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Mapping Particulate Matter at the Body Weld Department in an Automobile Assembly Plant

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A respiratory health survey conducted in an assembly plant in 2000–2001 found that welders had elevated rates of self-reported respiratory symptoms compared with painters and assembly workers. Subsequently, the ventilation system was improved at the body weld department. In a follow-up study, particle spatial distributions were analyzed, following a mapping protocol developed specifically for this workplace, to evaluate the effectiveness of the changes. Significant temporal and spatial variations were observed. Temporal variation during a shift was monitored with over-shift stationary sampling at fixed locations. Spatial variation was evaluated with 1-min time-weighted average particle concentrations measured throughout the process areas (212 locations). The arithmetic spatial mean across 212 locations for the respirable particles varied from 305 $\mu g/m^3$ to 501 $\mu g/m^3$ on 6 sampled days, with a standard deviation of 71 $\mu g/m^3$, indicating that the difference between before and after countermeasures must be at least 191 $\mu g/m^3$ to be considered statistically significant at the given sample sizes. The available data were not sufficient to evaluate the reduction of the particle concentrations after the countermeasures. The map of particle mass concentration revealed several high concentration areas, requiring further investigation and potentially higher level of controls. Resistance welding needed to be effectively controlled, as it could be the major particle emitting sources in the facility. The map of submicrometer (0.014 μm to 1.0 μm) particle count concentration presented different patterns from that of respirable particle mass concentration, indicating that the submicrometer particles tended to be more evenly distributed over the process areas. Workers not in proximity to intensive welding operations might be exposed to fine particles at levels higher than had traditionally been thought. Mapping was demonstrated to be an effective method to assess particle spatial distributions. A well-designed sampling protocol is critical to achieving the specific aims of a mapping study.

Keywords mapping, particulate matter, temporal and spatial variations, ventilation, welding

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INTRODUCTION

Welders are exposed to high concentrations of welding fumes, which are primarily fine and ultrafine particles. The exposure is associated with increased respiratory symptoms and illness, and, potentially, cardiovascular diseases, as well as reproductive and neurological effects.[1] The Occupational Safety and Health Administration (OSHA) currently has no permissible exposure limit (PEL) for welding fumes. The PELs for particles not otherwise regulated (15 mg/m^3 for total dust and 5 mg/m^3 for respirable fraction) may not be sufficient to protect workers from the adverse health effects associated with exposure to the fine and ultrafine particles in welding fumes.[2–4] At the same time, workers' exposures are highly variable, depending on the composition of the metal piece worked on, the welding method employed, and the work environment.[5] Ventilation is among the most critical factors influencing airborne particle concentration in a welding workplace; in an insufficiently ventilated workplace exposure levels can be very high.

A cross-sectional study conducted in 2000–2001 in an automobile assembly plant found that welders had increased rates of allergy symptoms, asthma symptoms, and cough compared with assembly workers.[2] As a result of the study, increasing ventilation and follow-up evaluation were recommended. Subsequently, ventilation was improved and a follow-up study was conducted to assess the effectiveness of the changes. Particle mapping was performed as part of the follow-up study. Aerosol mapping is a new technique to assess the spatial distribution of an aerosol at a workplace. Particle mapping utilizes direct-reading continuous particle monitors to measure particle air concentrations at predetermined locations in a sampling grid. This method has been used in several studies to assess the spatial variability in both particle count and mass concentrations.[6–12] Sources for different sizes of particles were identified, and effects of process and ventilation on particle size and spatial distributions were evaluated.[7,9,10] Constructed maps were used subsequently

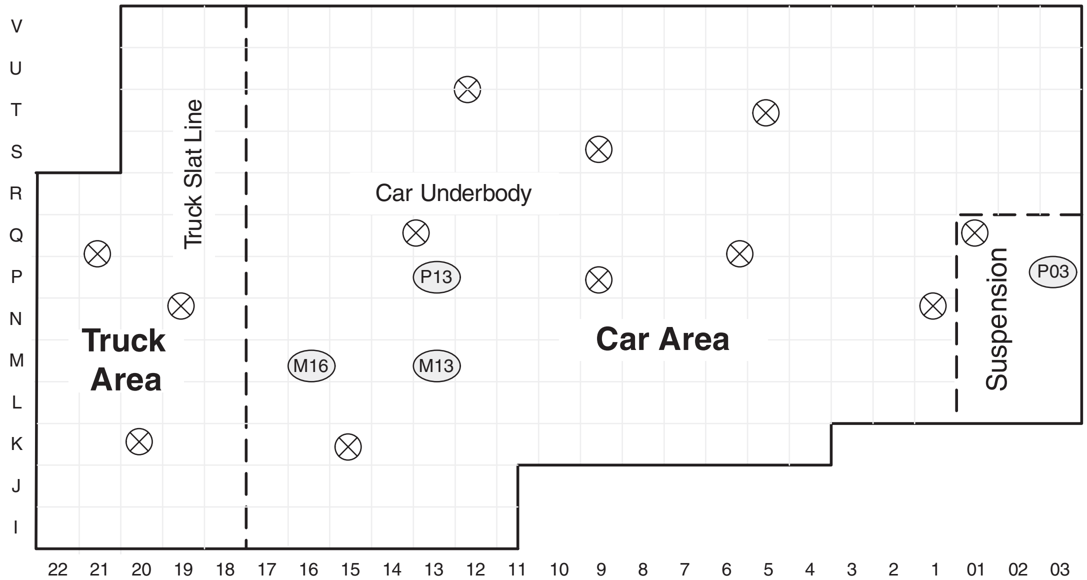

FIGURE 1. Facility layout of the body weld department. The dashed lines delineate the main areas defined by the facility based on operations/activities. ⬭ location for stationary monitoring over a shift. Locations are identified by letter/number combinations from the plant grid (columns are 13 m apart); ⊗ cartridge dust collector.

to guide control measures and evaluate the efficacy of the controls.[8]

While aerosol mapping appears to be a useful tool for researchers and industrial hygienists to assess particle exposure, its utilization and effectiveness highly depend on the mapping method. Mapping data collection grid size, location, sampling interval, and the number of replications are the main components of a method. The study aims will dictate the particular protocols and spatial resolutions needed. For example, when mapping is used as a screening tool to select locations for further intensive monitoring, data can be collected on a relatively coarse grid with a shorter sampling interval.[7] However, when the density of processes is high and mapping is expected to generate high resolution spatial maps, the grid size must be sufficiently fine.

Although several aforementioned papers have been written in which some mapping method issues were addressed, developing mapping protocols has not been systematically discussed, and the underlying temporal variability has often been neglected in the process of designing a mapping method. During pilot sampling in this study, the need to develop a specific mapping protocol for the body weld department became apparent due to the presence of temporal variations and the characteristics of the operations.

