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Development of a job-exposure matrix for exposure to total and fine particulate matter in the aluminum industry

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Abstract

Increasing evidence indicates that exposure to particulate matter (PM) at environmental concentrations increases the risk of cardiovascular disease, particularly PM with an aerodynamic diameter of less than 2.5μm ($PM_{2.5}$). Despite this, the health impacts of higher occupational exposures to $PM_{2.5}$ have rarely been evaluated. In part, this research gap derives from the absence of information on $PM_{2.5}$ exposures in the workplace. To address this gap, we have developed a job-exposure matrix (JEM) to estimate exposure to two size fractions of PM in the aluminum industry. Measurements of total PM (TPM) and $PM_{2.5}$ were used to develop exposure metrics for an epidemiologic study.

TPM exposures for distinct exposure groups (DEGs) in the JEM were calculated using 8,385 personal TPM samples collected at 11 facilities (1980-2011). For 8 of these facilities, simultaneous $PM_{2.5}$ and TPM personal monitoring was conducted from 2010-2011 to determine

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the percent of TPM that is composed of $PM_{2.5}$ (%$PM_{2.5}$) in each DEG. The mean TPM from the JEM was then multiplied by %$PM_{2.5}$ to calculate $PM_{2.5}$ exposure concentrations in each DEG.

Exposures in the smelters were substantially higher than in fabrication units; mean TPM concentrations in smelters and fabrication facilities were 3.86 mg/m^3 and 0.76 mg/m^3, and the corresponding mean $PM_{2.5}$ concentrations were 2.03 mg/m^3 and 0.40 mg/m^3. Observed occupational exposures in this study generally exceeded environmental $PM_{2.5}$ concentrations by an order of magnitude.

Introduction

This paper describes the development of a job-exposure matrix (JEM) created to quantify personal exposures to two size fractions of particulate matter (PM) – total PM (TPM) and PM with an aerodynamic diameter of less than 2.5μm ($PM_{2.5}$) – in the aluminum industry. Ultimately the JEM provides the basis of an exposure assessment linked to an epidemiologic study of possible work related health effects. To date, control of occupational exposure to particles has focused on the *composition* and specific toxicity of the constituents rather than the mass concentration or particle size. Occupational exposure limits for "particulates not otherwise regulated," or PNORs, are orders of magnitude greater than daily environmental limits, which have evolved from total suspended particles (150 μg/m^3, United States Environmental Protection Agency (USEPA), 1971) to PM_{10} (65 μg/m^3, USEPA 1987) to $PM_{2.5}$ (USEPA daily maximum 65 μg/m^3 in 1997 lowered to 35 μg/m^3 in 2006). By contrast, the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) for PNORs is 15,000 μg/m^3. Increasing evidence indicates that exposure to particles at environmental concentrations increases the risk of cardiovascular disease (1–11). The health impact of higher occupational exposures to particulate matter, however, has rarely been evaluated. To address this research gap, an epidemiological study was undertaken to assess the health effects of exposure to airborne PM for workers at an aluminum manufacturing company.

At each step of the modern aluminum manufacturing process there is occupational exposure to airborne PM (12). In mining the bauxite ore workers are exposed to particles from bauxite dust and to a lesser extent crystalline silica dust. During refining the PM exposures are primarily from inorganic dusts (bauxite, crystalline silica, alumina). Smelter workers are exposed to PM from many sources, including PM generated during the reduction of alumina to aluminum metal in the Hall-Heroult process. Although this reduction process takes place in carbon-lined steel pots that are hooded to decrease exposures to the mixture of dusts, metals, and fumes produced during smelting, these potroom exposures are among the highest PM exposures associated with aluminum manufacturing as employees work directly over the pots when replacing anodes. Following smelting, aluminum metal is fabricated into numerous diverse products, from aluminum used in can sheet to airplane parts, and workers may be exposed to metalworking fluids, lubricating oils and metal particles. These work processes are generally conducted at separate facilities, although smelting and fabrication sometimes take place in the same location. Research on PM exposures to workers throughout many stages of aluminum production is scant. Most field measurements reported in the literature have been taken in smelter potrooms and focused on exposures to PM

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constituents (e.g. fluorides, coal tar pitch volatiles) or metal exposures during welding or silica exposures (12–21).

Within the limited literature on PM exposures across the aluminum industry, there is very little information about the particle size distributions. What does exist is focused either on particle morphology or particle aging in smelters (22,23). Although respirable particulate, inhalable particulate, and total particulate concentrations have been reported, these have focused on a few potroom jobs (14,16). There have been no studies that present exposures of different particle sizes across multiple stages of the aluminum industry, nor with sufficient samples to construct a JEM for epidemiology studies.

The research we present in this paper fills both gaps. We measured concurrent personal $PM_{2.5}$ and TPM exposure in aluminium workers and integrated these data with a large company database of IH measurements. Using an expert-based approach, we have developed a job-exposure matrix (JEM) with exposures for two sizes of particulate matter – total particulate matter (TPM) and $PM_{2.5}$ – at facilities performing manufacturing operations as various as refining, smelting, and fabricating metal products.

Methods

The exposure assessment focused on PM exposure in 11 manufacturing facilities of a single aluminum manufacturing company in the United States (Table 1). Facilities were selected to encompass different manufacturing work processes throughout the company, from refining through fabrication. Of these 11 facilities, 1 is a refinery, 5 have smelters (all use the prebake technology), and 9 have fabrication units engaged in various processes, including rolling, extrusion, forging, and casting as well as lighter metalworking. Three facilities include both smelters and fabrication. Details of aluminum refining, smelting, and fabrication have been described elsewhere (12).

Within the company, industrial hygiene data have been collected for 60 years. Sampling conducted over the past 25 years has been compiled in an extensive industrial hygiene database, HYGenius (>300,000 samples). Samples were collected in each facility under the direction of certified industrial hygienists (CIH) and analyzed at an AIHA accredited IH laboratory (Clark Laboratories LLC, Jefferson Hills, PA). Samples were collected under one of the following three strategies: random, diagnostic, or worst case (as defined by the company). Random samples were meant to capture day-to-day regular work within the targeted job. Diagnostic and worst case samples were collected to answer specific questions about job exposures or to monitor exposures during specific tasks. The random samples form the basis for the JEM. However, sampling was generally targeted only for those jobs where 5% or more of the exposures were greater than 30% of the company's occupational exposure limit (OEL), of 10 mg/m^3 throughout the company for the duration of sampling presented, as judged at each facility under the direction of the facility IH. In general, sampling was not performed for jobs where, after inspection by the facility IH, neither TPM nor any of the specific chemical exposures (e.g., fluoride, oil mist, metals) was over 30% of the OEL, as judged by the facility IH unless the toxicity of the agent of interest warranted sampling at lower exposure levels.

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The HYGenius database contains detailed information including agent, purpose of sampling, duration of sampling, location of sampling (facility, department, job, task), whether personal or area sample, use and type of personal protective equipment, and sample result. The database contains over 100 agents of interest. Information in the database concerning particle mass concentration is limited to TPM and respirable particles (far fewer). Because each of the 11 facilities in the study was acquired by the company at different times, the dates of the earliest samples in HYGenius vary across facilities (Table 1).

The JEM was developed in the following five steps: standardization of job titles into distinct exposure groups (DEGs); categorization of DEGs into major manufacturing process categories; calculation of TPM from exposure from data in HYGenius; simultaneous $PM_{2.5}$ and TPM measurement on a subset of workers at 8 facilities to determine the percent of TPM in each DEG that is composed of $PM_{2.5}$ (%$PM_{2.5}$); and, calculation of $PM_{2.5}$ from the TPM and the percent $PM_{2.5}$ in each DEG. Each of these steps is described in more detail below.

Creation of Distinct Exposure Groups (DEGs)

As is true in many workplaces, hundreds to thousands of job title/department combinations existed in HYGenius database for each facility, and these did not readily correspond to the job titles in the various human resources databases that track job changes for all employees. In order to reconstruct the job–exposure history of each individual in the epidemiologic study, jobs judged to have qualitatively and quantitatively similar exposures were aggregated into distinct exposure groups (DEGs) and mappings developed between the human resources databases and HYGenius.

A senior industrial hygiene manager (CDE) at the corporation led the aggregation effort. She created a team of site managers, industrial hygienists, and health and safety experts and worked closely with another researcher (LC). This team of experts began by defining the core work processes within the company. Within each core process and facility, the team created distinct exposure groups (DEGs) that aggregated jobs by department, job title, and job tasks based on similarity of the work performed. The DEGs were chosen by the team to be facility-specific, rather than pooled across facilities, because the organization of the tasks within similar jobs and departments was not always comparable at different facilities. The final step linked these DEGs to over 10,000 different human resources job titles contained in the human resources database across locations (24).

