight departments (Concentrating, Crushing, Janitor, Mining, Office/control room, Pelletizing, Shop (mobile), Shop (stationary)). Within each mine-department, yearly EMP mean concentration in f/cc for each year of operation was predicted using two approaches. The first approach made predictions based on historical and present-day measurements using a regression model, while the second approach borrowed time-trend information from a related study of respirable dust exposures in the same mines and made predictions based on present-day measurements as well as the borrowed time trends.

Results: The performances of two approaches varied by situations. The overall range of the predicted time-trends in historical EMP exposures for mines by Approach 1 were from -8.3% to +10.2% (percent change per year), which was much wider than the estimations for historical dust exposure change (-3.0% to +3.0% per year) from the historical dust exposure study. The overall range of arithmetic mean EMP exposures varied significantly between the two approaches. The range provided by Approach 2 may be more plausible (0.01 and 0.23 f/cc).

Conclusion: In this study, a comprehensive reconstruction of the historical EMP exposures of all study locations was carried out using two different approaches. The results of this study are two different job exposure matrices (JEMs) by mine, department, and year for EMP. Both JEMs will be used to form the basis for future epidemiological studies.

INTRODUCTION

The Taconite Worker Health Study (TWHS), which was funded by the State of Minnesota in 2008, is by far the most comprehensive retrospective occupational epidemiological investigation into the cause(s) of the excess cases of respiratory diseases (mesothelioma, lung cancer, and non-malignant respiratory disease (NMRD)) among the taconite workers in Minnesota (University of Minnesota, 2014). Since its launching, a number of studies under the scope of this investigation have been published, ranging from occupational exposure assessments (Hwang *et al.*, 2013, 2014, 2017), a respiratory health survey (Odo *et al.*, 2013), a cancer incidence study(Elizabeth M. Allen *et al.*, 2015), retrospective case-control studies(E.M. Allen *et al.*, 2015; Lambert *et al.*, 2016), and mortality studies (Allen *et al.*, 2014; Mandel *et al.*, 2016a; Mandel *et al.*, 2016b). The main objective of this paper is to report another important piece of TWHS research – reconstructing the historical exposures to the elongate mineral particles (EMP) from the past to the present for different job locations of the study mines.

To conduct a historical EMP exposure reconstruction, especially for a long history that spans from 1955 to 2010 in this study, is challenging. The biggest challenge is that industrial hygiene (IH) measurement data are not available for every job for every time point of the study period in the job-exposure matrix (JEM). Researchers have used several different quantitative strategies to overcome the data sparsity: (1) data pooling: e.g., in the historical tremolite-actinolite exposure reconstruction work for the vermiculite miners and millers between 1930 and 1980 near Libby Montana, Amandus *et al.* (1987) estimated the 8-hr TWA fiber exposure for different jobs in each year of operation of the

Libby facility by pooling arithmetic averages of the fiber concentrations from filter samples for years when production processes and dust controls were assumed to be similar; (2) statistical modelling: e.g., in the historical fiber exposure reconstruction work for the chrysotile asbestos textile workers between 1940 and 1975 in Charleston South Carolina, Dement *et al*. (1982) first divided the textile operations into 16 exposure zones according to similarity of processes and exposures, and then applied a linear model to estimate the mean exposure levels over time for each of their exposure zones; (3) hybid methods: e.g., during the process of reconstructing the historical exposure to Libby vermiculite for the workers between 1972 and 2000, researchers first calculated the natural log-transformed mean for any year with 40 or more sample results, then fitted a smooth curve through these mean values, and final calculated the yearly fiber exposure levels by exponentiating the value on this curve for each year (Borton *et al.*, 2012; US Environmental Proection Agency, 2014).

In this paper, two mathematical modelling approaches are used to reconstruct the historical EMP exposure profiles from 1955 to 2010 for Minnesota taconite mines using sparse IH measurements and other information. The product of this work will form the foundation for estimating the life-time cumulative EMP exposure values for taconite workers in the epidemiological investigations of quantitatively assessing exposure-outcome associations.

METHODS

Taconite mines and different exposure groups

The TWHS study comprised seven taconite mines within two geological zones on the Mesabi Iron Range in Minnesota: ArcelorMittal, Hibbtac, Keetac, Minntac and Utac belong to the eastern zone and Northshore and LTV belong to the western zone (Table 3-1). The oldest mine started operating in 1955 and the youngest mine in 1977 (Sheehy, 1986). Six out of these seven mines were still in operation in 2010 when a comprehensive exposure monitoring was conducted (Hwang *et al.*, 2013, 2014, 2017). The mining process for each mine is quite similar, but workers with different tasks may experience different exposure situations. Hwang *et al.* (2013) grouped all taconite worker job titles into eight exposure departments: Mining, Crushing, Concentrating, Pelletizing, Shop (mobile), Shop (stationary) Janitor and Office/control room. The goal of this study was to create historical EMP reconstruction for each of these mine-department combinations.

TABLE 3-1 Profile of taconite mines in the study

#	Taconite Mine	Geological Zone	Year Opened	Status (as of 2010)	EMP Measurements Year Coverage
1	ArcelorMittal	Eastern	1977	Active	1979,1981,1983,1985,1986,1988,1992,1999-2001,2003,2004,2007,2010
2	Hibbtac	Eastern	1974	Active	1985,1986,1995,2000,2001,2003,2007,2010
3	Keetac	Eastern	1967	Active	1975-1977,1987,2000,2001,2003,2004,2007,2010
4	LTV	Western	1957	Closed in 2001	1979-1992,2000,2001
5	Minntac	Eastern	1967	Active	1990,1991,1994-1998,2000,2001,2003,2007,2010
6	Northshore	Western	1955	Active	1973-1976,1978-1980,1983-1986,1990-1993,1995,2000,2001,2003-2010
7	Utac	Eastern	1964	Active	1978,1979,1981-1983,1985-1990,1995,2000,2001,2003,2007,2010

* Mining Companies: http://www.taconite.org/mining-industry/mines;

Construction of historical exposure database

Historical EMP measurements included both personal and area samples. While personal samples estimated exposures over an eight-hour work shift, area samples varied from several minutes to a few hours. In this study, only historical personal EMP samples were considered, and all samples were analyzed by the standard Phase Contrast Microscopy (PCM) method as defined by the National Institute for Occupational Safety and Health (NIOSH, 1994).

Historical NIOSH-7400 EMP personal exposure data were extracted from two sources: (1) the Mine Safety and Health Administration (MSHA) online database records for all inspection results since 1978 with 655 EMP monitoring records from 1978 to 2010 under 13 MSHA Mine IDs associated with this study; and (2) the mining companies' internal monitoring reports contain 96 personal EMP exposure records with the earliest record in 1983. In total, there were only 751 historical EMP personal samples – a small number for the seven mines and eight departments over a 50-year time-span. The time distribution of these data can be found in Table 3-1 and their location distribution is listed in Table 3-2. The data gap was huge for several mines: The earliest EMP measurements for LTV mine was made in 1979, which was about 22 year later of its initial production. The Northshore, which was opened in 1964, also had no historical EMP measurements until 1978 – a 14 years' data gap.

Present-day EMP measurements

To assess present-day exposure levels as well as supplement the sparse historical data, personal EMP exposures in the six active mines on the Iron Range were measured from January 2010 to May 2011. The LTV mine, which was closed in 2001, had no present-day measurements. We collected a total of 1285 personal samples from a subset of workers in the seven of the eight departments (excluding "Janitor") of each active mine to assess present-day EMP exposures. All personal samples were analyzed using the same NIOSH 7400 PCM method by an accredited EMP testing laboratory. The details of the present-day measurements can be found elsewhere (Hwang *et al.*, 2013).

Handling data below the limit of detection

Among the 2036 historical and present-day measurements, 176 historical measurements and 463 present-day measurements were either below the limit of detection (LOD) or recorded as zero. Since we usually assume that IH measurements follow a lognormal distribution, and zero values cannot be log-transformed. Thus, the zeros and the values below LOD were replaced with a value of 0.001 fiber/cc, which was approximately one half of the lowest LOD among the present-day measurements.

Historical EMP reconstruction strategy

The objective was to reconstruct historical EMP exposures for each year in the study period for each mine-department combination. While the present-day measurements covered all departments and active mines and were sufficient in number, there were only 751 historical measurements which were not evenly distributed across mine-department combinations, and 13 combinations had no historical data at all (Table 3-2).

To address this difficulty, we used two different approaches. The first one (hereafter referred to as "Approach 1") was a regression-based approach. All 2036 data points were first sorted by mine, and within each mine, a categorical variable for department was created. For each mine, a log-linear regression model was run to obtain a fixed slope estimate (time trend) that is common to all departments and a varying intercept (magnitude) for each department (Eq. 1). The model is also adjusted for 'present-day' vs. 'historical' measurement. It is usually thought that there could be some systemic differences in the measurements of different year periods. The sampling strategy for the present-day exposure assessment was primarily designed to capture a wide ranges of exposure levels for epidemiological studies, while the historical measurements were for routine monitoring for compliances purposes. Therefore, the linear regression model for each mine included a term for whether the data represented present-day or historical measurements. A fixed slope (time trend) model was used so that estimates for departments with fewer monitoring data could borrow strength from departments with more monitoring data. The LTV mine had no present-day measurements and its historical data was very sparse as well. Therefore, we chose to use the data in Northshore as a surrogate to make predictions for this mine given their proximity in geological zone. In addition to the seven mines and the eight departments within each mine, an "All 8 departments" department category and an "All 7 mines" mine category were created during this reconstruction process (see Table 3-2). The results of these two categories will be used to provide exposure values for the workers whose work records were either missing or unclear in future epidemiological studies. The 'All 8 departments' department was modelled using the overall data within a mine. The 'All 7 mines' mine was modelled using all the data within the same department across all mines.

It’s worth noting that the term $\beta_{9,i}$ in Eq.1 is predicted time-trend for each mine of this study. Its value (in percentage) reflects the fixed annual mean EMP exposure change in a mine.

$$\log(y_{j,i,n}) = \beta_{0,i} + \sum_{j=1}^{8} \beta_{j,i} \times Department + \beta_{9,i} \times Year_i + \beta_{10,i} \times Present\_day + \varepsilon_i$$

(Eq.1)

where $y_{j,i,n}$ is the nth actual EMP measurement value at department j of mine i. $Department$ is a categorical variable for department. It has eight levels corresponding to the eight departments in the study. $\beta_{j,i}$ (j=1 to 8) are the model coefficients for the eight departments within each mine. The baseline department is the “mining” department. $Year_i$ is the sampling year, from 1955 or later to 2010 depending on the mine. $Present\_day$ is a binary variable with 0 for present-day measurements and 1 for historical measurements.

The second approach did not use any of the historical exposure measurements, but instead used the time-trend information from a companion study (Chapter 2) – Reconstructing Historical Exposures to Respirable Dust (RD) and Respirable Silica (RS) in the Taconite Mining Industry for 1955–2010. This approach assumed that dust exposures and EMP exposures in the same mine-department combination are correlated with each other and shared the same time-trend. For example, a yearly 1% increase/decrease in dust exposure would lead to the same 1% annual change in EMP exposure. The advantage of this assumption is that time-trend slopes from the dust study are very accurate given the large number of dust measurements (19,408 respirable dust (RD) measurements and 9,128 respirable silica (RS) measurements) used for modelling, and reflected the overall exposure changes over time in the taconite mining industry. EMP exposures, being a subset of the overall dust exposures, could reasonably be expected to follow the same general time-trends. However, there is no available evidence to support this assumed correlation of EMP exposure change and dust exposure change historically.

The model was conducted in the natural logarithmic scale. The modelling procedure is as follows: (1) For each mine-department combination, the mean exposure level at Year 2010 was given by the log of the geometric mean all present-day measurements of this location; (2) the mean exposure level in other year points was calculated using Eq.2; (3) the variance around the mean exposure in each year was fixed over the entire time period, and was given by the variance of all present-day measurements of this location.

$$\log\left(\hat{Y}_{i,j,k}\right) = \log(GM_{i,j,2010}) - \beta_{i,j,dust} \times (2010 - k) + \varepsilon_{i,j}$$

$$\varepsilon_{i,j} \in N(0, \log(GSD_{i,j,2010}))$$

(Eq.2)

Where $\hat{Y}_{i,j,k}$ is the predicted mean exposure level (fiber/cc) for department j of mine i in year k; $GM_{i,j,2010}$ is the geometric mean (GM) of all present-day measurements taken in the year 2010 at department j of mine i; $\beta_{i,j,dust}$ is the annual change rate value for department j of mine i listed in Table 3-3; $\varepsilon_{i,j}$ is the error term which follows a normal distribution with the mean of 0 and a standard deviation which equal to the log of geometric standard deviation (GSD) of all present-day measurements taken in the year 2010 at department j of mine i.

Similar to the first approach, the LTV mine was modelled based on the present-day data in Northshore. The ‘All 8 departments’ department was modelled using all the present-day data within a mine. The ‘All 7 mines’ mine was modelled using all the present-day data within the same departments across all mines. Janitor departments were modelled using ‘All 8 departments’ data.

Geometric mean (GM) to arithmetic mean (AM) conversion

Both reconstruction approaches were conducted in the log scale, and their model outputs after exponentiation (GMs and GSDs) were used to calculate the corresponding arithmetic means using Eq.3.

$$AM = GM \times \exp(\frac{1}{2}\log^2(GSD))$$

(Eq.3)

The final products of this study were two EMP job-exposure matrices (JEMs), each of which was associated with one of the two reconstruction approaches used in this study. Each table contains annual arithmetic mean EMP exposure values in fiber/cc for each of all possible year-department- mine combination in the study. These two JEMs, when linked to taconite workers’ employment histories, will allow us to calculate the cumulative exposure for the study population in future epidemiologic studies.

Statistical Analysis

Data cleaning was performed in SAS 9.3 (SAS Institute, Cary NC). EMP reconstruction process were performed in MATLAB R2014b (MATLAB e MathWorks, Inc., Natick, MA).

RESULTS & DISCUSSION

There are a total of 2,036 EMP data across all mines and departments as summarized in Table 3-2. The distribution of these samples, to some extent, reflects overall IH sampling priorities in the taconite industry. Most of IH samples were collected in the four main taconite processes – mining, crushing, concentrating and pelletizing. In contrast, there are no historical data available for all seven Office/control room departments (present-day measurements did greatly supplement the database for these departments). The entire LTV mine and Janitor departments in each of the other mines had no present-day measurement (shaded gray in Table 3-2). We borrowed data from other locations to address this issue. Meanwhile, an ‘All 7 mines’ column and an ‘All 8 departments’ row were created to provide exposure estimates for workers with unclear job titles or work histories.

TABLE 3-2 Numbers of historical and present-day EMP measurements

Mine-Department	ArcelorMittal	Hibbtac	Keetac	LTV	Minntac	Northshore	Utac	All 7 mines
	# of historical measurements (# of present-day measurements)							
Mining	31(11)	20(30)	15(42)	14(0)	46(36)	84(21)	21(24)	231(164)
Crushing	35(11)	6(23)	5(18)	19(0)	30(22)	109(54)	36(36)	240(164)
Concentrating	8(12)	4(24)	4(24)	3(0)	29(24)	13(32)	4(18)	65(134)
Pelletizing	5(29)	10(35)	2(54)	2(0)	35(55)	8(60)	3(57)	65(290)
Shop (mobile)	3(30)	3(52)	5(30)	1(0)	17(76)	54(42)	14(52)	97(282)
Shop (stationary)	1(18)	0(24)	0(23)	8(0)	0(30)	1(42)	12(22)	22(159)
Office/control room	0(18)	0(11)	0(12)	0(0)	0(24)	0(15)	0(12)	0(92)
Janitor	1(0)	3(0)	0(0)	0(0)	13(0)	10(0)	4(0)	31(0)
All 8 departments	84(129)	46(199)	31(203)	47(0)	170(267)	279(266)	94(221)	751(1285)

Model outputs

Some of the predicted historical EMP exposure values using the two different reconstruction approaches are shown side by side in Figure 3-1. The three pairs of plots in this figure demonstrate three typical scenarios in the study. The first scenario is when a mine-department combination had a fairly good exposure data coverage over its entire time period. In this scenario, as shown in the two first-row plots, the two approaches provided comparable prediction curves. The curves crossed through the area where most data points located, and the predicted EMP exposure slopes by Approach 1 were consistent with the borrowed dust exposure slopes in Approach 2. The second scenario is when a location only had present-day measurements. In this scenario, as shown in the two second-row plots, Approach 2 seemed to be more robust than Approach 1 for at least two reasons: (1) slopes: both slopes can be thought to be “borrowed” slopes. In Approach 1, the slope was determined by other departments where they had historical data. In Approach 2, by design, this slope was determined by the dust measurements of this location. As we know, in almost all study locations, we have much more historical dust measurements than EMP measurements. Therefore, we have more confident on the Approach 2’s slope than the one in Approach 1. The third scenario is when a mine-department combination’s present-day measurements are very different from its historical measurements. In such scenario, as shown in the two third-row plots, it may not be easy to decide which approach is better. On one hand, Approach 1 clearly provided a better fit to the data in comparison to Approach 2. Its prediction is closer to both historical data points and present-day data points. But this better data fit, however, resulted in a very sharp slope which could likely provide unrealistic predictions for the earlier operation years. Approach 2, while not over-extrapolating, had a very poor data fit. In summary, both approaches had pros and cons, and each alone might not handle all challenging scenarios in the study. Which one, the borrowed dust exposure slope or the predicted slope based on actual EMP measurements, is closer to the true slope of historical EMP exposure is the biggest question we were facing during this reconstruction process.

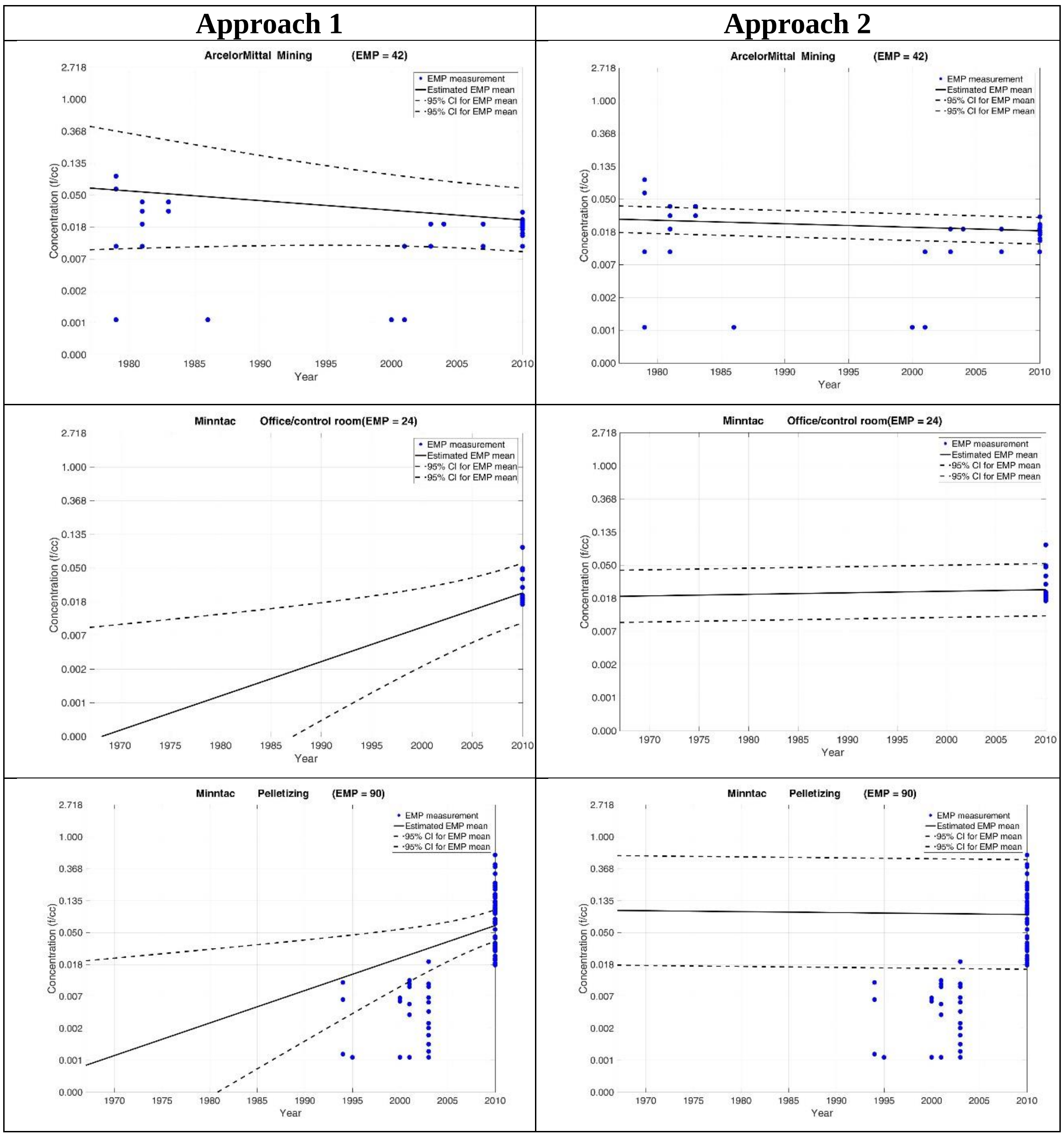


FIGURE 3-1 Historical EMP exposure reconstruction results for each of selected mine-department combinations using two approaches

Predicted annual exposure level change rate by exposure location

Approach 1 made time trend predictions for the historical exposure change in each mine based on historical and present-day EMP measurements. The results of these time trends are listed on the last row of Table 3-3. Compared to the time trends in historical respirable dust exposure used in Approach 2 (first 9 rows in Table 3-3), the predicted EMP trends based on limited EMP data tended to be significantly steeper, and some of the annual percent changes seem unrealistic. The overall range was from -8.2% to 10.2%. Time-trend results from historical respirable dust exposures suggest that the historical exposure change in taconite mining environment should not be excessive, and in most cases, this change should be within -3% to 3% per year.

TABLE 3-3 The time-trend in historical EMP exposures estimated by Approach 1 and the location-specific annual concentration change rate for historical exposure to airborne dusts used in Approach 2

Mine-Department	ArcelorMittal	Hibbtac	Keetac	LTV	Minntac	Northshore	Utac	All 7 mines
Mining	-1.1%	-0.1%	-1.8%	0.4%	-0.6%	0.4%	1.0%	-0.4%
Crushing	-0.8%	-2.5%	-3.3%	-0.1%	2.3%	-0.1%	2.2%	-0.7%
Concentrating	-2.7%	1.6%	-2.9%	3.2%	2.2%	3.2%	0.0%	2.0%
Pelletizing	-2.0%	0.9%	-1.5%	2.3%	-0.3%	2.3%	0.1%	0.2%
Shop (mobile)	-3.0%	-2.1%	-0.3%	-0.4%	-2.5%	-0.4%	-1.4%	-1.0%
Shop (stationary)	0.2%	1.1%	1.2%	1.5%	0.3%	1.5%	-2.6%	-0.2%
Office/control room	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%
Janitor	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%
All 8 departments	-1.8%	-1.0%	-2.0%	0.7%	0.5%	0.7%	0.8%	-0.2%
Approach 1	-3.0%	2.1%	-0.8%	-4.5%	10.2%	-4.5%	-8.2%	-3.9%

Predicted arithmetic mean of EMP exposure by exposure location

As suggested by several researchers (Rice *et al.*, 1984; Seixas, Robins and Moulton, 1988; Rappaport, 1991; Crump, 1998; Verma *et al.*, 2011), the arithmetic mean (AM), instead of geometric mean (GM), is a more appropriate exposure metric in creating a job-exposure matrix (JEM) for health studies. The predicted AM range for every mine-department combination are listed below (Table 3-4 for Approach 1, and Table 3-5 for Approach 2).

TABLE 3-4 The predicted AM range of historical EMP exposure levels by location (fiber/cc) –Approach 1

Mine-Department	ArcelorMittal		Hibbtac		Keetac		LTV		Minntac		Northshore		Utac		All 7 mines	
	Min	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***
Mining	0.03	0.10	0.02	0.07	0.03	10.89	0.13	1.82	0.00	0.04	0.08	2.10	0.05	7.00	0.04	0.41
Crushing	0.04	0.15	0.03	0.07	0.02	6.56	0.20	2.51	0.00	0.06	0.13	2.87	0.03	3.09	0.06	0.60
Concentrating	0.05	0.20	0.02	0.05	0.06	15.22	0.28	3.64	0.00	0.07	0.18	4.17	0.05	6.21	0.05	0.47
Pelletizing	0.02	0.08	0.03	0.07	0.11	30.89	0.12	1.58	0.00	0.06	0.08	1.81	0.03	3.61	0.04	0.45
Shop (mobile)	0.03	0.12	0.03	0.08	0.05	14.01	0.13	1.67	0.00	0.06	0.08	1.92	0.04	4.20	0.05	0.49
Shop (stationary)	0.02	0.09	0.02	0.06	0.03	9.14	0.12	1.58	0.00	0.04	0.08	1.82	0.04	3.69	0.04	0.41
Office/control room	0.03	0.12	0.02	0.06	0.02	7.42	0.03	0.44	0.00	0.03	0.02	0.50	0.03	3.17	0.02	0.23
Janitor	0.03	0.09	0.02	0.03	0.05	3.32	0.13	1.61	0.00	0.05	0.08	1.82	0.03	1.93	0.04	0.45
All 8 departments	0.03	0.09	0.02	0.03	0.05	3.32	0.13	1.61	0.00	0.05	0.08	1.82	0.03	1.93	0.04	0.45

For Approach 1, the overall AM range was in between 0.00 and 30.89 f/cc. Its upper bound was too high to be true. This is possibly due to the combined effect of multiple problems existed in the prediction process. These problems might include: some predicted slopes were too sharp, some locations had little raw data to rely on, no historical data for several locations, and huge variances in model outputs for some locations. In contrast, predictions from Approach 2 were much more stable. Its overall AM range was in between 0.01 and 0.23 f/cc. These narrower range suggests that by borrowing time-trend information from the dust exposure study greatly reduced the uncertain in prediction in this study. Given the poor quality of this EMP measurements, maybe Approach 2 was a more reliable than Approach 1 in reconstructing the historical EMP exposure profiles in this study.

TABLE 3-5 The predicted AM range of historical EMP exposure levels by location (fiber/cc) – Approach 2

Mine-Department	ArcelorMittal		Hibbtac		Keetac		LTV		Minntac		Northshore		Utac		All 7 mines	
	Min	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***	***Min***	***Max***
Mining	0.02	0.03	0.02	0.02	0.04	0.08	0.07	0.08	0.03	0.04	0.07	0.08	0.05	0.07	0.04	0.05
Crushing	0.04	0.05	0.03	0.07	0.03	0.13	0.22	0.22	0.03	0.08	0.21	0.22	0.01	0.03	0.09	0.13
Concentrating	0.04	0.10	0.01	0.02	0.07	0.23	0.04	0.15	0.02	0.05	0.04	0.20	0.05	0.05	0.03	0.08
Pelletizing	0.02	0.05	0.03	0.04	0.12	0.23	0.03	0.07	0.13	0.15	0.03	0.09	0.04	0.04	0.07	0.08
Shop (mobile)	0.03	0.08	0.04	0.08	0.06	0.07	0.16	0.20	0.07	0.22	0.16	0.20	0.05	0.10	0.06	0.11
Shop (stationary)	0.02	0.02	0.02	0.03	0.02	0.03	0.05	0.09	0.05	0.05	0.05	0.11	0.03	0.09	0.05	0.05
Office/control room	0.03	0.05	0.02	0.03	0.02	0.05	0.01	0.02	0.02	0.03	0.01	0.02	0.01	0.02	0.02	0.03
Janitor	0.03	0.05	0.03	0.04	0.06	0.15	0.09	0.13	0.06	0.07	0.09	0.14	0.03	0.04	0.06	0.07
All 8 departments	0.03	0.05	0.03	0.04	0.06	0.15	0.09	0.13	0.06	0.07	0.09	0.14	0.03	0.04	0.06	0.07

Limitations

LTV is a very important mine in the entire TWHS study as (1) it was the only mine in the mineralogical zone 2 of the Mesabi Iron Range in Minnesota. Its EMP exposure profile could be different from the mines in other zones; (2) nearly 1/3 of the study population in this mesothelioma cohort had some connection with LTV; (3) it had a very long operation history, from 1957 to 2001. This mine, however, had the worst data coverage in the study. It had no present-day measurements, and its historical measurements were very few (47 data points) as well. In this study, we modelled this mine's historical EMP exposure based on the data from Northshore mine which was considered to be geographically proximate to LTV.

CONCLUSION

In this study, we conducted a comprehensive reconstruction for the historical EMP exposures of all study locations using two different reconstruction approaches. The results of this study are two different JEMs by mine, department, and year for EMP. Both JEMs will be used to form the basis for future epidemiological studies and create more options for estimating the risk estimates under different exposure metrics in future research.

