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The Diesel Exhaust in Miners Study: II. Exposure Monitoring Surveys and Development of Exposure Groups

JOSEPH B. COBLE[1,3], PATRICIA A. STEWART[1,4], ROEL VERMEULEN[1,5], DANIEL YEREB[2,6], REBECCA STANEVICH[2], AARON BLAIR[1], DEBRA T. SILVERMAN[1,†] and MICHAEL ATTFIELD[2*,†]

[1]Division of Cancer Epidemiology and Genetics, US National Cancer Institute, Bethesda, 20892 MD, USA; [2]Surveillance Branch, Division of Respiratory Disease Studies, US National Institute for Occupational Safety and Health, Morgantown, WV 26505, USA

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Air monitoring surveys were conducted between 1998 and 2001 at seven non-metal mining facilities to assess exposure to respirable elemental carbon (REC), a component of diesel exhaust (DE), for an epidemiologic study of miners exposed to DE. Personal exposure measurements were taken on workers in a cross-section of jobs located underground and on the surface. Air samples taken to measure REC were also analyzed for respirable organic carbon (ROC). Concurrent measurements to assess exposure to nitric oxide (NO) and nitrogen dioxide (NO_2), two gaseous components of DE, were also taken. The REC measurements were used to develop quantitative estimates of average exposure levels by facility, department, and job title for the epidemiologic analysis. Each underground job was assigned to one of three sets of exposure groups from specific to general: (i) standardized job titles, (ii) groups of standardized job titles combined based on the percentage of time in the major underground areas, and (iii) larger groups based on similar area carbon monoxide (CO) air concentrations. Surface jobs were categorized based on their use of diesel equipment and proximity to DE. A total of 779 full-shift personal measurements were taken underground. The average REC exposure levels for underground jobs with five or more measurements ranged from 31 to 58 $\mu g\ m^{-3}$ at the facility with the lowest average exposure levels and from 313 to 488 $\mu g\ m^{-3}$ at the facility with the highest average exposure levels. The average REC exposure levels for surface workers ranged from 2 to 6 $\mu g\ m^{-3}$ across the seven facilities. There was much less contrast in the ROC compared with REC exposure levels measured between surface and underground workers within each facility, as well as across the facilities. The average ROC levels underground ranged from 64 to 195 $\mu g\ m^{-3}$, while on the surface, the average ROC levels ranged from 38 to 71 $\mu g\ m^{-3}$ by facility, an ∼2- to 3-fold difference. The average NO and NO_2 levels underground ranged from 0.20 to 1.49 parts per million (ppm) and from 0.10 to 0.60 ppm, respectively, and were ∼10 times higher than levels on the surface, which ranged from 0.02 to 0.11 ppm and from 0.01 to 0.06 ppm, respectively. The ROC, NO, and NO_2 concentrations underground were correlated with the REC levels ($r = 0.62$, 0.71, and 0.62, respectively). A total of 80% of the underground jobs were assigned an exposure estimate based on measurements

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*Author to whom correspondence should be addressed. Tel: +1-304-285-3737; fax: +1-304-285-6111; e-mail: mda1@cdc.gov
†Co-senior authors

[3]Present address: 1412 Harmony Lane, Annapolis, MD 21409, USA
[4]Present address: Stewart Exposure Assessments, LLC, Arlington, VA 22207, USA
[5]Present address: Institute for Risk Assessment Sciences, Utrecht University, 3584 CK Utrecht, The Netherlands
[6]Present address: US Department of Homeland Security, Washington, DC, USA

taken for the specific job title or for other jobs with a similar percentage of time spent in the major underground work areas. The average REC exposure levels by facility were from 15 to 64 times higher underground than on the surface. The large contrast in exposure levels measured underground versus on the surface, along with the differences between the mining facilities and between underground jobs within the facilities resulted in a wide distribution in the exposure estimates for evaluation of exposure–response relationships in the epidemiologic analyses.

Keywords: diesel exhaust; miners; elemental carbon; exposure assessment; job groups

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INTRODUCTION

Diesel engine exhaust is classified as 'probably carcinogenic in humans' (Group 2A) by the International Agency for Research on Cancer (IARC, 1989), as 'likely to pose a lung cancer hazard in humans' by the US Environmental Protection Agency (US EPA, 2002), and as a 'potential human carcinogen'' by the US National Institute for Occupational Safety and Health (NIOSH) (NIOSH, 1988). However, the risk of cancer associated with exposure to specific levels of diesel exhaust (DE) is not well understood due, in part, to difficulties in estimating historical exposure levels (Silverman, 1998; HEI, 2003). To evaluate the relationship between exposure to DE and the risk of cancer, an epidemiologic study of miners exposed to DE was conducted by the US National Cancer Institute (NCI) and US NIOSH (NCI/NIOSH, 1997). A primary objective of this study, the Diesel Exhaust in Miners Study (DEMS), was to develop quantitative exposure metrics to investigate the risk of lung cancer and other causes of mortality associated with exposure to DE.

Diesel-powered vehicles provide greater power and mobility than electric-powered equipment and therefore have been widely used in the mining industry since the 1960s (US CFR 30 Part 57, 2006). A variety of diesel-powered equipment is routinely used in underground mines, including utility vehicles, personnel carriers, tractors, front-end loaders, load-haul-dump vehicles, and haulage trucks. Exhaust emissions from diesel-powered equipment in underground operations can accumulate in areas with limited ventilation; thus, underground miners are potentially exposed to a much wider range of concentrations than is typically found in other workplaces (Pronk *et al.*, 2009). A survey conducted at a potash facility found average exposure levels to respirable elemental carbon (REC), a component of DE, were ~30 times higher among underground workers compared to workers on the surface (Stanevich *et al.*, 1997).

Air monitoring surveys were conducted between 1998 and 2001 at seven of the eight mining facilities included in the epidemiologic study (the DEMS surveys). One facility had closed in 1993 and therefore could not be monitored. The objective of the surveys was to collect full-shift personal samples to measure REC exposure levels of workers in a cross-section of jobs both underground and on the surface. REC was selected *a priori* as the primary surrogate of DE since REC is a component of DE that is specific to DE in mining and can be accurately measured over a wide range of ambient concentrations (Birch and Cary, 1996; Bunn *et al.*, 2002; Birch and Noll, 2004). Other components of DE, including respirable organic carbon (ROC), nitric oxide (NO), and nitrogen dioxide (NO_2) also were measured on the same workers during the same work shifts. In addition, area monitoring for these same agents was conducted at various locations underground and on the surface (Vermeulen *et al.*, 2010b).