The facility environmental health and safety (EHS) personnel collected two sets of mapping data in the body weld department, one before and one after the ventilation improvements. In the current study, to evaluate the effectiveness of the ventilation improvements and the reduction of the particle level, pilot sampling was conducted in June 2005, and intensive mapping data collection sessions were carried out in January 2006. The three specific aims of the study were: first, to develop a mapping protocol specifically for this workplace, with an emphasis on evaluating and incorporating temporal variations in the process of analyzing spatial distributions; second, to explore whether the reduction of particle concentration could be evaluated based on the data collected by the facility EHS personnel and in this study; and third, to identify potentially high concentration areas and thus to inform further ventilation evaluation, personal monitoring, and respiratory health surveys. The implications of process/ventilation conditions may be meaningful in general practice. This article reports the development of the mapping protocol and the results of the mapping.

METHODS

Facility/Process Description

The body weld department had a floor area of approximate 30,000 m^2 and comprised a car area, a truck area, and a suspension area (Figure 1). The car and the truck areas had their own underbody line, side member lines, roof and trunk line, flexible body line, and slat line. None of these areas was physically separated or enclosed by any barriers. There were more than 300 evenly spaced steel columns in the body weld department supporting the building structure. Each column was identified by a painted letter/number combination from the plant grid (Figure 1). Operations were usually set up between the columns. Within the major areas, some large robotic welding areas were semi-enclosed by 8-ft high plastic sheets (not shown in Figure 1) mainly for safety reasons. No manually operated workstations were set up within these enclosed areas.

Approximately 300 employees worked in the department on two shifts, the day shift from 6:00 a.m. to 2:30 p.m. and the evening shift from 4:30 p.m. to 1:00 a.m. The plant operated Monday through Friday and closed over weekends. The facility produced about 900 cars and 600 trucks per day. Day shifts and evening shifts were identical as to operations. Although no detailed production rates were obtained for the study period, the overall daily production rate appeared to be consistent, and there were no noticeable differences between shifts and days, or between the pilot sampling and the mapping period.

Two types of welding were used in the department: metal inert gas arc welding (MIG) and resistance welding. Robotic welding machines performed more than 80% of the welding. Numerous ventilation systems were installed throughout the facility to control welding fumes, including local exhaust systems and dilution systems. The local exhaust systems included canopy hoods and enclosing hoods. Canopy hoods were mainly over robotic MIG welding areas, while the enclosing hoods were over manual or semi-manual MIG welding operations. Exhausted air was typically routed to cartridge dust collectors (Downflo Oval Cartridge Dust and Fume Collector; Donaldson Torit Corp., Minneapolis, Minn.) adjacent to the welding areas with air passed through filter medium, and the cleaned air discharged back into the facility. Dilution air supply systems provided outdoor air through numerous inlets located throughout the facility. Many of the air supply inlets were located near the plant ceiling, while others were configured to deliver air into the "occupied zone" 3 to 4 meters above the floor.

Welding operations were the primary sources of the airborne particles. Resuspension from forklift traffic and the discharge from the cartridge dust collectors also contributed to the overall airborne particle concentration. The cartridge dust collectors and an air supply system at the truck slat line were newly installed to increase ventilation as recommended by the original study.

Sampling Instruments

Multiple instruments were used in the particle sampling. An aerosol photometer with a cyclone, Personal DataRam (model 1200AN; MIE Inc., Bedford, Mass.), was used to measure particle mass concentration with a size selection of $PM_{2.5}$. The DataRam was equipped with a filter (Teflo Membrane, polytetrafluoroethylene [PTFE] with polymethylpentene support ring, 37 mm; Pall Corporation, East Hills, N.Y.) to collect particles for gravimetric analysis. A personal sampling pump (Sidepak model 550; TSI Inc., Shoreview, Minn.) was used to draw air through the DataRam at a flow rate of 4 L/min. A light scattering direct-reading device (Microdust Pro Aerosol Monitoring System; Casella USA, Amherst, N.H.), was used to measure respirable particle mass concentration. Another light scattering device that was used by facility EHS personnel collecting mapping data before and after the countermeasures (DustTrak model 8520; TSI) was borrowed and used side-by-side with the Microdust Pro for 2 days during intensive mapping data collection to make comparison between the instruments.

An optical particle counter (OPC, PDM-1108; GRIMM Technologies, Inc., Douglasville, Ga.) was used to assess particle size distribution. The OPC measures particle concentration in either count or mass mode. Data are reported in 15 size channels ranging from 0.23 μm to 20 μm for mass and 0.30 μm to 20 μm for count. A built-in pump draws air through the OPC and a 47-mm PTFE filter (Grimm Technologies) is installed in the OPC to collect particles for gravimetric and chemical analyses. The flow rate is fixed at 2 L/min. A condensation particle counter (CPC) P-Trak Ultrafine Particle Counter (model 8525; TSI) was used to measure fine particle count concentration in a size range of 0.014 μm to 1.0 μm.

Two filter-based cassette samplers were operated in conjunction with the direct-reading instruments: a close-face total particle sampler (SKC, Eighty Four, Pa.) running at 2 L/min and a respirable fraction particle sampler (Cyclone Assembly, MSA, Pittsburgh, Pa.) running at 1.7 L/min. Samples were collected on 37-mm diameter Teflo Membrane filters described above. Battery-operated pumps (Sidepak model 550; TSI) were used to draw air through the cassette samplers at the specified flow rates. Instruments were zeroed and spanned following manufacturers' instructions. All mass concentrations reported here that were measured by the direct-reading instruments were gravimetrically corrected. As the DataRam and the OPC both had downstream filters, direct-reading output mass concentrations were corrected by their filter results. Respirable particle mass concentration measured by the Microdust Pro and the DustTrak was corrected by the filter results of the respirable cassette sampler (Cyclone Assembly).

Data Collection

Pilot sampling was conducted in June 2005. Researchers walked through the facility and collected process-related information. Particle concentration was measured during the walk-through and at selected locations. Temporal variation during a shift was monitored by over-shift stationary sampling using the DataRam and 1-min time-weighted average (TWA) log interval at Column M16, a midpoint chosen based on accessibility, minimal inconvenience for the production workers and material handling, and the availability of 120 VAC electrical power.

To determine an appropriate sampling interval for mapping data collection, particle concentration was measured using the Microdust Pro and 5-sec log interval at seven randomly selected locations for 10 min at each location to assess the short-term variations. Twenty-second and 1-min TWAs were calculated based on the data logged every 5 sec. Coefficients of variation (CVs) for 5-sec, 20-sec, and 1-min TWAs were calculated to evaluate the short-term variability associated with the different sampling intervals. Instruments were also tested during the pilot sampling for their feasibility and stability. A mapping protocol was developed based on the pilot sampling.