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DISCLAIMER

The authors declare that there are no conflicts of interest relating to the material in relation to this article.

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Chapter 4 :

A Bayesian Approach for Deriving Numerical Relationships between Different Elongate Mineral Particles (EMP) Definitions

OUTLINE

Objective: A variety of dimensions (lengths and widths) of elongate mineral particles (EMP) have been proposed as being related to health effects such as mesothelioma and lung cancer. As part of an epidemiologic study to investigate the effect of different EMP metrics (based on dimensional definitions) on the association between lung diseases among the taconite workers and their EMP exposures, the goal of this study is to develop a mathematical approach for deriving numerical conversion factors (CFs) between these exposure metrics. A previous study (the Minnesota Taconite Worker Health Study) has already characterized exposures according to the NIOSH-defined EMP exposure metric (length > 5 μm with an aspect ratio ≥ 3.0). These CFs will allow the creation of job exposure matrices (JEMs) for alternative EMP metrics using existing EMP measurements.

Methods: Filter samples have been collected from six taconite mines in the Iron Range of Minnesota, with each mine comprising 27 similar exposure groups (SEGs) (for a total of 162 mine-SEG combinations), and these have been previously analyzed using the NIOSH EMP definition using phase contrast microscopy (PCM) and transmission electron microscopy (TEM). Each mine-SEG combination needs a conversion factor to obtain exposures based on alternative EMP metrics. For each combination, we assume that the EMP dimensions (length and width) follow a bivariate lognormal distribution. A Bayesian approach was used to estimate these distributions based on priors for EMP dimensions derived from a limited number (N=92) of area samples that were then updated using SEG-specific personal EMP measurements (1267 personal samples). The Bayesian prediction comprises three steps: (1) area sample results from a previous study were sorted by mine, and used to form mine-specific model priors; (2) all personal sample filters were analyzed using TEM (ISO-10312/13794), by which the lengths and widths of all measurable EMP (width >0.01 μm, length > 0.3 μm, aspect ratio ≥ 3.0) were obtained. Personal samples results were sorted by mine and SEG to develop the model likelihoods; and (3) for each mine-SEG combination, the likelihoods for EMP length and width measurements were used to update mine-level priors to obtain a unique posterior bivariate lognormal distribution. Each posterior distribution is a probability density surface for the EMP length and width distribution for each mine-SEG combination. The total volume under each probability surface should always equal to 1 (100%). The volume under the curve corresponding to the length and width for each of the selected EMP dimensional definitions ('ISO-TEM EMP', 'NIOSH EMP', 'Chatfield asbestiform EMP', 'Chatfield non-asbestiform EMP' and 'Suzuki EMP') is the percentage of the total number of EMP for that definition. The derived numerical CFs between any two EMP definitions would then be the ratios of the volumes under the bivariate posterior EMP distribution for those two definitions.

Results: There are a total of 2,791 single EMP (ranging from 34 to 1,954 EMP by mine) identified from the area samples, and 11,190 single EMP (ranging from 0 – 844 EMP by mine-SEG combination) identified from the personal samples. For the final predicted conversion factors, the median "NIOSH EMP" to "ISO-TEM EMP" CF and interquartile range (IQR) was 0.07 [0.04-0.11] depending on the mine-SEG combination, and the median and IQR for the "Chatfield asbestiform EMP" to "ISO-TEM EMP" CF was 0.03 [0.01-0.05]. The interception of these CFs is that among every 100 single EMP collected in taconite mines, on average, 7 of them belong to NIOSH EMP and 3 of them belong to

Chatfield asbestiform EMP. The median [IQR] of the CF of the "NIOSH EMP" to "Chatfield asbestiform EMP", "Suzuki EMP", and "Chatfield non-asbestiform EMP" were 0.22 [0.06-0.68], 7.29 [2.78-13.88], and 10.68 [6.2-20.0] respectively. The interception is that if we can observe 100 NIOSH EMP under PCM on a filter, there will be, on average, around 22 Chatfield asbestiform EMP, 729 Suzuki EMP and 1068 Chatfield non-asbestiform EMP existing on that filter as well.

Conclusions: The comprehensive EMP exposure assessment conducted in this paper, particularly 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 epidemiological studies of mesothelioma, lung cancer, and non-malignant respiratory disease.

INTRODUCTION

Since the term "fiber" has been controversial in the context of asbestos (e.g., Eastern Research Group, 2003), the National Institute of Occupational Safety and Health (NIOSH) has proposed the use of the term "elongated mineral particles" or EMP 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 US, the current standard analytical method for measuring elongate mineral particles (EMP) is *the NIOSH Manual of Analytical Methods (NMAM) 7400: Asbestos and Other Fibers by Phase Contrast Microscopy (PCM)* with its latest update in 1994 (NIOSH, 1994).

EMP can be asbestiform or non-asbestiform. 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 from measurement reproducibility considerations rather than health relevance. 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, EMP 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 occurred and asbestiform in habit.

Non-asbestiform EMP are chemically no different from asbestiform EMP (Berndt & Brice, 2008), but are morphologically different and have needle-like (acicular) or prismatic crystalline habits (Ilgren, 2004; NIOSH, 2011). NIOSH has explicitly included EMP from the non-asbestiform analogs of asbestos in its recommended exposure limit (REL). Their rationale for this decision was three-fold (NIOSH, 2011): (1) the epidemiological evidence from studies where worker populations were exposed to non-asbestiform EMP (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; (2) 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, (3) 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 the 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 EMP. 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 92 new EMP area samples, and analyzing all personal samples 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% CI 0.97 to -1.24) (Lambert *et al.*, 2016).

Over the years, there have been several EMP definitions based on alternative size ranges (Stanton *et al.*, 1981; Lippmann, 1988; Berman *et al.*, 1995; Berman and Crump, 2003, 2008; Dodson, Atkinson and Levin, 2003; Eastern Research Group, 2003; Suzuki, Yuen and Ashley, 2005; Chatfield, 2008; Dement *et al.*, 2008; Loomis *et al.*, 2010, 2012; NIOSH, 2011). For example, Dodson et al. (2003) concluded that asbestos EMP of all lengths induce pathological responses and cautioned against ignoring EMP < 5 µm since they constituted the bulk of EMP exposures. Suzuki et al. (2005) concluded that short (≤5 µm), thin EMP (≤0.25 µm) 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 µm ≤width≤0.25 µm) and long (20≤aspect ratio≤1000) EMP 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 µm to > 40 µm and widths ranging from 0.25 - 3.0 µm 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 EMP > 5 μm in length, shorter EMP 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 (MMMF), EMP >3 μm in length, <1 μm in width, and >5:1 aspect ratio were carcinogenic.

A re-analysis of the 1200 filter samples collected during the TWHS to obtain the sizes of all EMP presents a unique opportunity to definitively address the various competing hypotheses regarding the health effects of different EMP dimensions. The objectives of this study are twofold. First, we propose a new approach for deriving numerical relationships between any two 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 each Mine-SEG unit of the Minnesota Taconite Worker Health Study. These factors will allow the creation of JEMs for alterative EMP metrics from our existing NIOSH-EMP JEM for our future epidemiologic study.

METHODS

Backgrounds

The TWHS comprises seven taconite mines (ArcelorMittal, Hibbtac, Keetac, LTV, Minntac, Northshore and Utac), of which one (LTV) was inactive in 2010 when onsite investigations were conducted. Northshore was in the Eastern zone and the rest six mines were in the Western zone. Hwang et al (2013) grouped all taconite workers job titles into 28 similar exposure groups (SEG) and collected EMP area as well as personal samples in all six active mines (Table 4-1). 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.

TABLE 4-1 EMP personal and area samples by mine

Zone	Mine	# of Area Samples	# of Personal Samples
Eastern	Northshore	23	253
	Keetac	14	200
	Minntac	15	270
Western	ArcelorMittal	8	130
	Hibbtac	12	198
	Utac	20	216
Total		92	1267

The detailed sampling procedures can be found 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 averaged sampling time was 6 hours, and EMP 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, and about 20% of the total were analyzed again using the NIOSH 7402 TEM method.

Area samples, taken during normal operating conditions at locations representative of each SEG, were collected in up to two samples per location during the same time period of the personal samples. The samples were obtained using a rotating cascade impactor (Model 125R MOUDI-II, MSP Co., Shoreview, MN, USA). The cut sizes of the 13 impactor stages ranged from 0.010 µm to 10 µm. Due to some budget issues, only a portion of the area sample filters were analyzed, but using the ISO 10312 or 13794 TEM methods (International Standard Organization, 1995, 1999). 2,791 single EMP with the length and width information of each were identified by these ISO TEM methods.

All above 1267 personal samples and dimensional information of all 2791 single EMP will be used as first-hand materials for the development of this study.

STEP 1: Obtain single EMP dimension information using ISO-TEM analysis

In this study, all archived personal samples were analyzed using the ISO 10312 or 13794 TEM methods in a local accredited EMP lab. Specifically, each personal sample was first screened by the ISO 10312 TEM method with 15 grid openings. If failed due to filter overloading, then samples would be analyzed again using the ISO 13794 method but with 10 grid openings. The total filter area needed for this ISO-TEM analysis was about ¼ of the original complete filter (complete filter area: 490mm^2). Under the high-resolution TEM microscope (~20,000X magnification), the lengths and widths of all eligible EMP (width (W) $\geq$ 0.01 µm, length (L) $\geq$ 0.3 µm, aspect ratio, AR = L/W $\geq$3) were measured and reported. As is shown in Figure 4-1, this new method allowed us to observe a much wider range of EMP compared to traditional NIOSH PCM method. Moreover, this ISO-TEM method can also report the chemical composition and crystal structure information for each of the reported EMP.

We are aware that there has been debates over whether there is a “observer effect” meaning the analytical method - ISO-TEM 13794 method might alter the original EMP structures during a EMP observation. People concerns that the EMP on the original filter, after water-wash and transferred to other new filter, might not be keep the same structures as they were originally. For example, a long fiber would be broken into several short fibers, or a EMP bundle would be separated as multiple single EMP. We thought this debate has been beyond the scope of this study, but we did not observe this “observer effect” comparing the size distributions between the EMP observed using ISO-10312 method vs. those using ISO-13794 in this study.

Another debate is that should we count EMP with different structures differently during an exposure assessment. The ISO-TEM methods classified EMP’s structures into four primary categories and multiple sub-categories: Fiber, Bundle, Cluster and Matrix. We are aware that EMP with different structures may play different roles in the disease development, but there is no guidelines to quantify this difference. In this study, we only focus on EMP numerical amounts and ignore their specific structures.

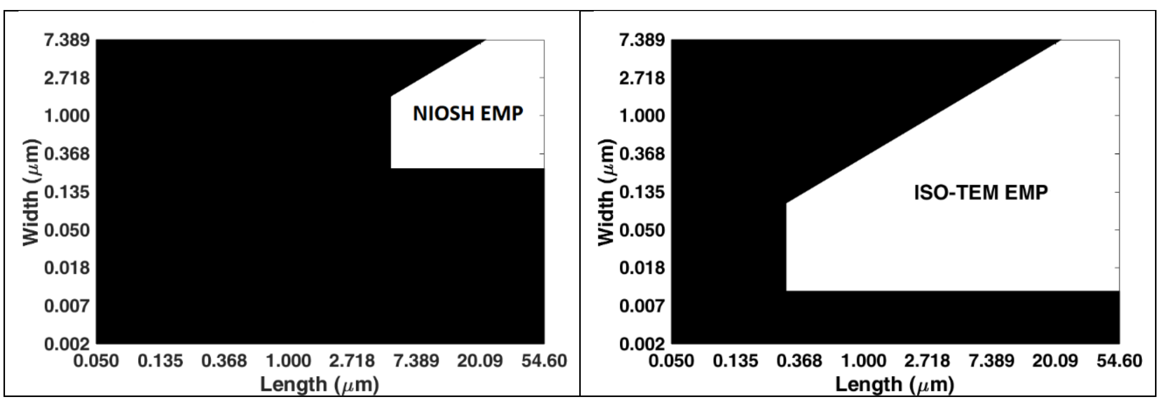

FIGURE 4-1 NIOSH 7400 PCM and ISO-TEM visible area comparison

STEP 2: Use bivariate lognormal distribution to characterize overall EMP size distribution

EMP size distributions can be simply 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, Skotte and Nissen, 1985; Cheng, 1986; Quinn *et al.*, 2010). The shape of a bivariate lognormal distribution is shown in Figure 4-2.

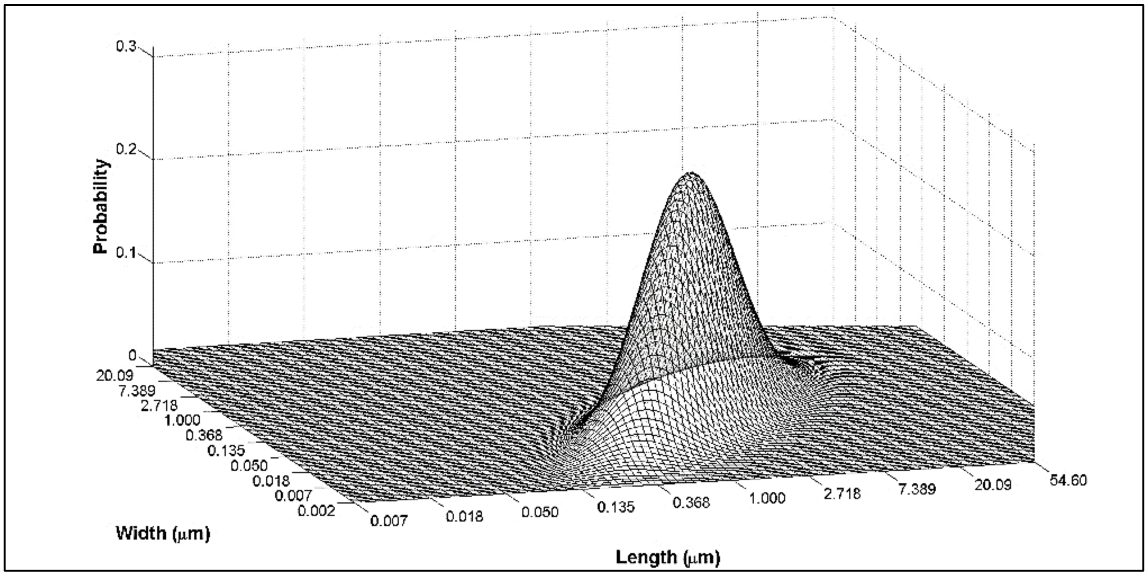

FIGURE 4-2 A bivariate lognormal distribution density plot example

An important property of a bivariate lognormal distribution is that if L and W are bivariate lognormally distributed, then *ln* L and *ln* W are bivariate normally distributed. 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:

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

where $\mu_L, \mu_W, \sigma_L, \sigma_W$ are the mean and standard deviation 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 (Eq.2).

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

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

$$GM(L) = e^{\mu_L}, \qquad GM(W) = e^{\mu_W}, \qquad GSD(L) = e^{\sigma_L}, \qquad GSD(W) = e^{\sigma_W} \tag{3}$$

STEP 3: Use Bayesian approach to facilitate the formation of the bivariate lognormal distribution

Not every mine/SEG combination has sufficient numbers of single EMP to derive the EMP size distribution. Bayesian statistical inference using prior knowledge is typically used when actual data are not adequate. The entire Bayesian models are listed in Eq 4- 8. For each mine-SEG location (i mine, j SEG), we assume that $\ln l, \ln w$ (see Eq. 4) follow a bivariate normal distribution with a mine-SEG-specific mean of (μ_L, μ_W) and a covariance matrix $\begin{pmatrix} \sigma_L^2 & \sigma_{LW} \\ \sigma_{LW} & \sigma_W^2 \end{pmatrix}$.

<u>Likelihood model:</u>

$$(\ln l, \ln w)_{i,j} \sim Bivariate\ N\left((\alpha_L, \alpha_W), \begin{pmatrix} \sigma_L^2 & \sigma_{LW} \\ \sigma_{LW} & \sigma_W^2 \end{pmatrix}\right)_{i,j}; \tag{4}$$

The correlation ($\rho_{i,j}$) between $\ln l$ and $\ln w$ can be calculated based on the element values in above covariance matrix using Eq.5.

$$\rho_{i,j} = \left(\frac{\sigma_{LW}}{\sigma_L \sigma_W}\right)_{i,j} \tag{5}$$

Eq 6-7 listed the priors for the Eq.4's parameters. The mine-SEG-specific mean EMP length $(\mu_L)_{i,j}$ is given by a normal distribution with a mine-specific mean length $(\mu_L)_i$, and a flat variance (see Eq.6) following an inverse gamma (0.1,0.1). Similarly, the mine-SEG-specific mean EMP width $(\mu_W)_{i,j}$ is given by a normal distribution with a mine-specific mean width $(\mu_W)_i$, and a flat variance following an inverse gamma (0.1,0.1). The likelihood covariance matrix follows an inverse wishart distribution.

<u>Weakly informative priors:</u>

$$(\alpha_L)_{i,j} \sim N((\mu_L)_i, \tau_L);\ (\alpha_W)_{i,j} \sim N((\mu_W)_i, \tau_W); \tag{6}$$

$$\begin{pmatrix} \sigma_L^2 & \sigma_L\sigma_W \\ \sigma_L\sigma_W & \sigma_W^2 \end{pmatrix}_{i,j} \sim Inverse\ Wishart\left(\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, 2\right); \tag{7}$$

The hyper-priors are listed in Eq.8. 2791 single EMP previously identified by the same ISO-TEM method in 92 area samples were used in this step. Specifically, all 2791 EMP were grouped by mine, and within each mine, we calculated their geometric mean length

GM(L) and width GM(W) (see Table 4-2), and plug them to Eq.8 for $\hat{\mu}_L$ and $\hat{\mu}_W$. τ_L and τ_W are uninformative hyper-priors defined by an inverse gamma distribution (0.1, 0.1).

TABLE 4-2 The mine-specific estimated parameter values for a bivariate lognormal distribution

Mine	# of EMP	GM(L)	GSD(L)	GM(W)	GSD(W)	ρ
ArcelarMittal	34	1.37	1.93	0.17	1.85	0.57
Hibbtac	61	1.60	1.87	0.21	2.09	0.65
Keetac	211	1.05	1.90	0.16	1.79	0.77
Minntac	155	1.19	2.06	0.19	1.94	0.76
Northshore	1954	1.79	1.99	0.24	2.07	0.70
Utac	376	1.88	1.99	0.24	1.94	0.55

<u>Weakly informative hyper-priors:</u>

$$(\mu_L)_i \sim N((\hat{\mu}_L)_i, 1000); (\mu_W)_i \sim N((\hat{\mu}_W)_i, 1000);$$

$$\tau_L \sim Inverse\ Gamma(.1, .1);\ \tau_W \sim Inverse\ Gamma(.1, .1);$$

(8)

STEP 4: EMP size-based definitions

The five study-focused EMP definitions are listed in Table 4-3. These definitions, to some extent, can be very representative: (1) the ISO-TEM EMP has the widest size range and can help us to see a nearly complete picture of the total EMP population; (2) the NIOSH EMP; (3) the Chatfield asbestiform EMP refers to long and thin fibers; (4) the Suzuki EMP refers to short fibers; (5) the Chatfield non-asbestiform EMP (referred to as cleavage fragments in Hwang et al., 2014) are created by the 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).

TABLE 4-3 EMP definitions in our study

#	EMP definitions	Width (μm)	Length (μm)	Aspect Ratio (AR)
1	ISO-TEM EMP (1995, 1999)	≥0.01*	≥0.3**	≥3***
2	NIOSH EMP (1994)	≥0.25****	>5	≥3
3	Chatfield asbestiform EMP (2008)	0.04-1.5	NA	20-1000
4	Suzuki EMP (2005)	≤0.25	≤5	NA
5	Chatfield non-asbestiform EMP or cleavage fragments (2008)	NA	NA	<20

* the actual minimum reported diameter in our study.
** the actual minimum reported length in our study. The method default value was 0.5 μm.
*** the actual AR used in our study. The method default AR was 5:1.
******** Fibers less than approximately 0.25 microns in diameter will not be detected by PCM

Figure 4-3 shows the regions of the hypothetical overall EMP distribution - a 2-d bivariate lognormal shape previously mentioned, 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.

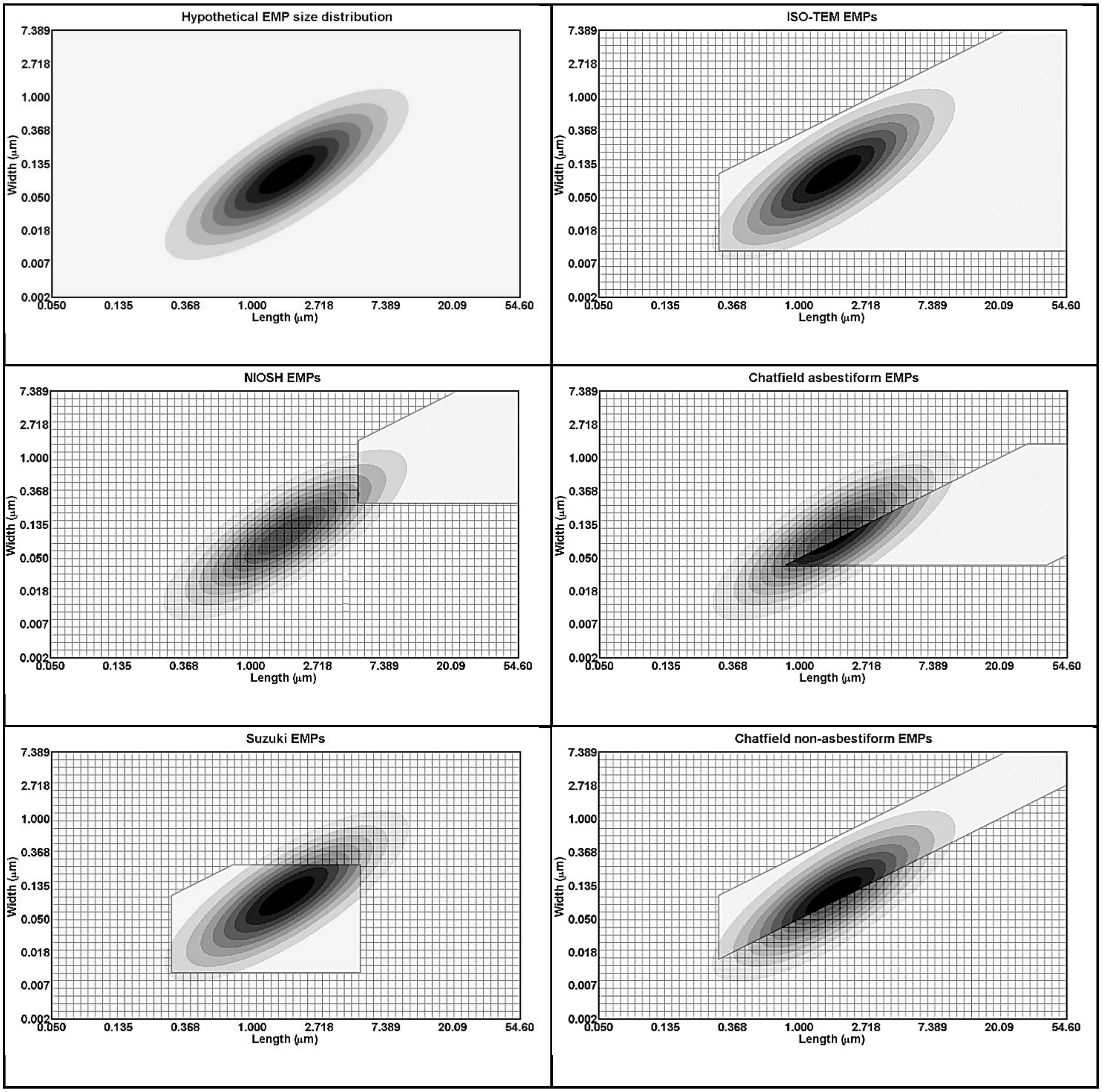

FIGURE 4-3 Specific area within the overall EMP size distribution corresponding to each EMP definition

STEP 5: Deriving conversion factors between any two EMP definitions

The final conversion factor between any two EMP definitions is the ratio of their volumes under the bivariate lognormal probability density function. For example, if for a given mine/SEG combination, 3% of the total EMP population falls under the NIOSH EMP range, and 60% of the total population falls under the Suzuki EMP range, then the conversion factor between the NIOSH EMP and the Suzuki EMP is 1:20. Thus, if a sample NIOSH 7400 result is 1 f/cc for example, then the corresponding Suzuki EMP concentration will be 20 f/cc.

Software used

In this study, the EMP length and width ISO-TEM result was stored and sorted using SAS statistical software (version 9.3, SAS Institute, Cary, North Carolina, United States). The Bayesian modelling 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 'dmnorm' function was used to define a bivariate normal distribution for ln L and ln W. STEP 4 and 5 were implemented in MATLAB with the multivariate normal probability density function 'mvnpdf' - (MATLAB version R2014b, the MathWorks, Inc., Natick, Massachusetts, United States).

RESULTS & DISCUSSION

EMP availability by exposure groups

The ISO-TEM analysis of the 1,267 EMP personal samples resulted in a total of 11,190 eligible ISO-TEM EMP by mine and SEG as listed in Table 4-4. Of the 162 mine-SEG combinations (6 mines by 27 SEGs), 37 (23%) had fewer than 4 available EMP. For these combinations, we did not carry out Bayesian updating, and instead used the mine-level priors for the parameter estimates listed in Table 4-2 as the final model output. The combination with the most available data is the SEG *Crusher maintenance* of the Northshore mine with 844 corresponding EMP. This high number is due to (1) an above-average 6 personal samples, and (2) the general exposure level in this SEG is high, so for the same 6-hr long sampling period, more EMP are expected to be collected and analyzed.

TABLE 4-4 Summary of the reported EMP counts collected by personal samples

Mine/SEG	ArcelorMittal	Hibbtac	Keetac	Minntac	Northshore	Utac	Total
Auto mechanic	13	60	7	16	55	10	161
Balling drum operator	39	0	57	79	226	55	456
Basin operator	0	20	2	11	0	30	63
Boiler technician	0	0	0	69	0	22	91
Carpenter	0	21	9	29	0	0	59
Concentrator maintenance	39	175	50	77	435	28	804
Concentrator operator	9	312	34	71	497	111	1034
Control room operator	13	5	1	16	147	23	205
Crusher maintenance	16	135	46	51	**844**	163	1255
Crusher operator	121	79	26	35	723	101	1085
Dock man	9	8	21	17	68	61	184
Electrician	12	43	12	105	434	67	673
Furnace operator	14	0	29	13	149	121	326
Lab analyst	17	108	29	1	**833**	41	1029
Lubricate technician	36	0	0	0	174	347	557
Maintenance technician	23	40	1	8	32	26	130
Mining operator 1	101	39	45	15	167	14	381
Mining operator 2	8	92	113	29	255	15	512
Office staff	0	43	5	9	5	0	62
Operating technician	0	0	0	0	99	125	224
Pelletizing maintenance	17	28	27	8	90	91	261
Pelletizing operator	97	17	63	46	242	34	499
Pipefitter/Plumber	0	0	0	44	0	70	114
Rail road	0	0	0	0	121	0	121
Repairman	31	117	0	54	0	0	202
Supervisor	3	7	5	71	554	6	646
Warehouse technician	13	19	0	4	16	4	56
Total	631	1368	582	878	6166	1565	11190

Actual and predicted EMP counts for different EMP definitions

A key assumption in this study is that the bivariate lognormal distribution can well describe the overall EMP size distribution for each mine-SEG combination. To test this assumption, for each of the four non-ISO-TEM EMP definitions, we compared the actual and the predicted definition-specific EMP counts given the actual total ISO-TEM EMP counts for each mine-SEG combination. The bubble plots of this comparison is shown in Figure 4-4, where the size of a bubble represents the actual total ISO-TEM EMP count in that mine-SEG combination. For three of the four plots, we rescaled the x and y-axis for a clearer display (surrounded by red dashed line).

The bivariate lognormal distribution assumption works very well for the NIOSH EMP, the Suzuki EMP, and the Chatfield non-asbestiform EMP. The predicted values and the actual values are highly consistent. The Chatfield asbestiform EMP are much rarer in the taconite mines compared to the other three EMP types, and therefore, more difficult to fit the bivariate lognormal.

Most of the EMP identified by the ISO-TEM method belong neither to the traditional regulated NIOSH fibers (median 7% with IQR 4%-11%) or long Chatfield asbestiform EMP (median 3% with IQR 1%-5%). The data suggest that a majority of the EMP collected in the taconite mines belongs to the short Suzuki EMP and/or the Chatfield non-asbestiform EMP.