Categorization into major manufacturing process categories

In addition to the quantitative values for TPM and $PM_{2.5}$ each DEG was assigned one of four qualitative major manufacturing process categories: smelting; fabricating; refining; or mixed smelting/fabrication (for DEGs in which an employee might work in either or both smelting and fabrication or be exposed to either operation type, e.g., electrician).

Generation of TPM Exposure for JEM

TPM sampling data from the HYGenius database was used to construct DEG-specific exposures for the JEM. Inclusion criteria for the TPM data were that samples had to be valid

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personal samples collected randomly (rather than as part of a specific diagnostic evaluation or as targeted worst case) for at least 70% of an employee's shift. We used only the random samples because they represent the day-to-day exposures of the workers, rather than specific events that diagnostic or worst case samples are designed to capture. TPM samples were collected using 37mm filters in traditional closed-face filter cassettes and analyzed gravimetrically (NIOSH Method 0500). Standard quality assurance methods were followed including calibrating pump flow before and after sampling, checking the integrity of the tubing and samplers, as well as following laboratory analysis protocols outlined in NIOSH 0500 (25). Samples analyzed prior to the first issue of NIOSH 0500 were analyzed in accordance with the NIOSH recommendations in the NIOSH Manual of Analytical Methods. The exposure metric in each cell was the arithmetic mean value of all the samples for each DEG. Because the exposure estimates are meant to capture annual average concentrations, arithmetic rather than geometric means are most appropriate for the JEM (26). However, there were 134 samples (approximately 1% of the total samples used, affecting a total of 42 DEGs) with extremely high values, >50 mg/m^3. We considered three options for handling these extreme values in the JEM: include them without adjustment, omit them, or adjust them by some factor. In the table S1 (supplemental material) we show the comparison of these three methods for the 42 DEGs. Since these samples are valid measurements, we chose to adjust them by the respirator used during the sample collection as reported by the IH. Using the style and type of respirator, we applied the OSHA respirator protection factor (27) as an adjustment. The OSHA respirator protection factor varies from 10 to 10,000, depending on the type of the respirator. Another way to include all values without the high measurements overly influencing the average exposure is to use the geometric mean of all of the samples; the geometric mean of the unadjusted samples are included as part of the JEM as an alternative exposure metric.

If TPM samples were not available for a particular DEG, TPM samples from a similar DEG at the same or comparable facility were used. If information at the same or a comparable facility did not exist for a particular DEG, a default concentration of 0.10 mg/m^3 was applied to the DEG cell of the JEM. We selected 0.10 mg/m^3 as our default because it is higher than average environmental concentrations, in the lowest 5% of the TPM samples in our JEM, and is a simple number with one significant figure.

In order to preserve the information about the source of the data, each DEG-TPM cell in the JEM was assigned a ranking reflecting confidence in the source. The three categories of data sources for TPM were: measured data; surrogate measurements from a comparable DEG; default value when no other data were available. This information on data sources can be used in sensitivity analyses to examine the impact of potential exposure misclassification in an epidemiologic study and to guide future sampling.

Measurement of $PM_{2.5}$ and $\%PM_{2.5}$

Personal sampling for $PM_{2.5}$ and TPM was conducted in 2010 and 2011 at 8 of the 11 facilities (Table 1); 3 facilities were not selected for sampling due to partial curtailment of operations at the facility or closure at the time of the monitoring campaign. This exposure monitoring campaign was designed both to measure personal exposures to $PM_{2.5}$ and to

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derive the percent of TPM that is $PM_{2.5}$ across jobs at these facilities. Two types of PM samplers were used to evaluate $PM_{2.5}$ exposures: the traditional closed-face 37 mm cassettes (TPM) operated at 2 liters per minute and SKC Personal Modular Impactors (PMIs) operated at 3 liters per minute with 3 stages: > 10 μm; 2.5 −10 μm, and < 2.5 μm ($PM_{2.5}$). These samplers were paired and worn simultaneously by each worker. Analysis of PMI filters was by NIOSH 0500, with the same procedures and quality controls listed above.

The percent of $PM_{2.5}$ in the TPM samples was calculated for each sample by dividing the concentration of $PM_{2.5}$ (from the PMI) by the concentration of paired TPM sample (cassette) in order to use the historical TPM cassette values to calculate the historical $PM_{2.5}$ exposures in each DEG. The percentages within each DEG were averaged to generate the $\%PM_{2.5}$ for the JEM. For DEGs in which the percent of the total particles that are composed of fine particles ($\% PM_{2.5}$) was not measured, we used data from similar jobs at other facilities or jobs judged to have similar size distribution (measurements from comparable jobs). If no such comparable measurements were available, we estimated the $\% PM_{2.5}$ from an understanding of processes and associated particle size distribution; thus, some processes (e.g. welding, combustion) emit predominantly fine particles, while other processes (e.g. grinding) emit larger particles. Knowledge of the predominant source of particles in each job informed *estimations* of the $\% PM_{2.5}$ particles in TPM for the remaining DEGs: those in which the sources were predominantly fine particles were assigned 80% $PM_{2.5}$, those in which the sources emit predominantly larger particles were assigned 20% $PM_{2.5}$ and those with mixed sources, or unknown size distributions were assigned 50% $PM_{2.5}$. In summary, the three methods used to assign %PM2.5: direct measurements in the DEG, measurements in *comparable* jobs, and estimations based on expert judgment. We did not estimate exposure at the three facilities that had no $PM_{2.5}$ sampling.

Generation of $PM_{2.5}$ exposure concentrations for JEM

The average TPM concentration for each DEG was multiplied by the corresponding $\%PM_{2.5}$ to generate the $PM_{2.5}$ concentration for the JEM. In order to preserve the information about the source of the data, ranked source codes were generated for $PM_{2.5}$ values; these combined the rankings for the underlying TPM and $\%PM_{2.5}$ data. For the calculated $PM_{2.5}$ concentration, we defined 5 ranks, with the highest (rank 1) defined as both TPM and $\%PM_{2.5}$ derived from sample measurements (TPM from HYGenius and $\%PM_{2.5}$ from 2010-2011 sampling campaign) in the given DEG, and the lowest (rank 5) where TPM was default value (regardless of $\%PM_{2.5}$ data source).

Influence of facility and DEG in PM exposure in smelters and fabrication facilities

To evaluate any increase in precision of the exposure estimates achieved by using facility-specific exposure groups, ie. DEGs, rather than exposure groups pooled across facilities, we systematically examined the sources of variability in the TPM measurement samples. To this end, we looked at the percent of total variance in TPM explained by facility and exposure group in a series of linear regression models. In models based on the measurement samples included in the development of the TPM exposure concentration estimate in the JEM, facility and exposure group were modeled as fixed effects. The coefficients of determination (r^2) of models with each fixed effect alone were compared to that of a model with both fixed

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effects, and then to the full model with both fixed effects plus their interaction. The series of models were stratified by the two main manufacturing process categories – smelter and fabrication.

Results

DEG creation and categorization into major manufacturing processes

In the 11 facilities in this study there were 2,780 unique job titles by department and facility in the industrial hygiene database and over 10,000 human resources job titles. These were reduced to 294 distinct exposure groups (DEGs). Of the 294 DEGs, 33% were assigned to smelting, 56% were assigned to fabricating, 7% to refining, and 4% to the mixed category of manufacturing processes (Table 1).

Generation of TPM Exposure for JEM

A total of 8,385 TPM personal samples were used to calculate TPM exposures for the DEGs. This represents 82% of personal TPM samples collected in DEGs of interest, excluding either specific diagnostic samples (15%) or worst case samples (3%). The TPM exposure estimates for most (210) the 294 DEGs in the JEM were calculated directly from TPM sample measurements, 55 were calculated from comparable DEGs, and 29 DEGs were given the default value (Table 2). Samples were collected from 1983 to 2011, with 50% collected from 2000-2011, 38% from 1990-1999, and 12% from 1983-1989. Approximately half of the TPM samples were collected in smelters (57%) and a third (36%) in fabrication units. Overall, TPM concentrations in smelters were higher than in fabrication units, with arithmetic means of 3.86 mg/m^3 (SD 4.43 mg/m^3) and 0.76 mg/m^3 (SD 1.25 mg/m^3), respectively (Figure 1); and geometric means of 1.63 mg/m^3 (GSD 4.84) and 0.35 mg/m^3 (GSD 3.22), respectively.