Six intensive mapping data collection sessions were conducted in January 2006, three on the day shifts and three on the evening shifts. One session was conducted per day. Each session lasted approximately 8 hr, during which a fixed route traversing 212 selected locations was followed, but each session started at a different, randomly selected location. One 1-min TWA concentration was measured by the OPC, the

Microdust Pro, and the CPC side-by-side (collocated with the cassette samplers) at each location, identified by the steel columns throughout the department. Data were collected column by column at the column locations, except in large storage areas or at the perimeter of the department where data were collected at every other column. Since the columns were 13 meters apart, one grid point in a constructed map represented an area of 169 m^2. Mapping data were not collected during the first 30 min of a shift, during the breaks, or within 20 min after the breaks. Over-shift temporal variation was further evaluated using the DataRam at three fixed locations, Columns P03, P13, and M13, selected based on potentially high particle concentrations, types of operation, input from the workers, and the accessibility. Due to the availability of the instrument, these three stationary sampling sessions occurred during the evening shifts.

Map Generation

Data were downloaded from the direct-reading instruments to a computer after each sampling session. Gravimetric correction was performed for mass concentrations based on the filter results. Then the data were matched with the locations and entered into a Microsoft Excel spreadsheet; a contour graphing function was used to generate particle concentration maps. Microdust Pro data were used to construct mass concentration maps for respirable particles. OPC data were used to generate count concentration maps for particles 0.30 μm to 20 μm. Particle count concentration measured by the CPC was used to construct maps for submicrometer particles in the size range of 0.014 μm to 1.0 μm. Maps were constructed for each day (not presented here), as well as for the arithmetic mean concentrations across multiple sessions for each type of measurement.

Statistical Analysis

Maps for one type of measurement were first graphically examined for the variations across days. Then the data were log transformed and analyzed by repeated measurements one-way analysis of variance (ANOVA) to assess the variations in the spatial distributions across the sessions. The null hypothesis of ANOVA was that the spatial means (logged) across 212 locations were the same for the six sessions. The ANOVA model can be defined as:

$$Y_{ij} = \ln(X_{ij}) = \mu_Y + b_i + e_{ij} \qquad \textbf{(Model1)}$$

for $i = 1, 2, \ldots, 212$ columns and $j = 1, 2, \ldots, 6$ shifts

where, X_{ij} represents the particle concentration (1-min TWA) for the i^{th} column on the j^{th} sampling session, the response variable Y_{ij} is the natural logarithm of X_{ij}, μ_Y represents the true mean particle concentration (logged) over 212 locations across time, b_i represents the random effect for the i^{th} column, and e_{ij} represents the random deviation of the observed logged particle concentration Y_{ij} on the j^{th} day for column i from μ_Y (i.e., $e_{ij} = Y_{ij} - \mu_Y$). Under Model 1, it is assumed that b_i and e_{ij} are mutually independent and normally distributed, with means of zero and variances $\sigma^2{}_{bY}$ and $\sigma^2{}_{wY}$, representing between-column and within-column variations, respectively. Thus, the total variations in logged particle concentration at 212 locations is given by $\sigma^2{}_Y = \sigma^2{}_{bY} + \sigma^2{}_{wY}$.

Box plot and fitted value vs. residual plot were used to check data distribution and constant variance assumption. Qnorm plot and Shapiro-Wilk test were used to check normality. Tukey's procedure was used for follow-up multiple comparisons to identify where the differences were and if there were any patterns in the differences. Simple arithmetic means of the particle concentrations over 212 locations were also calculated. Chi-square test for trend was applied on the simple arithmetic spatial means to examine the trend through a week. Student's *t*-test was conducted using the average and standard deviation of the simple arithmetic spatial means to determine the minimum significant reduction of mass concentration before and after the countermeasures.

RESULTS

This section comprises two parts: mapping method development and the results of the mapping. The latter includes spatial distributions of mass and count concentrations for particles with different sizes, day-to-day variations in the spatial distribution, and the particle size distribution. Comparison between before- and after-countermeasure is discussed in the next section.

Mapping Method Development

Short-Term Variation and Sampling Interval

Mapping is a time- and labor-consuming process, especially when the area to be evaluated is large. The sampling interval, defined as the sampling time at each location, has a major effect on the total amount of time required for mapping data collection. When multiple identical instruments are available, an interval of 1-min is usually used, as identical instruments can be used simultaneously to reduce the sample load.[9,10] In practice, health and safety personnel in a factory usually do not have multiple identical direct-reading devices, and much shorter intervals such as 5-sec or 20-sec have been used.[7] The EHS personnel in this automobile facility also used a 5-sec sampling interval to collect mapping data before and after the counter-measures.

During the pilot sampling, significant short-term variation was observed, as shown in Figure 2. Particle concentration varied dramatically during welding cycles. Therefore, to determine an appropriate sampling interval, we collected data at seven locations for 10 min each using a 5-sec log interval. The coefficients of variation (CVs) for 5-sec, 20-sec, and 1-min TWAs were calculated to evaluate short-term variations associated with different sampling intervals (Table I). For some locations, CVs were small for all sampling intervals, indicating small variations in particle concentration during the sampling periods. For some other locations, CVs varied moderately, but the differences between the CVs for the varying averaging times were small.