This paper summarizes the results of the personal samples taken to assess exposure to REC, ROC, NO, and NO_2 during the DEMS surveys and presents the average REC exposure levels measured for the underground jobs with five or more measurements. The grouping strategy that was used to develop exposure estimates for the time period 1998–2001 by mining facility, department, and job title is also described. These REC exposure estimates presented served as reference values for the retrospective assessment of historical exposure levels in the DEMS as described elsewhere (Stewart *et al.*, 2010; Vermeulen *et al.*, 2010a).

BACKGROUND

The seven non-metal mining facilities at which the air monitoring surveys were conducted included one limestone facility in Missouri (A), two potash facilities in New Mexico (B, D), one rock salt facility in Ohio (E), and three trona (trisodium hydrogen dicarbonate dehydrate) facilities in Wyoming (G, H, and I). One other potash facility and one salt facility also were monitored, but these facilities were not included in the epidemiologic study for reasons unrelated to the monitoring. The surveys were conducted in 1998 or 1999 at six of the facilities (A, D, E, G–I). At the seventh facility (B), a limited survey had been conducted in 1994 as part of a feasibility study (Stanevich *et al.*, 1997), so this facility was surveyed again in 2001. The eighth facility in the study (J) had ceased operations in 1993 and, thus, was not available for monitoring. Only the measurements from the seven facilities included in the study are presented here.

All eight facilities had both underground mining operations and surface operations in which the ore was processed and shipped. A summary of various characteristics of the facilities [the number of workers, estimates of diesel engine horsepower (HP) in use and total airflow rates exhausted from the underground operations] are presented elsewhere (Stewart *et al.*, 2010).

Ore extraction at the facilities involved both diesel- and electric-powered mining equipment and used various mining methods. At Facility A, the ore was extracted using a drill and blast technique with a room and pillar design. After blasting, the ore was loaded by diesel-powered front-end loaders into large haulage trucks, transported to an underground crusher, and then moved to the surface on conveyor belts. This facility used larger diesel-powered equipment than the other facilities in the study. Facility A had very high ceilings (up to 90 feet) after the ore was removed. Entry and egress was through an adit or horizontal portal; thus, large vehicles could be driven directly into the mine. In this respect, Facility A differed from the other study facilities, which used vertical elevator shafts for entry and egress and for hoisting ore to the surface.

The two potash facilities surveyed (B and D) used both the drill and blast mining method and electric-powered continuous mining equipment to extract ore from six- to nine-feet-high seams using a room and pillar design. Diesel-powered shuttle cars were used to load ore at the production face onto conveyor belts running to the production shafts, where the ore was hoisted to the surface.

The salt mining facility (E) used the drill and blast mining method and a room and pillar design with electric-powered drills and undercutters to remove ore from a seam of 18–20 feet. Diesel-powered front-end loaders were used to load the ore into large diesel-powered haulage trucks for transport to the underground crusher where it was then hoisted to the surface.

The three trona facilities (G, H, and I) used electric-powered continuous miners to remove ore from a 7- to 10-feet seam. One trona facility (I) also had a longwall mining section, in which electric-powered equipment was used for ore extraction, but diesel-powered front-end loaders were used for clean up and for moving the mining equipment. Conveyor belts transported the ore from the production faces to the ore shaft, where the ore was hoisted to the surface. One facility (G) also had an underground crusher.

All the underground operations had extensive haulage and travel ways that, in some cases, extended underground for several miles. Because of the long distances, diesel-powered vehicles, or man-trips, often were used for transport of miners and maintenance personnel to the production face and to other underground areas. Diesel-powered front-end loaders and small scoops were also used for clean up at the faces and around the conveyor belts and other ore transfer locations at all these facilities. Other miscellaneous types of diesel-powered equipment in use included tractors, scalers, dozers, graders, lube trucks, powder wagons, forklift trucks, generators, and water pumps.

The underground operations differed in the type of ventilation systems used to supply fresh air to the working areas. The trona operations had the highest ventilation rates due to the possible presence of methane released during the mining process. The ventilation systems in the trona operations were parallel in design in that the exhaust air from each face was vented directly back to the exhaust shafts. Little or no work was done by employees in the exhaust air at the trona operations, which reduced the potential of high exposure levels for support workers (i.e. maintenance, ventilation, etc.) in these facilities. The ventilation systems in the salt and potash operations were serial in design. Air circulated from one face to the next prior to discharge through the main exhaust shafts. The exhaust air from one work area provided air to the next area, thereby increasing the potential for high exposure levels to DE downstream from other working areas located upstream to the airflow. The high ceilings of the limestone operation had a series of air holes drilled from the surface to supply fresh air to the underground working areas. Some of the air holes were equipped with fans; however, the movement of exhaust air out of the mine through the other holes and the main entrance portal relied on natural air currents driven by temperature differences between the underground and surface air.

All the facilities had surface operations that utilized diesel-powered equipment that included a variety of heavy trucks, front-end loaders, forklift trucks, and other types of miscellaneous equipment. Diesel-powered locomotives and tractor trailer trucks were also present at the surface shipping operations. However, most surface jobs involved very limited or no routine contact with diesel-powered equipment.

METHODS

Sampling strategy

Exposure monitoring was conducted for four to five consecutive days at each of the underground operations and for three to five days at each of the surface operations. An average of 20 personal samples was collected per day on individuals who worked only underground during the work shift. Approximately 10 personal samples were collected per day on individuals who worked either entirely on the surface or who worked both on the surface and underground during the shift monitored. In general, more measurements were taken on workers in jobs expected to have higher exposure levels since the variability of the measurements was expected to increase with increasing exposure levels. A small number of workers located in underground shops and other areas close to fresh air intake shafts was monitored to assess the range in average exposure levels underground. Participation in the monitoring survey was voluntary, and in most cases, different workers were monitored each day. Personal identifying information was not collected, and therefore, the number of repeat measurements on individual workers could not be determined, and estimation of between versus within worker variance components could not be made.

The REC and ROC samples were collected using a 10-mm Dorr-Oliver nylon cyclone (cut point of 3.5 microns) at a flow rate of 1.7 l/min on a single quartz filter. The samples were analyzed using a thermal–optical method to quantify both the elemental and organic carbon fractions in the aerosol deposited on the filter (Schlecht and O'Connor, 2003). Full-shift personal samples for NO and NO_2 were collected concurrently on the same workers as the REC and ROC using Palmes passive dosimeters (Schlecht and O'Connor, 2003). NO or NO_2 measurements were not taken at Facility D due to technical problems with the sampling method prior to the survey.