Measurement of $PM_{2.5}$ and $\%PM_{2.5}$

The $PM_{2.5}$ personal sampling survey in 2010 and 2011 was conducted in 8 facilities; jobs in 2 facilities were resampled in a second season. There were 101 paired samples collected in smelter DEGs, 267 collected in fabrication DEGs, and 9 collected in refinery DEGs. The arithmetic mean $PM_{2.5}$ concentration for all 377 paired $PM_{2.5}$ and TPM personal samples was 0.50 mg/m^3 (standard deviation: 0.92 mg/m^3) and the geometric mean was 0.18 mg/m^3 (geometric standard deviation: 4.27). The fabrication facilities had lower arithmetic mean $PM_{2.5}$ concentrations than smelter or refinery facilities (0.21 mg/m^3, 1.19 mg/m^3, and 1.24 mg/m^3 respectively) and geometric means (0.10 mg/m^3, 0.73 mg/m^3, and 0.54 mg/m^3, respectively) (Figure 1). The percent of TPM that is $PM_{2.5}$ ($\%PM_{2.5}$) was highly variable among the DEGs and ranged from 1% to 100% for all 377 paired samples; the interquartile range was 25% to 84%. Fabrication facilities had higher mean $\%PM_{2.5}$ compared to either smelter or refinery facilities (59%, 38%, 25%, respectively) (Figure 2). There was no significant seasonal difference in the observed $PM_{2.5}$ concentrations or $\%PM_{2.5}$ when stratified by DEG.

The $\%PM_{2.5}$ values for a third of the 223 DEGs at these 8 facilities were directly measured during the 2010-2011 sampling campaign. An additional 48% of the DEGs were assigned

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values based on comparable measurements within the same facility or comparable facilities. Thus, the %$PM_{2.5}$ values for 79% of the DEGs in the JEM were based on measurements, and 21% were based on more qualitative assessment.

Generation of $PM_{2.5}$ exposure concentrations for the JEM

$PM_{2.5}$ exposure concentrations for each of 223 DEGs at the 8 facilities were derived by multiplying the TPM mean of the DEG by the corresponding %$PM_{2.5}$ (Table 2). The TPM and $PM_{2.5}$ exposures in the JEM are highly correlated, with a Spearman rank correlation coefficients of 0.93 in smelter DEGs and 0.82 in fabrication DEGs. Of the 223 DEGs at these 8 facilities, 30% were calculated directly using measured %$PM_{2.5}$ and measured TPM; an additional 28% were calculated from TPM measured and %$PM_{2.5}$ estimated. $PM_{2.5}$ in DEGs with higher data source rankings had higher median $PM_{2.5}$ concentrations (median $PM_{2.5}$ in source ranks 1-5 is, in order, 0.29 mg/m3, 0.20 mg/m^3, 0.19 mg/m^3, 0.15 mg/m^3, 0.04 mg/m^3).

Influence of facility and DEG in PM exposure in smelters and fabrication facilities

The 7,531 samples used to calculate the TPM exposure for 187 measured facility-specific exposure groups (DEGs) in the JEM were used in linear models to evaluate the sources of variability in the sampling data. Exposure group explains more of the total variability than facility for both smelter and fabrication facility (Table 3). The full model, including the interaction (facility* exposure group), explained 27% of the variability in smelters and 36% in fabrication units. Because the r^2 value increased 5% when the interaction term was added into the model, we conclude that there are facility-specific differences within TPM exposure groups. This finding corroborates the qualitative information that motivated the development of facility-specific exposure groups, i.e. DEGs, rather than pooling facilities within exposure groups.

Discussion

This paper presents a unique survey of personal exposures in aluminum manufacturing workers, specifically TPM and $PM_{2.5}$. Few studies of particulate matter exposures in manufacturing have presented size distribution data or distinguished $PM_{2.5}$ from TPM. Moreover, these measurement-based $PM_{2.5}$ and TPM exposures were estimated across many parts of the industry, in contrast to previous studies, which focused on smelters. The exposure assessments for TPM and $PM_{2.5}$ presented here have significant strengths. The TPM exposures in the JEM were based on 8,385 personal samples that were collected at 11 facilities and represent random full-shift exposures. The $PM_{2.5}$ exposures were based additionally on 377 pairs of personal $PM_{2.5}$ and TPM samples collected at 8 facilities. These are the first measured personal $PM_{2.5}$ exposure data reported in this industry.

The occupational exposure limits set by both the company and OSHA are used as guidance for routine personal exposure sampling. Jobs that are likely to exceed 30% of the OEL at least 5% of the time are targeted for sampling. For TPM, with an OEL of 10 mg/m^3, the 30% concentration is 3 mg/m^3, however more than three quarters of the TPM samples in this study are under 3 mg/m^3. This is because TPM was rarely the focus of sampling. It was

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collected when sampling for other contaminants (e.g. fluorides, metals), but this still did not generally capture low TPM concentrations. Thus in this study, there was less sampling of jobs with very low occupational exposures i.e. less than 0.150 mg/m^3 (the highest environmental PM standard that USEPA ever issued) and therefore more uncertainty in the lower exposure estimates. This sampling strategy is reflected in the fact only 13% of TPM samples used in the TPM JEM were less than or equal to 0.150 mg/m^3. Similarly, 21% of the $PM_{2.5}$ samples used in the JEM were less than or equal to 0.035 mg/m^3, the current USEPA daily $PM_{2.5}$ standard. Although less important for industrial hygiene activities aimed at meeting OSHA regulations, this uncertainty may be important in epidemiologic studies that seek to distinguish risk among employees exposed to the lower end of the exposure range. This uncertainty was reflected in our data source rankings (based on the source of the exposure information, not the level of exposure), which indicated higher confidence in the higher exposure estimates.

The focus of previous TPM research in the aluminum industry has been on personal exposure in the potrooms. The personal exposures to TPM in smelters reported here are similar to those reported previously. Donohogue *et al.* (14) evaluated personal exposures to inhalable PM (similar to TPM) at 6 pre-bake smelters in Australia and New Zealand. The range of median values of the geometric mean exposure concentrations (mg/m^3) from 1996-2006 was 2.17 – 4.50 mg/m^3. This is comparable to the geometric mean TPM in our 5 pre-bake smelters of 1.63 mg/m^3, with an interquartile range TPM of 0.60 – 4.48 mg/m^3. Personal exposures to TPM as measured in 15 personal samples in a pre-bake potroom in Iran ranged from 0.1-5.90 mg/m^3(16), which is also comparable to the range exposures we observed in our potrooms. Information on exposures in other departments in the smelters, fabrication units, refineries, and bauxite mines were unavailable in the literature. Information on the size distribution of particulate matter was limited to research on constituents in different size fractions in potrooms (17).

The three major limitations of this first assessment of $PM_{2.5}$ exposure in aluminum manufacturing are lack of consideration of temporal trends, respirator usage, or constituents. Although the TPM measurements available for this study had been collected over a period of 30 years, there has been little change in the aluminum processes conducted in these facilities over the time period of interest, from early 1980s until present. There may, however, have been temporal changes in exposure across the company as a whole, as well as for particular processes. Changes in TPM and $PM_{2.5}$ over the more recent past will be the subject of a subsequent, more formal, analysis. Second, we have not yet taken full advantage of information on respirator use. In this analysis we applied a respirator protection factor only to samples with extreme values (over 50mg/m^3) with reported respirator use. A more thorough evaluation of reported respirator use will be forthcoming.

Third, this exposure assessment does not consider the composition of $PM_{2.5}$, which is likely to be relevant to the toxicity of these exposures. Particles in the smelters are likely composed of inorganic materials, i.e. fluorides, alumina dust, metals and related fumes as well as coal tar pitch volatiles in some areas (13,18–21). The PM exposures in fabrication are predominantly water-based metalworking fluids and metals. The composition of both the TPM and $PM_{2.5}$ fractions is clearly an important aspect of the personal exposures to these individuals. Analyses of the constituent exposures in each DEG are underway to develop a JEM for chemical-specific exposures.

Despite these limitations, the exposure assessment for $PM_{2.5}$ presented in this report reflects a thorough examination of thousands of particle samples and contributes to our knowledge about the distribution of particle exposures in the US aluminum manufacturing industry. The ultimate objective of the exposure assessment described here was to provide the basis for an exposure-response analysis in an epidemiologic cohort study. Figure 3 presents the daily dose (mg) from a range of familiar sources of $PM_{2.5}$, using a conversion method for transforming mg/m^3 into units of daily dose (mg) recommended by Pope, *et. al.* to compare various epidemiologic studies of PM (8,28). Results from this study indicate that the range of $PM_{2.5}$ exposures within the US aluminum manufacturing industry fill the important gap in $PM_{2.5}$ intake identified by Pope between environmental air pollution and active smoking. The highest exposures in our study were equivalent to a daily $PM_{2.5}$ dose slightly greater than actively smoking 1.5 cigarettes/day, although the dose rates and composition would obviously be quite different.