Figure 4-4 clearly shows one big advantage of using this probability method vs. the traditional actual count method. In this study, we learned the EMP size distribution based on the ISO-TEM results. But we did not stop at this “sample result” level. We further relied on a bivariate lognormal assumption to create a possible probability-density plot for the overall EMP population. This method, compared with the traditional actual count method, can greatly increase the power of the statistical inferences we made in this study. For example, (see Figure 4-4, NIOSH-EMP plot), actual EMP counts can only be 0 ,1, 2…integers, but probability based EMP counts can be any numbers, such as 0.1, 1.3, 3.5… This change will greatly reduce occurrence of the same conversion factors derived, which in the end, can greatly eliminate some man-made factors that cause high correlation between future EMP definition-specific JEMs.

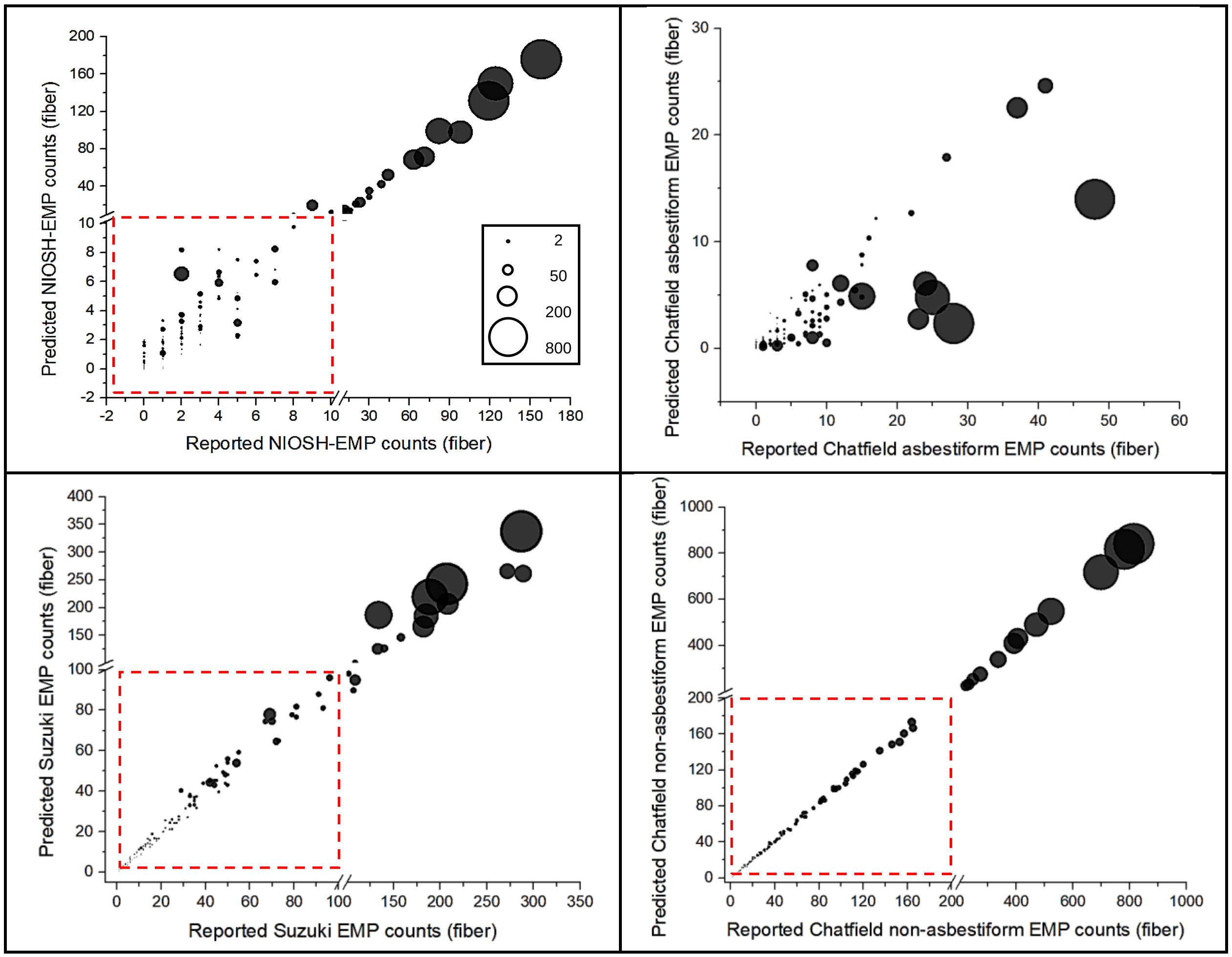

FIGURE 4-4 Actual and predicted definition-specific EMP counts given the total actual ISO-TEM EMP counts reported in each mine/SEG combination

Conversion factors from NIOSH 7400 to alternative EMP metrics

The ultimate goal of this study is to derive numerical conversion factors between various EMP definitions that will allow us to create alternative JEMs based on other EMP metrics from the existing NIOSH-EMP JEM for future epidemiologic analyses. Three tables (see Table 4-5, 4-6, 4-7) of conversion factors were derived for converting from the NIOSH EMP to Chatfield asbestiform EMP, the NIOSH EMP to Suzuki EMP, and the NIOSH EMP to Chatfield non-asbestiform, respectively.

In summary, the median [IQR] of the conversion factors to “Chatfield asbestiform EMP”, “Suzuki EMP”, and “Chatfield non-asbestiform EMP” from the “NIOSH EMP” were 0.22 [0.06-0.68], 7.29 [2.78-13.88], and 10.68 [6.2-20.0] respectively. The interception of these values is that if we can observe 100 NIOSH EMP under PCM on a filter, there will be, on average, around 22 Chatfield asbestiform EMP, 729 Suzuki EMP and 1068 Chatfield non-asbestiform EMP existing on that filter as well. From a EMP size probability standpoint, majority of taconite EMP are short Suzuki EMP and Chatfield non-asbestiform EMP (cleavage fragments). NIOSH EMP are rare among EMP overall population, and the long and thin Chatfield asbestiform EMP are even rarer than the NIOSH EMP in taconite mines. For these three tables, the within-table variation seems smaller than between-table variation. This means, for a rare EMP type, although the probability of observing this type of EMP may vary from location to location, the overall probability is still rare. This also indicates the natural correlation between the EMP of different types.

TABLE 4-5 The numerical conversion factors (NIOSH to Chatfield asbestiform)

Mine/SEG	ArcelorMittal	Hibbtac	Keetac	Minntac	Northshore	Utac
Auto mechanic	1.37	2.20	0.98	0.36	0.02	0.02
Balling drum operator	0.90	0.45	2.69	0.54	0.01	0.01
Basin operator	0.87	0.39	0.06	0.00	0.17	0.26
Boiler technician	0.87	0.39	0.06	0.06	0.17	0.05
Carpenter	0.87	0.73	0.26	0.03	0.17	0.17
Concentrator maintenance	0.11	2.44	1.45	0.29	0.26	0.15
Concentrator operator	0.03	2.90	1.34	0.19	0.05	0.01
Control room operator	0.88	0.15	0.06	1.19	0.15	0.02
Crusher maintenance	0.02	0.47	0.61	0.17	0.01	0.41
Crusher operator	0.35	0.07	0.24	0.17	0.02	0.03
Dock man	0.19	3.30	0.46	0.00	0.41	0.02
Electrician	0.17	0.27	5.45	0.35	0.03	0.08
Furnace operator	0.32	0.39	2.99	0.26	0.02	0.01
Lab analyst	5.28	1.05	0.43	0.07	0.08	0.01
Lubricate technician	1.61	0.39	0.06	0.07	0.01	0.00
Maintenance technician	0.71	0.51	0.06	11.99	0.01	0.01
Mining operator 1	2.80	0.67	0.44	0.19	0.00	0.25
Mining operator 2	0.72	0.52	0.23	0.10	0.01	0.02
Office staff	0.87	3.33	0.90	0.04	0.25	0.17
Operating technician	0.87	0.39	0.06	0.07	0.02	0.13
Pelletizing maintenance	1.58	0.80	0.21	0.67	0.13	0.30
Pelletizing operator	3.17	0.27	1.33	0.33	0.30	0.03
Pipefitter/Plumber	0.87	0.39	0.06	1.40	0.17	0.04
Rail road	0.87	0.39	0.06	0.07	0.03	0.17
Repairman	5.58	2.71	0.06	0.77	0.17	0.17
Supervisor	0.87	0.03	0.06	0.29	0.04	0.04
Warehouse technician	1.18	0.06	0.06	1.87	0.04	0.17

TABLE 4-6 The numerical conversion factors (NIOSH to Suzuki)

Mine/SEG	ArcelorMittal	Hibbtac	Keetac	Minntac	Northshore	Utac
Auto mechanic	29.30	25.50	5.69	4.73	0.64	0.64
Balling drum operator	33.22	7.84	11.06	11.27	3.61	3.61
Basin operator	12.34	7.64	25.04	1.35	4.65	2.76
Boiler technician	12.34	7.64	25.04	15.40	4.65	1.70
Carpenter	12.34	3.42	1.59	3.75	4.65	4.65
Concentrator maintenance	5.98	23.54	10.41	6.84	2.76	3.14
Concentrator operator	0.95	37.43	13.01	2.84	1.70	1.23
Control room operator	7.66	0.88	25.04	45.54	3.14	1.30
Crusher maintenance	0.65	10.31	13.68	2.05	1.23	6.26
Crusher operator	12.85	3.46	10.33	3.66	1.30	2.08
Dock man	4.01	8.41	7.92	3.41	6.26	4.10
Electrician	5.41	4.64	23.63	6.03	2.08	2.29
Furnace operator	41.12	7.64	26.41	6.11	4.10	1.15
Lab analyst	23.83	23.80	17.48	12.62	2.29	1.48
Lubricate technician	12.74	7.64	25.04	12.62	1.15	1.11
Maintenance technician	15.40	8.87	25.04	116.49	1.48	1.33
Mining operator 1	23.76	32.24	26.51	11.21	1.11	2.66
Mining operator 2	13.94	7.27	9.96	7.62	1.33	2.75
Office staff	12.34	25.28	2.58	14.32	2.66	4.65
Operating technician	12.34	7.64	25.04	12.62	2.75	2.41
Pelletizing maintenance	26.56	11.26	5.79	6.83	2.41	5.60
Pelletizing operator	30.36	7.31	9.52	16.44	5.60	1.37
Pipefitter/Plumber	12.34	7.64	25.04	28.48	4.65	1.69
Rail road	12.34	7.64	25.04	12.62	1.37	4.65
Repairman	31.12	24.92	25.04	18.28	4.65	4.65
Supervisor	12.34	16.52	6.68	16.83	1.69	0.32
Warehouse technician	21.34	7.83	25.04	5.47	0.32	4.65

TABLE 4-7 The numerical conversion factors (NIOSH to Chatfield non-asbestiform)

Mine/SEG	ArcelorMittal	Hibbtac	Keetac	Minntac	Northshore	Utac
Auto mechanic	36.76	30.95	7.33	7.34	3.04	3.04
Balling drum operator	46.03	10.47	10.28	15.51	8.87	8.87
Basin operator	17.11	12.47	35.74	4.19	8.85	5.66
Boiler technician	17.11	12.47	35.74	19.92	8.85	4.67
Carpenter	17.11	5.20	4.11	8.04	8.85	8.85
Concentrator maintenance	10.75	25.22	12.12	10.41	5.66	6.17
Concentrator operator	2.95	39.98	16.40	6.09	4.67	4.44
Control room operator	9.85	2.83	35.74	54.95	6.17	4.44
Crusher maintenance	2.71	14.01	18.36	5.59	4.44	9.35
Crusher operator	18.70	7.37	17.03	7.58	4.44	5.56
Dock man	7.27	7.06	10.57	7.90	9.35	9.73
Electrician	10.74	7.48	19.85	11.11	5.56	5.76
Furnace operator	57.20	12.47	25.85	8.57	9.73	3.84
Lab analyst	22.02	27.85	21.87	19.95	5.76	4.38
Lubricate technician	15.91	12.47	35.74	19.95	3.84	4.38
Maintenance technician	20.90	14.24	35.74	106.08	4.38	4.50
Mining operator 1	27.25	39.15	35.45	15.20	4.38	5.00
Mining operator 2	20.33	10.76	15.02	14.10	4.50	6.15
Office staff	17.11	25.27	7.17	18.43	5.00	8.85
Operating technician	17.11	12.47	35.74	19.95	6.15	5.39
Pelletizing maintenance	31.43	14.35	9.22	12.17	5.39	10.66
Pelletizing operator	34.31	10.62	10.69	22.73	10.66	3.92
Pipefitter/Plumber	17.11	12.47	35.74	33.12	8.85	5.12
Rail road	17.11	12.47	35.74	19.95	3.92	8.85
Repairman	27.76	25.96	35.74	24.50	8.85	8.85
Supervisor	17.11	24.80	13.29	22.55	5.12	2.28
Warehouse technician	28.76	13.27	35.74	7.62	2.28	8.85

Improvements from the previous study

One motivation of conducing this study was to improve the former conversion factors conducted by Hwang *et al.*in 2014. This previous study, subject to some historical limitations, have several drawbacks: (1) small EMP samples: only 2791 single EMP size information was obtained from the ISO-TEM analysis for 92 area samples; (2) not probability-based method: previous conversion factors were derived based on actual sample results, and many locations had zero EMP count. As a result, conversion factors themselves were not as diverse as they should had been; (3) high correlation between the prototype 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.

In this study, we addressed the above limitations by developing a probability-based Bayesian approach. It created probability density plots for each of all study locations based on a bivariate lognormal distribution for overall EMP population and 11190 personal EMP and 2791 area EMP. The new conversion factors varied by location, reducing some man-made correlations. The new created definition-specific JEMs based on the conversion factors of this study are mildly correlated (0.4 – 0.6), 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 area-sample based EMP size information from a previous study to develop priors and EMP dimensional information from personal measurements to update the priors. This method provides more robust estimates compared to both the prior estimates and the 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 non-malignant respiratory disease.

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Chapter 5 :

Mesothelioma Risks and Dimension-based Elongate Mineral Particle (EMP) Definitions in Minnesota Taconite Mining Industry: An update of the Minnesota Mesothelioma Case-Control Study

OUTLINE

Objectives: An excess of mesothelioma has been observed in iron ore miners in Northeastern Minnesota. Mining and processing of taconite iron ore generate exposures that include elongate mineral particles (EMP). As an update of the previous Minnesota mesothelioma study that evaluated the association between mesothelioma, employment and EMP exposures from taconite mining, the goal of this study is to conduct a preliminary evaluation of the association between mesothelioma and EMP of multiple types and latest EMP job-exposure matrices and an updated study population.

Methods: As of 2015, mesothelioma cases (N=104) were identified through the Minnesota Cancer Surveillance System (MCSS) and death certificates. Four controls of similar age were selected for each case with 410 controls ultimately eligible for inclusion. Mesothelioma risk specified by EMP definition was evaluated by estimating rate ratios and 95% CIs with conditional logistic regression in relation to duration of taconite industry employment and definition-specified cumulative EMP exposure [(EMP/cc)×years]. Four EMP definitions with different size inclusion criteria were used in this study (NIOSH EMP: Width≥0.25μm, Length>5μm, W/L≥3; Chatfield asbestiform EMP: 0.04 μm ≤W≤1.5 μm, 20≤W/L≤1000; c. Suzuki EMP: W≤0.25 μm, L≤5 μm; d. Chatfield non-asbestiform EMP: W/L<20). Models were adjusted for employment in hematite mining and potential exposure to commercial asbestos products used in the industry.

Results: All mesothelioma cases were male and 72 of the cases had work experience in the taconite industry. Mesothelioma was weakly associated with the number of years

employed in the taconite industry (RR = 1.02, 95% CI 1.00 to 1.05). A positive mesothelioma association was consistently observed with cumulative exposure to Suzuki EMP and Chatfield non-asbestiform EMP in models with no latency, a 20-year latency, and a 30-year latency as well as models adjusting for the cumulative NIOSH EMP exposure. These was a weak association between mesothelioma and cumulative NIOSH EMP exposure in taconite mining and processing (RR = 1.11, 95% CI 0.99 to 1.22).

Conclusions: This study confirms the main conclusions in the previous study: there was an association between mesothelioma and employment duration and possibly NIOSH EMP exposure in taconite mining and processing. This study further found an association between mesothelioma and cumulative exposure to Suzuki EMP and Cleavage fragments in Minnesota taconite worker population. The risk of exposure to long and thin fibers was not clear yet given the small samples of such fibers in our study. These associations will require further review of methods to characterize EMP exposures.

INTRODUCTION

Iron ore mining on the Mesabi Iron Range in Minnesota has produced a substantial portion of the iron for the US steel industry for more than a century. High grade iron ore, hematite, was depleted in the middle of the 20th Century and the industry moved toward mining and processing a lower grade ore, taconite, to be shipped to US steel mills. Potential health concerns related to taconite mining and processing date to the 1970s. (Berndt and Brice, 2008). To address these concerns, and particularly concerns about mesothelioma risk, a large study of the industry, the Taconite Worker Health Study (TWHS), was initiated in 2008 funded by the state of Minnesota. This study explored the association between the mesothelioma risks and working in the taconite industry and occupational exposures to the elongate mineral particles (EMP). The original study results were published in 2016 (Lambert *et al.*, 2016) and shown that mesothelioma was associated with the number of years employed in the taconite industry (RR=1.03, 95% CI 1.00 to 1.06) and cumulative elongate mineral particle (EMP) exposure (RR=1.10, 95% CI 0.97 to –1.24). The EMP in this study was defined by the National Institute for Occupational Safety and Health (NIOSH) EMP 7400 counting rules that only counted long fibers (length >5 μm, length/width ratio≥3) (hereafter referred as "NIOSH EMP"). After the 2016 study, the team, in the past few years, continued to improve study quality through multiple updates, and new research questions, such as whether EMP of other dimensions have the same potency as the NIOSH EMP in causing the mesothelioma, or how the dimensions of EMP are related to mesothelioma development in taconite mining worker population, would like to be answered this time.

In the literature, the question of how the dimensions of the EMP are related to carcinogenic lung disease development has been controversial. Stanton et al. (1981) hypothesized that carcinogenicity of EMP is related to dimension and durability and less with mineral type and ascribed carcinogenicity to EMP with a length > 8 μm and a diameter < 0.25 μm. Subsequently, Lippmann (1988) suggested that lung cancer was associated with associated with asbestos EMP longer than 10 μm with a diameter > 0.15 μm, while mesothelioma was associated with asbestos EMP longer than 5 μm with a diameter < 0.1μm. A series analyses by Berman et al. (1995, 2003, 2008) consistently suggested that it is likely that length categories with minimum cut points substantially longer than 10 μm contribute most heavily to both asbestos-induced lung cancer and mesothelioma. Loomis et al. (2010, 2012) also found that the occurrence of lung cancer is associated most strongly with exposure to long thin asbestos fibers (5-10 μm long and <0.25 μm in diameter) in workers at asbestos textile mills in North Carolina and South Carolina, USA. Chatfield (2008) suggested that thin (0.04 μm ≤width≤0.25 μm) and long (20≤aspect ratio≤1000) EMP are more dangerous. A panel of experts convened by ATSDR (Eastern Research Group, 2003) concluded that there is a weight of evidence that asbestos and synthetic vitreous fibers (SVFs) shorter than 5 μm are unlikely to cause cancer in humans.

Other researchers however have argued against ruling out the effect of short fibers. Dodson et al. (2003) concluded that asbestos EMP of all lengths induce pathological responses and cautioned against ignoring EMP < 5 μm since they constituted the bulk of EMP exposures. Suzuki et al. (2005) concluded that short (≤5 μm), thin EMP (≤0.25 μm) were more strongly associated with malignant mesothelioma through analysis of lung and mesothelial tissues in human patients. Dement et al. (2008) showed using a TEM analysis of chrysotile fibers that all combinations of lengths and widths (lengths ranging from <1.5 μm to > 40 μm and widths ranging from 0.25 - 3.0 μm 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 EMP > 5 μm in length, shorter EMP are not counted, but may contribute substantially to work exposure (Dement *et al.*, 1983). Pott (1987) proposed that for natural fibers and manmade mineral fibers (MMMF), EMP >3 μm in length, <1 μm in width, and >5:1 aspect ratio were carcinogenic.

To answer the above question as well as to update the previous findings, we have been improving the previous case-control study through multiple updates: (1) 24 additional cases were identified by the Minnesota Cancer Surveillance System (MCSS) from 2010 to 2015; (2) Historical EMP exposures were reconstructed using multiple methods; (3) multiple EMP job-exposure matrices (JEMs) based on different EMP definitions were created.

In this analysis we present a preliminary evaluation of the updated study population and some newly-developed exposure estimations how the dimensions of EMP are related to the mesothelioma development in Minnesota taconite worker population, and provide some new evidence to the “long fiber vs. short fiber” debate mentioned above.

METHODS

Study design and population

We conducted a nested case-control study of mesothelioma in a cohort of iron mining workers. The study cohort is a subset of the overall Minnesota iron worker cohort - Mineral Resources Health Assessment Program (MRHAP). This MRHAP cohort was enumerated by the University of Minnesota in 1983 with the support of the Iron Range Resources and Rehabilitation Board (IRRRB) and the cooperation of the seven mining companies then in operation, and included 68737 individuals identified in employee records from the mining industry in northeastern Minnesota between the 1930s and the end of 1982. It includes workers who were employed in both the hematite and taconite industry. The MRHAP cohort was followed for vital status through 2010 and causes of death were obtained through 2007. Vital status was ascertained using the Social Security Administration, the National Death Index, and the Minnesota Department of Health and state death certificates outside of Minnesota. All deaths were coded to the International Classification of Disease (ICD) codes in effect at the time of death. The new study is an expansion of the 2015 study by adding new 24 cases.

Selection of cases and controls

Cases of mesothelioma were identified through the Minnesota Cancer Surveillance System (MCSS) and/or death certificates for out of state cases. In addition to the original 80 mesothelioma cases, 24 additional cases were identified (23 through MCSS and one outside of Minnesota). Mesothelioma in MCSS was coded using ICD-O-3 histology codes 9050–9053 and death certificates had ICD 10^{th} Revision code C45. Four controls four controls were selected for each case using an incidence density sampling approach. For each case, controls were selected from risk sets of cohort members of similar age (years of birth±2 years) and who were alive and without a diagnosis of mesothelioma on the date of diagnosis or death of the case. All cases and controls were nested within the MRHAP cohort, and had to have clear evidence of employment in the mining industry, based on review of individual work history records. Finally, the new study population is constituted of 104 cases and 410 controls.

Exposure assessment

The detailed exposure assessment for taconite mining workers can be found elsewhere (Hwang *et al.*, 2013). In brief, there were seven taconite mines that are associated with this study: ArcelorMittal, Hibbtac, Keetac, Minntac and Utac in Zone 1, LTV in Zone 2 and Northshore in Zone 4 of the Mesabi Iron Range. As of 2010, when the comprehensive onsite investigation was conducted by the TWHS study, six of these seven mines were still in operation and LTV mine was closed in 2001. The mining process for each mine was similar, but workers with different tasks may experience different exposure situations. Hwang *et al.* (2013) grouped all taconite worker job titles into 28 similar exposure groups (SEG) within eight departments: Mining [Basin operator, Mining operator 1, Mining operator 2, Rail road] Crushing [Crusher maintenance, Crusher operator, Operating technician], Concentrating [Concentrator maintenance, Concentrator operator], Pelletizing [Balling drum operator, Dock man, Furnace operator, Pelletizing maintenance, Pelletizing operator], Shop (mobile) [Boiler technician, Carpenter, Electrician, Lubricate technician, Maintenance technician, Pipefitter/Plumber, Repairman, Supervisor], Shop (stationary) [Auto mechanic, Lab analyst, Warehouse technician] Janitor [Janitor] and Office/control room [Control room operator, Office staff]. The onsite exposure monitoring was conducted from January 2010 to May 2011 for nearly all SEGs (except Janitor) of all six active mines. 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 averaged sampling time was 6 hours, and EMP 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. Finally, 1185 present-day personal EMP samples were collected and analyzed using the NIOSH 7400 PCM method.

Historical NIOSH-7400 EMP personal exposure data were extracted from two sources (See Chapter 3): (1) the Mine Safety and Health Administration (MSHA) online database records for all inspection results since 1978 with 655 EMP monitoring records from 1978 to 2010 under 13 MSHA Mine IDs associated with this study; and (2) the mining companies' internal monitoring reports contain 96 personal EMP exposure records with the earliest record in 1983. In total, there were 751 historical EMP personal samples.

The detailed historical EMP reconstruction process based on above present-day and historical EMP measurements were described in detail elsewhere (Lambert et al. 2015, Chapter 3). In brief, historical NIOSH EMP exposures were reconstructed using three different reconstruction strategies.

The first reconstruction strategy (hereafter referred as "Strategy1") was the one used in the 2016 paper. All historical and present-day NIOSH 7400 personal EMP sample data were grouped by mine, and within each mine, a categorical variable was created to further assign these data into 28 SEGs. All data were log-transformed for subsequent modelling. For each mine, an intercept-varying regression model was used to fit these time-series data in estimating the mean exposure level at each year point over the entire mine history for each of all 28 SEGs. Different SEGs within the same mine shared the same regression slope but a different intercept. After this modeling, model outputs – geometric mean exposure values (GMs) were used to form a NIOSH EMP job-exposure matrix (JEM) for epidemiological studies.

The second strategy (hereafter referred as “Strategy2”) was a variation of the first strategy. All the monitoring data this time was grouped at department level. We hope, by doing this aggregation/ reducing the location number, more data would be available at each location for prediction and more precise prediction can be made for the study. But we also understand this aggregation to the department level may generate more exposure misclassification compared to Stategy1. Similar to Stategy1, all data were log-transformed first and was applied to an intercept-varying regression model in each mine-department combination. The model outputs – GMs were, in this strategy, converted to their corresponding arithmetic means (AMs) as AMs were suggested(Seixas, Robins and Moulton, 1988; Rappaport, 1991; Crump, 1998) to be a better metric for in creating a job-exposure matrix (JEM) for future health studies. We formed the second NIOSH EMP JEM using these AMs.

The third strategy (hereafter referred as “Strategy3”) did not use any of the historical monitoring data, but instead used the time-trend information from the historical dust reconstruction work in Chapter 2. This strategy assumed that dust exposures and EMP exposures in the same mine-department combination are correlated with each other and shared the same time-trend. The advantage of this assumption is that time-trend slopes from the dust study are very accurate given the large number of dust measurements (19,408 respirable dust (RD) measurements and 9,128 respirable silica (RS) measurements) used for modelling, and reflected the overall exposure changes over time in the taconite mining industry. The reconstruction model was conducted in the natural logarithmic scale. The modelling procedure is as follows: (1) For each mine-department combination, the mean exposure level at Year 2010 was given by the log of the geometric mean all present-day measurements of this location; (2) the mean exposure level in other year points was calculated based on Year 2010 value and the slope value; (3) the variance around the mean exposure in each year was fixed over the entire time period, and was given by the variance of all present-day measurements of this location. Similar to the second strategy, the model outputs – GMs were converted to their corresponding AMs, we formed the third NIOSH EMP JEM using these AMs.

The next step was to create JEMs based on alternative EMP definitions from the NIOSH EMP JEMs using the conversion factors (CFs) derived in another study (Chapter 3). Table 5-1 listed the EMP definitions of our interest. These selected definitions, to some extent, can be very representative: (1) the NIOSH EMP, defined by NIOSH, is by far the most frequent exposure metric used in exposure assessment and health studies; (2) the Chatfield asbestiform EMP refers to long and thin fibers; (3) the Suzuki EMP refers to short fibers; (4) the Chatfield non-asbestiform EMP (referred to as cleavage fragments in Hwang et al., 2014) are created by the 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).

TABLE 5-1 Selected EMP definitions

#	EMP definitions	Width (µm)	Length (µm)	Aspect Ratio (AR)
1	NIOSH EMP (1994)	NA	>5	≥3
2	Chatfield asbestiform EMP (2008)	0.04-1.5	NA	20-1000
3	Suzuki EMP (2005)	≤0.25	≤5	NA
4	Chatfield non-asbestiform EMP (2008)/ Cleavage fragments	NA	NA	<20

The entire CF derivation process can be briefly summarized as five steps: (1) Obtain single EMP dimension information using ISO-TEM analysis (identifies EMP with width >0.01 µm, length > 0.3 µm, aspect ratio ≥ 3.0); (2) Use bivariate lognormal distribution to characterize overall EMP size distribution; (3) Use Bayesian approach to facilitate the formation of the bivariate lognormal distribution; (4) apply each of EMP definitions to the overall distribution plot; (5) Deriving conversion factors between any two EMP definitions. After these five steps, for each mine-department, we got three CFs ('NIOSH EMP' to 'Chatfield asbestiform EMP', 'NIOSH EMP' to 'Suzuki EMP' and 'NIOSH EMP' to 'Chatfield non-asbestiform EMP').