Standard quality control and quality assurance procedures during the sampling and analyses were used, including the collection of duplicates and blanks. Field blanks were analyzed in batches by sample type and facility, and the corresponding average value was subtracted from the measured data to give corrected results. The limit of detection (LOD) for REC and ROC is $\sim$2.0 $\mu g\ m^{-3}$ for a 960-l air sample (Schlecht and O'Connor, 2003). The LOD for the NO and NO_2 is $\sim$0.01 parts per million (ppm) for a 480-min sample (Schlecht and O'Connor, 2003). The LOD divided by $\sqrt{2}$ was substituted for the non-detectable measurement results for calculation of the summary statistics (Hornung and Reed, 1990).

Sampling devices were placed on workers prior to their entry into their work area and retrieved at the end of the work shift. Typical sampling durations ranged from 420 to 480 min, with an average duration of 460 min. There were 11 samples of $<$240 min that were excluded from calculation of the full-shift concentrations presented in this paper.

Most of the workers monitored during these surveys worked either underground or on the surface over their entire work shift. However, some workers spent time both underground and on the surface during the work shift monitored. These workers are identified as 'mixed', and since the percent of time spent underground during the sampling period was not known, these results were excluded from the calculation of average exposure levels for the surface and underground workers.

The personal samples collected during the DEMS surveys were coded by facility, department, and job title. The coding was conducted without regard to the measurement results using the same set of facility, department, and job codes that were used to code the work histories for the epidemiologic analysis (Stewart *et al.*, 2010). Each job code was associated with a standardized job title that was matched with the facility-specific job titles from the work histories based on job descriptions and employee interviews. The department code indicated whether the job was primarily underground or on the surface and whether it was a production, maintenance, support, or one of a few other functions.

Summary statistics calculated were the number of samples, the number below the LOD, the arithmetic mean (AM), the geometric mean (GM), and the geometric standard deviation (GSD) for the REC, ROC, NO, and NO_2 measurements by facility and type of worker (i.e. underground, surface, or mixed). For underground jobs with five or more REC measurements, the AM was calculated to estimate the mean exposure level, and the standard error of the mean (SEM) was calculated to quantify the precision of the exposure estimate. In addition, the GM was calculated for comparison with the AM to evaluate the shape of the sampling distribution, and the GSD was calculated to evaluate the scatter in the measurements themselves.

An analysis of variance was conducted to compare the distributions of the underground REC measurements between the facilities. Pearson correlation coefficients were calculated on the log-transformed REC, ROC, NO, and NO_2 underground measurements to evaluate the relationship of REC to these other agents.

Area samples for REC and other agents were taken at various locations within the facilities during the same surveys and using the same sampling methods described above or elsewhere (Vermeulen *et al.*, 2010b). The locations of the area samples were selected to evaluate the range of DE concentrations within the facilities, including areas with heavy usage of diesel-powered equipment and areas with little or no diesel equipment. Area samples on the surface generally were taken near loading docks, in the auto shops, and at other locations where diesel-powered equipment was operated typically. All area measurements were coded using MSHA location codes (Watts and Parker, 1995) without regard to the measurement results. AMs were calculated for the REC area samples: three for underground areas (i.e. production face, haulage and travel ways, and shops and offices) and one for the surface. A more detailed analysis of the interrelationships between REC and the other agents sampled as area measurements is presented elsewhere (Vermeulen *et al.*, 2010b).

Development of exposure groups

Due to logistical constraints, not all jobs in the facilities were measured during the DEMS surveys. A grouping strategy was therefore necessary to ensure that every job at each of the facilities could be assigned an exposure estimate. A hierarchical strategy was used for the development of exposure groups to ensure that the estimates of average REC exposure levels used for the epidemiologic analysis were based on the average of at least five measurements. The ROC, NO, and NO_2 results were not used in the exposure assessment process but are nonetheless presented for comparison with REC results. The most specific estimates, designated as U1 groups, were based directly on the standardized job titles developed for the work histories (Stewart *et al.*, 2010). The next set of groups, designated as U2 groups, comprised standardized job titles grouped based on the usual percentage of the work shift (<30%, 30–59%, and >59%) spent in each of four underground areas (i.e. face, haulage and travel ways, shop and offices, and, in three facilities, crusher). The third set of groups, designated as U3, combined various U2 groups based on similarities in historical CO levels measured in these three or four underground areas. CO was used for assessing the similarity between areas because there were no REC measurements before the 1990s, CO has been used as a surrogate for DE historically (Pronk *et al.*, 2009), and there were more CO measurements than of any other DE component (Stewart et al., 2010; Vermeulen *et al.*, 2010a). The U4 group included jobs assigned the average of all underground measurements at a particular facility, and the U5 group were a small set of low exposed jobs for which an exposure estimate was assigned based on <5 measurements.

The assignment of exposure estimates was conditioned on the number of REC measurements taken during the DEMS surveys. For standardized job titles with five or more REC measurements, the AM of the REC measurements associated with each standardized job title was assigned as the estimated average exposure level from the DEMS survey for 1998–2001. For a standardized job title with fewer than five measurements, the AM of the measurements taken on all the jobs associated with that job's respective U2 group was used as the exposure estimate if there were at least five measurements associated with the group. If there were fewer than five measurements in a U2 group, then the exposure estimate for a job was based on its respective U3 group average. Any jobs with fewer than five measurements in the U3 group were assigned the AM of all underground measurements for that facility (designated as U4 groups). All grouping and the estimation for the U1–U4 groups was done without reference to the REC measurement results. After all the AMs were assigned, the assignments were reviewed to determine if they were consistent with the job descriptions. For a small number of low exposed jobs held by workers who spent most of their time in underground shops or offices, the review indicated that the AM assigned was not consistent with the job description. For these jobs (designated as U5 groups, or overrides), the average exposure levels were estimated based on fewer than five measurements. An example of the grouping strategy for one facility is provided in the Appendix.