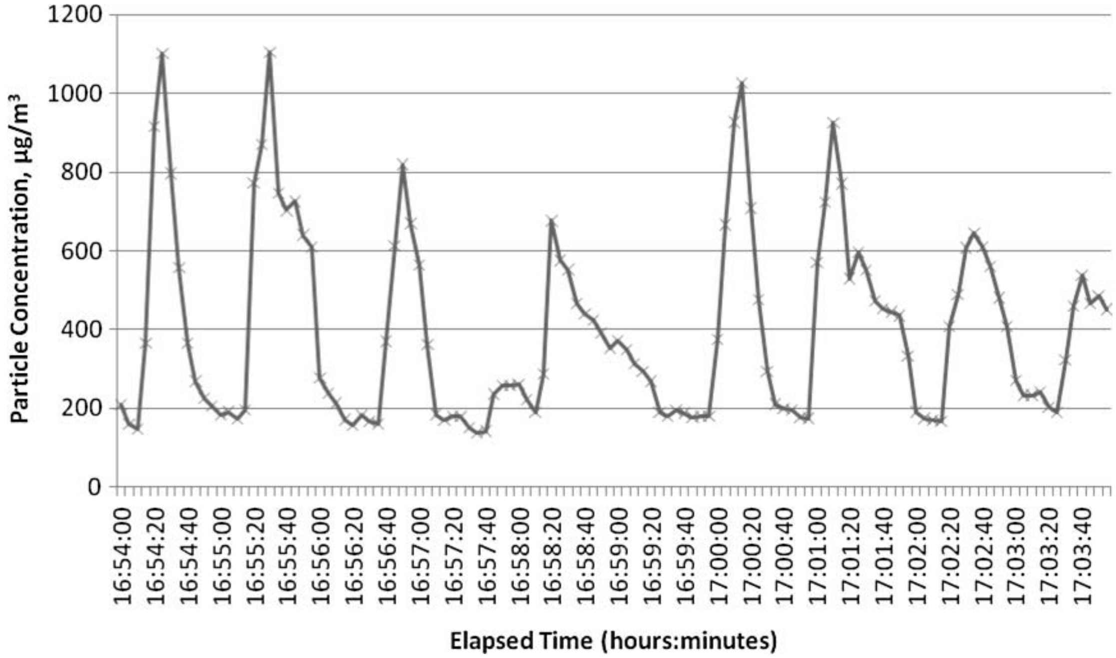

FIGURE 2. Short-term variation at a fixed location (Column M02), measured by Microdust Pro.

However, there were locations where CVs varied substantially with the CVs for 1-min TWAs much smaller than those for 5 or 20 sec TWAs. These locations were more likely to be within the major operation areas. These results implied that if data were collected for 5 or 20 sec at each location during mapping data collection, particle concentration at some locations could vary as much as 67% in 10 min. Furthermore, an instrument requires time to respond when it is moved from one location to another. In the pilot sampling, 20–30 sec were needed for the Microdust Pro, the OPC, and the CPC to stabilize between readings. Based on these results, 1-min sampling interval and 30-sec instrument stabilization time were chosen.

Temporal Variation During a Shift

Temporal variation during a shift was first evaluated at Column M16 during the pilot sampling and further assessed at Columns P03, P13, and M13 during the mapping data collection using the DataRam (Figure 3). Reported data were gravimetrically corrected by a factor of 1.52 (gravimetric: direct-reading output). The early break and the lunch break were apparent in the temporal plot (Figure 3). The $PM_{2.5}$ mass concentration decreased 3- to 6-fold during the 15-min early break and 10- to 30-fold during the 45-min lunch break. As the goal of mapping was to assess spatial variations in the particle concentrations, data should be collected during steady-state conditions, and thus, measurements made during the breaks would not be comparable to those collected during the operations and would lead to underestimation of concentrations at the corresponding locations. Therefore, mapping data were not collected during or within 20 min after the breaks or within 30 min of the start of a shift.

After the data during these times of low production ("resumption periods," which were the first 30 min of a shift and during and within 20 min after a break) were excluded, particle concentration still varied substantially during the work time of a shift (Table II). To better capture this variation and incorporate it into the maps, repeated measurements were necessary. Based on the moderate CV at Column M16 measured during the pilot sampling, the consistency of the overall operation from day to day observed during the pilot sampling, and the feasibility, we decided to collect mapping data three times on each of two shifts (day shift and evening shift). Assuming the difference between the day shift and evening shift was minimal because they were operated identically, the total of six replications were believed to be sufficient to evaluate variations across days.

Since there were 212 locations to be evaluated by 1-min TWAs and data could be gathered only during steady-state periods, an 8-hr work shift could accommodate one mapping

TABLE I. Coefficients of Variation (CVs) for Different Sampling Intervals at Multiple Locations

Location	5-Sec	20-Sec	1-Min
L5	0.06	0.05	0.04
T20	0.07	0.06	0.05
N14	0.15	0.13	0.12
N5	0.16	0.16	0.17
Q20	0.24	0.20	0.18
P03	0.51	0.41	0.26
M02	0.67	0.60	0.28

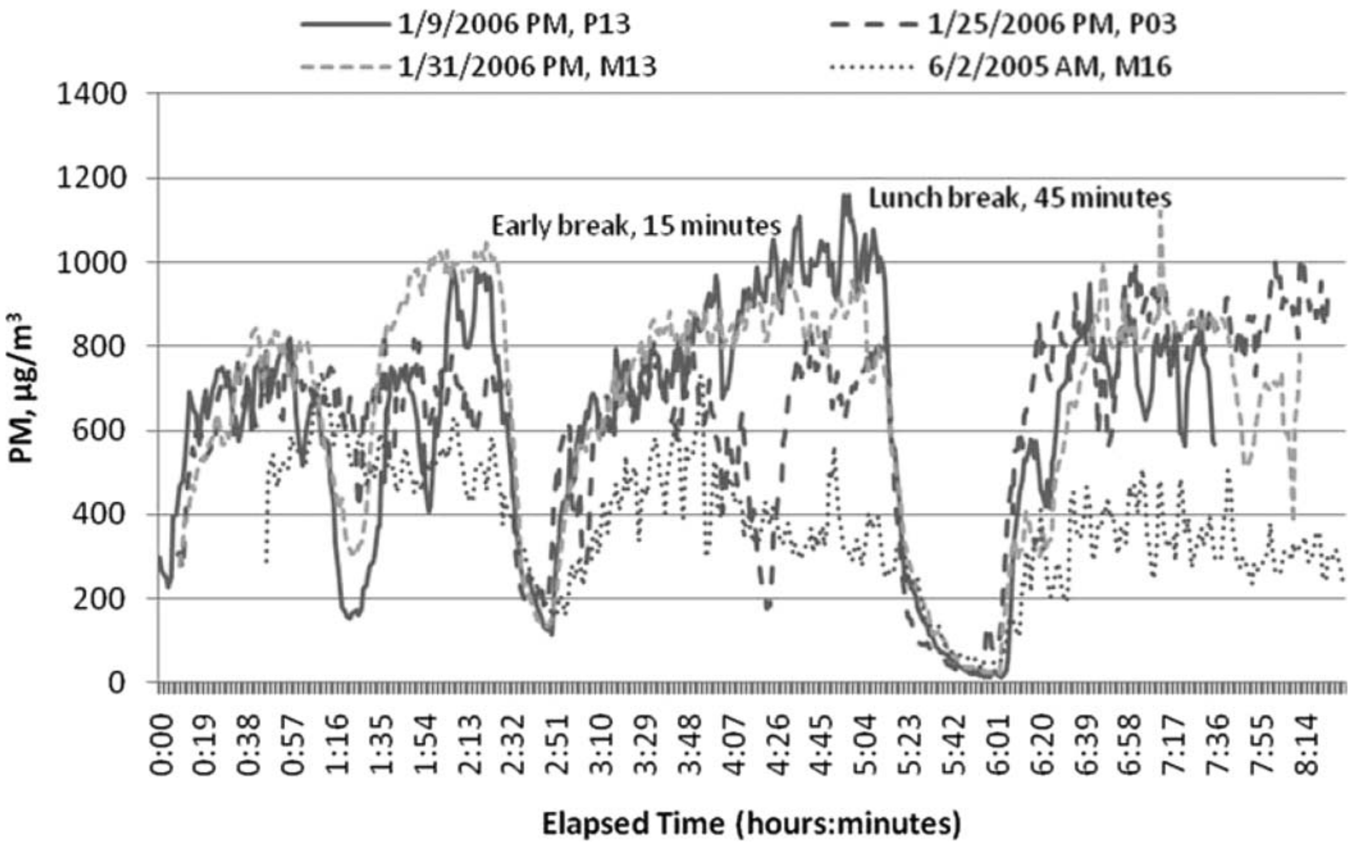

FIGURE 3. Over-shift temporal variation at fixed locations, measured by DataRam.