In conclusion, we have presented information on exposure to two fractions of particulate matter – TPM and $PM_{2.5}$ – in 11 aluminum manufacturing facilities with different manufacturing operations. As anticipated, occupational exposures exceeded environmental PM and $PM_{2.5}$ levels by an order of magnitude in most jobs. Additionally, both TPM and $PM_{2.5}$ are highest in smelters and both vary significantly by distinct exposure group, even within the same facility. These differences underscore the importance of understanding the roles that different processes and sources may play in the PM exposure profile for aluminum workers.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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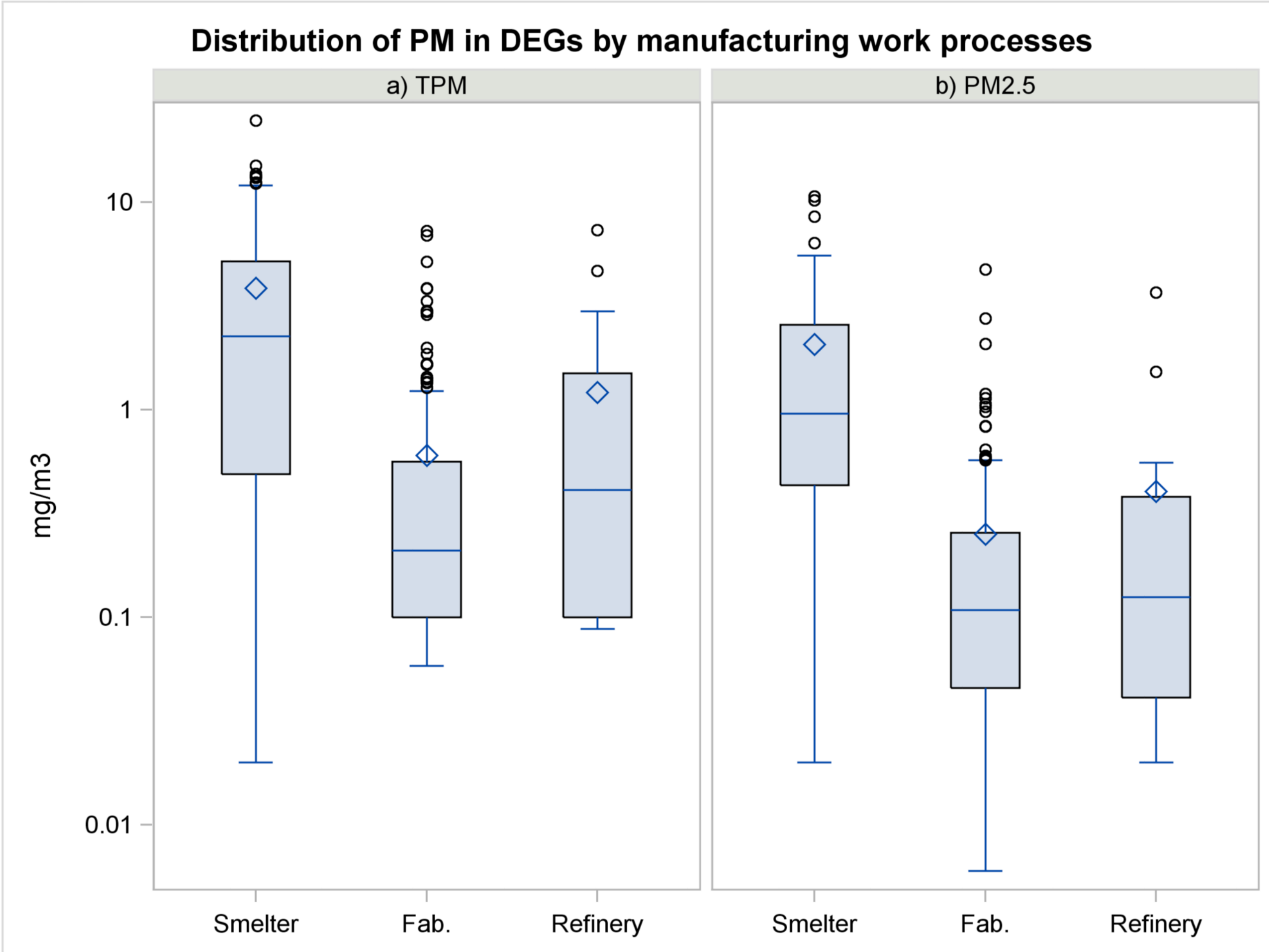

Figure 1.

Box-and-whiskers plot of the overall facility-wide distribution of the arithmetic mean (a) TPM (mg/m^3) and (b) $PM_{2.5}$ (mg/m^3) by DEG in the 3 predominant aluminum manufacturing work processes (smelter, fabrication (note: abbreviated as Fab), and refinery), plotted with a lognormal scale. The bottom and top edges of the box indicate the intra-quartile range. The diamond inside the box indicates the mean concentration, the line inside the box indicates the median concentration.

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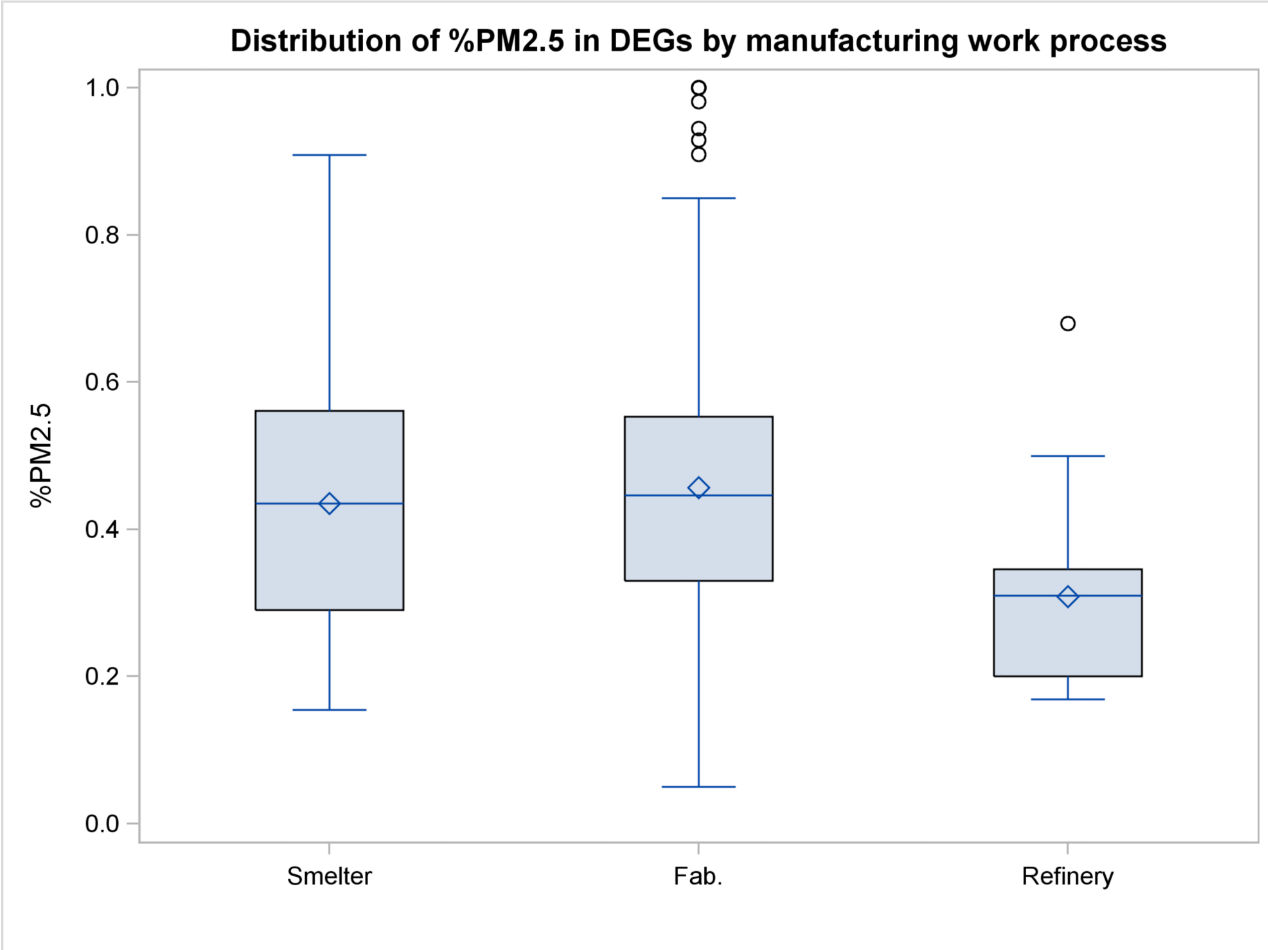

Figure 2.