A smaller number of measurements was taken during the DEMS surveys on surface workers since contact with diesel equipment among these workers was much more limited than it was underground. Standardized surface job titles were therefore grouped to one of three mutually exclusive exposure groups based on the amount of contact with diesel-powered equipment. The first exposure group comprised standardized job titles held by workers who had no or very limited contact with diesel equipment (exposure group A); the second group comprised standardized job titles held by workers drove a diesel forklift truck indoors or operated heavy diesel equipment (>75 HP) <4 h/shift, drove light diesel equipment, or worked in close proximity to diesel-powered equipment on a regular basis (exposure group B); the third group comprised standardized job titles held by workers who operated heavy diesel equipment or drove a diesel forklift truck indoors, on average, for ≥4 h/shift or who repaired diesel equipment (exposure group C). These groups were developed without reference to the measurement data.

A similar approach to that used for underground jobs was used to assign exposure levels to surface jobs. Each A–C group remained distinct in the estimation process. If at least five full-shift personal REC measurements were available on all the jobs comprising a facility's surface exposure group, the AM of those pooled measurements was assigned to all the jobs in the group (S1 estimation group). If there were fewer than five measurements, all measurements associated with the respective surface exposure group across all facilities of the same ore type were pooled, and if there were at least five measurements, the AM of these measurements assigned (S2 estimation group). The remaining jobs were assigned the AM of the pooled measurements from all facilities associated with their respective surface exposure group (S3 estimation group). The assignment of the surface estimates, the exposure groups (A–C), and the estimation groups (S1–S3) were made only on the basis of the number of REC measurements and not on the results of the REC measurement results.

RESULTS

A total of 779 full-shift personal REC measurements was taken at the seven mining facilities on workers who spent the entire shift underground (Table 1). The average REC exposure level measured underground by facility ranged from 40 μg m^{-3} at Facility G to 384 μg m^{-3} at Facility A, an ~10-fold range across the facilities. Only 16 (2%) of the REC measurements on underground workers were below the LOD.

A total of 265 full-shift personal REC measurements was taken on workers who spent the entire shift on the surface (Table 1). The average REC exposure level measured for surface workers ranged from 2 μg m^{-3} at Facilities G and H to 6 μg m^{-3} at Facility A. Sixty-three percent of the measurements taken on the surface were below the LOD. There were 101 measurements taken on workers who worked both underground and on the surface during the work shift and these means ranged from 3 to 160 μg m^{-3} across facilities.

The distribution of the exposure measurements taken underground and on the surface by facility is displayed in Fig. 1. Average REC levels underground ranged from 20 to 64 times higher than the average levels measured on the surface across the seven facilities, and the highest levels measured underground were >100 times higher than on the surface. There was an ~10-fold variation between the facilities in the average exposure levels for the underground jobs monitored. An analysis of variance on the log-transformed underground measurements demonstrated a statistically significant difference ($P < 0.001$) between facilities.

Table 1. Measured personal respirable elemental carbon exposure levels (μg m^{-3}) for underground, mixed, and surface workers by mining facility: full-shift time-weighted average concentrations

Mining facility	*n*	*n* < LOD	AM	GM	GSD
Underground					
A—limestone	108	0	384	347	1.6
B—potash	124	3	191	88	6.0
D—potash	84	2	94	68	2.4
E—salt	118	3	82	53	3.1
G—trona	126	2	40	27	2.6
H—trona	116	4	84	53	3.1
I—trona	103	2	71	54	2.5
Mixed underground and surface[a]					
A—limestone	31	0	160	93	3.3
B—potash	4	0	30	13	4.7
E—salt	11	4	5	4	2.0
G—trona	18	15	3	2	2.2
H—trona	19	6	39	10	5.8
I—trona	18	9	21	6	5.8
Surface					
A—limestone	33	4	6	4	2.2
B—potash	61	22	4	1	3.9
D—potash	35	31	3	2	1.8
E—salt	25	19	4	3	2.0
G—trona	31	27	2	2	2.0
H—trona	33	25	2	2	1.6
I—trona	47	38	3	2	2.0

n, Number of measurements.

[a] Mixed workers spent time both underground and on the surface during the work shift monitored. No mixed workers were sampled at Facility D.

There was much less contrast between the ROC levels measured on the underground and surface workers, as compared with REC (Table 2). The AM of the ROC levels measured underground ranged from 64 to 195 μg m^{-3}, while the AM of the ROC levels measured on the surface ranged from 38 to 71 μg m^{-3} by facility. The average ROC levels measured underground were approximately twice the levels measured on the surface; however, at one

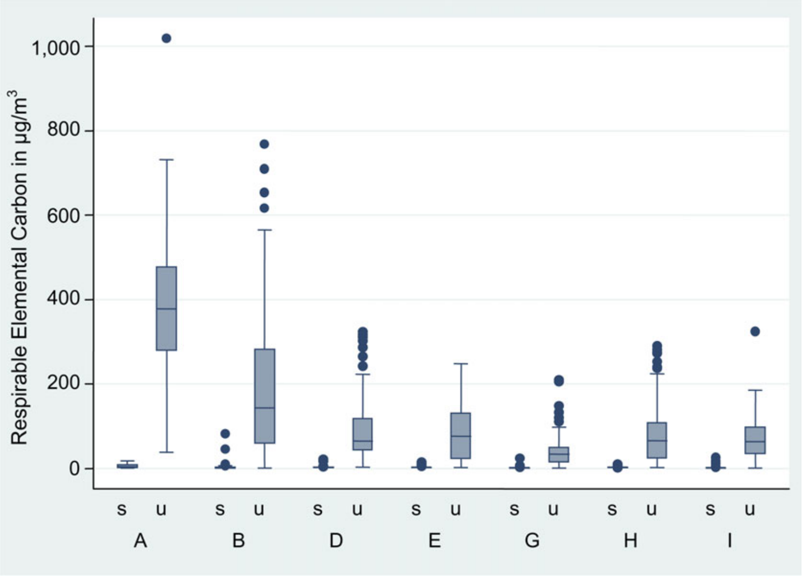


Fig. 1. Personal respirable elemental carbon measurements (µg m^{-3}) for surface and underground jobs by mining facility (A–I). Full-shift time-weighted concentrations. s, surface, u, underground. The boxes display the 25th and 75th percentiles, and the horizontal line within each box displays the median. The vertical whiskers extend 1.5 times the interquartile range above and below the boxes. Low or high values located outside the vertical whisker lines are displayed as points.

facility (G), the AM of the ROC concentrations on the surface (70 µg m^{-3}) was somewhat higher than the ROC AM underground (64 µg m^{-3}), despite a 20-fold difference in the average REC level on the surface (2 µg m^{-3}) compared with that underground (40 µg m^{-3}) at this facility.