In summary, we first created three NIOSH-EMP JEMs using three different reconstruction strategies ('Strategy1', 'Strategy2' and 'Strategy3'). For each NIOSH-EMP JEM, we then used the CFs to create three additional JEMs (one 'Chatfield asbestiform EMP' JEM, one 'Suzuki EMP' JEM and one 'Chatfield non-asbestiform EMP'). A total of 12 different EMP JEMs were created this time.

Work history and cumulative EMP exposure calculation

Work history information for cases and controls, including all job titles and dates, was abstracted from available mining company work records through the end of 1982, the time the MRHAP cohort was enumerated. All job titles were standardized into 28 SEGs of 8 departments. Some study subjects worked in the earlier hematite industry. Hematite as a "direct shipping ore" does not require the processing and concentrating techniques of taconite and does not have the same EMP exposures. Therefore, hematite and taconite work histories were separated. The exposure value for the hematite SEG was set as zero as no data were available on exposures within hematite operations. For each study subject, we estimated his cumulative exposure values based on each of the 12 JEMs developed. These values include: three cumulative 'NIOSH EMP' exposures ('Strategy1', 'Strategy2', 'Strategy3'), three cumulative "Chatfield asbestiform EMP" exposures ('Strategy1', 'Strategy2', 'Strategy3'), three cumulative "Suzuki EMP" exposures ('Strategy1', 'Strategy2', 'Strategy3') and three cumulative "Chatfield non-asbestiform EMP" exposures ('Strategy1', 'Strategy2', 'Strategy3'). A cumulative exposure was calculated as the sum of the products of time/location-specific exposure concentrations and the time each individual spent in each exposure category. The unit of cumulative exposure is (EMP/cc)×years, which reflects both the duration and the intensity of exposure. Commercial asbestos was likely used in the processing operations buildings as well as in some of the processes and was an important potential confounder. No quantitative data exist on commercial asbestos exposure in these operations so a qualitative scale was established to estimate exposures by job title. The study team and taconite company industrial hygienists estimated the probability and frequency of exposure to commercial asbestos within each SEG, and assigned a commercial asbestos score of low, medium or high based on these estimates. Several metrics were evaluated, and the number of years worked in an SEG with a high commercial asbestos score was ultimately used as a metric to control for the potential effects of asbestos exposure.

Analysis

Descriptive analyses compared cases and controls by demographic and occupational factors. The effect of employment duration in taconite mining and each of the multiple (EMP/cc)× years exposure metrics on mesothelioma risk was estimated using conditional logistic regression to account for the person-time matching of cases and controls within risk sets. Risk estimates were expressed as estimated rate ratios and 95% CIs. In addition to the main effect variables, final models included terms for the number of years employed in hematite mining and number of years spent working in SEGs with a high commercial asbestos score. Employment and (EMP/cc)× years models were run without lag, with a 20-year lag and with a 30-year lag. All analyses were conducted with SAS V.9.4.

RESULTS

Characteristics of cases and controls

A total of 104 cases and 410 controls were included in the study (Table 5-2). All cases and 94% of controls were males. Compared to the control population, higher percentage in the case population were taconite related workers. The duration of hematite employment was similar for cases and controls, but cases had a longer mean taconite-years. The cumulative exposure values of all kind for cases were almost always higher than the values for controls. The cumulative exposure values based on Strategy1 were similar those based on Strategy3. Strategy2 tends to provide higher exposure values for both cases and controls compared with other two versions. Mean years spent in SEGs with a high commercial asbestos score were greater for cases.

TABLE 5-2 Characteristics of all cases and controls in study population, and cases and controls who worked in taconite

All workers	**Cases N (%)**	**Controls N (%)**
Total	104	410
Female	0 (0.0)	23 (5.6)
Male	104 (100.0)	387 (94.4)
Type of ore mining		
Hematite only	33 (31.7)	174 (42.4)
Hematite and Taconite	28 (27.0)	96 (23.4)
Taconite only	43 (41.3)	140 (34.2)
Years of employment (years)†	**Mean (Min, Max)**	**Mean (Min, Max)**
Taconite employment	7.1 (0.0, 27.6)	5.2 (0.0, 36.3)
Hematite employment	2.6 (0.0, 27.7)	2.7 (0.0, 27.7)
Total employment	9.7 (0.0, 35.2)	7.9 (0.0, 37.3)
Taconite workers	**Cases N (%)**	**Controls N (%)**
Total	71	236
Female	0 (0.0)	12 (5.0)
Male	71 (100.0)	224 (95.0)
Geological zone-ever worked*		
Zone 1	24 (32.0)	93 (37.5)
Zone 2	37 (49.3)	69 (27.8)
Zone 4	14 (18.7)	86 (34.7)
Years of employment (years)	**Mean (Min, Max)**	**Mean (Min, Max)**
Taconite employment	10.4 (0.0, 27.6)	9.0 (0.0, 36.3)
Hematite employment	2.8 (0.0, 22.3)	3.4 (0.0, 27.7)
Total employment	13.2 (0.0, 35.2)	12.3 (0.0, 37.3)
Employment by geological zone		
Zone 1	3.3 (0, 17.2)	3.0 (0, 17.5)
Zone 2	5.1 (0, 26.0)	2.4 (0, 26.0)
Zone 4	2.0 (0, 27.6)	3.6 (0, 36.3)
Cumulative exposure (EMP/cc) ×years_Strategy1	**Mean (Min, Max)**	**Mean (Min, Max)**
NIOSH 7400 EMP	2.1 (0.0, 8.3)	1.6 (0.0, 11.3)

Chatfield asbestiform EMP	1.1 (0.0, 11.4)	0.7 (0, 13.4)
Suzuki EMP	19.4 (0.0, 148.3)	12.3 (0.0, 169.7)
Chatfield non-asbestiform EMP	27.4 (0.0, 166.3)	18.1 (0.0, 187.2)
NIOSH 7400 (EMP/cc) ×years_Strategy1 by geological zone		
Zone 1	0.4 (0, 5.3)	0.1 (0, 4.2)
Zone 2	1.2 (0, 7.4)	0.5 (0, 6.9)
Zone 4	0.5 (0, 8.3)	1.0 (0, 11.3)
Cumulative exposure (EMP/cc) ×years_Strategy2	**Mean (Min, Max)**	**Mean (Min, Max)**
NIOSH 7400 EMP	10.7 (0.0, 62.1)	8.9 (0.0, 79.1)
Chatfield asbestiform EMP	4.4 (0.0, 38.6)	3.5 (0, 82.3)
Suzuki EMP	110.3 (0.0, 933.2)	88.8 (0.0, 1966.8)
Chatfield non-asbestiform EMP	161.0 (0.0, 1331.9)	133.0 (0.0, 2504.1)
NIOSH 7400 (EMP/cc) ×years_Strategy2 by geological zone		
Zone 1	3.7 (0, 62.1)	3.0 (0, 17.5)
Zone 2	5.2 (0, 27.8)	2.4 (0, 26.0)
Zone 4	1.8 (0, 25.6)	3.6 (0, 36.3)
Cumulative exposure (EMP/cc) ×years_Strategy3	**Mean (Min, Max)**	**Mean (Min, Max)**
NIOSH 7400 EMP	1.1 (0, 4.7)	0.9 (0, 5.4)
Chatfield asbestiform EMP	0.9 (0, 16.8)	0.9 (0, 32.1)
Suzuki EMP	15.9 (0, 163.2)	14.1 (0, 311.9)
Chatfield non-asbestiform EMP	20.5 (0, 148.6)	17.5 (0, 284.2)
NIOSH 7400 (EMP/cc) ×years_Strategy3 by geological zone		
Zone 1	0.3 (0, 2.9)	0.3 (0, 2.7)
Zone 2	0.6 (0, 4.7)	0.2 (0, 4.8)
Zone 4	0.2 (0, 4.7)	0.4 (0, 5.4)
Employment in SEGs with high commercial asbestos **(years)	1.2 (0, 16.4)	0.6 (0, 22.0)

†Employment records were only available till the end of 1982.
*Cases and controls may have worked in multiple zones.
**SEGs with a high asbestos score are crusher maintenance, furnace operator, electrician, carpenter, auto mechanic, pipefitter/plumber, and lubricate technician.

Taconite employment duration

Table 5-3 showed that the risk of mesothelioma was associated with the number of years of employment in the taconite mining industry (RR = 1.02, 95% CI 1.00 to 1.05). This is consistent with what we found previously. Model dividing workers into categories based on the median and tertiles of length of employment of cases, suggested an association between employment length in taconite mines and mesothelioma risk. All risk estimates were adjusted for age and years of employment in hematite operations. The zone-specific risk estimates were also consistent with the previous study. The mesothelioma risk was increased with duration of employment in both Zone 1 and Zone 2, but not associated with duration of employment in Zone 4.

TABLE 5-3 Overall and zone specific rate ratio estimates for mesothelioma by years of employment in taconite

	Cases	Controls	Rate Ratio†	95% CI
Taconite years*	104	410	1.02	1.00 to 1.05
Hematite years**	104	410	0.99	0.94 to 1.04
High vs. Low taconite employment‡				
< 7.70 and >0 year	36	128	1	
≥ 7.70 years	35	108	1.04	0.58 to 1.86
0 year (hematite-only workers)	33	174	0.62	0.35 to 1.11
Taconite years employment tertiles§				
< 3.90 years	24	100	1	
≥ 3.90 to <13.39 years	23	65	1.56	0.78 to 3.13
≥13.39 years	24	71	1.24	0.63 to 2.46
0 year (hematite-only workers)	33	174	0.73	0.39 to 1.36
Exposure by geological zone***				
Zone 1 taconite years	104	410	1.05	0.99 to 1.11
Zone 2 taconite years	104	410	1.05	1.02 to 1.08
Zone 4 taconite years	104	410	0.98	0.94 to 1.02

†adjusted for age, employment in hematite, and potential for commercial asbestos exposure.
* include entire study population, taconite-year equals to 0 for the hematite only workers.
** include entire study population, hematite-year equals to 0 for the taconite only workers.
‡High group represents workers with employment duration greater than the taconite case median duration.
§Based on the lower, middle and upper third of the taconite case employment duration distribution.
***include entire study population, zone-specific year equals to 0 for those who never worked in this zone.

(EMP/CC)×years of exposure

Three versions of cumulative NIOSH EMP exposure values were calculated, and the mesothelioma risks under each of these three versions were estimated respectively (Table 5-4). One unit increase in cumulative NIOSH EMP exposure values, regardless of which EMP reconstruction method used, were weakly associated with the risk of mesothelioma (‘Strategy1’: RR=1.10, 95% CI 0.99 to 1.22; ‘Strategy2’: RR=1.01, 95% CI 1.00 to 1.03; ‘Strategy3’: RR=1.20, 95% CI 0.99 to 1.46). Model dividing workers into categories based on the median and tertiles of cumulative exposure values of cases, suggested an association between cumulative NIOSH EMP exposure and mesothelioma risk, still regardless of which exposure reconstruction method used. Mesothelioma risk among the workers in the highest exposure category were higher than those in the lowest exposure categories. All risk estimates were adjusted for age and years of employment in hematite operations. The Zone-specific risks were in the same fashion with what we found in above *Taconite employment duration* section. Workers in Zone 2 shows a very strong exposure-response association for all three EMP reconstruction methods, but we did not found this association in Zone 4. Zone 1’s results varied depending on which EMP reconstruction method used. Results based on ‘Strategy1’ and ‘Strategy3’ exposure estimations showed a significant positive association (‘Strategy1’: RR=1.87, 95% CI 1.20 to 2.93; ‘Strategy3’: RR=1.77, 95% CI 1.04 to 3.03), but results got attenuated after we switched to use ‘Strategy2’ exposure estimations. As mentioned in the method section, ‘Strategy2’ and ‘Strategy1’ were very similar in the mathematical models they used, their main difference were how the raw data aggregated. By aggregated data from a SEG level to a higher department level, the prediction accuracy may increase, but we in the same time may introduced more misclassification in exposure into the epidemiological analysis as well. These introduced misclassifications caused the attenuation in the final risk estimates.

TABLE 5-4 Mesothelioma risk estimates for cumulative EMP* exposure as a continuous, categorical and geological zone specific

Cumulative NIOSH EMP exposure_Strategy1	**Cases**	**Controls**	**Rate Ratio†**	**95% CI**
1 unit increase in (EMP/cc)×year*	104	410	1.10	0.99 to 1.22
High vs. Low‡				
Low:>0 to < 1.1 (EMP/cc) ×years	35	160	1	
High:≥ 1.1 (EMP/cc) ×years	36	76	2.10	1.13 to 3.87
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.85	0.48 to 1.53
Cumulative exposure tertiles§				
Low:>0 to < 0.3 (EMP/cc) ×years	23	118	1	
Medium: ≥0.3 to <2.1 (EMP/cc) ×years	24	58	2.07	1.07 to 4.00
High: ≥2.1 (EMP/cc) ×years	24	60	1.78	0.86 to 3.69
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.92	0.48 to 1.75
Exposure by geological zone**				
Zone 1 (EMP/cc)×years	104	410	1.87	1.20 to 2.93
Zone 2 (EMP/cc)×years	104	410	1.30	1.12 to 1.50
Zone 4 (EMP/cc)×years	104	410	0.95	0.80 to 1.11
Cumulative NIOSH EMP exposure_Strategy2	**Cases**	**Controls**	**Rate Ratio†**	**95% CI**
1 unit increase in (EMP/cc)×year	104	410	1.01	1.00 to 1.03
High vs. Low				
Low:>0 to < 4.3 (EMP/cc) ×years	35	140	1	
High:≥ 4.3 (EMP/cc) ×years	36	96	1.37	0.77 to 2.42
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.72	0.40 to 1.29
Cumulative exposure tertiles				
Low:>0 to < 1.3 (EMP/cc) ×years	24	114	1	
Medium: ≥1.3 to <17.0 (EMP/cc) ×years	23	65	1.68	0.85 to 3.31
High: ≥17.0 (EMP/cc) ×years	24	57	1.75	0.88 to 3.51
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.87	0.46 to 1.64
Exposure by geological zone				

Zone 1 (EMP/cc)×years	104	410	1.01	0.98 to 1.03
Zone 2 (EMP/cc)×years	104	410	1.06	1.02 to 1.09
Zone 4 (EMP/cc)×years	104	410	0.97	0.93 to 1.02
Cumulative NIOSH EMP exposure_Strategy3	**Cases**	**Controls**	**Rate Ratio†**	**95% CI**
1 unit increase in (EMP/cc)×year	104	410	1.20	0.99 to 1.46
High vs. Low				
Low:>0 to < 0.8 (EMP/cc) ×years	36	148	1	
High:≥ 0.8 (EMP/cc) ×years	35	88	1.51	0.85 to 2.69
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.73	0.41 to 1.29
Cumulative exposure tertiles				
Low:>0 to < 0.3 (EMP/cc) ×years	23	109	1	
Medium: ≥0.3 to <2.1 (EMP/cc) ×years	24	65	1.76	0.91 to 3.42
High: ≥2.1 (EMP/cc) ×years	24	62	1.66	0.83 to 3.32
Hematite-only workers: 0 (EMP/cc) ×years	33	174	0.84	0.45 to 1.56
Exposure by geological zone				
Zone 1 (EMP/cc)×years	104	410	1.77	1.04 to 3.03
Zone 2 (EMP/cc)×years	104	410	1.52	1.15 to 1.99
Zone 4 (EMP/cc)×years	104	410	0.85	0.61 to 1.20

†adjusted for age, employment in hematite, and potential for commercial asbestos exposure.
* include entire study population, the cumulative EMP exposure equals to 0 for the hematite only workers.
‡High group represents workers with cumulative exposure greater than the case median exposure.
§Based on the lower, middle and upper third of the case exposure distribution.
**include entire study population, zone-specific cumulative EMP exposure equals to 0 for those who never worked in this zone.

Different EMP definitions

For each EMP reconstruction method, we developed 4 different JEMs based on different EMP definitions. We evaluated the mesothelioma risk under each of these definitions to determine which definition or which size range of EMP has the strongest association with the mesothelioma in our taconite worker population. Although the results varied a little bit by EMP reconstruction method used, Table 5-5 shown that cumulative exposures to the Suzuki EMP and the Chatfield non-asbestiform EMP were significantly associated with mesothelioma in the Minnesota taconite worker population. Cumulative exposures to the NIOSH EMP and the Chatfield asbestiform EMP were not significantly associated with the risk of mesothelioma. This findings, for the first time, provided some evidences to support the ideas that the ‘short fibers’, ‘non-asbestiform’ EMP and Cleavage fragments created by taconite mining process, may contribute to the development of the mesothelioma found among taconite worker population in Minnesota. Traditionally, these fibers, compared to the long and thin fibers, have not been regulated and have been thought to be safe.

TABLE 5-5 The mesothelioma risk estimates under different EMP definitions

Cumulative exposure	Exposure model	Rate Ratio	95% CI
NIOSH EMP	Strategy 1	1.099	0.988 to 1.223
	Strategy 2	1.014	0.995 to 1.032
	Strategy 3	1.199	0.985 to 1.459
Chatfield asbestiform EMP	Strategy 1	1.089	0.976 to 1.216
	Strategy 2	1.013	0.988 to 1.039
	Strategy 3	1.016	0.939 to 1.099
Suzuki EMP	Strategy 1	**1.009**	**1.001 to 1.017**
	Strategy 2	**1.001**	**1.000 to 1.002**
	Strategy 3	1.004	0.996 to 1.011
Chatfield non-asbestiform	Strategy 1	**1.008**	**1.001 to 1.015**
	Strategy 2	**1.001**	**1.000 to 1.001**
	Strategy 3	**1.005**	**0.998 to 1.012**

All adjusted for age, hematite years, commercial asbestos.
Single EMP exposure term was used in each model

Model with two cumulative EMP exposure terms

To further verify what we found above regarding the risk of Suzuki EMP and the Cleavage fragments, in this section, we would like to estimate their risks after adjusting for the NIOSH EMP. We were aware of mild correlations between the NIOSH EMP and either of these two EMP among study population (Pearson Correlation Coefficients (R) between cumulative exposure to NIOSH EMP and cumulative exposure to Suzuki EMP was 0.46, R =0.6 between NIOSH EMP and Chatfield non-asbestiform EMP). The results (Table 5-6) strength our above findings that the risk of mesothelioma was significantly associated with the cumulative exposure to Suzuki EMP as well as the cumulative exposure to Chatfield non-asbestiform EMP after adjust for cumulative exposure to NIOSH EMP.

TABLE 5-6 The mesothelioma risk estimates after including two (EMP/cc)×years exposure metrics

Primary exposure	Adjusted for	Rate Ratio
NIOSH EMP	Chatfield asbestiform EMP	1.074 (0.947, 1.219)
NIOSH EMP	Suzuki EMP	1.038 (0.901, 1.196)
NIOSH EMP	Chatfield non-asbestiform	1.002 (0.845, 1.189)
Chatfield asbestiform EMP	NIOSH EMP	1.048 (0.920, 1.193)
Suzuki EMP	NIOSH EMP	1.007 (0.996, 1.018)
Chatfield non-asbestiform	NIOSH EMP	1.008 (0.997, 1.019)

All further adjusted for age, hematite years and commercial asbestos.

Lagged model

Besides models without lag, we also ran the models with a 20-year lagged exposure and a 30-year lagged exposure. Similar to what we found in the regular model, both lagged models found that the risk of mesothelioma was associated with the cumulative exposure to Suzuki EMP as well as the cumulative exposure to Chatfield non-asbestiform EMP. However, the risk of mesothelioma was no longer associated with the number of years of employment in the taconite mining industry in these lag models. It's also worth noting that cumulative exposure to Chatfield asbestiform EMP in the 30-year lag model was also associated with the risk of mesothelioma. We did not see this association in the regular models. In Minnesota taconite mines, as shown in Table 5-2, long and thin fibers such as Chatfield asbestiform EMP were very rare. Their small numbers in our personal samples made us hard to estimate its present-day concentrations, let alone its historical values. So more research is needed to further test this association in the future.

TABLE 5-7 The mesothelioma risk estimates from lag-effect models

#	Exposure metric used in the model	Time lag	Updated study population (104 cases + 410 controls)
1	Taconite years	20 years	1.02 (0.99, 1.05)
	NIOSH (EMP/cc)×years_Strategy1		1.10 (0.98, 1.23)
	Chatfield asbestiform (EMP/cc)×years_Strategy1		1.11 (0.99, 1.25)
	Suzuki (EMP/cc)×years_Strategy1		**1.01 (1.00, 1.02)**
	Chatfield non-asbestiform (EMP/cc)×years_Strategy1		**1.01 (1.00, 1.02)**
2	Taconite years	30 years	1.02 (0.97, 1.07)
	NIOSH (EMP/cc)×years_Strategy1		1.13 (0.98, 1.29)
	Chatfield asbestiform (EMP/cc)×years_Strategy1		**1.20 (1.02, 1.41)**
	Suzuki (EMP/cc)×years_Strategy1		**1.02 (1.00, 1.03)**
	Chatfield non-asbestiform (EMP/cc)×years_Strategy1		**1.01 (1.00, 1.02)**

All adjusted for age, hematite years, commercial asbestos.
Single EMP exposure term in each model

DISCUSSION

In this paper, historical EMP exposures were reconstructed using three different strategies ('Strategy1', 'Strategy2' and 'Strategy3'). As a result, a worker's cumulative exposures to, the same NIOSH EMP for example, estimated based on these different reconstructions were also different. We estimated the disease risk under each of these different cumulative exposures, and their results are not exactly the same (see Table 5-4). Take the risk values in the "1 unit increase in (EMP/cc)×year" rows in Table 5-4 as an example. For Strategy 1, its estimated risk is 1.10 with 95% CI of 0.99 to 1.22. the result for Strategy 2, however, is 1.01 with 95% CI of 1.00 to 1.03. For these two different results, we attempt to explain it by the difference in these two reconstruction strategies themselves. First, in Table 5-2, we found that these two strategies produced very different cumulative exposure values. For Strategy 1, its mean cumulative NIOSH EMP exposure in the case group is 2.1 f/cc×year, while this value jump to 10.7 f/cc×year for Strategy 2. Meanwhile, these two strategies conducted their EMP reconstructions at different data level: the SEG level for Strategy 1 and the department level for Strategy 2. Another difference between them is their different exposure metric selected: Strategy 2 uses AMs while Strategy 1 uses GMs. For health study, in theory, AM could be a better exposure metric than its GM as suggested by several researchers (Seixas, Robins and Moulton, 1988; Rappaport, 1991; Crump, 1998). During the GM to AM conversion process, however, the variances (GSDs) associated with the mean exposures (GMs) will be added to AMs to be calculated. In this study, the variances could be huge for the locations where had no/little EMP monitoring data. The calculated AMs, in these locations, could become very high or low – far beyond a reasonable EMP exposure range. Because of both the GM to AM conversion and data aggregation to the department level mentioned above, we believe, Strategy 2 will bring more exposure misclassification than Strategy 1 to our epidemiological analysis. The attenuated results for Strategy 2 in Table 5-4 support our viewpoints.

The mesothelioma risk for Strategy 3 is 1.20 with 95% CI of 0.99 to 1.46, which is similar with or even better than Strategy 1's result. Its point estimate is further away from the null, and it has a wider CIs. This may suggest that Strategy 3, compared to Strategy 1, reduces the exposure misclassification to some extent in the study.

One improvement of this study, compared to the previous study, is that we estimated taconite workers' cumulative exposures to different sized EMP listed in Table 5-1 thanks to the conversion factors described in Chapter 4. These cumulative exposure values were mildly to strongly (see Table 5-8) correlated with each other among taconite worker population due to, we believe, the natural link between these EMP definitions. For example, in nature, the short fiber - Suzuki EMP, approximately, a complement to the long and thin fiber – Chatfield asbestiform EMP. It is also, approximately, quite similar to Chatfield non-asbestiform EMP as both of them focus on short EMP. Because of these high correlations, the results, in Table 5-5, for Suzuki EMP are almost identical to the Chatfield non-asbestiform EMP's results. This suggests that perhaps we could have deleted one, either Suzuki EMP or Chatfield non-asbestiform EMP, in the study. But it's worth noticing that the NIOSH EMP is not highly correlated with any of other three EMP. This makes the adjustment in Table 5-6 meaningful. We saw results changed before and after adjusting a second exposure term.

TABLE 5-8 Pearson Correlation Coefficients between different cumulative EMP exposures (CE)

	CE_NIOSH EMP	CE_Chatfield asbestiform EMP	CE_Suzuki EMP	CE_Chatfield non-asbestiform EMP
CE_NIOSH EMP	1.00	0.30(<.0001)	0.46(<.0001)	0.60(<.0001)
CE_Chatfield asbestiform EMP	0.30(<.0001)	1.00	0.95(<.0001)	0.88(<.0001)
CE_Suzuki EMP	0.46(<.0001)	0.95(<.0001)	1.00	0.98(<.0001)
CE_Chatfield non-asbestiform EMP	0.60(<.0001)	0.88(<.0001)	0.98(<.0001)	1.00

CE refers to cumulative exposure

Table 5-5 compared the risk estimates using the previous study population vs. updated study population. General speaking, they are consistent with each other. For example, for the same exposure information (NIOSH (EMP/cc)×years_Strategy1), the risk in the previous study population is 1.11 with 95% CI of 0.98 to 1.26. The same risk in the updated study population was 1.10 with 95% CI of 0.99 to 1.22. Their mean estimates are comparable, but by using the updated study population with more cases and controls, the new 95% CIs became narrower with less variances compared to the previous one. This changes illustrates the improvement of this study.

Limitations

In this study, we did not update the vital status of the entire MRHAP cohort through the agencies (ie. NDI) as we did previously. All new mesothelioma cases were in state cases which were identified through MCSS system in Minnesota. Therefore, it is possible that we missed some out-of-state cases this time. Among the 80 old cases, 17 cases were diagnosed out of Minnesota. Given this ratio, we may miss about 6 out-of- state cases. Another potential issue of not updating vital status is that maybe some new controls who were alive by 2010 may had been dead afterwards. For example, a case who was dead in

2013 may matched with a control who may have been dead in 2012. But this will have little effects on our final results as all study population by this time point have been retired and their exposure information would not be changing anymore.

Exposure reconstruction in this investigation was based on all available work history information. This information was available through the end of 1982. It's very likely that some study subjects were still working after this cutting point. If it is the case, then the life-time exposure values estimated for these subjects could be lower than their real received exposures. To partially address this study defect, besides models with no latency, we also ran models with a 20-year latency as well as with a 30-year latency. By doing that (the date of diagnosis – 20 or 30 years), nearly all study subjects would have a complete exposure history. Meanwhile, we found that results from the lag models are consistent with those from the regular models.

The LTV mine is a puzzle compared to all other six mines in the taconite study. We had no present-day measurements and very little historical measurements for this mine. It was also the only mine in Zone 2 of the Mesabi Iron Range. In the meantime, nearly 50% of the mesothelioma cases were found in this mine. The zone-specific mesothelioma risks in Table 5-4 for zone 2 are all significant regardless of which reconstruction strategy used. For this mine, more research and information collected are needed.

CONCLUSION

This study re-confirmed the main conclusions in the previous study: there was an association between mesothelioma and employment duration and possibly NIOSH EMP exposure in taconite mining and processing. This initial analysis additionally described a potential association between mesothelioma and cumulative exposure to Suzuki EMP and Cleavage fragments in Minnesota taconite worker population. The methods to characterize these exposures will require further consideration.

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DISCLAIMER

The authors declare that there are no conflicts of interest relating to the material in relation to this article.

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Chapter 6 :

Conclusions and Future Directions

Overall conclusions

The primary research question in this work is whether long-term exposure to non-asbestiform EMP contributes to the development of mesothelioma observed in the taconite mining workers. Secondarily, which EMP exposure metric (i.e., what size range in terms of length and width of the EMP) is most associated with the mesothelioma cases among taconite workers? Chapters 2-5 of this dissertation report on four studies addressing the four specific aims of this work.

Specific aim 1: To reconstruct the historical respirable silica (RS) and respirable dust (RD) exposures of workers in Minnesota taconite industry from 1955-2010 by developing job-exposure matrices (JEM) that uses 9,128 RS and 19,408 RD industrial hygiene monitoring data. The result of this study is a JEM by mine, department, and year for RD and RS that will form the basis for future epidemiological studies.

Specific aim 2: To reconstruct the historical NIOSH EMP exposures of workers in Minnesota taconite industry from 1955-2010 based on 751 historical and 1285 present-day EMP measurements, and some time-trend information learned from specific aim1 using two different reconstruction strategies. The result of this study is two strategy-specific NIOSH-EMP based JEMs. These two JEMs will form the basis for future epidemiological studies.