data collection event, so only one complete set of samples during one shift per day was feasible. Therefore, six repeated mapping data collection sessions were carried out on 6 different days in January 2006. To avoid a location being sampled at the same time during a shift, we designed a fixed route that traversed 212 selected locations. The route was followed in each session but started at a different, randomly selected location. Data were collected at the column locations rather than between column locations, as the operations were often set up between the columns, thus limiting accessibility. Data were collected at every other column in the large storage area and at the perimeter of the department, as particle concentrations varied little at these locations as observed during the pilot sampling.

TABLE II. Over-Shift Temporal Variation at Fixed Locations, Measured by DataRam, μg/m^3

Date	Location	Shift	TWA	SD	CV
June 2, 2005	M16	Day	399	122	0.30
January 9, 2006	P13	Evening	734	196	0.27
January 25, 2006	P03	Evening	707	149	0.21
January 31, 2006	M13	Evening	757	177	0.23

Note: Unsteady-state periods excluded.

Mapping Results

Spatial Variations

Figure 4 presents a contour map of respirable mass concentration as measured by the Microdust Pro. Each grid point was an arithmetic mean of six mass concentrations collected on six shifts, and the data were gravimetrically corrected by a factor of 0.92 (gravimetric: direct-reading output) based on the filter results of the respirable cassette sampler. Five "hot spots" appeared on the map, located at Columns U6, N14/P13, T14, N6, and P03. Mass concentrations at these locations are presented in Table III. All the hot spots were located in the car area. The arithmetic mean for the car area and the truck area were 403μg/m^3 and 249 μg/m^3, respectively. The mass concentration in the car "underbody" area was especially high.

A map of count concentration for particles 0.30 μm to 20 μm as measured by the OPC (Figure 5) exhibits very similar patterns to those in the map of respirable mass concentration (Figure 4). Data were the arithmetic means of four sessions (OPC was on the mass mode during the other two sessions). All five hot spots appeared. However, the particle count concentration at T14 was only about 60% of that at N14/P13, whereas the respirable mass concentration at these two locations were comparable (Table III).

Secondly, the hot spot at P03 suspension area in the Figure 4 split into two areas: one centered at M02 with a relatively low concentration, and the other centered at P03 with a much

TABLE III. Particle Concentrations at Specific Locations

	Respirable Particle Mass		Particle Count (0.30–20 μm)		Particle Count (0.014–1.0 μm)	
High Concentration Area	Concentration, μg/m^3	Ratio to Mean	Concentration, m^{-3}	Ratio to Mean	Concentration, m^{-3}	Ratio to Mean
U6	1330	3.58	3.1×10^9	4.92	3.6×10^{11}	2.77
N14	1127	3.03	2.4×10^9	3.81	2.8×10^{11}	2.15
T14	1182	3.18	1.5×10^9	2.38	1.6×10^{11}	1.23
N6	819	2.20	1.3×10^9	2.06	1.6×10^{11}	1.23
P03	697	1.87	1.7×10^9	2.70	2.0×10^{11}	1.54
Arithmetic mean over 212 locations	372		6.3×10^8		1.3×10^{11}	
90th percentile /mean		2.1		2.4		1.8
90th to 10th percentile		4.5		5.2		3.3

higher count concentration. The arithmetic mean for the car area and the truck area were 7.0×10^8/m^3 and 4.2×10^8/m^3, respectively.

The patterns of spatial variation presented in Figures 4 and 5 were barely identifiable in a map of submicrometer particle count concentration as measured by the CPC (0.014 μm to 1.0 μm). The count concentrations in Figure 6 were the arithmetic means of six sessions. Although still relatively high at U6, P03/M02 (suspension) and N14/P13 (car underbody), the submicrometer particle count was much more evenly dispersed and tended to spread over a larger area. No distinguishable peaks appeared at Column T14 and Column N6 in the map. The arithmetic mean was 1.4×10^{11}/m^3 and 1.1×10^{11}/m^3 in the car area and the truck area, respectively. The count concentrations at T14 and N6 were just 1.23-fold of the arithmetic mean count concentration across the 212 locations (Table III).