Box-and-whiskers plot of the overall facility-wide distribution of mean $\%PM_{2.5}$ by DEGS in the 3 predominant types of DEGs for which $\%PM_{2.5}$ was determined (smelter, fabrication (note: abbreviated as Fab), and refinery), in the aluminum industry. The bottom and top edges of the box indicate the intra-quartile range. The diamond inside the box indicates the mean concentration, the line inside the box indicates the median concentration.

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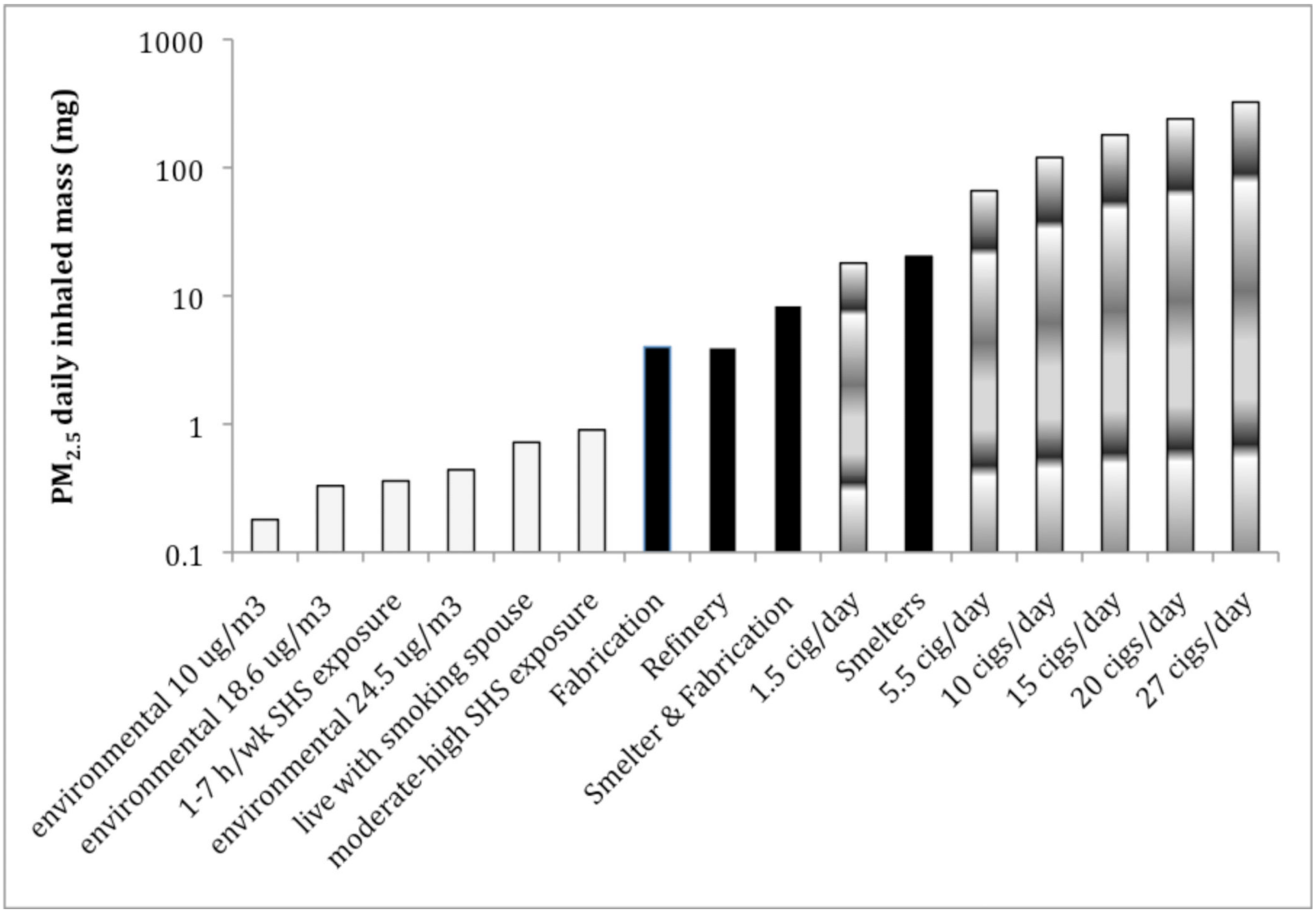

Figure 3. Distribution of exposure to estimated daily PM2.5 in different settings

Distribution of exposures to estimated daily $PM_{2.5}$ (mg daily dose equivalent, calculated using 10 m^3/day as the average daily breathing rate for a single-shift worker (Adams 1993)). White columns are environmental and SHS (second-hand smoke) exposures, black are aluminum manufacturing exposures, and black and white columns are active smoking exposures. Figure based on data from Pope, *et. al.* (2009).

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Table 1

The 11 facilities in the study that span the aluminum manufacturing industry in the United States from refining to fabrication.

Facility	Total # of DEGs	# Smelter DEGs	# Fabrication DEGs	# Smelter/Fabrication DEGs	# Refinery DEGs	Years of historical industrial hygiene exposure data used in TPM JEM	Sampled PM2.5 in 2010-2011
A	33	20	8	5	0	1984-2011	-
B	16	16	0	0	0	1999-2008	-
C	38	21	11	6	0	1980-2011	Yes
D	22	22	0	0	0	1981-2008	-
E	30	19	9	2	0	1991-2011	Yes
F	17	0	17	0	0	1986-2011	Yes
G	22	0	22	0	0	1988-2010	Yes
H	40	0	40	0	0	2002-2011	Yes
I	21	0	21	0	0	1985-2011	Yes
J	36	0	36	0	0	2002-2011	Yes
K	19	0	0	0	19	1983-2010	Yes

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Table 2

JEM of arithmetic and geometric mean TPM and $PM_{2.5}$ exposure concentrations estimates (mg/m^3) for all DEGs derived from random personal exposure samples TPM, in the aluminum industry. See footnote for explanation of combined data sources.

Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	$\%PM_{2.5}$	$PM_{2.5}$	Combined data source
DEGs in smelters											
Anode Assembly Operator	A	114	5.62	*11.1*	2.54	*3.20*	2.54	*3.20*			
Anode Assembly Operator	B	16	6.98	*3.25*	4.60	*5.38*	4.60	*5.38*			
Anode Assembly Operator	C	5	1.54	*0.99*	1.31	*1.89*	1.31	*1.89*	80%	1.23	3
Anode Assembly Operator	D	123	2.01	*2.51*	1.50	*2.08*	1.50	*2.08*			
Anode Assembly Operator	E	19	1.61	*2.22*	0.95	*2.62*	1.07	*3.82*	80%	1.29	3
Anode Changer	A	96	9.32	*12.0*	5.35	*3.09*	5.35	*3.09*			
Anode Changer	C	41	13.1	*13.3*	8.93	*2.36*	8.93	*2.36*	25%	3.30	1
Anode Changer	D	290	7.58	*9.11*	4.62	*3.18*	4.73	*3.28*			
Anode Changer	E	144	6.19	*8.80*	3.30	*4.09*	3.41	*4.26*	32%	1.97	1
Baked Anode Furnace Repairer	C	81	5.18	*10.4*	2.62	*2.92*	2.62	*2.92*	72%	3.76	2
Baked Anode Furnace Repairer	E	61	4.64	*9.54*	1.65	*4.00*	1.65	*4.00*	72%	3.36	1
Baked Anode Furnace Repairers	B	12	1.35	*0.55*	1.24	*1.57*	1.24	*1.57*			
Baked Anode Operator	A	20	1.00	*1.38*	0.60	*2.55*	0.60	*2.55*			
Baked Anode Operator	B	58	2.34	*7.41*	0.71	*3.10*	0.71	*3.10*			
Baked Anode Operator	C	198	2.36	*2.88*	1.44	*2.89*	1.44	*2.89*	31%	0.72	1
Baked Anode Operator	D	137	1.59	*2.17*	0.80	*3.53*	0.82	*3.85*			
Baked Anode Operator	E	35	0.64	*0.59*	0.45	*2.27*	0.45	*2.27*	79%	0.51	1
Caster Furnace Operator	A	8	11.0	*22.3*	1.34	*9.37*	1.34	*9.37*			
Caster Furnace Operator	D	123	0.91	*2.24*	0.42	*3.24*	0.42	*3.24*			
Caster Furnace Operator	E	35	3.36	*7.80*	0.89	*4.53*	0.89	*4.53*	31%	1.04	2
Caster Operator	B	13	0.39	*0.38*	0.29	*2.17*	0.29	*2.17*			
Caster Operator	E	21	1.83	*1.87*	1.41	*1.92*	1.41	*1.92*	56%	1.03	2
Crane Operator	C	118	1.90	*1.74*	1.39	*2.39*	1.39	*2.39*	49%	0.94	2
Crane Operator	D	203	2.65	*8.81*	0.76	*4.69*	0.76	*4.69*			

Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	%$PM_{2.5}$	$PM_{2.5}$	Combined data source
Crane Operator	E	99	8.08	*17.9*	1.78	*7.26*	2.04	*9.28*	49%	3.98	1
Electrical Maintenance	A	11	0.37	*0.32*	0.24	*3.19*	0.24	*3.19*			
Electrical Maintenance	D	21	0.59	*0.74*	0.40	*2.56*	0.40	*2.56*			
Electrical Maintenance	E	71	3.38	*10.6*	0.42	*5.95*	0.45	*7.17*	43%	1.47	2
Facilities and Grounds Operators	D	14	0.63	*0.91*	0.26	*4.03*	0.26	*4.03*			
Fume Control Servicer	A	10	4.87	*3.92*	3.16	*3.08*	5.00	*6.31*			
Fume Control Servicer	B	34	7.96	*9.65*	3.94	*3.56*	3.94	*3.56*			
Fume Control Servicer	C	19	6.02	*8.80*	2.35	*4.23*	2.35	*4.23*	41%	2.48	1
Fume Control Servicer	D	151	10.4	*21.4*	3.50	*4.82*	3.96	*4.96*			
Fume Control Servicer	E	78	12.0	*21.3*	4.07	*5.13*	7.15	*9.69*	41%	4.95	2
Furnace Operator	A	1	0.22	.	0.22	.	0.22				
Furnace Repairer	A	39	2.73	*3.03*	1.78	*2.57*	1.89	*3.04*			
Green Anode Operator	A	85	1.55	*2.49*	0.62	*3.94*	0.65	*4.50*			
Green Anode Operator	B	16	1.08	*1.92*	0.44	*3.32*	0.44	*3.32*			
Green Anode Operator	C	59	3.27	*4.08*	1.69	*3.93*	1.69	*3.93*	26%	0.84	1
Green Anode Operator	D	155	1.06	*1.31*	0.66	*2.66*	0.66	*2.66*			
Green Anode Operator	E	108	12.4	*35.9*	1.86	*7.30*	2.87	*11.1*	37%	4.58	1
Laboratory Operator	E	6	0.49	*0.34*	0.41	*1.88*	0.41	*1.88*	72%	0.35	2
Machinist	B	1	0.13		0.13		0.13				
Machinist	D	8	0.22	*0.08*	0.21	*1.47*	0.21	*1.47*			
Mechanical Maintenance	B	47	1.12	*1.00*	0.85	*2.07*	0.85	*2.07*			
Mechanical Maintenance	D	112	4.10	*24.5*	0.86	*3.72*	0.86	*3.72*			
Mechanical Maintenance	E	166	5.97	*23.6*	0.73	*6.44*	0.80	*8.09*	43%	2.59	2
Mobile Equipment Operator	A	161	4.70	*17.6*	1.00	*4.83*	1.01	*5.02*			
Mobile Equipment Operator	B	8	2.67	*5.35*	0.78	*4.29*	0.78	*4.29*			
Mobile Equipment Operator	C	19	3.02	*3.52*	1.63	*3.12*	1.63	*3.12*	64%	1.92	2
Mobile Equipment Operator	D	258	9.83	*39.5*	3.69	*4.16*	3.75	*4.24*			
Mobile Equipment Operator	E	91	9.31	*33.4*	1.64	*5.16*	1.82	*6.55*	56%	5.23	1
Potline Repairer	A	25	4.78	*9.11*	2.36	*2.69*	2.36	*2.69*			
Potline Repairer	B	3	2.28	*1.42*	2.02	*1.79*	2.02	*1.79*			

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Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	%$PM_{2.5}$	$PM_{2.5}$	Combined data source
Potline Repairer	C	87	3.06	*6.96*	1.32	*3.50*	1.32	*3.50*	19%	0.58	1
Potline Repairer	D	103	4.23	*17.7*	1.33	*3.19*	13.6	*3.51*			
Potline Repairer	E	77	13.6	*67.0*	2.68	*5.05*	2.91	*5.75*	47%	6.42	1
Potroom Bake In Operator	A	18	0.80	*0.66*	0.49	*4.06*	0.49	*4.06*			
Potroom Bake In Operator	C	41	1.34	*1.05*	0.99	*2.41*	0.99	*2.41*	50%	0.67	4
Potroom Operator	A	38	3.08	*2.86*	1.63	*3.90*	1.63	*3.90*			
Potroom Operator	B	54	6.94	*5.47*	4.81	*2.70*	4.81	*2.70*			
Potroom Operator	C	17	2.14	*1.21*	1.85	*1.75*	1.85	*1.75*	28%	0.60	1
Potroom Operator	D	264	4.92	*6.82*	2.72	*3.02*	2.72	*3.02*			
Potroom Operator	E	101	4.73	*6.14*	2.40	*3.33*	2.51	*3.66*	41%	1.96	1
Potroom Service Operator	A	49	15.0	*52.6*	2.37	*4.78*	2.37	*4.78*			
Potroom Service Operator	C	87	12.3	*24.7*	3.99	*4.26*	3.99	*4.26*	42%	5.20	1
Potroom Service Operator	D	18	1.35	*0.71*	1.18	*1.74*	1.18	*1.74*			
Power Plant Maintenance	D	1	0.02		0.02		0.02				
Power Plant Operator	C	9	13.3	*17.4*	5.63	*4.64*	8.05	*5.52*	20%	2.66	3
Power Plant Operator	D	8	0.24	*0.25*	0.09	*5.90*	0.09	*5.90*			
Production Supervisor	A	49	0.65	*2.61*	0.11	*5.32*	0.11	*5.32*			
Production Supervisor	D	60	2.24	*5.04*	0.77	*4.67*	0.77	*4.67*			
Raw Material Operator	E	19	4.73	*8.64*	1.25	*5.83*	1.41	*7.37*	64%	3.01	2
Reclamation Furnace Operator	A	95	11.9	*58.0*	1.29	*5.17*	1.40	*6.44*			
Tapper	C	29	4.63	*9.52*	2.44	*2.59*	2.44	*2.59*	38%	1.75	1
Tapper	E	52	24.7	*98.1*	5.25	*3.49*	5.49	*4.16*	38%	9.38	2
Utility Servicer	A	19	5.18	*8.00*	2.57	*3.38*	2.90	*4.13*			
Utility Servicer	B	22	6.60	*4.72*	4.99	*2.27*	5.54	*2.78*			
Utility Servicer	C	1	0.39		0.39		0.39		50%	0.20	4
Utility Servicer	E	7	0.22	*0.12*	0.20	*1.66*	0.20	*1.66*	50%	0.11	4
DEGs in mixed smelter and fabrication											
Electrical Maintenance	C	21	0.79	*0.81*	0.55	*2.29*	0.55	*2.29*	43%	0.34	2
Facilities and Grounds Operator	C	1	1.07		1.07		1.07		50%	0.54	4
Facilities and Grounds Operators	A	4	0.31	*0.13*	0.28	*1.84*	0.28	*1.84*			