Specific aim 3: A variety of dimensions (lengths and widths) of elongate mineral particles (EMP) have been proposed as being related to health effects such as mesothelioma and lung cancer. The goal of third study is to develop a mathematical approach for deriving numerical conversion factors (CFs) between these exposure metrics. These CFs will allow us to develop dimensional-specific EMP JEMs based on existing NIOSH-EMP based JEM developed in specific aim 2.

Specific aim 4: An excess of mesothelioma has been observed in iron ore miners in Northeastern Minnesota. Mining and processing of taconite iron ore generate exposures that include elongate mineral particles (EMP). As an update of the 2010 Minnesota mesothelioma study that evaluated the association between mesothelioma, employment and EMP exposures from taconite mining, the goal of this study is to re-evaluate this association for the EMP of different size ranges using the updated study cohort and new dimension-specific EMP JEMs developed in specific aim 3.

The historical RD and RS reconstruction study (Chapter 2) focused on creating an accurate JEM by mine, department and year for RD and RS using 19,408 RD and 9,128 RS industrial hygiene monitoring data. These two JEMs provide basis for calculating life-time exposure to dust and/or silica for taconite workers for epidemiological studies. In this study, we proposed a novel joint RS - RD reconstruction strategy and the prediction results were very encouraging. This study also describes how the historical dust exposure changed over time in each of mine-department combinations. The time-trends confirmed that the overall and location-specific historical exposure in taconite mining industry were decreasing over time. These time-trend estimates were also used in the historical EMP reconstruction work.

The historical EMP reconstruction study (Chapter 3) focused on creating an accurate JEM by mine, department and year for NIOSH defined EMP using limited historical and present-day NIOSH 7400 EMP monitoring data. In this study, two reconstruction strategies were used, one (Approach 1) based on only historical and present-day EMP data, and the other one (Approach 2) further borrowed the time-trend information from the historical dust reconstruction study (Chapter 2). Both strategies had pros and cons, and each alone might not handle all challenging scenarios in the study. For example, Approach 1 tends to fit data better, but sometimes when data is not enough, the fitted slope can be unrealistic. In contrast, Approach 2 does not need to predict a slope, but sometime its borrowed slope does not fit the data well. Each of the strategies generated a JEM for the NIOSH defined EMP. These two different JEMs set the foundation for calculating life-time exposure to NIOSH-EMP for taconite workers in epidemiological studies. The different JEMs also creates research opportunities for investigating how the selection of different exposure reconstruction strategies would affect final risk estimates in epidemiological studies.

The conversion factor derivation study (Chapter 4) focused on creating reasonable conversion factors (CFs) between EMP of different size ranges based on our understanding on how the overall EMP size would distributed at different locations in taconite mines. To gain this understanding, we sent all 1285 achieved EMP samples to an accredited lab for ISO-TEM analysis, obtained size information for 11,190 single EMP. We sorted them by location, and for each location, we assumed that the EMP dimensions (length and width) follow a bivariate lognormal distribution. A Bayesian approach was used to estimate these distributions based on priors for EMP dimensions derived from a limited number (N=92) of area samples that were then updated using SEG-specific personal EMP measurements (1267 personal samples). Each predicted distribution is a probability density surface for the EMP length and width distribution for each location. We then derived CFs of our interest based on these distribution plots. The comprehensive EMP exposure assessment conducted in this study, particularly the mathematical relationships between the NIOSH EMP and other EMP definitions using the new ISO-TEM results, provides 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.

The updated mesothelioma case-control study focused on investigating the association between the long-term exposures to non-asbestiform EMP and the development of mesothelioma observed in the taconite mines. Compared to the 2010 study, case ascertainment was updated using the Minnesota Cancer Surveillance System (MCSS). Secondly, twelve different EMP JEMs were used in the study to estimating worker's cumulative exposures to EMP of different size ranges. The result of this study re-confirmed our previous findings: there was an association between mesothelioma and employment duration and possibly NIOSH EMP exposure in taconite mining and processing. This study also found a possible association between mesothelioma and cumulative exposure to Suzuki EMP and cleavage fragments in the Minnesota taconite worker population. This provides epidemiological evidence in support the long-term speculation that short EMP may also be implicated in development of mesothelioma.

Future directions

In this study, multiple JEMs for a series of different exposure metrics were created. This enables several additional disease risk investigations based on these exposure metrics.

We can examine, for example, the risk of plural abnormality due to airborne iron exposure or the lung cancer risk due to mixed exposures (respirable dust, silica, iron, and EMP).

Detailed dimensional, chemical compositional and morphological information was obtained for 11,190 single EMP. While the studies conducted in this dissertation focused only on the relationship between EMP dimensions and disease risk, future studies could also explore EMP chemical and compositional differences by zone to see if these factors could explain the difference in mesothelioma risks between zones.

Uncertainties in the exposure assessment and their impacts on the epidemiological results will also be worth exploring. In this dissertation, we estimated the cumulative exposures using the mean predicted exposure values from the exposure prediction models. In this process, we did not introduce the model variances into the calculation. In the future, perhaps we could incorporate this variance part when calculating the cumulative exposure, and assess how it will change the final risk estimates in an epidemiological study.

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APPENDICES

Appendix A: RD JEM (Chapter 2)

Table A-1 The job-exposure matrix for respirable dust in ArcelorMittal (all values in the table are arithmetic means in mg/m^3)

mg/ m3	ArcelorMittal								
RD	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	/	/	/	/	/	/	/	/	/
1975	/	/	/	/	/	/	/	/	/
1976	/	/	/	/	/	/	/	/	/
1977	0.11	0.27	0.31	0.37	0.38	0.10	0.22	0.24	0.24
1978	0.11	0.27	0.30	0.36	0.36	0.10	0.21	0.23	0.23
1979	0.11	0.26	0.30	0.36	0.35	0.10	0.21	0.23	0.23
1980	0.11	0.26	0.29	0.35	0.34	0.10	0.20	0.22	0.22
1981	0.11	0.26	0.28	0.34	0.33	0.10	0.20	0.22	0.22
1982	0.10	0.26	0.27	0.33	0.31	0.10	0.20	0.22	0.22
1983	0.10	0.25	0.26	0.33	0.30	0.10	0.19	0.21	0.21
1984	0.10	0.25	0.26	0.32	0.29	0.10	0.19	0.21	0.21
1985	0.10	0.25	0.25	0.31	0.28	0.10	0.19	0.20	0.20
1986	0.10	0.25	0.24	0.31	0.27	0.10	0.18	0.20	0.20
1987	0.10	0.24	0.24	0.30	0.26	0.10	0.18	0.20	0.20
1988	0.10	0.24	0.23	0.30	0.26	0.10	0.18	0.19	0.19
1989	0.10	0.24	0.22	0.29	0.25	0.10	0.17	0.19	0.19
1990	0.10	0.24	0.22	0.28	0.24	0.10	0.17	0.19	0.19
1991	0.10	0.24	0.21	0.28	0.23	0.10	0.17	0.18	0.18
1992	0.09	0.23	0.21	0.27	0.22	0.10	0.16	0.18	0.18
1993	0.09	0.23	0.20	0.27	0.22	0.10	0.16	0.18	0.18
1994	0.09	0.23	0.19	0.26	0.21	0.10	0.16	0.17	0.17
1995	0.09	0.23	0.19	0.26	0.20	0.10	0.16	0.17	0.17
1996	0.09	0.23	0.18	0.25	0.20	0.10	0.15	0.17	0.17
1997	0.09	0.22	0.18	0.25	0.19	0.10	0.15	0.16	0.16
1998	0.09	0.22	0.17	0.24	0.18	0.10	0.15	0.16	0.16
1999	0.09	0.22	0.17	0.24	0.18	0.10	0.14	0.16	0.16
2000	0.09	0.22	0.17	0.23	0.17	0.10	0.14	0.16	0.16
2001	0.09	0.22	0.16	0.23	0.17	0.10	0.14	0.15	0.15
2002	0.08	0.22	0.16	0.23	0.16	0.10	0.14	0.15	0.15
2003	0.08	0.21	0.15	0.22	0.16	0.10	0.13	0.15	0.15
2004	0.08	0.21	0.15	0.22	0.15	0.10	0.13	0.14	0.14
2005	0.08	0.21	0.15	0.21	0.15	0.10	0.13	0.14	0.14
2006	0.08	0.21	0.14	0.21	0.14	0.10	0.13	0.14	0.14
2007	0.08	0.21	0.14	0.21	0.14	0.11	0.12	0.14	0.14
2008	0.08	0.21	0.14	0.20	0.14	0.11	0.12	0.13	0.13
2009	0.08	0.21	0.13	0.20	0.13	0.11	0.12	0.13	0.13
2010	0.08	0.20	0.13	0.19	0.13	0.11	0.12	0.13	0.13

Table A-2 The job-exposure matrix for respirable dust in Hibbtac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Hibbtac								
RD	**Mini ng**	**Crushi ng**	**Concentra ting**	**Pelletiz ing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	0.18	0.74	0.25	0.32	0.46	0.15	0.16	0.56	0.56
1975	0.17	0.72	0.26	0.33	0.45	0.15	0.16	0.55	0.55
1976	0.17	0.71	0.26	0.33	0.44	0.15	0.16	0.55	0.55
1977	0.17	0.69	0.26	0.33	0.43	0.15	0.16	0.54	0.54
1978	0.17	0.67	0.27	0.33	0.42	0.15	0.16	0.54	0.54
1979	0.17	0.65	0.27	0.34	0.41	0.15	0.16	0.53	0.53
1980	0.17	0.64	0.28	0.34	0.40	0.16	0.16	0.53	0.53
1981	0.17	0.62	0.28	0.34	0.40	0.16	0.15	0.52	0.52
1982	0.17	0.61	0.29	0.35	0.39	0.16	0.15	0.52	0.52
1983	0.17	0.59	0.29	0.35	0.38	0.16	0.15	0.51	0.51
1984	0.17	0.58	0.30	0.35	0.37	0.16	0.15	0.51	0.51
1985	0.17	0.56	0.30	0.36	0.36	0.16	0.15	0.50	0.50
1986	0.17	0.55	0.31	0.36	0.35	0.16	0.15	0.50	0.50
1987	0.17	0.53	0.31	0.36	0.35	0.16	0.14	0.49	0.49
1988	0.17	0.52	0.32	0.36	0.34	0.16	0.14	0.49	0.49
1989	0.17	0.51	0.32	0.37	0.33	0.16	0.14	0.48	0.48
1990	0.17	0.49	0.33	0.37	0.33	0.16	0.14	0.48	0.48
1991	0.17	0.48	0.33	0.37	0.32	0.16	0.14	0.47	0.47
1992	0.17	0.47	0.34	0.38	0.31	0.16	0.14	0.47	0.47
1993	0.17	0.46	0.34	0.38	0.31	0.17	0.14	0.46	0.46
1994	0.17	0.45	0.35	0.38	0.30	0.17	0.13	0.46	0.46
1995	0.17	0.43	0.35	0.39	0.29	0.17	0.13	0.45	0.45
1996	0.17	0.42	0.36	0.39	0.29	0.17	0.13	0.45	0.45
1997	0.17	0.41	0.37	0.40	0.28	0.17	0.13	0.44	0.44
1998	0.17	0.40	0.37	0.40	0.28	0.17	0.13	0.44	0.44
1999	0.17	0.39	0.38	0.40	0.27	0.17	0.13	0.44	0.44
2000	0.17	0.38	0.38	0.41	0.26	0.18	0.13	0.43	0.43
2001	0.17	0.37	0.39	0.41	0.26	0.18	0.13	0.43	0.43
2002	0.17	0.36	0.40	0.41	0.25	0.18	0.12	0.42	0.42
2003	0.17	0.35	0.40	0.42	0.25	0.18	0.12	0.42	0.42
2004	0.17	0.35	0.41	0.42	0.24	0.19	0.12	0.41	0.41
2005	0.17	0.34	0.42	0.42	0.24	0.19	0.12	0.41	0.41
2006	0.17	0.33	0.42	0.43	0.23	0.19	0.12	0.41	0.41
2007	0.17	0.32	0.43	0.43	0.23	0.19	0.12	0.40	0.40
2008	0.17	0.31	0.44	0.44	0.22	0.20	0.12	0.40	0.40
2009	0.17	0.30	0.45	0.44	0.22	0.20	0.12	0.39	0.39
2010	0.17	0.30	0.45	0.44	0.22	0.20	0.12	0.39	0.39

Table A-3 The job-exposure matrix for respirable dust in Keetac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Keetac								
RD	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.23	0.51	0.51	0.38	0.22	0.10	0.27	0.36	0.36
1968	0.23	0.49	0.49	0.37	0.22	0.11	0.27	0.36	0.36
1969	0.22	0.48	0.48	0.37	0.22	0.11	0.26	0.35	0.35
1970	0.22	0.46	0.47	0.36	0.22	0.11	0.26	0.34	0.34
1971	0.21	0.45	0.45	0.36	0.22	0.11	0.25	0.33	0.33
1972	0.21	0.43	0.44	0.35	0.22	0.11	0.25	0.33	0.33
1973	0.21	0.42	0.43	0.34	0.22	0.11	0.24	0.32	0.32
1974	0.20	0.40	0.41	0.34	0.22	0.11	0.24	0.31	0.31
1975	0.20	0.39	0.40	0.33	0.22	0.11	0.23	0.31	0.31
1976	0.20	0.38	0.39	0.33	0.21	0.11	0.23	0.30	0.30
1977	0.19	0.36	0.38	0.32	0.21	0.12	0.22	0.30	0.30
1978	0.19	0.35	0.37	0.32	0.21	0.12	0.22	0.29	0.29
1979	0.19	0.34	0.36	0.32	0.21	0.12	0.21	0.28	0.28
1980	0.18	0.33	0.35	0.31	0.21	0.12	0.21	0.28	0.28
1981	0.18	0.32	0.34	0.31	0.21	0.12	0.21	0.27	0.27
1982	0.18	0.31	0.33	0.30	0.21	0.12	0.20	0.27	0.27
1983	0.17	0.30	0.32	0.30	0.21	0.12	0.20	0.26	0.26
1984	0.17	0.29	0.31	0.29	0.21	0.13	0.19	0.26	0.26
1985	0.17	0.28	0.30	0.29	0.21	0.13	0.19	0.25	0.25
1986	0.16	0.27	0.29	0.28	0.21	0.13	0.19	0.25	0.25
1987	0.16	0.26	0.29	0.28	0.20	0.13	0.18	0.24	0.24
1988	0.16	0.25	0.28	0.28	0.20	0.13	0.18	0.24	0.24
1989	0.16	0.25	0.27	0.27	0.20	0.13	0.17	0.23	0.23
1990	0.15	0.24	0.26	0.27	0.20	0.13	0.17	0.23	0.23
1991	0.15	0.23	0.26	0.26	0.20	0.14	0.17	0.22	0.22
1992	0.15	0.22	0.25	0.26	0.20	0.14	0.16	0.22	0.22
1993	0.15	0.22	0.24	0.26	0.20	0.14	0.16	0.21	0.21
1994	0.14	0.21	0.23	0.25	0.20	0.14	0.16	0.21	0.21
1995	0.14	0.20	0.23	0.25	0.20	0.14	0.15	0.20	0.20
1996	0.14	0.20	0.22	0.25	0.20	0.14	0.15	0.20	0.20
1997	0.14	0.19	0.22	0.24	0.20	0.15	0.15	0.20	0.20
1998	0.13	0.18	0.21	0.24	0.20	0.15	0.14	0.19	0.19
1999	0.13	0.18	0.20	0.24	0.20	0.15	0.14	0.19	0.19
2000	0.13	0.17	0.20	0.23	0.20	0.15	0.14	0.18	0.18
2001	0.13	0.17	0.19	0.23	0.20	0.15	0.14	0.18	0.18
2002	0.12	0.16	0.19	0.23	0.20	0.16	0.13	0.18	0.18
2003	0.12	0.16	0.18	0.22	0.19	0.16	0.13	0.17	0.17
2004	0.12	0.15	0.18	0.22	0.19	0.16	0.13	0.17	0.17
2005	0.12	0.15	0.17	0.22	0.19	0.16	0.13	0.17	0.17
2006	0.12	0.14	0.17	0.21	0.19	0.16	0.12	0.16	0.16
2007	0.11	0.14	0.16	0.21	0.19	0.17	0.12	0.16	0.16
2008	0.11	0.14	0.16	0.21	0.19	0.17	0.12	0.16	0.16
2009	0.11	0.13	0.15	0.20	0.19	0.17	0.12	0.15	0.15
2010	0.11	0.13	0.15	0.20	0.19	0.17	0.11	0.15	0.15

Table A-4 The job-exposure matrix for respirable dust in LTV (all values in the table are arithmetic means in mg/m^3)

mg/ m3	LTV								
RD	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	0.10	0.18	0.05	0.17	0.29	0.06	0.14	0.14	0.14
1958	0.10	0.18	0.05	0.17	0.28	0.06	0.14	0.14	0.14
1959	0.10	0.18	0.05	0.18	0.28	0.06	0.14	0.14	0.14
1960	0.10	0.18	0.05	0.18	0.28	0.06	0.15	0.15	0.15
1961	0.10	0.18	0.06	0.18	0.27	0.07	0.15	0.15	0.15
1962	0.10	0.18	0.06	0.19	0.27	0.07	0.15	0.15	0.15
1963	0.10	0.18	0.06	0.19	0.27	0.07	0.15	0.15	0.15
1964	0.10	0.17	0.06	0.20	0.27	0.07	0.15	0.15	0.15
1965	0.10	0.17	0.06	0.20	0.26	0.07	0.15	0.15	0.15
1966	0.10	0.17	0.07	0.21	0.26	0.07	0.15	0.15	0.15
1967	0.10	0.17	0.07	0.21	0.26	0.07	0.15	0.15	0.15
1968	0.10	0.17	0.07	0.22	0.26	0.07	0.15	0.15	0.15
1969	0.10	0.17	0.07	0.22	0.26	0.07	0.15	0.15	0.15
1970	0.10	0.17	0.07	0.22	0.25	0.07	0.16	0.16	0.16
1971	0.10	0.17	0.08	0.23	0.25	0.07	0.16	0.16	0.16
1972	0.10	0.17	0.08	0.24	0.25	0.08	0.16	0.16	0.16
1973	0.10	0.17	0.08	0.24	0.25	0.08	0.16	0.16	0.16
1974	0.10	0.17	0.08	0.25	0.25	0.08	0.16	0.16	0.16
1975	0.10	0.17	0.09	0.25	0.24	0.08	0.16	0.16	0.16
1976	0.10	0.17	0.09	0.26	0.24	0.08	0.16	0.16	0.16
1977	0.10	0.17	0.09	0.26	0.24	0.08	0.16	0.16	0.16
1978	0.10	0.17	0.09	0.27	0.24	0.08	0.16	0.16	0.16
1979	0.10	0.17	0.10	0.28	0.24	0.08	0.17	0.17	0.17
1980	0.10	0.17	0.10	0.28	0.23	0.08	0.17	0.17	0.17
1981	0.10	0.17	0.10	0.29	0.23	0.09	0.17	0.17	0.17
1982	0.10	0.17	0.11	0.29	0.23	0.09	0.17	0.17	0.17
1983	0.11	0.17	0.11	0.30	0.23	0.09	0.17	0.17	0.17
1984	0.11	0.17	0.11	0.31	0.23	0.09	0.17	0.17	0.17
1985	0.11	0.17	0.12	0.32	0.23	0.09	0.17	0.17	0.17
1986	0.11	0.17	0.12	0.32	0.23	0.09	0.17	0.17	0.17
1987	0.11	0.17	0.12	0.33	0.22	0.09	0.18	0.18	0.18
1988	0.11	0.17	0.13	0.34	0.22	0.09	0.18	0.18	0.18
1989	0.11	0.17	0.13	0.35	0.22	0.10	0.18	0.18	0.18
1990	0.11	0.17	0.14	0.35	0.22	0.10	0.18	0.18	0.18
1991	0.11	0.17	0.14	0.36	0.22	0.10	0.18	0.18	0.18
1992	0.11	0.17	0.15	0.37	0.22	0.10	0.18	0.18	0.18
1993	0.11	0.17	0.15	0.38	0.22	0.10	0.18	0.18	0.18
1994	0.11	0.17	0.15	0.39	0.21	0.10	0.18	0.18	0.18
1995	0.11	0.17	0.16	0.40	0.21	0.11	0.19	0.19	0.19
1996	0.11	0.17	0.16	0.41	0.21	0.11	0.19	0.19	0.19
1997	0.11	0.17	0.17	0.41	0.21	0.11	0.19	0.19	0.19
1998	0.11	0.17	0.18	0.42	0.21	0.11	0.19	0.19	0.19
1999	0.11	0.17	0.18	0.43	0.21	0.11	0.19	0.19	0.19
2000	0.11	0.17	0.19	0.44	0.21	0.11	0.19	0.19	0.19
2001	0.11	0.17	0.19	0.45	0.21	0.12	0.19	0.19	0.19
2002	/	/	/	/	/	/	/	/	/
2003	/	/	/	/	/	/	/	/	/
2004	/	/	/	/	/	/	/	/	/
2005	/	/	/	/	/	/	/	/	/
2006	/	/	/	/	/	/	/	/	/
2007	/	/	/	/	/	/	/	/	/
2008	/	/	/	/	/	/	/	/	/
2009	/	/	/	/	/	/	/	/	/
2010	/	/	/	/	/	/	/	/	/

Table A-5 The job-exposure matrix for respirable dust in Minntac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Minntac								
RD	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.12	0.10	0.08	0.27	0.46	0.14	0.11	0.15	0.15
1968	0.12	0.11	0.08	0.26	0.44	0.14	0.11	0.15	0.15
1969	0.12	0.11	0.09	0.26	0.43	0.14	0.11	0.15	0.15
1970	0.12	0.11	0.09	0.26	0.42	0.14	0.11	0.15	0.15
1971	0.12	0.11	0.09	0.26	0.41	0.14	0.11	0.15	0.15
1972	0.12	0.12	0.09	0.26	0.40	0.14	0.11	0.15	0.15
1973	0.12	0.12	0.09	0.26	0.39	0.14	0.11	0.15	0.15
1974	0.12	0.12	0.09	0.26	0.38	0.14	0.11	0.15	0.15
1975	0.12	0.12	0.10	0.26	0.37	0.14	0.11	0.15	0.15
1976	0.12	0.13	0.10	0.26	0.36	0.14	0.11	0.15	0.15
1977	0.11	0.13	0.10	0.25	0.35	0.14	0.11	0.15	0.15
1978	0.11	0.13	0.10	0.25	0.34	0.14	0.12	0.15	0.15
1979	0.11	0.13	0.10	0.25	0.33	0.14	0.12	0.15	0.15
1980	0.11	0.14	0.11	0.25	0.32	0.14	0.12	0.16	0.16
1981	0.11	0.14	0.11	0.25	0.31	0.14	0.12	0.16	0.16
1982	0.11	0.14	0.11	0.25	0.30	0.14	0.12	0.16	0.16
1983	0.11	0.15	0.11	0.25	0.29	0.14	0.12	0.16	0.16
1984	0.11	0.15	0.12	0.25	0.29	0.14	0.12	0.16	0.16
1985	0.11	0.15	0.12	0.25	0.28	0.14	0.12	0.16	0.16
1986	0.11	0.16	0.12	0.25	0.27	0.14	0.12	0.16	0.16
1987	0.11	0.16	0.12	0.25	0.26	0.14	0.12	0.16	0.16
1988	0.11	0.16	0.12	0.24	0.26	0.14	0.12	0.16	0.16
1989	0.11	0.17	0.13	0.24	0.25	0.14	0.12	0.16	0.16
1990	0.11	0.17	0.13	0.24	0.24	0.14	0.12	0.16	0.16
1991	0.10	0.17	0.13	0.24	0.24	0.14	0.12	0.16	0.16
1992	0.10	0.18	0.14	0.24	0.23	0.14	0.12	0.16	0.16
1993	0.10	0.18	0.14	0.24	0.23	0.14	0.12	0.17	0.17
1994	0.10	0.19	0.14	0.24	0.22	0.14	0.12	0.17	0.17
1995	0.10	0.19	0.14	0.24	0.21	0.14	0.12	0.17	0.17
1996	0.10	0.19	0.15	0.24	0.21	0.14	0.13	0.17	0.17
1997	0.10	0.20	0.15	0.24	0.20	0.15	0.13	0.17	0.17
1998	0.10	0.20	0.15	0.24	0.20	0.15	0.13	0.17	0.17
1999	0.10	0.21	0.16	0.24	0.19	0.15	0.13	0.17	0.17
2000	0.10	0.21	0.16	0.24	0.19	0.15	0.13	0.17	0.17
2001	0.10	0.22	0.17	0.24	0.18	0.15	0.13	0.17	0.17
2002	0.10	0.22	0.17	0.23	0.18	0.15	0.13	0.17	0.17
2003	0.10	0.23	0.17	0.23	0.18	0.15	0.13	0.17	0.17
2004	0.10	0.23	0.18	0.23	0.17	0.15	0.13	0.17	0.17
2005	0.10	0.24	0.18	0.23	0.17	0.15	0.13	0.17	0.17
2006	0.10	0.24	0.18	0.23	0.16	0.15	0.13	0.18	0.18
2007	0.10	0.25	0.19	0.23	0.16	0.15	0.13	0.18	0.18
2008	0.10	0.26	0.19	0.23	0.16	0.15	0.13	0.18	0.18
2009	0.10	0.26	0.20	0.23	0.15	0.15	0.13	0.18	0.18
2010	0.09	0.27	0.20	0.23	0.15	0.15	0.13	0.18	0.18

Table A-6 The job-exposure matrix for respirable dust in Northshore (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Northshore								
RD	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	0.10	0.18	0.05	0.16	0.29	0.06	0.09	0.14	0.14
1956	0.10	0.18	0.05	0.16	0.29	0.06	0.09	0.14	0.14
1957	0.10	0.18	0.05	0.17	0.29	0.06	0.09	0.14	0.14
1958	0.10	0.18	0.05	0.17	0.28	0.06	0.09	0.14	0.14
1959	0.10	0.18	0.05	0.18	0.28	0.06	0.09	0.14	0.14
1960	0.10	0.18	0.05	0.18	0.28	0.06	0.09	0.15	0.15
1961	0.10	0.18	0.06	0.18	0.27	0.07	0.10	0.15	0.15
1962	0.10	0.18	0.06	0.19	0.27	0.07	0.10	0.15	0.15
1963	0.10	0.18	0.06	0.19	0.27	0.07	0.10	0.15	0.15
1964	0.10	0.17	0.06	0.20	0.27	0.07	0.10	0.15	0.15
1965	0.10	0.17	0.06	0.20	0.26	0.07	0.10	0.15	0.15
1966	0.10	0.17	0.07	0.21	0.26	0.07	0.10	0.15	0.15
1967	0.10	0.17	0.07	0.21	0.26	0.07	0.10	0.15	0.15
1968	0.10	0.17	0.07	0.22	0.26	0.07	0.10	0.15	0.15
1969	0.10	0.17	0.07	0.22	0.26	0.07	0.10	0.15	0.15
1970	0.10	0.17	0.07	0.22	0.25	0.07	0.10	0.16	0.16
1971	0.10	0.17	0.08	0.23	0.25	0.07	0.10	0.16	0.16
1972	0.10	0.17	0.08	0.24	0.25	0.08	0.10	0.16	0.16
1973	0.10	0.17	0.08	0.24	0.25	0.08	0.10	0.16	0.16
1974	0.10	0.17	0.08	0.25	0.25	0.08	0.10	0.16	0.16
1975	0.10	0.17	0.09	0.25	0.24	0.08	0.11	0.16	0.16
1976	0.10	0.17	0.09	0.26	0.24	0.08	0.11	0.16	0.16
1977	0.10	0.17	0.09	0.26	0.24	0.08	0.11	0.16	0.16
1978	0.10	0.17	0.09	0.27	0.24	0.08	0.11	0.16	0.16
1979	0.10	0.17	0.10	0.28	0.24	0.08	0.11	0.17	0.17
1980	0.10	0.17	0.10	0.28	0.23	0.08	0.11	0.17	0.17
1981	0.10	0.17	0.10	0.29	0.23	0.09	0.11	0.17	0.17
1982	0.10	0.17	0.11	0.29	0.23	0.09	0.11	0.17	0.17
1983	0.11	0.17	0.11	0.30	0.23	0.09	0.11	0.17	0.17
1984	0.11	0.17	0.11	0.31	0.23	0.09	0.11	0.17	0.17
1985	0.11	0.17	0.12	0.32	0.23	0.09	0.11	0.17	0.17
1986	0.11	0.17	0.12	0.32	0.23	0.09	0.11	0.17	0.17
1987	0.11	0.17	0.12	0.33	0.22	0.09	0.12	0.18	0.18
1988	0.11	0.17	0.13	0.34	0.22	0.09	0.12	0.18	0.18
1989	0.11	0.17	0.13	0.35	0.22	0.10	0.12	0.18	0.18
1990	0.11	0.17	0.14	0.35	0.22	0.10	0.12	0.18	0.18
1991	0.11	0.17	0.14	0.36	0.22	0.10	0.12	0.18	0.18
1992	0.11	0.17	0.15	0.37	0.22	0.10	0.12	0.18	0.18
1993	0.11	0.17	0.15	0.38	0.22	0.10	0.12	0.18	0.18
1994	0.11	0.17	0.15	0.39	0.21	0.10	0.12	0.18	0.18
1995	0.11	0.17	0.16	0.40	0.21	0.11	0.12	0.19	0.19
1996	0.11	0.17	0.16	0.41	0.21	0.11	0.12	0.19	0.19
1997	0.11	0.17	0.17	0.41	0.21	0.11	0.12	0.19	0.19
1998	0.11	0.17	0.18	0.42	0.21	0.11	0.12	0.19	0.19
1999	0.11	0.17	0.18	0.43	0.21	0.11	0.13	0.19	0.19
2000	0.11	0.17	0.19	0.44	0.21	0.11	0.13	0.19	0.19
2001	0.11	0.17	0.19	0.45	0.21	0.12	0.13	0.19	0.19
2002	0.11	0.17	0.20	0.47	0.21	0.12	0.13	0.20	0.20
2003	0.11	0.17	0.21	0.48	0.21	0.12	0.13	0.20	0.20
2004	0.12	0.17	0.21	0.49	0.21	0.12	0.13	0.20	0.20
2005	0.12	0.17	0.22	0.50	0.20	0.12	0.13	0.20	0.20
2006	0.12	0.17	0.23	0.51	0.20	0.13	0.13	0.20	0.20
2007	0.12	0.17	0.23	0.52	0.20	0.13	0.13	0.20	0.20
2008	0.12	0.17	0.24	0.53	0.20	0.13	0.13	0.20	0.20
2009	0.12	0.17	0.25	0.55	0.20	0.13	0.13	0.21	0.21
2010	0.12	0.17	0.26	0.56	0.20	0.13	0.14	0.21	0.21