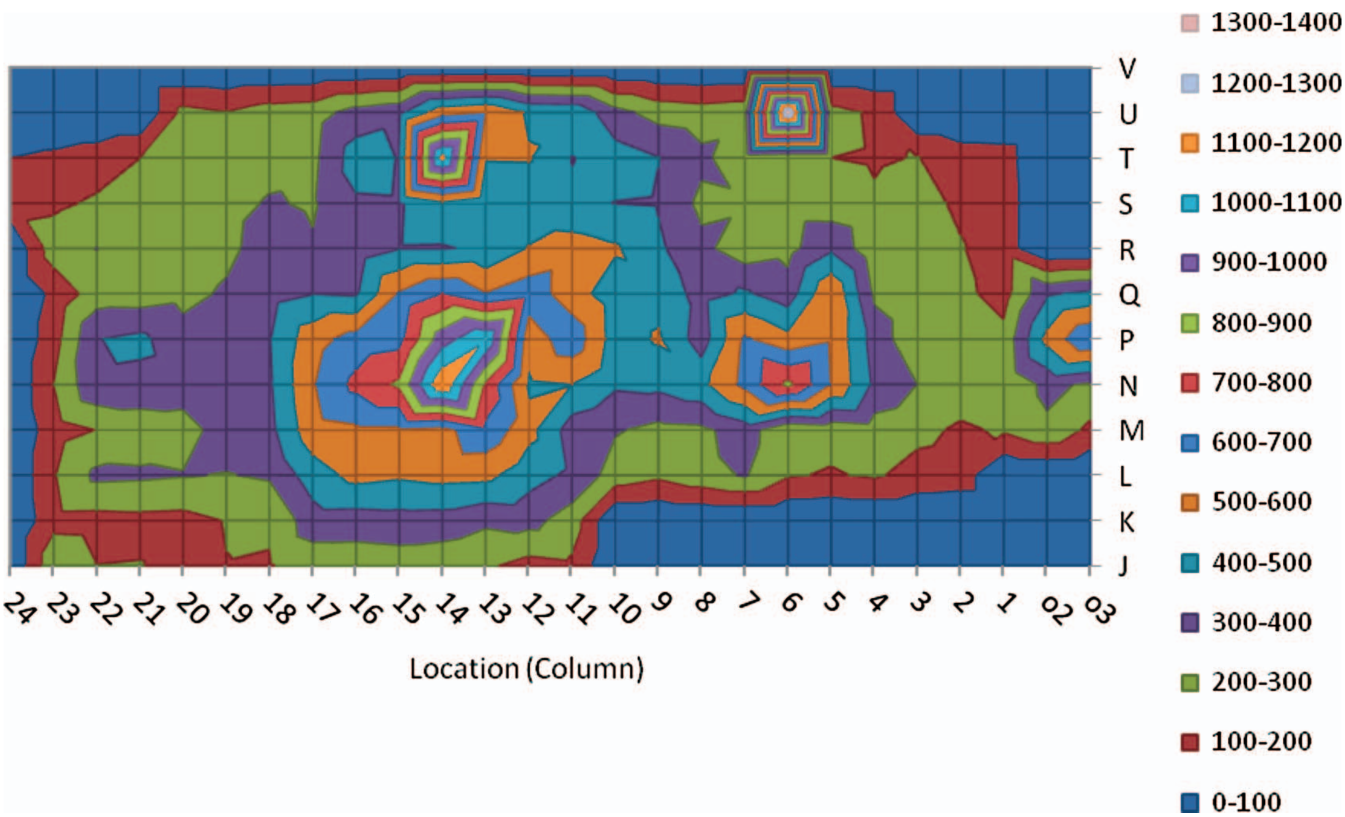

FIGURE 4. Respirable particle mass concentration, measured by Microdust Pro, μg/m^3.

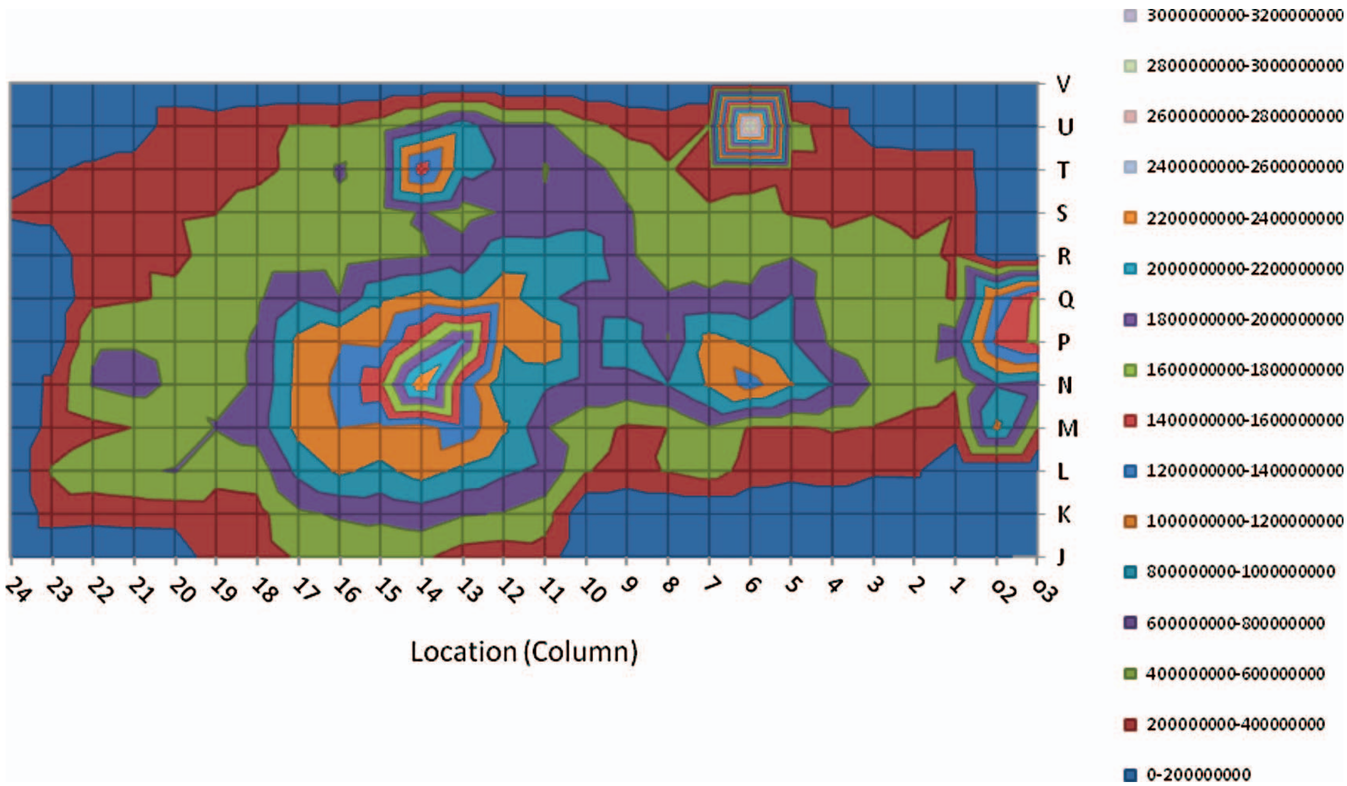

FIGURE 5. Particle count concentration, measured by OPC (0.30–20 μm), /m^3.