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Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	%$PM_{2.5}$	$PM_{2.5}$	Combined data source
Machinist	A	27	0.82	*1.19*	0.32	*4.32*	0.32	*4.32*			
Machinist	C	6	0.33	*0.19*	0.28	*1.91*	0.28	*1.91*	43%	0.14	2
Machinist	E	3	0.17	*0.09*	0.14	*2.12*	0.14	*2.12*	43%	0.07	2
Mechanical Maintenance	A	119	2.96	*7.51*	0.86	*4.99*	0.88	*5.25*			
Mechanical Maintenance	C	55	4.13	*6.44*	1.64	*4.32*	1.64	*4.32*	43%	1.79	2
Power House Operator	A	4	9.35	*17.5*	1.64	*7.83*	1.64	*7.83*			
Railroad Engineer	A	6	0.09	*0.05*	0.07	*2.67*	0.07	*2.67*			
DEGs in fabrication											
Administration	J	1	0.20		0.20		0.20		20%	0.04	3
Air Melt Operator	H	19	0.72	*0.76*	0.44	*2.83*	0.44	*2.83*	30%	0.22	2
Alloy Control Operator	H	20	0.43	*0.40*	0.35	*1.79*	0.35	*1.79*	30%	0.13	1
Axis Grinder	J	55	0.76	*1.71*	0.36	*3.11*	0.36	*3.11*	69%	0.52	1
Caster Furnace Operator	C	47	1.07	*1.06*	0.79	*2.19*	0.79	*2.19*	31%	0.33	2
Caster Furnace Operator	G	22	0.96	*1.22*	0.70	*2.04*	0.70	*2.04*	22%	0.21	1
Caster Furnace Operator	I	15	3.82	*9.12*	1.03	*4.60*	1.03	*4.60*	54%	2.07	1
Caster Operator	H	32	0.41	*0.64*	0.26	*2.47*	0.26	*2.47*	31%	0.13	2
Caster Operator	I	18	1.43	*0.76*	1.24	*1.76*	1.24	*1.76*	14%	0.19	1
Caster Operator	J	19	0.22	*0.18*	0.16	*2.78*	0.16	*2.78*	31%	0.07	2
Charge Prep Operator	H	3	0.36	*0.06*	0.36	*1.17*	0.36	*1.17*	64%	0.23	2
Chip and Trim Operator	F	52	2.98	*5.32*	0.74	*7.01*	0.74	*7.01*	55%	1.63	2
Coater Operator	E	14	0.07	*0.05*	0.06	*2.24*	0.06	*2.24*	47%	0.04	2
Cold Mill Oil Attendant	G	1	0.07		0.07		0.07		43%	0.03	2
Cold Mill Operator	A	4	0.12	*0.05*	0.11	*1.64*	0.11	*1.64*			
Cold Mill Operator	E	43	0.15	*0.11*	0.12	*1.88*	0.12	*1.88*	47%	0.07	2
Cold Mill Operator	G	26	0.29	*0.62*	0.17	*2.37*	0.17	*2.37*	47%	0.14	1
Crane Operator	A	100	3.84	*15.4*	1.18	*3.47*	1.18	*3.47*			
Crane Operator	F	5	0.64	*0.19*	0.62	*1.38*	0.62	*1.38*	100%	0.64	1
Crane Operator	I	9	0.19	*0.23*	0.11	*3.33*	0.11	*3.33*	94%	0.18	1
Crucible Manufacturing Operator	J	3	0.28	*0.07*	0.28	*1.26*	0.28	*1.26*	50%	0.14	3
Cut-Off	H	49	1.40	*4.14*	0.46	*3.97*	0.46	*3.97*	37%	0.52	1
Cut-Off	J	35	0.88	*1.46*	0.40	*3.75*	0.40	*3.75*	55%	0.48	1

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Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	$\%PM_{2.5}$	$PM_{2.5}$	Combined data source
CVD Furnace Operator	J	7	0.39	*0.51*	0.17	*4.12*	0.17	*4.12*	75%	0.29	2
Die Operator	C	5	0.72	*0.94*	0.44	*2.69*	0.44	*2.69*	43%	0.31	2
Dip Operator	J	9	0.14	*0.12*	0.09	*3.44*	0.09	*3.44*	50%	0.07	4
Draw Bench Operator	I	12	0.14	*0.13*	0.10	*2.35*	0.10	*2.35*	75%	0.11	1
Electrical Maintenance	F	23	0.39	*0.30*	0.30	*2.23*	0.30	*2.23*	43%	0.17	2
Electrical Maintenance	G	11	0.15	*0.19*	0.08	*3.39*	0.08	*3.39*	43%	0.06	2
Extrusion Press Operator	I	39	0.21	*0.20*	0.16	*2.28*	0.16	*2.28*	75%	0.16	1
Facilities and Grounds Operator	G	15	0.79	*0.74*	0.51	*2.76*	0.51	*2.76*	50%	0.39	4
Final Finish Operator	H	13	0.34	*0.46*	0.17	*3.48*	0.17	*3.48*	48%	0.16	1
Foil Mill Operator	G	27	0.27	*0.70*	0.13	*2.77*	0.13	*2.77*	47%	0.13	2
Forge Press Operator	F	242	0.40	*0.45*	0.29	*2.23*	0.29	*2.23*	55%	0.22	1
FPI Operator	H	4	0.07	*0.02*	0.07	*1.26*	0.07	*1.26*	100%	0.07	1
FPI Operator	J	3	0.11	*0.01*	0.48	*1.02*	0.48	*1.02*	30%	0.03	1
Furnace Operator	F	34	0.32	*0.28*	0.25	*1.97*	0.25	*1.97*	91%	0.29	1
Furnace Operator	I	34	0.28	*0.23*	0.19	*2.60*	0.19	*2.60*	67%	0.19	1
Furnace Operator	J	48	0.22	*0.36*	0.13	*2.67*	0.13	*2.67*	91%	0.20	2
Furnace Repairer	G	23	6.92	*10.7*	2.60	*4.24*	2.60	*4.24*	72%	5.02	2
Hand Grinding	J	20	0.87	*0.84*	0.54	*3.20*	0.54	*3.20*	69%	0.60	1
Hot Mill Furnace Operator	E	3	0.17	*0.07*	0.17	*1.43*	0.17	*1.43*	91%	0.16	2
Hot Mill Oil Attendant	A	9	0.09	*0.07*	0.06	*2.90*	0.06	*2.90*			
Hot Mill Oil Attendant	E	4	0.11	*0.04*	0.10	*1.39*	0.10	*1.39*	69%	0.07	2
Hot Mill Operator	A	5	0.74	*0.46*	0.51	*3.43*	0.51	*3.43*			
Hot Mill Operator	E	57	0.15	*0.17*	0.10	*2.78*	0.10	*2.78*	69%	0.11	1
Hot Mill Operator	G	13	0.36	*0.27*	0.28	*2.12*	0.28	*2.12*	69%	0.25	2
Injection	J	9	0.16	.	0.15	*1.47*	0.15	*1.47*	100%	0.16	1
Inspection Operator	F	14	1.41	*3.40*	0.38	*4.27*	0.38	*4.27*	72%	1.01	2
Inspection Operator	H	10	0.15	*0.06*	0.13	*1.84*	0.13	*1.84*	55%	0.08	1
Inspection Operator	I	8	1.23	*2.66*	0.33	*4.46*	0.33	*4.46*	72%	0.88	2
Inspection Operator	J	10	0.16	*0.12*	0.42	*1.18*	0.42	*1.18*	88%	0.14	1
Inspection/Pack/ Ship Operator	F	5	1.67	*2.38*	0.70	*4.32*	0.70	*4.32*	64%	1.06	2