The average levels of NO and NO_2 by facility are displayed in Table 3. The average levels underground were ~15 times higher than on the surface. The AM of the NO concentrations measured underground ranged by facility from 0.20 to 1.49 ppm, compared with a range of 0.02 to 0.11 ppm by facility on the surface. The AM of the NO_2 concentrations measured underground ranged from 0.10 to 0.60 ppm, compared with a range of 0.01–0.06 ppm on the surface.

The measurements of REC, ROC, NO, and NO_2 taken underground on the same workers on the same days were significantly correlated (i.e. P value $<$ 0.05), indicating a consistent pattern in exposure levels among the particulate and gaseous components of DE monitored. The Pearson correlation coefficients between the log-transformed concentrations of REC with ROC, NO, and NO_2 were 0.62, 0.71, and 0.62, respectively, based on just the measurements taken underground. Fig. 2 contains scatter plots of both the underground and surface measurements that display the distribution of the NO and NO_2 samples and the corresponding REC samples by facility. Stronger correlations were seen at the mines with the higher REC concentrations (A, B, and E) compared with the mines with lower REC concentrations (G, H, and I).

The AM of the REC measurements for all underground jobs with five or more measurements are presented in Table 4. The highest exposed jobs were located primarily in the face area, while maintenance and support jobs that spent less time at the face, in general, had lower AMs. The highest REC exposure levels were measured at Facility A for workers located in the production areas near the face, where average exposure levels ranged from 313 µg m^{-3} for the drill operator to 488 µg m^{-3} for the loader operator, with GSDs for these jobs that ranged from 1.3 to 2.1, indicating relatively homogeneous exposure levels. The mean REC exposure levels at the potash facilities ranged from 118 to 263 µg m^{-3} at Facility B and from 48 to 216 µg m^{-3} at Facility D. The GSDs for two of the jobs in Facility B were relatively high compared to other jobs (i.e. 5.6 and 6.9), indicating a greater range in the daily average exposure levels for these jobs. The REC levels at the salt mine, Facility E, ranged from 29 to 140 µg m^{-3} with GSDs that ranged from 1.4 to 4.3. The lowest REC levels underground were measured in the three trona mines, with AMs that ranged from 31 to 58 µg m^{-3} at

Table 2. Measured personal ROC exposure levels (μg m^{-3}) for underground, mixed, and surface workers by mining facility: full-shift time-weighted average concentrations

Mining facility	*n*	*n* < LOD	AM	GM	GSD
Underground					
A	108	0	167	137	1.8
B	124	0	195	99	3.0
D	84	0	101	87	1.7
E	118	0	128	114	1.7
G	126	0	64	58	1.6
H	116	0	110	89	2.1
I	103	0	89	76	1.9
Mixed underground and surface[a]					
A	31	0	102	87	1.8
B	4	0	82	68	2.0
E	11	0	92	85	1.5
G	18	0	64	56	1.8
H	19	0	77	65	1.8
I	18	0	63	57	1.6
Surface					
A	33	0	54	47	2.0
B	63	6	38	32	1.9
D	35	0	48	42	1.6
E	25	0	69	61	1.6
G	31	0	70	67	1.3
H	33	0	71	59	1.8
I	47	0	66	55	1.9

n, Number of measurements.

[a] Mixed workers spent time both underground and on the surface during the work shift monitored. No mixed workers were sampled at Facility D.

Facility G, from 62 to 116 μg m^{-3} at Facility H, and from 42 to 146 μg m^{-3} at Facility I, with GSDs that were mostly <3.0. The SEMs were generally ≤20% of the AM value, indicating reasonably good precision in the exposure estimates by job title.

There was much less variation between jobs with each facility and across facilities in the surface REC measurements. The highest exposed job with measurements among the surface workers at the seven facilities was the crusher operator at Facility B (29 μg m^{-3}, $N = 3$), followed by the shift truck driver at Facility A (17 μg m^{-3}, $N = 1$). The AMs for all other surface jobs monitored were ≤10 μg m^{-3}. The results by job title for measurements on surface workers are not presented since the measurements were not used as exposure estimates.

The area samples taken underground and on the surface to measure REC are summarized in Table 5 by face, haulage and travel ways, underground shop and office areas, and surface. The averages of the area samples display a similar gradient in REC air levels as the personal samples. The highest concentrations were measured underground at the face, with AM concentrations ranging from 50 to 661 μg m^{-3} by facility. These concentrations were ~30–80% higher than the AM concentrations in the haulage and travel ways. The results for the shop and office samples were substantially lower for all but Facilities A and I, but the number of measurements in all facilities was small. The area measurements were not used for estimation of personal exposure levels, but nonetheless provided an indication of the range of REC concentrations to which the underground workers at these facilities were potentially exposed. The AMs of the area samples taken at the face generally were equal to or greater than the respective AMs of the personal samples taken on workers in production jobs primarily at the face.

After grouping of the underground jobs based the number of measurements, 40% of the underground exposure-years (0–68% by facility) were assigned exposure estimates based on standardized job titles (U1); 40% (0–63%) were based on time spent in four underground areas (U2), and 6% (0–27%) were from groups formed based on similar CO air concentrations (Stewart et al., 2010a) (U3). Only 12% (0–71%) of the exposure-years were assigned estimates based on the average of all underground measurements (U4), and only 1% (<1–2%) were assigned an estimate based on <5 measurements (U5). For surface jobs, 69% (36–90% by facility) of the exposure-years were based on a mean from exposure group A (minimal contact), 23% (4–46%) were based on an exposure group B (light equipment or bystander) mean, and 4% (0–21%) were based on an exposure group C (heavy equipment) mean. A total of 75% of the surface exposure-years were attributed to the S1 estimation group (facility-specific).

DISCUSSION

At the seven facilities surveyed, the average REC exposure levels underground were 20–64 times higher than the average exposure levels measured on the surface. In addition, an ~10-fold range in the average REC exposure levels measured underground was observed across the seven facilities. The variation seen in exposure levels across the facilities can most likely be attributed to differences in the number and size of diesel-powered equipment in use and the design of the underground ventilation systems (Haney *et al.*, 1997).