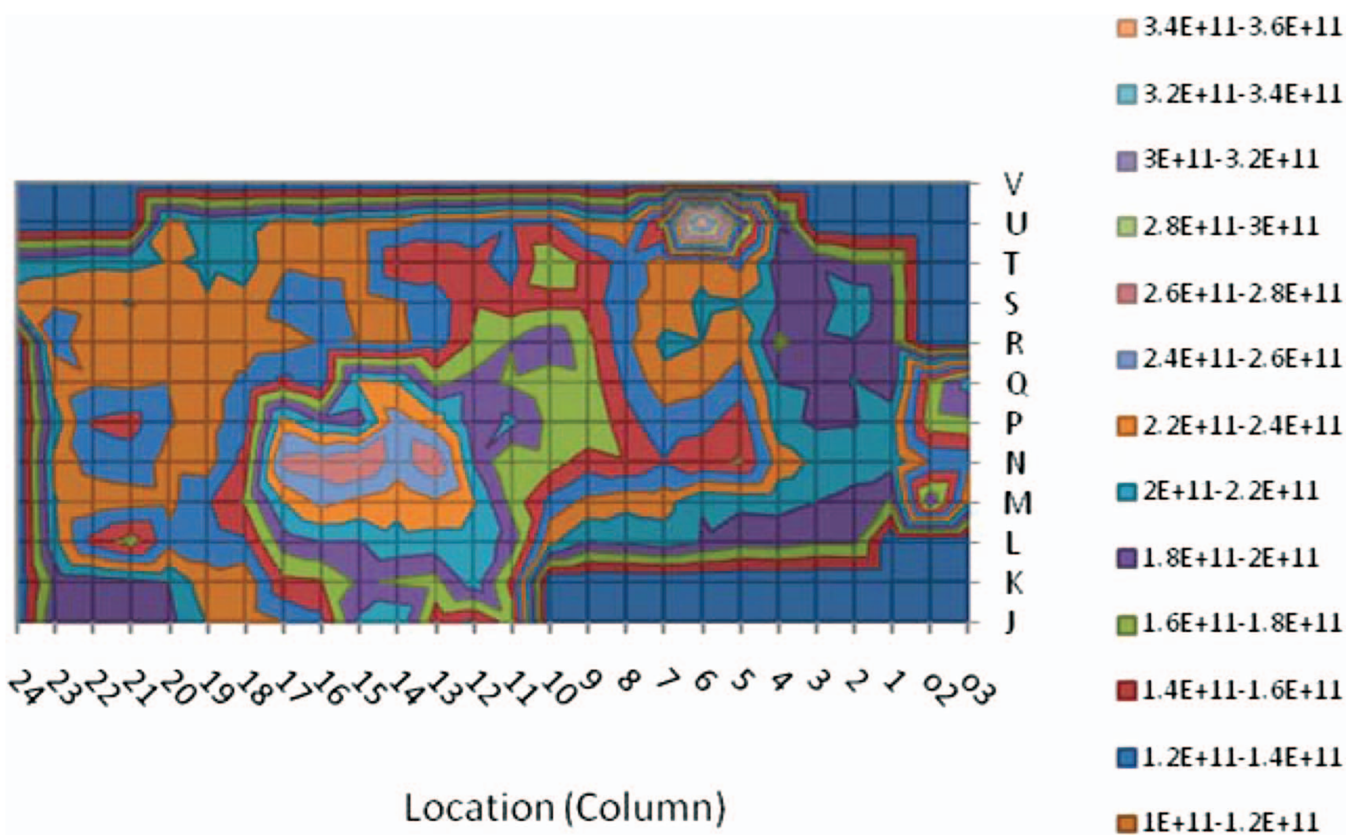

FIGURE 6. Submicrometer particle count concentration, measured by CPC (0.014–1.0 μm), /m^3.

TABLE IV. Spatial Mean and Variation of Respirable Particle Mass Concentration, Measured by Microdust Pro, μg/m^3

Date	Day	Shift	n	Mean	SD	CV	Range
January 5	Thursday	Day	212	501	462	0.92	94–4517
January 9	Monday	Evening	212	310	202	0.65	16–1719
January 11	Wednesday	Day	212	384	193	0.50	98–1319
January 23	Monday	Day	212	305	176	0.58	86–952
January 25	Wednesday	Evening	212	357	145	0.41	153–970
January 31	Tuesday	Evening	212	377	239	0.63	94–1519

A comparison between peak-to-mean ratios of submicrometer particles and those of larger particles (Microdust Pro and OPC data) indicated that the ratios of the submicrometer particles were much smaller (Table III). In other words, submicrometer particles distributed more evenly across the workplace than the large particles. The ratios of highest 10% concentrations (90th percentile) to the mean and highest 10% concentrations to the lowest 10% ones (10th percentile) are the alternatives of the peak-to-mean ratio and reflect the spatial gradients. While the ratio of 90th percentile to 10th percentile for large particle count (0.3–20 μm) was 5, it was 3 for submicrometer particles (0.014–1.0 μm), further illustrating the more uniform distribution of the submicrometer particles.

Day-to-Day Variations of the Spatial Distribution

Temporal variations could exist within a shift, between the two shifts in a day (day shift and evening shift), from day to day and from season to season. Particle concentrations measured during the six sessions in January 2006 were used to assess daily variations, which contained variations between shifts and from day to day within the same season. Results are summarized in Table IV. These two types of variations could not be evaluated separately, as the data were not collected in both shifts on a same day due to the feasibility. The daily arithmetic spatial mean varied from 305 μg/m^3 to 501 μg/m^3, with an average of 372 μg/m^3 and a standard deviation (SD) of 71 μg/m^3. Repeated measurements ANOVA indicated that the spatial means (logged) were statistically different ($p < 0.0005$). Tukey's procedure revealed that the mean of the January 5 day shift was significantly higher than all other means; the means of the January 11 day shift and the January 31 evening shift were significantly higher than those of the January 9 evening shift and the January 23 day shift. Chi-square test for trend further indicated that there was

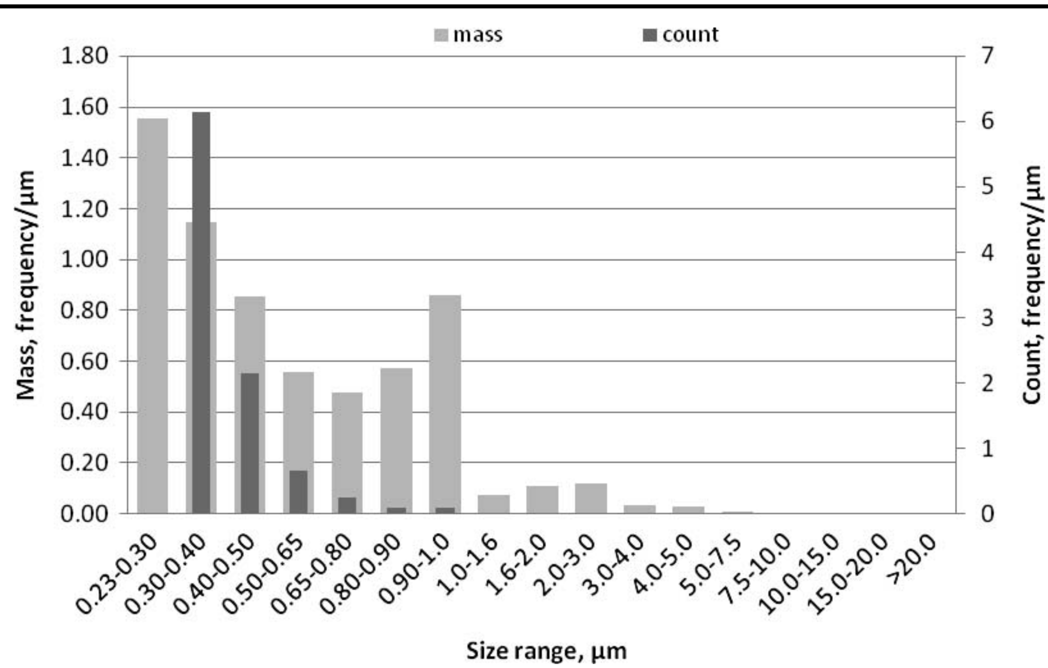

FIGURE 7. Particle mass (0.23–20 μm) and count (0.30–20 μm) distributions as functions of particle size, measured by OPC.

a trend through the week ($p < 0.05$). However, there was no evidence that the day shifts differed from the evening shifts in general.