Table A-7 The job-exposure matrix for respirable dust in Utac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Utac								
RD	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	0.12	0.16	0.26	0.26	0.37	0.35	0.08	0.17	0.17
1965	0.12	0.16	0.25	0.26	0.36	0.34	0.08	0.17	0.17
1966	0.12	0.17	0.25	0.25	0.36	0.33	0.08	0.18	0.18
1967	0.12	0.17	0.25	0.25	0.35	0.32	0.08	0.18	0.18
1968	0.12	0.17	0.25	0.25	0.35	0.31	0.08	0.18	0.18
1969	0.12	0.18	0.25	0.25	0.34	0.30	0.08	0.18	0.18
1970	0.12	0.18	0.25	0.25	0.33	0.29	0.08	0.18	0.18
1971	0.12	0.19	0.24	0.25	0.33	0.29	0.08	0.18	0.18
1972	0.13	0.19	0.24	0.25	0.32	0.28	0.08	0.18	0.18
1973	0.13	0.19	0.24	0.25	0.32	0.27	0.08	0.19	0.19
1974	0.13	0.20	0.24	0.25	0.31	0.26	0.08	0.19	0.19
1975	0.13	0.20	0.24	0.25	0.31	0.26	0.08	0.19	0.19
1976	0.13	0.21	0.24	0.26	0.30	0.25	0.08	0.19	0.19
1977	0.13	0.21	0.24	0.26	0.30	0.24	0.08	0.19	0.19
1978	0.13	0.21	0.24	0.26	0.30	0.24	0.09	0.19	0.19
1979	0.14	0.22	0.24	0.26	0.29	0.23	0.09	0.19	0.19
1980	0.14	0.22	0.23	0.26	0.29	0.22	0.09	0.20	0.20
1981	0.14	0.23	0.23	0.26	0.28	0.22	0.09	0.20	0.20
1982	0.14	0.23	0.23	0.26	0.28	0.21	0.09	0.20	0.20
1983	0.14	0.24	0.23	0.26	0.27	0.21	0.09	0.20	0.20
1984	0.14	0.24	0.23	0.26	0.27	0.20	0.09	0.20	0.20
1985	0.14	0.25	0.23	0.26	0.27	0.20	0.09	0.20	0.20
1986	0.15	0.25	0.23	0.26	0.26	0.19	0.09	0.21	0.21
1987	0.15	0.26	0.23	0.26	0.26	0.19	0.09	0.21	0.21
1988	0.15	0.27	0.23	0.26	0.26	0.18	0.09	0.21	0.21
1989	0.15	0.27	0.23	0.26	0.25	0.18	0.09	0.21	0.21
1990	0.15	0.28	0.23	0.26	0.25	0.17	0.09	0.21	0.21
1991	0.15	0.28	0.23	0.26	0.24	0.17	0.09	0.21	0.21
1992	0.15	0.29	0.23	0.26	0.24	0.16	0.10	0.22	0.22
1993	0.16	0.30	0.23	0.26	0.24	0.16	0.10	0.22	0.22
1994	0.16	0.30	0.23	0.26	0.23	0.16	0.10	0.22	0.22
1995	0.16	0.31	0.23	0.26	0.23	0.15	0.10	0.22	0.22
1996	0.16	0.32	0.23	0.26	0.23	0.15	0.10	0.22	0.22
1997	0.16	0.32	0.23	0.26	0.23	0.14	0.10	0.22	0.22
1998	0.16	0.33	0.23	0.26	0.22	0.14	0.10	0.23	0.23
1999	0.17	0.34	0.23	0.26	0.22	0.14	0.10	0.23	0.23
2000	0.17	0.35	0.23	0.26	0.22	0.13	0.10	0.23	0.23
2001	0.17	0.35	0.23	0.26	0.21	0.13	0.10	0.23	0.23
2002	0.17	0.36	0.23	0.26	0.21	0.13	0.10	0.23	0.23
2003	0.17	0.37	0.23	0.26	0.21	0.12	0.10	0.24	0.24
2004	0.18	0.38	0.23	0.26	0.21	0.12	0.10	0.24	0.24
2005	0.18	0.39	0.23	0.26	0.20	0.12	0.11	0.24	0.24
2006	0.18	0.40	0.23	0.26	0.20	0.12	0.11	0.24	0.24
2007	0.18	0.41	0.23	0.26	0.20	0.11	0.11	0.24	0.24
2008	0.18	0.42	0.23	0.26	0.19	0.11	0.11	0.24	0.24
2009	0.19	0.43	0.23	0.27	0.19	0.11	0.11	0.25	0.25
2010	0.19	0.44	0.23	0.27	0.19	0.11	0.11	0.25	0.25

Table A-8 The job-exposure matrix for respirable dust in All 7 mines (all values in the table are arithmetic means in mg/m^3)

mg/m3	All 7 mines								
RD	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	0.16	0.47	0.14	0.31	0.34	0.15	0.14	0.32	0.32
1956	0.16	0.47	0.15	0.31	0.34	0.15	0.14	0.32	0.32
1957	0.16	0.46	0.15	0.31	0.34	0.15	0.14	0.32	0.32
1958	0.16	0.46	0.15	0.31	0.33	0.15	0.14	0.32	0.32
1959	0.16	0.46	0.16	0.31	0.33	0.15	0.14	0.32	0.32
1960	0.16	0.46	0.16	0.31	0.33	0.15	0.14	0.32	0.32
1961	0.16	0.45	0.16	0.31	0.32	0.15	0.14	0.32	0.32
1962	0.16	0.45	0.17	0.31	0.32	0.15	0.14	0.32	0.32
1963	0.16	0.45	0.17	0.31	0.32	0.15	0.14	0.32	0.32
1964	0.15	0.44	0.17	0.31	0.31	0.15	0.14	0.32	0.32
1965	0.15	0.44	0.18	0.31	0.31	0.15	0.14	0.32	0.32
1966	0.15	0.44	0.18	0.31	0.31	0.15	0.14	0.32	0.32
1967	0.15	0.43	0.18	0.32	0.30	0.15	0.14	0.32	0.32
1968	0.15	0.43	0.19	0.32	0.30	0.14	0.14	0.31	0.31
1969	0.15	0.43	0.19	0.32	0.30	0.14	0.14	0.31	0.31
1970	0.15	0.42	0.19	0.32	0.29	0.14	0.14	0.31	0.31
1971	0.15	0.42	0.20	0.32	0.29	0.14	0.14	0.31	0.31
1972	0.15	0.42	0.20	0.32	0.29	0.14	0.14	0.31	0.31
1973	0.15	0.42	0.20	0.32	0.28	0.14	0.13	0.31	0.31
1974	0.15	0.41	0.21	0.32	0.28	0.14	0.13	0.31	0.31
1975	0.15	0.41	0.21	0.32	0.28	0.14	0.13	0.31	0.31
1976	0.15	0.41	0.22	0.32	0.27	0.14	0.13	0.31	0.31
1977	0.15	0.41	0.22	0.32	0.27	0.14	0.13	0.31	0.31
1978	0.15	0.40	0.23	0.32	0.27	0.14	0.13	0.31	0.31
1979	0.15	0.40	0.23	0.32	0.27	0.14	0.13	0.31	0.31
1980	0.14	0.40	0.23	0.32	0.26	0.14	0.13	0.31	0.31
1981	0.14	0.39	0.24	0.33	0.26	0.14	0.13	0.31	0.31
1982	0.14	0.39	0.24	0.33	0.26	0.14	0.13	0.30	0.30
1983	0.14	0.39	0.25	0.33	0.26	0.14	0.13	0.30	0.30
1984	0.14	0.39	0.25	0.33	0.25	0.14	0.13	0.30	0.30
1985	0.14	0.38	0.26	0.33	0.25	0.14	0.13	0.30	0.30
1986	0.14	0.38	0.26	0.33	0.25	0.14	0.13	0.30	0.30
1987	0.14	0.38	0.27	0.33	0.25	0.14	0.13	0.30	0.30
1988	0.14	0.38	0.27	0.33	0.24	0.14	0.13	0.30	0.30
1989	0.14	0.37	0.28	0.33	0.24	0.14	0.13	0.30	0.30
1990	0.14	0.37	0.29	0.33	0.24	0.14	0.13	0.30	0.30
1991	0.14	0.37	0.29	0.33	0.24	0.14	0.13	0.30	0.30
1992	0.14	0.37	0.30	0.33	0.23	0.14	0.13	0.30	0.30
1993	0.14	0.36	0.30	0.33	0.23	0.14	0.13	0.30	0.30
1994	0.14	0.36	0.31	0.34	0.23	0.14	0.13	0.30	0.30
1995	0.14	0.36	0.31	0.34	0.23	0.14	0.13	0.30	0.30
1996	0.14	0.36	0.32	0.34	0.22	0.14	0.13	0.30	0.30
1997	0.14	0.35	0.33	0.34	0.22	0.14	0.13	0.29	0.29
1998	0.13	0.35	0.33	0.34	0.22	0.14	0.13	0.29	0.29
1999	0.13	0.35	0.34	0.34	0.22	0.14	0.13	0.29	0.29
2000	0.13	0.35	0.35	0.34	0.22	0.14	0.13	0.29	0.29
2001	0.13	0.34	0.35	0.34	0.21	0.14	0.13	0.29	0.29
2002	0.13	0.34	0.36	0.34	0.21	0.14	0.13	0.29	0.29
2003	0.13	0.34	0.37	0.34	0.21	0.14	0.13	0.29	0.29
2004	0.13	0.34	0.37	0.34	0.21	0.14	0.13	0.29	0.29
2005	0.13	0.34	0.38	0.34	0.20	0.14	0.13	0.29	0.29
2006	0.13	0.33	0.39	0.35	0.20	0.14	0.13	0.29	0.29
2007	0.13	0.33	0.40	0.35	0.20	0.14	0.13	0.29	0.29
2008	0.13	0.33	0.41	0.35	0.20	0.14	0.12	0.29	0.29
2009	0.13	0.33	0.41	0.35	0.20	0.14	0.12	0.29	0.29
2010	0.13	0.32	0.42	0.35	0.19	0.14	0.12	0.29	0.29

Appendix B: RS JEM (Chapter 2)

Table B-1 The job-exposure matrix for respirable silica in ArcelorMittal (all values in the table are arithmetic means in mg/m^3)

mg/ m3	ArcelorMittal								
RS	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	/	/	/	/	/	/	/	/	/
1975	/	/	/	/	/	/	/	/	/
1976	/	/	/	/	/	/	/	/	/
1977	0.02	0.08	0.04	0.02	0.05	0.01	0.02	0.04	0.04
1978	0.02	0.08	0.03	0.02	0.05	0.01	0.02	0.04	0.04
1979	0.02	0.08	0.03	0.02	0.04	0.01	0.02	0.04	0.04
1980	0.02	0.08	0.03	0.02	0.04	0.01	0.02	0.04	0.04
1981	0.02	0.08	0.03	0.02	0.04	0.01	0.02	0.04	0.04
1982	0.02	0.08	0.03	0.02	0.04	0.01	0.02	0.03	0.03
1983	0.02	0.07	0.03	0.02	0.04	0.01	0.02	0.03	0.03
1984	0.02	0.07	0.03	0.02	0.04	0.01	0.02	0.03	0.03
1985	0.02	0.07	0.03	0.02	0.04	0.01	0.02	0.03	0.03
1986	0.02	0.07	0.03	0.02	0.03	0.01	0.02	0.03	0.03
1987	0.02	0.07	0.03	0.02	0.03	0.01	0.02	0.03	0.03
1988	0.02	0.07	0.03	0.02	0.03	0.01	0.02	0.03	0.03
1989	0.02	0.07	0.03	0.02	0.03	0.01	0.02	0.03	0.03
1990	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1991	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1992	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1993	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1994	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1995	0.02	0.07	0.02	0.02	0.03	0.01	0.02	0.03	0.03
1996	0.02	0.07	0.02	0.02	0.02	0.01	0.02	0.03	0.03
1997	0.02	0.07	0.02	0.02	0.02	0.01	0.02	0.03	0.03
1998	0.02	0.07	0.02	0.02	0.02	0.01	0.02	0.03	0.03
1999	0.02	0.06	0.02	0.02	0.02	0.01	0.01	0.03	0.03
2000	0.02	0.06	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2001	0.02	0.06	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2002	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.02	0.02
2003	0.01	0.06	0.02	0.01	0.02	0.01	0.01	0.02	0.02
2004	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2005	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2006	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2007	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2008	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2009	0.01	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2010	0.01	0.06	0.01	0.01	0.02	0.02	0.01	0.02	0.02

Table B-2 The job-exposure matrix for respirable silica in Hibbtac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Hibbtac								
RS	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	0.01	0.06	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1975	0.01	0.06	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1976	0.01	0.06	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1977	0.01	0.06	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1978	0.01	0.06	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1979	0.01	0.05	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1980	0.01	0.05	0.01	0.01	0.05	0.02	0.02	0.03	0.03
1981	0.01	0.05	0.01	0.01	0.04	0.02	0.02	0.03	0.03
1982	0.01	0.05	0.01	0.01	0.04	0.02	0.02	0.03	0.03
1983	0.01	0.05	0.01	0.01	0.04	0.02	0.02	0.03	0.03
1984	0.01	0.05	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1985	0.01	0.05	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1986	0.01	0.05	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1987	0.01	0.04	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1988	0.01	0.04	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1989	0.01	0.04	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1990	0.01	0.04	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1991	0.01	0.04	0.02	0.01	0.04	0.02	0.01	0.03	0.03
1992	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.03	0.03
1993	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.03	0.03
1994	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.03	0.03
1995	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1996	0.01	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1997	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1998	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1999	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2000	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2001	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2002	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2003	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2004	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2005	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2006	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2007	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2008	0.01	0.03	0.02	0.01	0.03	0.02	0.01	0.02	0.02
2009	0.01	0.03	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2010	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02

Table B-3 The job-exposure matrix for respirable silica in Keetac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Keetac								
RS	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.03	0.10	0.07	0.03	0.03	0.01	0.03	0.04	0.04
1968	0.03	0.10	0.07	0.03	0.03	0.01	0.03	0.04	0.04
1969	0.03	0.09	0.07	0.03	0.03	0.01	0.03	0.04	0.04
1970	0.03	0.09	0.07	0.03	0.03	0.01	0.03	0.04	0.04
1971	0.03	0.09	0.07	0.03	0.03	0.01	0.03	0.04	0.04
1972	0.03	0.08	0.06	0.03	0.03	0.01	0.02	0.04	0.04
1973	0.03	0.08	0.06	0.03	0.03	0.01	0.02	0.04	0.04
1974	0.03	0.08	0.06	0.03	0.03	0.01	0.02	0.04	0.04
1975	0.03	0.08	0.06	0.03	0.02	0.01	0.02	0.04	0.04
1976	0.02	0.07	0.06	0.03	0.02	0.01	0.02	0.03	0.03
1977	0.02	0.07	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1978	0.02	0.07	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1979	0.02	0.07	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1980	0.02	0.06	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1981	0.02	0.06	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1982	0.02	0.06	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1983	0.02	0.06	0.05	0.03	0.02	0.01	0.02	0.03	0.03
1984	0.02	0.06	0.04	0.03	0.02	0.01	0.02	0.03	0.03
1985	0.02	0.05	0.04	0.03	0.02	0.01	0.02	0.03	0.03
1986	0.02	0.05	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1987	0.02	0.05	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1988	0.02	0.05	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1989	0.02	0.05	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1990	0.02	0.05	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1991	0.02	0.04	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1992	0.02	0.04	0.04	0.02	0.02	0.01	0.02	0.03	0.03
1993	0.02	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02
1994	0.02	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02
1995	0.02	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02
1996	0.02	0.04	0.03	0.02	0.02	0.01	0.02	0.02	0.02
1997	0.02	0.04	0.03	0.02	0.02	0.01	0.01	0.02	0.02
1998	0.02	0.04	0.03	0.02	0.02	0.01	0.01	0.02	0.02
1999	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2000	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2001	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2002	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2003	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2004	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.02	0.02
2005	0.02	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2006	0.01	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2007	0.01	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2008	0.01	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2009	0.01	0.03	0.02	0.02	0.02	0.01	0.01	0.02	0.02
2010	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02

Table B-4 The job-exposure matrix for respirable silica in LTV (all values in the table are arithmetic means in mg/m^3)

mg/ m3	LTV								
RS	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1958	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1959	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1960	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1961	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1962	0.01	0.03	0.00	0.00	0.03	0.01	0.01	0.01	0.01
1963	0.01	0.03	0.00	0.00	0.03	0.01	0.01	0.01	0.01
1964	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1965	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1966	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1967	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1968	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1969	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1970	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1971	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1972	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1973	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1974	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1975	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1976	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1977	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1978	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1979	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1980	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1981	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1982	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1983	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1984	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1985	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1986	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1987	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1988	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1989	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1990	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1991	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1992	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1993	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1994	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1995	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1996	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1997	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1998	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
1999	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
2000	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
2001	0.02	0.03	0.01	0.01	0.03	0.01	0.02	0.02	0.02
2002	/	/	/	/	/	/	/	/	/
2003	/	/	/	/	/	/	/	/	/
2004	/	/	/	/	/	/	/	/	/
2005	/	/	/	/	/	/	/	/	/
2006	/	/	/	/	/	/	/	/	/
2007	/	/	/	/	/	/	/	/	/
2008	/	/	/	/	/	/	/	/	/
2009	/	/	/	/	/	/	/	/	/
2010	/	/	/	/	/	/	/	/	/

Table B-5 The job-exposure matrix for respirable silica in Minntac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Minntac								
RS	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.02	0.02	0.01	0.02	0.06	0.01	0.01	0.02	0.02
1968	0.02	0.02	0.01	0.02	0.06	0.01	0.01	0.02	0.02
1969	0.02	0.03	0.01	0.02	0.06	0.01	0.01	0.02	0.02
1970	0.02	0.03	0.01	0.02	0.06	0.01	0.01	0.02	0.02
1971	0.02	0.03	0.01	0.02	0.06	0.01	0.01	0.02	0.02
1972	0.02	0.03	0.02	0.02	0.06	0.01	0.01	0.02	0.02
1973	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1974	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1975	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1976	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1977	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1978	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.02	0.02
1979	0.02	0.03	0.02	0.01	0.05	0.01	0.01	0.03	0.03
1980	0.02	0.03	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1981	0.02	0.03	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1982	0.02	0.03	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1983	0.02	0.03	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1984	0.02	0.03	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1985	0.02	0.04	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1986	0.02	0.04	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1987	0.02	0.04	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1988	0.02	0.04	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1989	0.02	0.04	0.02	0.01	0.04	0.01	0.01	0.03	0.03
1990	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1991	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1992	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1993	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1994	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1995	0.02	0.04	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1996	0.02	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1997	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
1998	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
1999	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
2000	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
2001	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
2002	0.02	0.05	0.03	0.01	0.03	0.01	0.01	0.03	0.03
2003	0.02	0.05	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2004	0.02	0.05	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2005	0.02	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2006	0.02	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2007	0.02	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2008	0.01	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2009	0.01	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03
2010	0.01	0.06	0.03	0.01	0.02	0.01	0.01	0.03	0.03

Table B-6 The job-exposure matrix for respirable silica in Northshore (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Northshore								
RS	Mini ng	Crushi ng	Concentra ting	Pelletiz ing	Shop (mobile)	Shop (stationary)	Office/control room	Janit or	All 8 departments
1955	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1956	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1957	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1958	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1959	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1960	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1961	0.01	0.03	0.00	0.00	0.04	0.01	0.01	0.01	0.01
1962	0.01	0.03	0.00	0.00	0.03	0.01	0.01	0.01	0.01
1963	0.01	0.03	0.00	0.00	0.03	0.01	0.01	0.01	0.01
1964	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1965	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1966	0.01	0.03	0.00	0.01	0.03	0.01	0.01	0.01	0.01
1967	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1968	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1969	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1970	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1971	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1972	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1973	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1974	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1975	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1976	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1977	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1978	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1979	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1980	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1981	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1982	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
1983	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1984	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1985	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1986	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1987	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1988	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1989	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1990	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1991	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1992	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1993	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1994	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1995	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1996	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1997	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1998	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
1999	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
2000	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
2001	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
2002	0.02	0.03	0.01	0.01	0.03	0.01	0.01	0.02	0.02
2003	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2004	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2005	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2006	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2007	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2008	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2009	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02
2010	0.02	0.03	0.02	0.01	0.03	0.01	0.01	0.02	0.02

Table B-7 The job-exposure matrix for respirable silica in Utac (all values in the table are arithmetic means in mg/m^3)

mg/ m3	Utac								
RS	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	0.01	0.03	0.02	0.01	0.04	0.04	0.01	0.02	0.02
1965	0.01	0.03	0.02	0.01	0.04	0.04	0.01	0.02	0.02
1966	0.01	0.03	0.02	0.01	0.04	0.04	0.01	0.02	0.02
1967	0.01	0.03	0.02	0.01	0.04	0.04	0.01	0.02	0.02
1968	0.01	0.03	0.02	0.01	0.04	0.04	0.01	0.02	0.02
1969	0.01	0.03	0.02	0.01	0.04	0.03	0.01	0.02	0.02
1970	0.01	0.03	0.02	0.01	0.04	0.03	0.01	0.02	0.02
1971	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1972	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1973	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1974	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1975	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1976	0.01	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1977	0.02	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1978	0.02	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1979	0.02	0.03	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1980	0.02	0.04	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1981	0.02	0.04	0.02	0.01	0.03	0.03	0.01	0.02	0.02
1982	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1983	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1984	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1985	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1986	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1987	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1988	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1989	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1990	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1991	0.02	0.04	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1992	0.02	0.05	0.02	0.01	0.03	0.02	0.01	0.02	0.02
1993	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1994	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1995	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1996	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1997	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1998	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
1999	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2000	0.02	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2001	0.02	0.06	0.02	0.01	0.02	0.02	0.01	0.02	0.02
2002	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2003	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2004	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2005	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2006	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2007	0.02	0.06	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2008	0.02	0.07	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2009	0.02	0.07	0.02	0.01	0.02	0.01	0.01	0.03	0.03
2010	0.02	0.07	0.02	0.01	0.02	0.01	0.01	0.03	0.03

Table B-8 The job-exposure matrix for respirable silica in All 7 mines (all values in the table are arithmetic means in mg/m^3)

mg/ m3	All 7 mines								
RS	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1956	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1957	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1958	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1959	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1960	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1961	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1962	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1963	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1964	0.02	0.06	0.01	0.01	0.04	0.02	0.01	0.03	0.03
1965	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1966	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1967	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1968	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1969	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1970	0.01	0.06	0.01	0.01	0.04	0.01	0.01	0.03	0.03
1971	0.01	0.05	0.01	0.01	0.03	0.01	0.01	0.03	0.03
1972	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1973	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1974	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1975	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1976	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1977	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1978	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1979	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1980	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1981	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.03	0.03
1982	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1983	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1984	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1985	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1986	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1987	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1988	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1989	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1990	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1991	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1992	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1993	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1994	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1995	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1996	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1997	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1998	0.01	0.05	0.02	0.01	0.03	0.01	0.01	0.02	0.02
1999	0.01	0.05	0.03	0.01	0.03	0.01	0.01	0.02	0.02
2000	0.01	0.05	0.03	0.01	0.03	0.01	0.01	0.02	0.02
2001	0.01	0.04	0.03	0.01	0.03	0.01	0.01	0.02	0.02
2002	0.01	0.04	0.03	0.01	0.03	0.01	0.01	0.02	0.02
2003	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2004	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2005	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2006	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2007	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2008	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2009	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02
2010	0.01	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.02

Appendix C: NIOSH-EMP JEM – Approach 1 (Chapter 3)

Table C-1 The job-exposure matrix for EMP in ArcelorMittal (all values in the table are arithmetic means in f/cc)

f/cc	ArcelorMittal								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	/	/	/	/	/	/	/	/	/
1975	/	/	/	/	/	/	/	/	/
1976	/	/	/	/	/	/	/	/	/
1977	0.10	0.15	0.20	0.08	0.12	0.09	0.12	0.09	0.09
1978	0.10	0.14	0.19	0.08	0.11	0.09	0.11	0.08	0.08
1979	0.09	0.13	0.18	0.08	0.11	0.08	0.10	0.08	0.08
1980	0.09	0.13	0.17	0.07	0.10	0.08	0.10	0.08	0.08
1981	0.08	0.12	0.16	0.07	0.10	0.08	0.09	0.07	0.07
1982	0.08	0.12	0.15	0.07	0.09	0.07	0.09	0.07	0.07
1983	0.07	0.11	0.14	0.06	0.09	0.07	0.09	0.07	0.07
1984	0.07	0.11	0.14	0.06	0.08	0.07	0.08	0.07	0.07
1985	0.07	0.10	0.13	0.06	0.08	0.06	0.08	0.06	0.06
1986	0.06	0.10	0.13	0.05	0.07	0.06	0.07	0.06	0.06
1987	0.06	0.09	0.12	0.05	0.07	0.06	0.07	0.06	0.06
1988	0.06	0.09	0.11	0.05	0.07	0.06	0.07	0.06	0.06
1989	0.06	0.09	0.11	0.05	0.07	0.05	0.07	0.05	0.05
1990	0.05	0.08	0.10	0.05	0.06	0.05	0.06	0.05	0.05
1991	0.05	0.08	0.10	0.04	0.06	0.05	0.06	0.05	0.05
1992	0.05	0.08	0.10	0.04	0.06	0.05	0.06	0.05	0.05
1993	0.05	0.07	0.09	0.04	0.05	0.04	0.06	0.05	0.05
1994	0.05	0.07	0.09	0.04	0.05	0.04	0.05	0.04	0.04
1995	0.04	0.07	0.08	0.04	0.05	0.04	0.05	0.04	0.04
1996	0.04	0.07	0.08	0.04	0.05	0.04	0.05	0.04	0.04
1997	0.04	0.06	0.08	0.03	0.05	0.04	0.05	0.04	0.04
1998	0.04	0.06	0.07	0.03	0.04	0.04	0.05	0.04	0.04
1999	0.04	0.06	0.07	0.03	0.04	0.04	0.04	0.04	0.04
2000	0.04	0.06	0.07	0.03	0.04	0.03	0.04	0.04	0.04
2001	0.04	0.06	0.07	0.03	0.04	0.03	0.04	0.03	0.03
2002	0.03	0.05	0.06	0.03	0.04	0.03	0.04	0.03	0.03
2003	0.03	0.05	0.06	0.03	0.04	0.03	0.04	0.03	0.03
2004	0.03	0.05	0.06	0.03	0.04	0.03	0.04	0.03	0.03
2005	0.03	0.05	0.06	0.03	0.03	0.03	0.04	0.03	0.03
2006	0.03	0.05	0.06	0.02	0.03	0.03	0.03	0.03	0.03
2007	0.03	0.05	0.05	0.02	0.03	0.03	0.03	0.03	0.03
2008	0.03	0.05	0.05	0.02	0.03	0.03	0.03	0.03	0.03
2009	0.03	0.04	0.05	0.02	0.03	0.03	0.03	0.03	0.03
2010	0.03	0.04	0.05	0.02	0.03	0.02	0.03	0.03	0.03