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Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	%$PM_{2.5}$	$PM_{2.5}$	Combined data source
Laboratory Operator	G	12	0.16	*0.14*	0.09	*3.71*	0.09	*3.71*	72%	0.11	2
Laboratory Operator	H	1	0.11		0.11		0.11		72%	0.08	2
Laboratory Operator	I	1	0.28		0.31		0.31		64%	0.18	1
Machinist	F	14	0.56	*0.62*	0.41	*2.05*	0.41	*2.05*	43%	0.24	2
Machinist	F	50	0.56	*1.03*	0.35	*2.19*	0.35	*2.19*	42%	0.23	1
Machinist	F	38	1.27	*3.16*	0.37	*4.55*	0.37	*4.55*	52%	0.66	1
Machinist	G	8	0.37	*0.26*	0.29	*2.19*	0.29	*2.19*	43%	0.16	2
Mechanical Maintenance	H	3	0.16	*0.06*	0.16	*1.48*	0.16	*1.48*	43%	0.07	2
Mechanical Maintenance	H	18	1.36	*3.61*	0.29	*6.79*	0.29	*6.79*	43%	0.59	2
Mechanical Maintenance	I	14	2.96	*6.12*	1.19	*3.41*	1.19	*3.41*	93%	2.75	1
Mechanical Maintenance	J	6	0.29	*0.28*	0.20	*2.57*	0.20	*2.57*	43%	0.12	2
Metal Cell Operator	H	24	0.22	*0.20*	0.14	*2.64*	0.14	*2.64*	80%	0.17	1
Metal Cell Operator	J	57	0.45	*1.97*	0.15	*2.92*	0.15	*2.92*	36%	0.16	1
Metal Control Operator	J	11	0.56	*0.71*	0.26	*3.75*	0.26	*3.75*	80%	0.45	2
Metal Weigher	H	5	0.43	*0.15*	0.41	*1.39*	0.41	*1.39*	50%	0.22	1
Mobile Equipment Operator	G	90	0.61	*0.87*	0.34	*2.82*	0.34	*2.82*	61%	0.37	1
Mobile Equipment Operator	I	9	0.26	*0.29*	0.18	*2.34*	0.18	*2.34*	100%	0.26	1
Monoshell Operator	H	22	2.86	*4.32*	1.16	*4.53*	1.16	*4.53*	20%	0.58	1
Monoshell Operator	J	19	1.85	*5.28*	0.42	*4.98*	0.42	*4.98*	72%	1.34	1
Pack/Ship Operator	A	4	0.11	*0.07*	0.07	*3.72*	0.07	*3.72*			
Plating Technician	J	17	0.07	*0.04*	0.06	*1.98*	0.06	*1.98*	100%	0.07	1
Powder Prep Technician	J	14	3.34	*10.6*	0.57	*4.18*	0.57	*4.18*	13%	0.43	1
Production Supervisor	G	3	0.13	*0.04*	0.12	*1.38*	0.12	*1.38*	47%	0.06	2
Production Supervisor	H	3	0.12	*0.14*	0.07	*3.22*	0.07	*3.22*	80%	0.10	2
Production Supervisor	J	3	0.70	*0.24*	0.67	*1.40*	0.67	*1.40*	57%	0.40	2
Raw Material Operator	C	19	0.31	*0.25*	0.23	*2.22*	0.23	*2.22*	64%	0.20	2
Repair Operator	F	39	1.03	*3.58*	0.40	*2.61*	0.40	*2.61*	45%	0.47	1
Repair Operator	I	30	0.34	*0.55*	0.20	*2.72*	0.20	*2.72*	57%	0.19	1
Repair Operator	I	99	0.17	*0.14*	0.12	*2.52*	0.12	*2.52*	53%	0.09	1
Roll Service Operator	A	20	0.32	*0.57*	0.19	*2.40*	0.19	*2.40*			
Roll Service Operator	E	12	0.10	*0.08*	0.08	*1.82*	0.08	*1.82*	43%	0.04	2

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Distinct exposure groups	facility id	# TPM samples	TPM AM	*TPM STD*	TPM GM	*TPM GSD*	crude TPM GM*	*crude TPM GSD**	%$PM_{2.5}$	$PM_{2.5}$	Combined data source
Roll Service Operator	G	11	0.11	*0.05*	0.09	*2.02*	0.09	*2.02*	43%	0.05	2
Sandblast	H	7	0.44	*0.47*	0.33	*1.99*	0.33	*1.99*	36%	0.16	1
Sandblast	J	5	0.18	.	0.12	*8.70*	0.12	*8.70*	62%	0.11	1
Saw Operator	C	10	0.22	*0.15*	0.18	*1.88*	0.18	*1.88*	57%	0.12	2
Saw Operator	F	17	0.43	*0.33*	0.34	*1.92*	0.34	*1.92*	56%	0.24	1
Sheet/Plate Mill Operator	G	59	0.35	*0.70*	0.18	*2.62*	0.18	*2.62*	35%	0.12	1
Slitter Operator	A	2	0.17	*0.01*	0.17	*1.09*	0.17	*1.09*			
Slitter Operator	E	13	0.16	*0.23*	0.09	*2.92*	0.09	*2.92*	47%	0.07	2
Straightner	H	3	0.14	*0.03*	0.14	*1.31*	0.14	*1.31*	80%	0.11	2
Strander Operator	C	1	0.22		0.22		0.22		69%	0.15	2
Thermatech Operator	J	4	0.11	*0.01*	0.11	*1.13*	0.11	*1.13*	100%	0.11	2
Tube Press Operator	I	24	0.08	*0.09*	0.06	*2.51*	0.06	*2.51*	70%	0.06	1
Vacuum Furnace Operator	H	19	7.24	*8.44*	2.03	*8.71*	2.92	*10.6*	11%	0.83	1
Vacuum Furnace Operator	J	6	0.06	*0.06*	0.04	*2.85*	0.04	*2.85*	11%	0.01	2
Wastewater Treatment Operator	H	3	0.06	*0.02*	0.06	*1.42*	0.06	*1.42*	50%	0.03	4
Waterblast	J	5	0.67	*0.80*	0.71	*1.46*	0.71	*1.46*	21%	0.14	1
Wax Cell Operator	J	10	0.15	*0.08*	0.38	*1.54*	0.38	*1.54*	96%	0.14	1
Welder	C	10	5.14	*7.16*	1.70	*6.24*	1.70	*6.24*	20%	1.03	1
Welder	F	7	2.97	*3.27*	1.27	*6.08*	1.27	*6.08*	43%	1.29	2
Welder	G	102	1.04	*4.22*	0.31	*3.37*	0.31	*3.37*	43%	0.45	2
Welder	H	2	0.57		0.36	*1.68*	0.36	*1.68*	35%	0.20	1
Wire Coil Operator	C	6	0.40	*0.62*	0.21	*2.96*	0.21	*2.96*	69%	0.27	2
Wire Draw Operator	C	33	0.29	*0.11*	0.26	*1.50*	0.26	*1.50*	69%	0.20	2
DEGS in refining											
Calcination Operator	K	29	2.97	*5.76*	1.03	*3.80*	1.11	*4.46*	17%	0.50	1
Chemical Operator	K	39	1.38	*1.36*	0.83	*3.69*	0.83	*3.69*	20%	0.28	3
Clarification Operator	K	15	0.60	*0.55*	0.43	*2.30*	0.43	*2.30*	20%	0.12	3
Digestion Heater/Cleaner Repairer	K	11	0.46	*0.15*	0.43	*1.51*	0.43	*1.51*	21%	0.10	2
Digestion Operator	K	12	0.75	*0.55*	0.47	*3.40*	0.47	*3.40*	20%	0.15	1
Electrical Maintenance	K	16	0.43	*0.39*	0.27	*2.93*	0.27	*2.93*	43%	0.18	2
Machinist	K	7	0.39	*0.55*	0.24	*2.56*	0.24	*2.56*	43%	0.17	2

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Distinct exposure groups	**facility id**	**# TPM samples**	**TPM AM**	***TPM STD***	**TPM GM**	***TPM GSD***	**crude TPM GM***	***crude TPM GSD****	**%$PM_{2.5}$**	**$PM_{2.5}$**	**Combined data source**
Mechanical Maintenance	K	68	1.63	*2.75*	0.69	*3.52*	0.69	*3.52*	34%	0.56	1
Mobile Equipment Operator	K	2	0.12	*0.04*	0.11	*1.37*	0.11	*1.37*	64%	0.07	2
Mud Tank Cleaner	K	6	0.38	*0.12*	0.37	*1.36*	0.37	*1.36*	20%	0.08	3
Precipitation Operator	K	24	2.31	*4.12*	0.67	*4.59*	0.67	*4.59*	21%	0.49	2
Raw Material Operator	K	59	4.65	*8.80*	1.38	*4.91*	1.49	*5.54*	16%	0.76	1
Utility Servicer	K	24	7.31	*9.08*	3.05	*4.47*	3.05	*4.47*	50%	3.66	4

Note: Combined data source for $PM_{2.5}$: 1=both TPM and %PM2.5 measured (30% of $PM_{2.5}$ DEGs); 2= TPM measured and %$PM_{2.5}$ estimated (28% of $PM_{2.5}$ DEGs); 3=both TPM and %$PM_{2.5}$ estimated from same or comparable facilities (22% of $PM_{2.5}$ DEGs); 4=both TPM and %o$PM_{2.5}$ estimated from expert judgment (8% of $PM_{2.5}$ DEGs). Not shown are DEGs with rank 5 for which TPM was given a default value and %$PM_{2.5}$ was estimated (12% of $PM_{2.5}$ DEGs).

*TPM concentrations without adjustment for respirator use.

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Table 3

Percent of total variance in TPM (modeled as log-transformed TPM) explained by facility and exposure group in a series of linear regression models, stratified by work process type in the aluminum industry.

	Smelter (N=5,172)					Fabrication (N= 2,359)				
Model	**Model DF**	**Model p-value**	r^2	**adjusted** r^2	**AIC**	**model DF**	**Model p-value**	r^2	**adjusted** r^2	**AIC**
Facility only	4	0.0001	0.004	0.004	9737	8	<0.0001	0.10	0.10	3382
Exposure group only	27	<0.0001	0.20	0.19	8681	60	<0.0001	0.27	0.25	2993
Facility + exposure group	31	<0.0001	0.21	0.20	8623	68	<0.0001	0.31	0.29	2891
Facility + exposure group + Facility * exposure group	79	<0.001	0.27	0.26	8303	103	<0.0001	0.36	0.33	2785