Table 3. Measured personal NO and NO_2 exposure levels (ppm) for underground, mixed, and surface workers by mining facility: full-shift time-weighted average concentrations

Mining facility[a]	NO measurements					NO_2 measurements				
	n	*n* < LOD	AM	GM	GSD	*n*	*n* < LOD	AM	GM	GSD
Underground										
A	105	0	1.07	1.00	1.5	108	0	0.60	0.52	1.8
B	117	1	1.49	0.83	4.4	120	10	0.22	0.12	3.8
E	109	1	1.11	0.64	3.6	115	2	0.28	0.20	2.6
G	127	11	0.20	0.11	3.6	127	8	0.10	0.05	3.6
H	118	3	0.68	0.47	2.9	118	1	0.13	0.09	2.4
I	90	1	0.57	0.40	2.7	101	3	0.18	0.13	2.5
Mixed underground and surface[b]										
A	30	1	0.5	0.29	3.8	30	0	0.28	0.12	4.8
B	4	0	0.37	0.29	2.2	4	0	0.06	0.05	1.6
E	11	4	0.07	0.03	4.4	11	3	0.07	0.04	3.4
G	18	5	0.05	0.02	3.3	18	1	0.04	0.03	2.7
H	16	2	0.33	0.07	6.9	16	1	0.07	0.03	3.7
I	15	4	0.16	0.06	5.1	18	5	0.07	0.03	3.4
Surface										
A	34	9	0.11	0.04	4.5	34	0	0.01	0.01	2.0
B	61	1	0.09	0.05	2.6	61	19	0.02	0.02	2.0
E	24	15	0.03	0.01	3.1	26	3	0.05	0.03	2.3
G	31	15	0.02	0.01	2.4	31	7	0.02	0.01	2.4
H	33	8	0.04	0.03	2.8	33	1	0.04	0.03	2.2
I	42	20	0.09	0.03	4.5	48	14	0.06	0.03	3.1

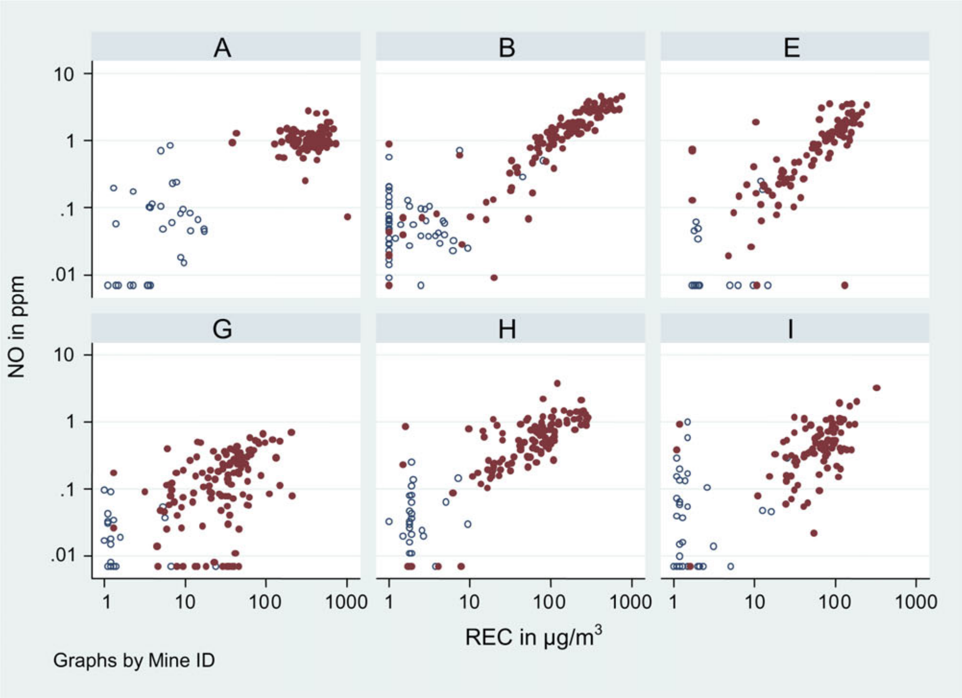
n, Number of measurements.

[a] No NO or NO_2 measurements were taken at Facility D due to technical problems with the sampling method prior to the survey.

[b] Mixed workers spent time both underground and on the surface during the work shift monitored.

The REC levels were generally consistent with the ranking by NO and NO_2 levels across the facilities. The limestone operation had higher levels, followed by the potash and salt operations, while the trona operations had lower average levels for all three agents. This pattern is consistent with the facilities' characteristics. The limestone facility (A) was characterized as having the largest production equipment and the lowest likely total exhaust airflow rate because of the extensive reliance on natural air movement (Stewart *et al.*, 2010). In contrast, much of the equipment in the trona facilities (G, H, and I) was electric, and total exhaust airflow rates were the highest in the study facilities. The REC levels in the potash and salt operations were generally in between these two types of facilities. The substantial contrast in exposure levels seen with REC and the gases, however, was not seen with ROC. Organic carbon may have sources other than DE (e.g. pyrolysis products of lubricants and hydraulic oils) (Noll *et al.*, 2007). Nitrogen oxide gases are present in blasting fumes; however, blasting occurred between shifts and workers did not enter the blasted area until the fumes had dissipated. We found moderate to strong correlations between REC and ROC, NO, and NO_2. The correlations were very similar to those we found for area measurements (Vermeulen et al., 2010b). These findings suggest that relationship between the DE components was similar for both area and for personal measurements.

Within each of the underground operations, we generally measured the highest exposure levels at the production faces where large diesel-powered equipment often was used for loading and transporting ore. The exposure levels measured on workers located primarily in the haulage or travel ways were generally lower than for workers located at the face. Workers in the maintenance shop and offices typically had the lowest exposure levels due, most likely, to the proximity of these areas to the fresh air intake shafts. The exception was