Table C-2 The job-exposure matrix for EMP in Hibbtac (all values in the table are arithmetic means in f/cc)

f/cc	Hibbtac								
EMP	Min ing	Crus hing	Concentra ting	Pelletizi ng	Shop (mobile)	Shop (stationary)	Office/control room	Janit or	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	0.07	0.07	0.05	0.07	0.08	0.06	0.06	0.02	0.02
1975	0.06	0.06	0.05	0.07	0.07	0.06	0.06	0.02	0.02
1976	0.06	0.06	0.05	0.06	0.07	0.06	0.05	0.02	0.02
1977	0.05	0.05	0.04	0.06	0.06	0.05	0.05	0.02	0.02
1978	0.05	0.05	0.04	0.06	0.06	0.05	0.05	0.02	0.02
1979	0.05	0.05	0.04	0.05	0.06	0.05	0.04	0.02	0.02
1980	0.04	0.05	0.04	0.05	0.05	0.04	0.04	0.02	0.02
1981	0.04	0.04	0.03	0.05	0.05	0.04	0.04	0.02	0.02
1982	0.04	0.04	0.03	0.05	0.05	0.04	0.04	0.02	0.02
1983	0.04	0.04	0.03	0.04	0.05	0.04	0.04	0.02	0.02
1984	0.04	0.04	0.03	0.04	0.04	0.04	0.03	0.02	0.02
1985	0.03	0.04	0.03	0.04	0.04	0.03	0.03	0.02	0.02
1986	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.02
1987	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.02
1988	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.02
1989	0.03	0.03	0.02	0.03	0.04	0.03	0.03	0.02	0.02
1990	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02
1991	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02
1992	0.03	0.03	0.02	0.03	0.03	0.03	0.03	0.02	0.02
1993	0.03	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.02
1994	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.02	0.02
1995	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
1996	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
1997	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
1998	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
1999	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2000	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2001	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2002	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2003	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2004	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2005	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2006	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2007	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2008	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2009	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.02	0.02
2010	0.02	0.03	0.02	0.03	0.03	0.03	0.02	0.03	0.03

Table C-3 The job-exposure matrix for EMP in Keetac (all values in the table are arithmetic means in f/cc)

f/cc	Keetac								
EMP	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	10.89	6.56	15.22	30.89	14.01	9.14	7.42	3.32	3.32
1968	8.41	5.10	11.82	23.96	10.86	7.09	5.75	2.80	2.80
1969	6.54	3.98	9.24	18.69	8.47	5.52	4.49	2.38	2.38
1970	5.11	3.13	7.26	14.67	6.65	4.33	3.52	2.02	2.02
1971	4.02	2.47	5.74	11.58	5.24	3.42	2.77	1.73	1.73
1972	3.18	1.97	4.56	9.19	4.16	2.71	2.20	1.48	1.48
1973	2.53	1.57	3.65	7.34	3.32	2.16	1.76	1.27	1.27
1974	2.02	1.26	2.93	5.89	2.67	1.74	1.41	1.10	1.10
1975	1.63	1.02	2.37	4.76	2.15	1.40	1.14	0.95	0.95
1976	1.32	0.83	1.93	3.87	1.75	1.14	0.92	0.82	0.82
1977	1.07	0.68	1.58	3.16	1.43	0.93	0.75	0.72	0.72
1978	0.88	0.56	1.30	2.60	1.17	0.76	0.62	0.63	0.63
1979	0.72	0.46	1.08	2.15	0.97	0.63	0.51	0.55	0.55
1980	0.60	0.39	0.90	1.79	0.81	0.52	0.43	0.48	0.48
1981	0.50	0.32	0.75	1.49	0.67	0.44	0.36	0.42	0.42
1982	0.42	0.27	0.63	1.26	0.57	0.37	0.30	0.38	0.38
1983	0.35	0.23	0.54	1.06	0.48	0.31	0.25	0.33	0.33
1984	0.30	0.20	0.46	0.91	0.41	0.26	0.22	0.30	0.30
1985	0.25	0.17	0.39	0.78	0.35	0.23	0.18	0.27	0.27
1986	0.22	0.15	0.34	0.67	0.30	0.20	0.16	0.24	0.24
1987	0.19	0.13	0.29	0.58	0.26	0.17	0.14	0.21	0.21
1988	0.16	0.11	0.26	0.50	0.23	0.15	0.12	0.19	0.19
1989	0.14	0.10	0.22	0.44	0.20	0.13	0.10	0.17	0.17
1990	0.13	0.09	0.20	0.39	0.18	0.11	0.09	0.16	0.16
1991	0.11	0.08	0.18	0.35	0.16	0.10	0.08	0.14	0.14
1992	0.10	0.07	0.16	0.31	0.14	0.09	0.07	0.13	0.13
1993	0.09	0.06	0.14	0.28	0.12	0.08	0.07	0.12	0.12
1994	0.08	0.05	0.13	0.25	0.11	0.07	0.06	0.11	0.11
1995	0.07	0.05	0.12	0.23	0.10	0.07	0.05	0.10	0.10
1996	0.06	0.05	0.11	0.21	0.09	0.06	0.05	0.09	0.09
1997	0.06	0.04	0.10	0.19	0.08	0.05	0.04	0.09	0.09
1998	0.05	0.04	0.09	0.17	0.08	0.05	0.04	0.08	0.08
1999	0.05	0.04	0.08	0.16	0.07	0.05	0.04	0.08	0.08
2000	0.05	0.03	0.08	0.15	0.07	0.04	0.04	0.07	0.07
2001	0.04	0.03	0.07	0.14	0.06	0.04	0.03	0.07	0.07
2002	0.04	0.03	0.07	0.13	0.06	0.04	0.03	0.06	0.06
2003	0.04	0.03	0.07	0.13	0.06	0.04	0.03	0.06	0.06
2004	0.04	0.03	0.06	0.12	0.05	0.04	0.03	0.06	0.06
2005	0.04	0.03	0.06	0.12	0.05	0.03	0.03	0.05	0.05
2006	0.03	0.03	0.06	0.11	0.05	0.03	0.03	0.05	0.05
2007	0.03	0.02	0.06	0.11	0.05	0.03	0.03	0.05	0.05
2008	0.03	0.02	0.06	0.11	0.05	0.03	0.03	0.05	0.05
2009	0.03	0.02	0.06	0.11	0.05	0.03	0.02	0.05	0.05
2010	0.03	0.02	0.06	0.11	0.05	0.03	0.02	0.05	0.05

Table C-4 The job-exposure matrix for EMP in LTV (all values in the table are arithmetic means in f/cc)

f/cc	Hibbtac								
EMP	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	1.82	2.51	3.64	1.58	1.67	1.58	0.44	1.61	1.61
1958	1.70	2.35	3.40	1.47	1.56	1.48	0.41	1.51	1.51
1959	1.58	2.20	3.18	1.38	1.46	1.38	0.38	1.43	1.43
1960	1.48	2.05	2.97	1.29	1.37	1.30	0.36	1.34	1.34
1961	1.38	1.92	2.78	1.20	1.28	1.21	0.33	1.26	1.26
1962	1.29	1.80	2.60	1.13	1.20	1.13	0.31	1.19	1.19
1963	1.20	1.69	2.44	1.06	1.12	1.06	0.29	1.12	1.12
1964	1.13	1.58	2.28	0.99	1.05	1.00	0.27	1.06	1.06
1965	1.05	1.49	2.14	0.93	0.99	0.93	0.26	1.00	1.00
1966	0.99	1.39	2.01	0.87	0.92	0.88	0.24	0.94	0.94
1967	0.92	1.31	1.88	0.81	0.87	0.82	0.23	0.89	0.89
1968	0.86	1.23	1.77	0.76	0.81	0.77	0.21	0.83	0.83
1969	0.81	1.15	1.66	0.72	0.77	0.72	0.20	0.79	0.79
1970	0.76	1.09	1.56	0.67	0.72	0.68	0.19	0.74	0.74
1971	0.71	1.02	1.47	0.63	0.68	0.64	0.18	0.70	0.70
1972	0.67	0.96	1.38	0.59	0.64	0.60	0.16	0.66	0.66
1973	0.63	0.90	1.30	0.56	0.60	0.57	0.16	0.62	0.62
1974	0.59	0.85	1.22	0.53	0.56	0.53	0.15	0.59	0.59
1975	0.55	0.80	1.15	0.49	0.53	0.50	0.14	0.56	0.56
1976	0.52	0.76	1.08	0.47	0.50	0.47	0.13	0.52	0.52
1977	0.49	0.71	1.02	0.44	0.47	0.44	0.12	0.50	0.50
1978	0.46	0.67	0.96	0.41	0.44	0.42	0.11	0.47	0.47
1979	0.43	0.63	0.91	0.39	0.42	0.40	0.11	0.44	0.44
1980	0.41	0.60	0.85	0.37	0.39	0.37	0.10	0.42	0.42
1981	0.38	0.57	0.81	0.35	0.37	0.35	0.10	0.39	0.39
1982	0.36	0.53	0.76	0.33	0.35	0.33	0.09	0.37	0.37
1983	0.34	0.51	0.72	0.31	0.33	0.31	0.09	0.35	0.35
1984	0.32	0.48	0.68	0.29	0.31	0.30	0.08	0.33	0.33
1985	0.30	0.45	0.64	0.28	0.30	0.28	0.08	0.31	0.31
1986	0.29	0.43	0.61	0.26	0.28	0.27	0.07	0.30	0.30
1987	0.27	0.41	0.58	0.25	0.27	0.25	0.07	0.28	0.28
1988	0.25	0.38	0.54	0.23	0.25	0.24	0.07	0.27	0.27
1989	0.24	0.36	0.52	0.22	0.24	0.23	0.06	0.25	0.25
1990	0.23	0.34	0.49	0.21	0.23	0.21	0.06	0.24	0.24
1991	0.22	0.33	0.46	0.20	0.21	0.20	0.06	0.23	0.23
1992	0.20	0.31	0.44	0.19	0.20	0.19	0.05	0.21	0.21
1993	0.19	0.29	0.42	0.18	0.19	0.18	0.05	0.20	0.20
1994	0.18	0.28	0.40	0.17	0.18	0.17	0.05	0.19	0.19
1995	0.17	0.27	0.38	0.16	0.17	0.16	0.04	0.18	0.18
1996	0.16	0.25	0.36	0.15	0.17	0.16	0.04	0.17	0.17
1997	0.16	0.24	0.34	0.15	0.16	0.15	0.04	0.16	0.16
1998	0.15	0.23	0.32	0.14	0.15	0.14	0.04	0.15	0.15
1999	0.14	0.22	0.31	0.13	0.14	0.13	0.04	0.15	0.15
2000	0.13	0.21	0.29	0.12	0.14	0.13	0.03	0.14	0.14
2001	0.13	0.20	0.28	0.12	0.13	0.12	0.03	0.13	0.13
2002	/	/	/	/	/	/	/	/	/
2003	/	/	/	/	/	/	/	/	/
2004	/	/	/	/	/	/	/	/	/
2005	/	/	/	/	/	/	/	/	/
2006	/	/	/	/	/	/	/	/	/
2007	/	/	/	/	/	/	/	/	/
2008	/	/	/	/	/	/	/	/	/
2009	/	/	/	/	/	/	/	/	/
2010	/	/	/	/	/	/	/	/	/

Table C-5 The job-exposure matrix for EMP in Minntac (all values in the table are arithmetic means in f/cc)

f/cc	Minntac								
EMP	**Mining**	**Crushing**	**Concentrating**	**Pelletizing**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janitor**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1968	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1969	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1970	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1971	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1972	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1973	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1974	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1975	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1976	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00
1979	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00
1980	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
1981	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
1982	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
1983	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
1984	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00
1985	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1986	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1987	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1988	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1989	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1990	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1991	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
1992	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1993	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1994	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
1995	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
1996	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01
1997	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01
1998	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02
1999	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02
2000	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.02	0.02
2001	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.02	0.02
2002	0.02	0.03	0.03	0.03	0.03	0.02	0.01	0.02	0.02
2003	0.02	0.03	0.03	0.03	0.03	0.02	0.01	0.03	0.03
2004	0.02	0.03	0.04	0.04	0.03	0.02	0.01	0.03	0.03
2005	0.03	0.03	0.04	0.04	0.03	0.03	0.02	0.03	0.03
2006	0.03	0.04	0.04	0.04	0.04	0.03	0.02	0.03	0.03
2007	0.03	0.04	0.05	0.05	0.04	0.03	0.02	0.04	0.04
2008	0.04	0.05	0.05	0.05	0.05	0.03	0.02	0.04	0.04
2009	0.04	0.05	0.06	0.06	0.05	0.04	0.02	0.04	0.04
2010	0.04	0.06	0.07	0.06	0.06	0.04	0.03	0.05	0.05

Table C-6 The job-exposure matrix for EMP in Northshore (all values in the table are arithmetic means in f/cc)

f/cc	Northshore								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	2.10	2.87	4.17	1.81	1.92	1.82	0.50	1.82	1.82
1956	1.95	2.69	3.90	1.69	1.79	1.70	0.47	1.71	1.71
1957	1.82	2.51	3.64	1.58	1.67	1.58	0.44	1.61	1.61
1958	1.70	2.35	3.40	1.47	1.56	1.48	0.41	1.51	1.51
1959	1.58	2.20	3.18	1.38	1.46	1.38	0.38	1.43	1.43
1960	1.48	2.05	2.97	1.29	1.37	1.30	0.36	1.34	1.34
1961	1.38	1.92	2.78	1.20	1.28	1.21	0.33	1.26	1.26
1962	1.29	1.80	2.60	1.13	1.20	1.13	0.31	1.19	1.19
1963	1.20	1.69	2.44	1.06	1.12	1.06	0.29	1.12	1.12
1964	1.13	1.58	2.28	0.99	1.05	1.00	0.27	1.06	1.06
1965	1.05	1.49	2.14	0.93	0.99	0.93	0.26	1.00	1.00
1966	0.99	1.39	2.01	0.87	0.92	0.88	0.24	0.94	0.94
1967	0.92	1.31	1.88	0.81	0.87	0.82	0.23	0.89	0.89
1968	0.86	1.23	1.77	0.76	0.81	0.77	0.21	0.83	0.83
1969	0.81	1.15	1.66	0.72	0.77	0.72	0.20	0.79	0.79
1970	0.76	1.09	1.56	0.67	0.72	0.68	0.19	0.74	0.74
1971	0.71	1.02	1.47	0.63	0.68	0.64	0.18	0.70	0.70
1972	0.67	0.96	1.38	0.59	0.64	0.60	0.16	0.66	0.66
1973	0.63	0.90	1.30	0.56	0.60	0.57	0.16	0.62	0.62
1974	0.59	0.85	1.22	0.53	0.56	0.53	0.15	0.59	0.59
1975	0.55	0.80	1.15	0.49	0.53	0.50	0.14	0.56	0.56
1976	0.52	0.76	1.08	0.47	0.50	0.47	0.13	0.52	0.52
1977	0.49	0.71	1.02	0.44	0.47	0.44	0.12	0.50	0.50
1978	0.46	0.67	0.96	0.41	0.44	0.42	0.11	0.47	0.47
1979	0.43	0.63	0.91	0.39	0.42	0.40	0.11	0.44	0.44
1980	0.41	0.60	0.85	0.37	0.39	0.37	0.10	0.42	0.42
1981	0.38	0.57	0.81	0.35	0.37	0.35	0.10	0.39	0.39
1982	0.36	0.53	0.76	0.33	0.35	0.33	0.09	0.37	0.37
1983	0.34	0.51	0.72	0.31	0.33	0.31	0.09	0.35	0.35
1984	0.32	0.48	0.68	0.29	0.31	0.30	0.08	0.33	0.33
1985	0.30	0.45	0.64	0.28	0.30	0.28	0.08	0.31	0.31
1986	0.29	0.43	0.61	0.26	0.28	0.27	0.07	0.30	0.30
1987	0.27	0.41	0.58	0.25	0.27	0.25	0.07	0.28	0.28
1988	0.25	0.38	0.54	0.23	0.25	0.24	0.07	0.27	0.27
1989	0.24	0.36	0.52	0.22	0.24	0.23	0.06	0.25	0.25
1990	0.23	0.34	0.49	0.21	0.23	0.21	0.06	0.24	0.24
1991	0.22	0.33	0.46	0.20	0.21	0.20	0.06	0.23	0.23
1992	0.20	0.31	0.44	0.19	0.20	0.19	0.05	0.21	0.21
1993	0.19	0.29	0.42	0.18	0.19	0.18	0.05	0.20	0.20
1994	0.18	0.28	0.40	0.17	0.18	0.17	0.05	0.19	0.19
1995	0.17	0.27	0.38	0.16	0.17	0.16	0.04	0.18	0.18
1996	0.16	0.25	0.36	0.15	0.17	0.16	0.04	0.17	0.17
1997	0.16	0.24	0.34	0.15	0.16	0.15	0.04	0.16	0.16
1998	0.15	0.23	0.32	0.14	0.15	0.14	0.04	0.15	0.15
1999	0.14	0.22	0.31	0.13	0.14	0.13	0.04	0.15	0.15
2000	0.13	0.21	0.29	0.12	0.14	0.13	0.03	0.14	0.14
2001	0.13	0.20	0.28	0.12	0.13	0.12	0.03	0.13	0.13
2002	0.12	0.19	0.26	0.11	0.12	0.12	0.03	0.12	0.12
2003	0.11	0.18	0.25	0.11	0.12	0.11	0.03	0.12	0.12
2004	0.11	0.17	0.24	0.10	0.11	0.11	0.03	0.11	0.11
2005	0.10	0.16	0.23	0.10	0.11	0.10	0.03	0.11	0.11
2006	0.10	0.16	0.22	0.09	0.10	0.10	0.03	0.10	0.10
2007	0.09	0.15	0.21	0.09	0.10	0.09	0.02	0.10	0.10
2008	0.09	0.14	0.20	0.09	0.09	0.09	0.02	0.09	0.09
2009	0.09	0.14	0.19	0.08	0.09	0.08	0.02	0.09	0.09
2010	0.08	0.13	0.18	0.08	0.08	0.08	0.02	0.08	0.08

Table C-7 The job-exposure matrix for EMP in Utac (all values in the table are arithmetic means in f/cc)

f/cc	Utac								
EMP	Min ing	Crus hing	Concentra ting	Pelletizi ng	Shop (mobile)	Shop (stationary)	Office/control room	Janit or	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	7.00	3.09	6.21	3.61	4.20	3.69	3.17	1.93	1.93
1965	6.16	2.73	5.49	3.19	3.72	3.27	2.80	1.75	1.75
1966	5.43	2.41	4.85	2.82	3.29	2.90	2.47	1.59	1.59
1967	4.79	2.13	4.30	2.49	2.91	2.58	2.19	1.44	1.44
1968	4.23	1.88	3.81	2.20	2.58	2.29	1.94	1.31	1.31
1969	3.74	1.67	3.37	1.95	2.29	2.04	1.72	1.19	1.19
1970	3.31	1.48	2.99	1.73	2.03	1.82	1.52	1.08	1.08
1971	2.93	1.31	2.66	1.54	1.81	1.62	1.35	0.99	0.99
1972	2.59	1.16	2.37	1.37	1.61	1.45	1.20	0.90	0.90
1973	2.30	1.03	2.11	1.22	1.43	1.30	1.07	0.82	0.82
1974	2.04	0.92	1.88	1.08	1.28	1.16	0.95	0.74	0.74
1975	1.82	0.82	1.67	0.96	1.14	1.04	0.85	0.68	0.68
1976	1.62	0.73	1.49	0.86	1.02	0.93	0.76	0.62	0.62
1977	1.44	0.65	1.33	0.77	0.91	0.83	0.68	0.56	0.56
1978	1.28	0.58	1.19	0.69	0.81	0.75	0.61	0.51	0.51
1979	1.14	0.52	1.07	0.61	0.73	0.67	0.54	0.47	0.47
1980	1.02	0.46	0.96	0.55	0.65	0.60	0.49	0.43	0.43
1981	0.91	0.42	0.86	0.49	0.59	0.54	0.43	0.39	0.39
1982	0.82	0.37	0.77	0.44	0.53	0.49	0.39	0.36	0.36
1983	0.73	0.33	0.69	0.40	0.47	0.44	0.35	0.33	0.33
1984	0.65	0.30	0.62	0.36	0.43	0.40	0.31	0.30	0.30
1985	0.59	0.27	0.56	0.32	0.38	0.36	0.28	0.27	0.27
1986	0.53	0.24	0.50	0.29	0.35	0.33	0.26	0.25	0.25
1987	0.47	0.22	0.45	0.26	0.31	0.30	0.23	0.23	0.23
1988	0.43	0.20	0.41	0.23	0.28	0.27	0.21	0.21	0.21
1989	0.38	0.18	0.37	0.21	0.25	0.24	0.19	0.19	0.19
1990	0.35	0.16	0.33	0.19	0.23	0.22	0.17	0.17	0.17
1991	0.31	0.14	0.30	0.17	0.21	0.20	0.15	0.16	0.16
1992	0.28	0.13	0.27	0.16	0.19	0.18	0.14	0.15	0.15
1993	0.25	0.12	0.25	0.14	0.17	0.17	0.13	0.13	0.13
1994	0.23	0.11	0.23	0.13	0.16	0.15	0.11	0.12	0.12
1995	0.21	0.10	0.20	0.12	0.14	0.14	0.10	0.11	0.11
1996	0.19	0.09	0.19	0.11	0.13	0.13	0.09	0.10	0.10
1997	0.17	0.08	0.17	0.10	0.12	0.11	0.09	0.09	0.09
1998	0.16	0.07	0.15	0.09	0.11	0.11	0.08	0.09	0.09
1999	0.14	0.07	0.14	0.08	0.10	0.10	0.07	0.08	0.08
2000	0.13	0.06	0.13	0.07	0.09	0.09	0.06	0.07	0.07
2001	0.12	0.06	0.12	0.07	0.08	0.08	0.06	0.07	0.07
2002	0.11	0.05	0.11	0.06	0.07	0.07	0.05	0.06	0.06
2003	0.10	0.05	0.10	0.06	0.07	0.07	0.05	0.06	0.06
2004	0.09	0.04	0.09	0.05	0.06	0.06	0.05	0.05	0.05
2005	0.08	0.04	0.08	0.05	0.06	0.06	0.04	0.05	0.05
2006	0.07	0.04	0.08	0.04	0.05	0.05	0.04	0.04	0.04
2007	0.07	0.03	0.07	0.04	0.05	0.05	0.03	0.04	0.04
2008	0.06	0.03	0.06	0.04	0.04	0.05	0.03	0.04	0.04
2009	0.06	0.03	0.06	0.03	0.04	0.04	0.03	0.03	0.03
2010	0.05	0.03	0.05	0.03	0.04	0.04	0.03	0.03	0.03

Table C-8 The job-exposure matrix for EMP in All 7 mines (all values in the table are arithmetic means in f/cc)

f/cc	All 7 mines								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	0.41	0.60	0.47	0.45	0.49	0.41	0.23	0.45	0.45
1956	0.39	0.57	0.45	0.43	0.47	0.40	0.22	0.43	0.43
1957	0.37	0.54	0.43	0.41	0.45	0.38	0.21	0.41	0.41
1958	0.36	0.52	0.41	0.39	0.43	0.36	0.20	0.39	0.39
1959	0.34	0.50	0.39	0.38	0.41	0.34	0.19	0.38	0.38
1960	0.32	0.47	0.37	0.36	0.39	0.33	0.18	0.36	0.36
1961	0.31	0.45	0.36	0.34	0.37	0.32	0.17	0.35	0.35
1962	0.30	0.43	0.34	0.33	0.36	0.30	0.17	0.33	0.33
1963	0.28	0.41	0.33	0.31	0.34	0.29	0.16	0.32	0.32
1964	0.27	0.40	0.31	0.30	0.33	0.28	0.15	0.30	0.30
1965	0.26	0.38	0.30	0.29	0.31	0.26	0.15	0.29	0.29
1966	0.25	0.36	0.29	0.27	0.30	0.25	0.14	0.28	0.28
1967	0.24	0.35	0.27	0.26	0.29	0.24	0.13	0.27	0.27
1968	0.23	0.33	0.26	0.25	0.27	0.23	0.13	0.25	0.25
1969	0.22	0.32	0.25	0.24	0.26	0.22	0.12	0.24	0.24
1970	0.21	0.30	0.24	0.23	0.25	0.21	0.12	0.23	0.23
1971	0.20	0.29	0.23	0.22	0.24	0.20	0.11	0.22	0.22
1972	0.19	0.28	0.22	0.21	0.23	0.19	0.11	0.21	0.21
1973	0.18	0.27	0.21	0.20	0.22	0.19	0.10	0.20	0.20
1974	0.17	0.25	0.20	0.19	0.21	0.18	0.10	0.20	0.20
1975	0.17	0.24	0.19	0.18	0.20	0.17	0.09	0.19	0.19
1976	0.16	0.23	0.18	0.18	0.19	0.16	0.09	0.18	0.18
1977	0.15	0.22	0.18	0.17	0.18	0.16	0.09	0.17	0.17
1978	0.15	0.21	0.17	0.16	0.18	0.15	0.08	0.16	0.16
1979	0.14	0.21	0.16	0.15	0.17	0.14	0.08	0.16	0.16
1980	0.13	0.20	0.15	0.15	0.16	0.14	0.08	0.15	0.15
1981	0.13	0.19	0.15	0.14	0.15	0.13	0.07	0.14	0.14
1982	0.12	0.18	0.14	0.14	0.15	0.13	0.07	0.14	0.14
1983	0.12	0.17	0.14	0.13	0.14	0.12	0.07	0.13	0.13
1984	0.11	0.17	0.13	0.12	0.14	0.12	0.06	0.13	0.13
1985	0.11	0.16	0.12	0.12	0.13	0.11	0.06	0.12	0.12
1986	0.10	0.15	0.12	0.11	0.13	0.11	0.06	0.12	0.12
1987	0.10	0.15	0.11	0.11	0.12	0.10	0.06	0.11	0.11
1988	0.09	0.14	0.11	0.11	0.12	0.10	0.05	0.11	0.11
1989	0.09	0.13	0.11	0.10	0.11	0.09	0.05	0.10	0.10
1990	0.09	0.13	0.10	0.10	0.11	0.09	0.05	0.10	0.10
1991	0.08	0.12	0.10	0.09	0.10	0.09	0.05	0.09	0.09
1992	0.08	0.12	0.09	0.09	0.10	0.08	0.05	0.09	0.09
1993	0.08	0.11	0.09	0.09	0.09	0.08	0.04	0.09	0.09
1994	0.07	0.11	0.09	0.08	0.09	0.08	0.04	0.08	0.08
1995	0.07	0.11	0.08	0.08	0.09	0.07	0.04	0.08	0.08
1996	0.07	0.10	0.08	0.08	0.08	0.07	0.04	0.08	0.08
1997	0.07	0.10	0.08	0.07	0.08	0.07	0.04	0.07	0.07
1998	0.06	0.09	0.07	0.07	0.08	0.06	0.04	0.07	0.07
1999	0.06	0.09	0.07	0.07	0.07	0.06	0.03	0.07	0.07
2000	0.06	0.09	0.07	0.06	0.07	0.06	0.03	0.06	0.06
2001	0.06	0.08	0.06	0.06	0.07	0.06	0.03	0.06	0.06
2002	0.05	0.08	0.06	0.06	0.06	0.06	0.03	0.06	0.06
2003	0.05	0.08	0.06	0.06	0.06	0.05	0.03	0.06	0.06
2004	0.05	0.07	0.06	0.05	0.06	0.05	0.03	0.05	0.05
2005	0.05	0.07	0.06	0.05	0.06	0.05	0.03	0.05	0.05
2006	0.05	0.07	0.05	0.05	0.06	0.05	0.03	0.05	0.05
2007	0.04	0.07	0.05	0.05	0.05	0.05	0.02	0.05	0.05
2008	0.04	0.06	0.05	0.05	0.05	0.04	0.02	0.05	0.05
2009	0.04	0.06	0.05	0.04	0.05	0.04	0.02	0.04	0.04
2010	0.04	0.06	0.05	0.04	0.05	0.04	0.02	0.04	0.04

Appendix D: NIOSH-EMP JEM – Approach 2 (Chapter 3)

Table D-1 The job-exposure matrix for EMP in ArcelorMittal (all values in the table are arithmetic means in f/cc)

f/cc	ArcelorMittal								
EMP	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	/	/	/	/	/	/	/	/	/
1975	/	/	/	/	/	/	/	/	/
1976	/	/	/	/	/	/	/	/	/
1977	0.03	0.05	0.10	0.05	0.08	0.02	0.05	0.05	0.05
1978	0.03	0.05	0.10	0.05	0.08	0.02	0.05	0.05	0.05
1979	0.03	0.05	0.10	0.04	0.08	0.02	0.05	0.05	0.05
1980	0.03	0.05	0.09	0.04	0.07	0.02	0.05	0.05	0.05
1981	0.03	0.04	0.09	0.04	0.07	0.02	0.05	0.05	0.05
1982	0.03	0.04	0.09	0.04	0.07	0.02	0.05	0.05	0.05
1983	0.03	0.04	0.09	0.04	0.07	0.02	0.05	0.05	0.05
1984	0.03	0.04	0.08	0.04	0.07	0.02	0.05	0.04	0.04
1985	0.03	0.04	0.08	0.04	0.06	0.02	0.05	0.04	0.04
1986	0.03	0.04	0.08	0.04	0.06	0.02	0.04	0.04	0.04
1987	0.02	0.04	0.08	0.04	0.06	0.02	0.04	0.04	0.04
1988	0.02	0.04	0.08	0.04	0.06	0.02	0.04	0.04	0.04
1989	0.02	0.04	0.07	0.04	0.06	0.02	0.04	0.04	0.04
1990	0.02	0.04	0.07	0.04	0.05	0.02	0.04	0.04	0.04
1991	0.02	0.04	0.07	0.04	0.05	0.02	0.04	0.04	0.04
1992	0.02	0.04	0.07	0.03	0.05	0.02	0.04	0.04	0.04
1993	0.02	0.04	0.07	0.03	0.05	0.02	0.04	0.04	0.04
1994	0.02	0.04	0.06	0.03	0.05	0.02	0.04	0.04	0.04
1995	0.02	0.04	0.06	0.03	0.05	0.02	0.04	0.04	0.04
1996	0.02	0.04	0.06	0.03	0.05	0.02	0.04	0.04	0.04
1997	0.02	0.04	0.06	0.03	0.04	0.02	0.04	0.04	0.04
1998	0.02	0.04	0.06	0.03	0.04	0.02	0.04	0.03	0.03
1999	0.02	0.04	0.06	0.03	0.04	0.02	0.03	0.03	0.03
2000	0.02	0.04	0.06	0.03	0.04	0.02	0.03	0.03	0.03
2001	0.02	0.04	0.05	0.03	0.04	0.02	0.03	0.03	0.03
2002	0.02	0.04	0.05	0.03	0.04	0.02	0.03	0.03	0.03
2003	0.02	0.04	0.05	0.03	0.04	0.02	0.03	0.03	0.03
2004	0.02	0.04	0.05	0.03	0.04	0.02	0.03	0.03	0.03
2005	0.02	0.04	0.05	0.03	0.03	0.02	0.03	0.03	0.03
2006	0.02	0.04	0.05	0.03	0.03	0.02	0.03	0.03	0.03
2007	0.02	0.04	0.05	0.03	0.03	0.02	0.03	0.03	0.03
2008	0.02	0.04	0.04	0.03	0.03	0.02	0.03	0.03	0.03
2009	0.02	0.04	0.04	0.02	0.03	0.02	0.03	0.03	0.03
2010	0.02	0.04	0.04	0.02	0.03	0.02	0.03	0.03	0.03

Table D-2 The job-exposure matrix for EMP in Hibbtac (all values in the table are arithmetic means in f/cc)

f/cc	**Hibbtac**								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	/	/	/	/	/	/	/	/	/
1968	/	/	/	/	/	/	/	/	/
1969	/	/	/	/	/	/	/	/	/
1970	/	/	/	/	/	/	/	/	/
1971	/	/	/	/	/	/	/	/	/
1972	/	/	/	/	/	/	/	/	/
1973	/	/	/	/	/	/	/	/	/
1974	0.02	0.07	0.01	0.03	0.08	0.02	0.03	0.04	0.04
1975	0.02	0.07	0.01	0.03	0.08	0.02	0.03	0.04	0.04
1976	0.02	0.07	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1977	0.02	0.07	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1978	0.02	0.07	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1979	0.02	0.06	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1980	0.02	0.06	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1981	0.02	0.06	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1982	0.02	0.06	0.01	0.03	0.07	0.02	0.03	0.04	0.04
1983	0.02	0.06	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1984	0.02	0.06	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1985	0.02	0.05	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1986	0.02	0.05	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1987	0.02	0.05	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1988	0.02	0.05	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1989	0.02	0.05	0.01	0.03	0.06	0.02	0.03	0.04	0.04
1990	0.02	0.05	0.02	0.03	0.06	0.02	0.03	0.04	0.04
1991	0.02	0.05	0.02	0.03	0.05	0.02	0.03	0.04	0.04
1992	0.02	0.05	0.02	0.03	0.05	0.02	0.02	0.04	0.04
1993	0.02	0.04	0.02	0.03	0.05	0.02	0.02	0.03	0.03
1994	0.02	0.04	0.02	0.03	0.05	0.02	0.02	0.03	0.03
1995	0.02	0.04	0.02	0.03	0.05	0.02	0.02	0.03	0.03
1996	0.02	0.04	0.02	0.03	0.05	0.03	0.02	0.03	0.03
1997	0.02	0.04	0.02	0.03	0.05	0.03	0.02	0.03	0.03
1998	0.02	0.04	0.02	0.03	0.05	0.03	0.02	0.03	0.03
1999	0.02	0.04	0.02	0.03	0.05	0.03	0.02	0.03	0.03
2000	0.02	0.04	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2001	0.02	0.04	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2002	0.02	0.04	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2003	0.02	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2004	0.02	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2005	0.02	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2006	0.02	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2007	0.02	0.03	0.02	0.03	0.04	0.03	0.02	0.03	0.03
2008	0.02	0.03	0.02	0.04	0.04	0.03	0.02	0.03	0.03
2009	0.02	0.03	0.02	0.04	0.04	0.03	0.02	0.03	0.03
2010	0.02	0.03	0.02	0.04	0.04	0.03	0.02	0.03	0.03

Table D-3 The job-exposure matrix for EMP in Keetac (all values in the table are arithmetic means in f/cc)

f/cc	Keetac								
EMP	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.08	0.13	0.23	0.23	0.07	0.02	0.05	0.15	0.15
1968	0.07	0.12	0.22	0.23	0.07	0.02	0.05	0.15	0.15
1969	0.07	0.12	0.21	0.23	0.07	0.02	0.05	0.14	0.14
1970	0.07	0.11	0.21	0.22	0.06	0.02	0.05	0.14	0.14
1971	0.07	0.11	0.20	0.22	0.06	0.02	0.05	0.14	0.14
1972	0.07	0.11	0.20	0.22	0.06	0.02	0.05	0.14	0.14
1973	0.07	0.10	0.19	0.21	0.06	0.02	0.05	0.13	0.13
1974	0.07	0.10	0.18	0.21	0.06	0.02	0.05	0.13	0.13
1975	0.07	0.10	0.18	0.21	0.06	0.02	0.05	0.13	0.13
1976	0.06	0.09	0.17	0.20	0.06	0.02	0.04	0.13	0.13
1977	0.06	0.09	0.17	0.20	0.06	0.02	0.04	0.12	0.12
1978	0.06	0.09	0.16	0.20	0.06	0.02	0.04	0.12	0.12
1979	0.06	0.08	0.16	0.20	0.06	0.02	0.04	0.12	0.12
1980	0.06	0.08	0.16	0.19	0.06	0.02	0.04	0.12	0.12
1981	0.06	0.08	0.15	0.19	0.06	0.02	0.04	0.11	0.11
1982	0.06	0.08	0.15	0.19	0.06	0.02	0.04	0.11	0.11
1983	0.06	0.07	0.14	0.18	0.06	0.02	0.04	0.11	0.11
1984	0.06	0.07	0.14	0.18	0.06	0.02	0.04	0.11	0.11
1985	0.05	0.07	0.13	0.18	0.06	0.02	0.04	0.10	0.10
1986	0.05	0.07	0.13	0.18	0.06	0.02	0.04	0.10	0.10
1987	0.05	0.07	0.13	0.17	0.06	0.03	0.04	0.10	0.10
1988	0.05	0.06	0.12	0.17	0.06	0.03	0.03	0.10	0.10
1989	0.05	0.06	0.12	0.17	0.06	0.03	0.03	0.10	0.10
1990	0.05	0.06	0.12	0.17	0.06	0.03	0.03	0.09	0.09
1991	0.05	0.06	0.11	0.16	0.06	0.03	0.03	0.09	0.09
1992	0.05	0.06	0.11	0.16	0.06	0.03	0.03	0.09	0.09
1993	0.05	0.05	0.11	0.16	0.06	0.03	0.03	0.09	0.09
1994	0.05	0.05	0.10	0.16	0.06	0.03	0.03	0.09	0.09
1995	0.05	0.05	0.10	0.15	0.06	0.03	0.03	0.08	0.08
1996	0.05	0.05	0.10	0.15	0.06	0.03	0.03	0.08	0.08
1997	0.04	0.05	0.10	0.15	0.06	0.03	0.03	0.08	0.08
1998	0.04	0.05	0.09	0.15	0.06	0.03	0.03	0.08	0.08
1999	0.04	0.04	0.09	0.15	0.06	0.03	0.03	0.08	0.08
2000	0.04	0.04	0.09	0.14	0.06	0.03	0.03	0.08	0.08
2001	0.04	0.04	0.09	0.14	0.06	0.03	0.03	0.08	0.08
2002	0.04	0.04	0.08	0.14	0.06	0.03	0.03	0.07	0.07
2003	0.04	0.04	0.08	0.14	0.06	0.03	0.03	0.07	0.07
2004	0.04	0.04	0.08	0.14	0.06	0.03	0.03	0.07	0.07
2005	0.04	0.04	0.08	0.13	0.06	0.03	0.02	0.07	0.07
2006	0.04	0.04	0.07	0.13	0.06	0.03	0.02	0.07	0.07
2007	0.04	0.03	0.07	0.13	0.06	0.03	0.02	0.07	0.07
2008	0.04	0.03	0.07	0.13	0.06	0.03	0.02	0.07	0.07
2009	0.04	0.03	0.07	0.13	0.06	0.03	0.02	0.06	0.06
2010	0.04	0.03	0.07	0.12	0.06	0.03	0.02	0.06	0.06

Table D-4 The job-exposure matrix for EMP in LTV (all values in the table are arithmetic means in f/cc)

f/cc	LTV								
EMP	Min ing	Crus hing	Concentra ting	Pelletizi ng	Shop (mobile)	Shop (stationary)	Office/control room	Janit or	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1958	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1959	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.10	0.10
1960	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1961	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1962	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1963	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1964	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1965	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1966	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1967	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1968	0.07	0.22	0.05	0.03	0.19	0.06	0.01	0.10	0.10
1969	0.07	0.22	0.05	0.04	0.19	0.06	0.01	0.10	0.10
1970	0.07	0.22	0.06	0.04	0.19	0.06	0.01	0.10	0.10
1971	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.10	0.10
1972	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.10	0.10
1973	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.11	0.11
1974	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.11	0.11
1975	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1976	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1977	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1978	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1979	0.07	0.22	0.08	0.04	0.18	0.07	0.01	0.11	0.11
1980	0.07	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1981	0.07	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1982	0.08	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1983	0.08	0.22	0.09	0.05	0.18	0.07	0.01	0.11	0.11
1984	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.11	0.11
1985	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.11	0.11
1986	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.12	0.12
1987	0.08	0.22	0.10	0.05	0.17	0.07	0.01	0.12	0.12
1988	0.08	0.22	0.10	0.05	0.17	0.08	0.01	0.12	0.12
1989	0.08	0.22	0.10	0.06	0.17	0.08	0.01	0.12	0.12
1990	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1991	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1992	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1993	0.08	0.22	0.12	0.06	0.17	0.08	0.01	0.12	0.12
1994	0.08	0.22	0.12	0.06	0.17	0.08	0.01	0.12	0.12
1995	0.08	0.22	0.13	0.06	0.17	0.08	0.02	0.12	0.12
1996	0.08	0.22	0.13	0.07	0.17	0.08	0.02	0.12	0.12
1997	0.08	0.22	0.13	0.07	0.16	0.09	0.02	0.12	0.12
1998	0.08	0.22	0.14	0.07	0.16	0.09	0.02	0.13	0.13
1999	0.08	0.22	0.14	0.07	0.16	0.09	0.02	0.13	0.13
2000	0.08	0.22	0.15	0.07	0.16	0.09	0.02	0.13	0.13
2001	0.08	0.22	0.15	0.07	0.16	0.09	0.02	0.13	0.13
2002	/	/	/	/	/	/	/	/	/
2003	/	/	/	/	/	/	/	/	/
2004	/	/	/	/	/	/	/	/	/
2005	/	/	/	/	/	/	/	/	/
2006	/	/	/	/	/	/	/	/	/
2007	/	/	/	/	/	/	/	/	/
2008	/	/	/	/	/	/	/	/	/
2009	/	/	/	/	/	/	/	/	/
2010	/	/	/	/	/	/	/	/	/

Table D-5 The job-exposure matrix for EMP in Minntac (all values in the table are arithmetic means in f/cc)

f/cc	Minntac								
EMP	Min ing	Crus hing	Concentra ting	Pelletizi ng	Shop (mobile)	Shop (stationary)	Office/control room	Janit or	All 8 departments
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	/	/	/	/	/	/	/	/	/
1965	/	/	/	/	/	/	/	/	/
1966	/	/	/	/	/	/	/	/	/
1967	0.04	0.03	0.02	0.15	0.22	0.05	0.02	0.06	0.06
1968	0.04	0.03	0.02	0.15	0.21	0.05	0.02	0.06	0.06
1969	0.04	0.03	0.02	0.15	0.21	0.05	0.02	0.06	0.06
1970	0.04	0.03	0.02	0.14	0.20	0.05	0.02	0.06	0.06
1971	0.04	0.04	0.02	0.14	0.20	0.05	0.02	0.06	0.06
1972	0.04	0.04	0.02	0.14	0.19	0.05	0.02	0.06	0.06
1973	0.04	0.04	0.02	0.14	0.19	0.05	0.02	0.06	0.06
1974	0.04	0.04	0.02	0.14	0.18	0.05	0.02	0.06	0.06
1975	0.04	0.04	0.02	0.14	0.18	0.05	0.02	0.06	0.06
1976	0.04	0.04	0.02	0.14	0.18	0.05	0.02	0.06	0.06
1977	0.04	0.04	0.02	0.14	0.17	0.05	0.02	0.06	0.06
1978	0.03	0.04	0.02	0.14	0.17	0.05	0.02	0.06	0.06
1979	0.03	0.04	0.02	0.14	0.16	0.05	0.02	0.06	0.06
1980	0.03	0.04	0.02	0.14	0.16	0.05	0.02	0.06	0.06
1981	0.03	0.04	0.03	0.14	0.15	0.05	0.02	0.06	0.06
1982	0.03	0.05	0.03	0.14	0.15	0.05	0.02	0.06	0.06
1983	0.03	0.05	0.03	0.14	0.15	0.05	0.02	0.06	0.06
1984	0.03	0.05	0.03	0.14	0.14	0.05	0.02	0.06	0.06
1985	0.03	0.05	0.03	0.14	0.14	0.05	0.02	0.06	0.06
1986	0.03	0.05	0.03	0.14	0.14	0.05	0.02	0.06	0.06
1987	0.03	0.05	0.03	0.14	0.13	0.05	0.02	0.06	0.06
1988	0.03	0.05	0.03	0.14	0.13	0.05	0.02	0.06	0.06
1989	0.03	0.05	0.03	0.14	0.13	0.05	0.02	0.06	0.06
1990	0.03	0.05	0.03	0.14	0.12	0.05	0.02	0.06	0.06
1991	0.03	0.06	0.03	0.14	0.12	0.05	0.02	0.06	0.06
1992	0.03	0.06	0.03	0.14	0.12	0.05	0.02	0.06	0.06
1993	0.03	0.06	0.03	0.14	0.11	0.05	0.02	0.06	0.06
1994	0.03	0.06	0.03	0.13	0.11	0.05	0.02	0.06	0.06
1995	0.03	0.06	0.03	0.13	0.11	0.05	0.02	0.06	0.06
1996	0.03	0.06	0.04	0.13	0.11	0.05	0.02	0.06	0.06
1997	0.03	0.06	0.04	0.13	0.10	0.05	0.02	0.06	0.06
1998	0.03	0.06	0.04	0.13	0.10	0.05	0.02	0.06	0.06
1999	0.03	0.07	0.04	0.13	0.10	0.05	0.02	0.06	0.06
2000	0.03	0.07	0.04	0.13	0.10	0.05	0.02	0.07	0.07
2001	0.03	0.07	0.04	0.13	0.09	0.05	0.02	0.07	0.07
2002	0.03	0.07	0.04	0.13	0.09	0.05	0.02	0.07	0.07
2003	0.03	0.07	0.04	0.13	0.09	0.05	0.02	0.07	0.07
2004	0.03	0.07	0.04	0.13	0.09	0.05	0.03	0.07	0.07
2005	0.03	0.08	0.04	0.13	0.08	0.05	0.03	0.07	0.07
2006	0.03	0.08	0.04	0.13	0.08	0.05	0.03	0.07	0.07
2007	0.03	0.08	0.04	0.13	0.08	0.05	0.03	0.07	0.07
2008	0.03	0.08	0.05	0.13	0.08	0.05	0.03	0.07	0.07
2009	0.03	0.08	0.05	0.13	0.08	0.05	0.03	0.07	0.07
2010	0.03	0.08	0.05	0.13	0.07	0.05	0.03	0.07	0.07

Table D-6 The job-exposure matrix for EMP in Northshore (all values in the table are arithmetic means in f/cc)

f/cc	Northshore								
EMP	Mining	Crushing	Concentrating	Pelletizing	Shop (mobile)	Shop (stationary)	Office/control room	Janitor	All 8 departments
1955	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1956	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1957	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1958	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.09	0.09
1959	0.07	0.22	0.04	0.03	0.20	0.05	0.01	0.10	0.10
1960	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1961	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1962	0.07	0.22	0.04	0.03	0.19	0.05	0.01	0.10	0.10
1963	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1964	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1965	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1966	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1967	0.07	0.22	0.05	0.03	0.19	0.05	0.01	0.10	0.10
1968	0.07	0.22	0.05	0.03	0.19	0.06	0.01	0.10	0.10
1969	0.07	0.22	0.05	0.04	0.19	0.06	0.01	0.10	0.10
1970	0.07	0.22	0.06	0.04	0.19	0.06	0.01	0.10	0.10
1971	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.10	0.10
1972	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.10	0.10
1973	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.11	0.11
1974	0.07	0.22	0.06	0.04	0.18	0.06	0.01	0.11	0.11
1975	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1976	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1977	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1978	0.07	0.22	0.07	0.04	0.18	0.06	0.01	0.11	0.11
1979	0.07	0.22	0.08	0.04	0.18	0.07	0.01	0.11	0.11
1980	0.07	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1981	0.07	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1982	0.08	0.22	0.08	0.05	0.18	0.07	0.01	0.11	0.11
1983	0.08	0.22	0.09	0.05	0.18	0.07	0.01	0.11	0.11
1984	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.11	0.11
1985	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.11	0.11
1986	0.08	0.22	0.09	0.05	0.17	0.07	0.01	0.12	0.12
1987	0.08	0.22	0.10	0.05	0.17	0.07	0.01	0.12	0.12
1988	0.08	0.22	0.10	0.05	0.17	0.08	0.01	0.12	0.12
1989	0.08	0.22	0.10	0.06	0.17	0.08	0.01	0.12	0.12
1990	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1991	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1992	0.08	0.22	0.11	0.06	0.17	0.08	0.01	0.12	0.12
1993	0.08	0.22	0.12	0.06	0.17	0.08	0.01	0.12	0.12
1994	0.08	0.22	0.12	0.06	0.17	0.08	0.01	0.12	0.12
1995	0.08	0.22	0.13	0.06	0.17	0.08	0.02	0.12	0.12
1996	0.08	0.22	0.13	0.07	0.17	0.08	0.02	0.12	0.12
1997	0.08	0.22	0.13	0.07	0.16	0.09	0.02	0.12	0.12
1998	0.08	0.22	0.14	0.07	0.16	0.09	0.02	0.13	0.13
1999	0.08	0.22	0.14	0.07	0.16	0.09	0.02	0.13	0.13
2000	0.08	0.22	0.15	0.07	0.16	0.09	0.02	0.13	0.13
2001	0.08	0.22	0.15	0.07	0.16	0.09	0.02	0.13	0.13
2002	0.08	0.21	0.16	0.07	0.16	0.09	0.02	0.13	0.13
2003	0.08	0.21	0.16	0.08	0.16	0.09	0.02	0.13	0.13
2004	0.08	0.21	0.17	0.08	0.16	0.10	0.02	0.13	0.13
2005	0.08	0.21	0.17	0.08	0.16	0.10	0.02	0.13	0.13
2006	0.08	0.21	0.18	0.08	0.16	0.10	0.02	0.13	0.13
2007	0.08	0.21	0.18	0.08	0.16	0.10	0.02	0.13	0.13
2008	0.08	0.21	0.19	0.09	0.16	0.10	0.02	0.14	0.14
2009	0.08	0.21	0.20	0.09	0.16	0.10	0.02	0.14	0.14
2010	0.08	0.21	0.20	0.09	0.16	0.11	0.02	0.14	0.14

Table D-7 The job-exposure matrix for EMP in Utac (all values in the table are arithmetic means in f/cc)

f/cc	Utac								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	/	/	/	/	/	/	/	/	/
1956	/	/	/	/	/	/	/	/	/
1957	/	/	/	/	/	/	/	/	/
1958	/	/	/	/	/	/	/	/	/
1959	/	/	/	/	/	/	/	/	/
1960	/	/	/	/	/	/	/	/	/
1961	/	/	/	/	/	/	/	/	/
1962	/	/	/	/	/	/	/	/	/
1963	/	/	/	/	/	/	/	/	/
1964	0.05	0.01	0.05	0.04	0.10	0.09	0.01	0.03	0.03
1965	0.05	0.01	0.05	0.04	0.10	0.09	0.01	0.03	0.03
1966	0.05	0.01	0.05	0.04	0.10	0.08	0.01	0.03	0.03
1967	0.05	0.01	0.05	0.04	0.09	0.08	0.01	0.03	0.03
1968	0.05	0.01	0.05	0.04	0.09	0.08	0.01	0.03	0.03
1969	0.05	0.01	0.05	0.04	0.09	0.08	0.01	0.03	0.03
1970	0.05	0.01	0.05	0.04	0.09	0.07	0.01	0.03	0.03
1971	0.05	0.01	0.05	0.04	0.09	0.07	0.01	0.03	0.03
1972	0.05	0.01	0.05	0.04	0.09	0.07	0.01	0.03	0.03
1973	0.05	0.01	0.05	0.04	0.09	0.07	0.01	0.03	0.03
1974	0.05	0.02	0.05	0.04	0.09	0.07	0.01	0.03	0.03
1975	0.05	0.02	0.05	0.04	0.08	0.07	0.01	0.03	0.03
1976	0.05	0.02	0.05	0.04	0.08	0.06	0.01	0.03	0.03
1977	0.05	0.02	0.05	0.04	0.08	0.06	0.01	0.03	0.03
1978	0.05	0.02	0.05	0.04	0.08	0.06	0.02	0.03	0.03
1979	0.05	0.02	0.05	0.04	0.08	0.06	0.02	0.03	0.03
1980	0.05	0.02	0.05	0.04	0.08	0.06	0.02	0.03	0.03
1981	0.05	0.02	0.05	0.04	0.08	0.06	0.02	0.03	0.03
1982	0.06	0.02	0.05	0.04	0.08	0.05	0.02	0.03	0.03
1983	0.06	0.02	0.05	0.04	0.08	0.05	0.02	0.03	0.03
1984	0.06	0.02	0.05	0.04	0.08	0.05	0.02	0.03	0.03
1985	0.06	0.02	0.05	0.04	0.07	0.05	0.02	0.03	0.03
1986	0.06	0.02	0.05	0.04	0.07	0.05	0.02	0.04	0.04
1987	0.06	0.02	0.05	0.04	0.07	0.05	0.02	0.04	0.04
1988	0.06	0.02	0.05	0.04	0.07	0.05	0.02	0.04	0.04
1989	0.06	0.02	0.05	0.04	0.07	0.05	0.02	0.04	0.04
1990	0.06	0.02	0.05	0.04	0.07	0.04	0.02	0.04	0.04
1991	0.06	0.02	0.05	0.04	0.07	0.04	0.02	0.04	0.04
1992	0.06	0.02	0.05	0.04	0.07	0.04	0.02	0.04	0.04
1993	0.06	0.02	0.05	0.04	0.07	0.04	0.02	0.04	0.04
1994	0.06	0.02	0.05	0.04	0.07	0.04	0.02	0.04	0.04
1995	0.06	0.02	0.05	0.04	0.06	0.04	0.02	0.04	0.04
1996	0.06	0.02	0.05	0.04	0.06	0.04	0.02	0.04	0.04
1997	0.06	0.03	0.05	0.04	0.06	0.04	0.02	0.04	0.04
1998	0.07	0.03	0.05	0.04	0.06	0.04	0.02	0.04	0.04
1999	0.07	0.03	0.05	0.04	0.06	0.04	0.02	0.04	0.04
2000	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2001	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2002	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2003	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2004	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2005	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2006	0.07	0.03	0.05	0.04	0.06	0.03	0.02	0.04	0.04
2007	0.07	0.03	0.05	0.04	0.05	0.03	0.02	0.04	0.04
2008	0.07	0.03	0.05	0.04	0.05	0.03	0.02	0.04	0.04
2009	0.07	0.03	0.05	0.04	0.05	0.03	0.02	0.04	0.04
2010	0.07	0.03	0.05	0.04	0.05	0.03	0.02	0.04	0.04

Table D-8 The job-exposure matrix for EMP in All 7 mines (all values in the table are arithmetic means in f/cc)

f/cc	All 7 mines								
EMP	**Min ing**	**Crus hing**	**Concentra ting**	**Pelletizi ng**	**Shop (mobile)**	**Shop (stationary)**	**Office/control room**	**Janit or**	**All 8 departments**
1955	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1956	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1957	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1958	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1959	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1960	0.05	0.13	0.03	0.07	0.11	0.05	0.03	0.07	0.07
1961	0.05	0.13	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1962	0.05	0.13	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1963	0.05	0.13	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1964	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1965	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1966	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1967	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1968	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1969	0.05	0.12	0.03	0.07	0.10	0.05	0.03	0.07	0.07
1970	0.05	0.12	0.03	0.07	0.10	0.05	0.02	0.07	0.07
1971	0.05	0.12	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1972	0.05	0.12	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1973	0.05	0.12	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1974	0.05	0.12	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1975	0.05	0.12	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1976	0.05	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1977	0.04	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1978	0.04	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1979	0.04	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1980	0.04	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1981	0.04	0.11	0.04	0.07	0.09	0.05	0.02	0.07	0.07
1982	0.04	0.11	0.04	0.07	0.08	0.05	0.02	0.07	0.07
1983	0.04	0.11	0.04	0.08	0.08	0.05	0.02	0.07	0.07
1984	0.04	0.11	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1985	0.04	0.11	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1986	0.04	0.11	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1987	0.04	0.11	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1988	0.04	0.11	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1989	0.04	0.10	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1990	0.04	0.10	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1991	0.04	0.10	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1992	0.04	0.10	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1993	0.04	0.10	0.05	0.08	0.08	0.05	0.02	0.07	0.07
1994	0.04	0.10	0.05	0.08	0.07	0.05	0.02	0.06	0.06
1995	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
1996	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
1997	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
1998	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
1999	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
2000	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
2001	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
2002	0.04	0.10	0.06	0.08	0.07	0.05	0.02	0.06	0.06
2003	0.04	0.10	0.07	0.08	0.07	0.05	0.02	0.06	0.06
2004	0.04	0.09	0.07	0.08	0.07	0.05	0.02	0.06	0.06
2005	0.04	0.09	0.07	0.08	0.07	0.05	0.02	0.06	0.06
2006	0.04	0.09	0.07	0.08	0.07	0.05	0.02	0.06	0.06
2007	0.04	0.09	0.07	0.08	0.07	0.05	0.02	0.06	0.06
2008	0.04	0.09	0.07	0.08	0.06	0.05	0.02	0.06	0.06
2009	0.04	0.09	0.07	0.08	0.06	0.05	0.02	0.06	0.06
2010	0.04	0.09	0.08	0.08	0.06	0.05	0.02	0.06	0.06