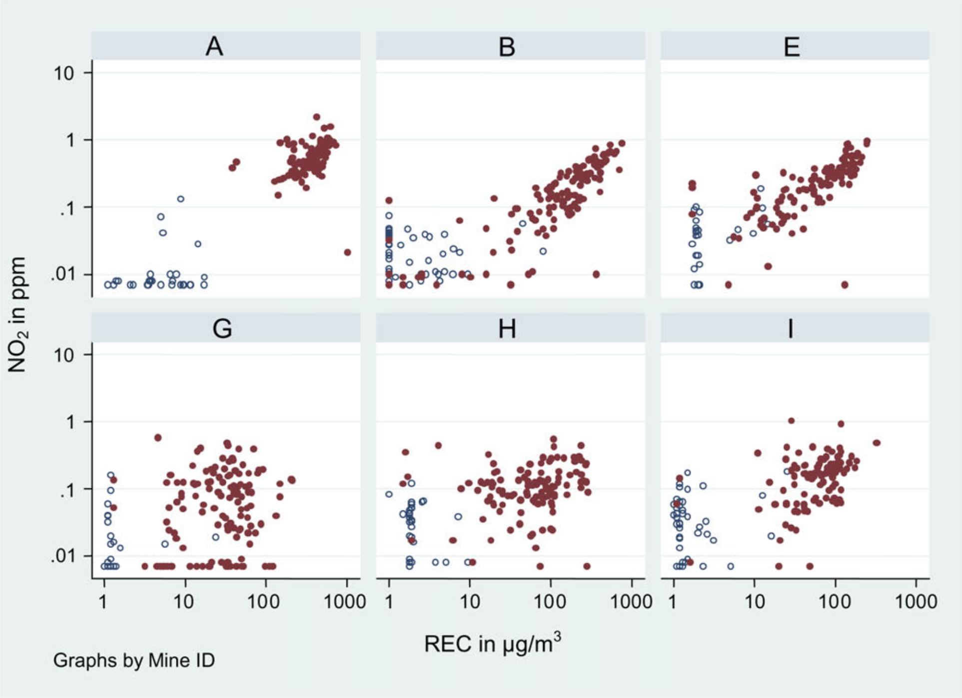


Fig. 2. Personal NO and NO_2 (in ppm) versus REC (in µg m^{-3}) exposure levels measured underground and on the surface by mining facility. Full-shift time-weighted average concentrations. Solid circles are underground and open circles are surface measurements. NO and NO_2 measurements not taken at Facility D.

Table 4. Measured personal respirable elemental carbon exposure levels (μg m^{-3}) by mining facility and job title for underground jobs with five or more measurements: full-shift time-weighted average concentrations

Facility	Job title	Face[a]	*n*	AM	SEM	GM	GSD
A—limestone	Loader operator	X	6	488	130	426	1.8
	Powderman/shooter/blaster	X	10	428	39	414	1.3
	Truck driver		15	412	52	344	2.1
	Diesel mechanic		13	411	32	400	1.3
	Crusher operator		5	394	88	358	1.7
	Scaler	X	18	388	32	362	1.5
	Utility operator		15	372	24	361	1.3
	Drill operator	X	15	313	37	270	1.9
B—potash	Continuous miner	X	62	263	25	130	6.9
	Production supervisor	X	6	170	52	131	2.3
	Mechanic/area and panel		6	134	57	80	3.6
	Maintenance supervisor		5	128	36	116	1.6
	Maintenance		39	118	17	58	5.6
D—potash	Loader operator	X	5	216	49	196	1.7
	Shuttle car operator	X	7	179	35	165	1.5
	Electrician	X	9	95	30	74	2.0
	Belt crew	X	11	55	8	50	1.6
	Mechanic	X	26	54	7	40	2.6
	Maintenance area foreman	X	7	48	4	47	1.2
E—salt	Mine operator	X	27	140	9	126	1.8
	Production foreman	X	7	116	15	110	1.4
	Laborer	X	12	93	23	49	4.3
	Utility operator	X	10	90	17	62	3.8
	Electrician		7	62	11	54	1.8
	Mechanic		20	49	9	34	2.5
	Cleanup		5	31	8	27	1.9
	Truck driver	X	5	29	6	26	1.8
G—trona	Mine operator	X	6	58	9	55	1.4
	Roof bolter	X	7	54	12	43	2.5
	Utility operator		36	46	6	36	2.1
	Shuttle car operator	X	10	35	6	31	1.8
	Mechanic	X	47	31	6	19	2.9
H—trona	Utility operator	X	13	116	28	64	4.3
	Maintenance machine operator	X	8	107	30	77	2.6
	Production machine operator	X	10	100	29	75	2.2
	Roof bolter	X	10	97	31	60	3.1
	Continuous miner operator	X	9	85	25	62	2.4
	Electrician	X	7	84	19	66	2.5
	Maintenance	X	25	74	14	48	2.7
	Support foreman	X	5	72	40	30	6.6
	Laborer	X	7	69	23	47	2.7
	Maintenance foreman	X	7	62	23	34	4.4
I—trona	Loader operator	X	7	146	36	129	1.7
	Continuous miner operator	X	10	111	14	102	1.5
	Shuttle car operator	X	7	83	12	77	1.5
	Mechanic	X	23	70	10	44	3.7

Table 4. *Continued*

Facility	Job title	Face[a]	*n*	AM	SEM	GM	GSD
	Production foreman	X	5	56	18	47	2
	Belt crew	X	13	55	7	42	3.1
	Electrician		7	42	8	37	1.8

n, Number of measurements.

[a] Jobs that worked at least 50% of their time at the face.

Table 5. Measured area respirable elemental carbon concentrations (μg m^{-3}) by mining facility and sampling site

Mining facility	Underground face				Underground haulage/travel ways				Underground shop and offices				Surface			
	n	AM	GM	GSD	*n*	AM	GM	GSD	*n*	AM	GM	GSD	*n*	AM	GM	GSD
A	14	661	69	1.4	10	412	307	2.8	2	424	424	1.0	4	2	2	1.2
B	6	230	226	1.2	17	158	98	3.5	1	3	3	NA	4	4	2	4.0
D	14	111	97	1.7	2	45	45	1.0	3	6	6	1.6	12	4	4	1.5
E	19	145	106	2.5	5	67	34	4.7	2	28	28	1.2	4	4	3	1.4
G	12	50	42	1.9	8	41	34	2.0	6	18	13	2.8	4	2	2	1.1
H	17	138	68	5.6	9	52	30	4.0	0	NA	NA	NA	5	5	4	1.5
I	3	98	94	1.4	25	27	18	3.1	1	94	94	NA	4	6	5	2.1

n, Number of measurements; NA, not applicable.

Facility A, in which the maintenance shop was located near the mine exhaust and near the staging area where the production equipment was parked at the end of each shift and restarted in the morning. Also, one area measurement taken in the maintenance shop at Facility I measured 94 μg m^{-3}, indicating the potential for higher intermittent exposures in this maintenance shop. Thus, we observed similar patterns of the area measurements between the face, haulage and travel ways, and shop and office areas to those seen with personal measurements, which supports the use of area measurements for developing the exposure groups and for using the area measurements to estimate relative trends of change in REC levels over time.

The results of the REC monitoring presented here are similar to the results from a previously published report on monitoring conducted on the same days at five of the facilities by independent investigators (Cohen *et al.*, 2002). Because these data were not used in the estimation process, we used them to evaluate the reliability of our measurements. When grouped by the general job categories of production, maintenance, and surface, the AMs from the two surveys showed close agreement, differing by <25% for the underground production and underground maintenance jobs monitored (Stewart *et al.*, 2010). This level of disagreement among side-by-side samples may be typical as a similar level was reported for side-by-side samples of acrylonitrile (Zey *et al.*, 2002). The REC exposure levels measured by Cohen *et al.* for surface workers also were similar to ours, except for at Facility A, where the AM for workers on the surface was 39 μg m^{-3} in the survey by Cohen *et al.* compared with 6 μg m^{-3} in the DEMS survey. Several of the maintenance workers measured at Facility A worked both on the surface and underground within a shift, and therefore, the workers classified as ''surface'' may have differed between the two surveys.

A feasibility study conducted in 1994 at one of the potash facilities (B) used similar sampling methods as those used in the DEMS surveys (Stanevich *et al.*, 1997). During the earlier survey, the average of 46 personal underground samples for REC was 190 μg m^{-3}. In the DEMS survey, the 124 personal REC samples taken underground averaged 191 μg m^{-3}. There was little difference in the amount of diesel equipment being run or the ventilation rates between the two surveys. Thus, the close agreement in average exposure levels measured on underground workers under similar environmental conditions during the two surveys suggested that the DEMS monitoring results provided reasonable estimates of the average exposure levels at this facility at the time of measurement.

We developed quantitative estimates of average REC exposure levels by job title for the underground jobs at each of the seven active study mining facilities using a grouping strategy. The grouping strategy ensured that the estimates of the average exposure levels were based on at least five measurements. For underground jobs with five or more measurements, these estimates were based directly on the AM of the measurements taken on the jobs. Eighty-four percent of the SEMs listed in Table 4 were $<30\%$ of the AM, indicating good precision. However, for jobs in which the GM was much lower than the AM, indicating a skewed distribution, the SEM may be underestimated when based on sample sizes of <30.

The surface jobs were assigned to exposure groups based on the amount of daily contact with diesel-powered equipment from job descriptions and interviews. As such, the exposure levels within each facility were expected to increase with increasing contact. This pattern was found overall, with estimates of average exposure levels of 1, 3, and 5 $\mu g\ m^{-3}$, for job groups with increasing contact with diesel equipment. The monotonic trend indicates that the overall assignment of the measured jobs to the three measured surface groups was accurate (Stewart *et al.*, 2010).

In summary, the REC measurements from the DEMS monitoring surveys were used to estimate exposure levels in 1998–2001 by job title for an epidemiologic study of DE and lung cancer risk. These estimates by job title were used as baseline reference values for the retrospective assessment of historical exposure levels. The large contrast in exposure levels measured underground versus on the surface, along with the differences between the mining facilities and between underground jobs within the facilities resulted in a wide distribution in the exposure estimates for evaluation of exposure–response relationships in the epidemiologic analyses.

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Disclaimer—The findings and conclusions in this report/presentation have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy.

APPENDIX

Example of assignment of the 1998–2001 exposure estimates for respirable elemental carbon (in $\mu g\ m^{-3}$) for Facility E using the underground job grouping strategy

All underground jobs (identified as standardized job titles) monitored at Facility E are listed below along with their corresponding face/haulage and travel ways/shop and offices/crusher (FHSC) code. This code designates the percentage of time workers with the job held at each of these four underground areas (H refers to $>59\%$ of work shift, M refers to 30–59% of work shift, L refers to $<30\%$ of work shift). The column labeled U1 displays the number of measurements and the AM by standardized job title. The column labeled U2 displays the number of measurements and the AM for jobs grouped by the same FHSC code. The column labeled U3 displays the number of measurements and the AM for jobs assigned to a group based on combined U2 groups with similar CO air concentrations (CO concentrations not shown). The column labeled '1998–2001 estimate' indicates each job's exposure group and the REC exposure estimate assigned to that job for the epidemiologic analysis for the 1998–2001 year measured in the DEMS survey. For example, there were 27 measurements on the mine operator job, and therefore, the AM of 140 $\mu g\ m^{-3}$ associated with the U1 group was used as the REC exposure estimate for this job. By contrast, the roof bolter and powderman had only three and two measurements, respectively. Workers with these jobs worked similar percentages of time in the face, haulage and travel ways, shop and office, and crusher areas as the mine operator, truck driver, foreman—production, and utility operator. The two jobs, therefore, were assigned the U2 exposure estimate of 118 $\mu g\ m^{-3}$, based on the 54 measurements taken on these six jobs. Workers with the tool room job were measured four times. These workers worked percentages of time in the four underground areas different from all other workers with any other job, so they could not be assigned the AM of the respective U2 group. Similar levels of CO led to the MMLL U2 group being combined with the MMLM, MMML, and MLML U2 groups to form a U3 group that was associated with 55 measurements and an overall AM of 54 $\mu g\ m^{-3}$, which was then assigned to the tool room job.

Standardized Job title	FHSC[a] code	Grouping						1998–2001 Estimate	
		U1		U2		U3		Group	REC Estimate
		n	REC AM	*n*	REC AM	*n*	REC AM		
Mine operator	HLLL	27	140	54	118	54	118	U1	140
Roof bolter	HLLL	3	108					U2	118
Powderman	HLLL	2	201					U2	118
Truck driver	HLLL	5	29					U1	29
Foreman—production	HLLL	7	116					U1	116
Utility operator	HLLL	10	90					U1	90
Cleanup	MMLM	5	31	5	31	55	54	U1	31
Foreman—maintenance	MMML	4	26	16	76			U2	76
Laborer	MMML	12	93					U1	93
Tool room	MMLL	4	24	4	24			U3	54
Mechanic	MLML	20	49	30	51			U1	49
Electrician	MLML	7	62					U1	62
Oiler/lubricator	MLML	3	34					U2	51
Mine general operator	LHLL	4	82	4	82	9	42	U3	42
Bin and skip operator	LLLH	2	11	5	10			U2	10
Crusher operator	LLLH	3	9					U2	10

n, number of measurements; REC, respirable elemental carbon.

[a] FHSC = face/haulage/shop/crusher areas: H (high) refers to >59% of work shift, M (medium) refers to 30–59% of work shift, and L (low) refers to <30% of work shift.

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