Particle Size Distribution

The OPC measures particle count or mass concentration in multiple channels. Figure 7 presents the particle size distribution as arithmetic means of four sessions for count and two sessions for mass collected in January 2006. Data were averaged over 212 locations. Particle count median aerodynamic diameter (CMAD) was 0.38 μm. Geometric mean diameter for count concentration was 0.42 μm with a geometric standard deviation (GSD) of 1.32. Ninty-nine percent of the particles had an aerodynamic diameter smaller than 1.0 μm. These particles accounted for 61% of the particle mass.

Meanwhile, particle mass median aerodynamic diameter (MMAD) was 0.85 μm, and geometric mean diameter for mass concentration was 1.12 μm, with a GSD of 3.33. Respirable and thoracic particles (as defined by ACGIH size-selective criteria) accounted for 93% and 97% of OPC measured particles, respectively. When the fine particles measured by the CPC (0.014–1.0 μm) were considered, 99.99% and 99.5% of the count were particles smaller than 1.0 μm and 0.3 μm, respectively.

DISCUSSION

While using mapping as a method to characterize particle spatial distributions and thus to inform the ventilation evaluation, four types of variations were analyzed:

1. short-term variation (10 min in this study) at a fixed location
2. temporal variation during a shift at each sampling location
3. spatial variation from location to location (spatial distribution)
4. and the temporal variations of the spatial distributions across shifts and days.

Therefore, the research questions became whether mapping could be used effectively to assess particle spatial distributions given the significant temporal variation during a shift at sampling locations; how a map represented the spatial distribution across shifts and days; and how particle size might affect assessing particle spatial distribution.

Temporal Variations and Mapping Implications

It is sometimes assumed that particle concentration is stabilized shortly after an operation resumes. During the data collection in this study, we observed that although the overall production rate was fairly constant across days, the individual production lines were frequently interrupted due to machinery issues and adjustments of the production paces. These interruptions were the major contributors to the fluctuations in the particle concentrations during a shift. The patterns of temporal variation over a shift shown in Figure 3 were similar to those reported by Dasch and D'Arcy[12] for steel resistance welding in other automobile assembly plants. These variations suggested that, during the mapping data collection, a single data point measured at a random moment during a shift was less likely to represent an 8-hr TWA concentration at a given location, compared with a mean of multiple repeated measurements. The sampling interval is determined by the short-term variation and the feasibility. The average of the repeated measurements needs to be a close approximation of the TWA concentration at a given location over time. Furthermore, due to substantial particle reduction during the breaks, mapping data should not be collected either during or shortly after breaks.

Variations of Spatial Average and Evaluation of Reduction

One of the primary goals of mapping in this study was to characterize particle spatial distribution and thus to evaluate the reduction after the counter-measures. Repeated measurements ANOVA identified that the spatial mean (logged) varied significantly from day to day ($p < 0.0005$), indicating that data from a single shift or a single day might not represent particle spatial distribution across days. Graphical examination of the maps from 6 days for respirable mass concentrations revealed missing peaks on some days (data not shown). Repeated measurements over days were necessary for a map to be representative.

Moreover, as the six full-shift sessions differed significantly, evaluation of the efficacy of the ventilation countermeasures requires that, rather than comparing the means of particle air concentration measured before and after directly, statistical tests incorporating temporal variations are needed to better evaluate the reduction. Two sets of mapping data were collected by facility EHS personnel using 5-sec sampling intervals. Data were collected at 204 locations during both mapping events, with 88% of overlap with the sampling locations selected in the current study. Spatial means were 273 $\mu g/m^3$ (SD: 153 $\mu g/m^3$) and 216 $\mu g/m^3$ (SD: 184 $\mu g/m^3$) for data collected before and after the counter-measures, respectively.

In the current study, the arithmetic average of the spatial means for the six sets of mapping data was 372 $\mu g/m^3$, with a SD of 71 $\mu g/m^3$. Since only one set of pre-counter-measure data was available for the comparison, Student's *t*-test indicated that the reduction needed to be at least 191 $\mu g/m^3$ to be considered statistically significant, given the sample size of 1 and 6 before and after the counter-measures and with the assumption that the SD was same before and after the counter-measures. The difference between the spatial means of two sets of mapping data collected by facility EHS personnel (273 $\mu g/m^3$ and 216 $\mu g/m^3$) was not significant and could not be distinguished from the daily fluctuation of the spatial mean.

When pre-countermeasure data were compared with the data collected in the current study, no reduction was indicated. Although fluctuations in the production rate could be a potential explanation, underestimation of the concentrations could have resulted because pre- and post-countermeasure data were collected using 5-sec sampling intervals without replications, and data collection was carried out during breaks. Therefore, we concluded that the available data were not adequate to evaluate the reduction of the particle concentration. This further emphasized the importance of designing an appropriate mapping protocol. Although the statistical significance is affected by the sample size and may not be the main concern during ventilation evaluation, and the goal of reduction should be the best achievable given the technologies and feasibility, temporal variations in particle concentrations should be considered in assessing the reduction appropriately.

Spatial Variations and Ventilation Conditions

In this study, five high concentration areas (hot spots) were identified by the contour maps. These areas were related to specific ventilation conditions that required further attention. The implications associated with these specific ventilation conditions can be meaningful in other facilities or industrial settings in general. First, our data indicated that the particle concentrations in the car area were much higher than those in the truck area. All five hot spots were located in the car area. The car underbody area (Figure 1) was the major subarea with high concentrations. Ventilation in this area seemed insufficient even after the installation of the cartridge dust collectors. However, the newly installed air supply system at the truck slat line appeared to be effective.

Second, in the body weld department, local exhaust ventilation was mainly over MIG welding operations, whereas resistance welding operations were often ventilated by mechanical fans or general ventilation, as they were considered less hazardous. Figure 4 revealed that three out of five hot spots were related to resistance welding (Columns U6, T14, and P6/N6). At Column U6 a single resistance welding station was manually operated intermittently, running 20 min each hour. No process ventilation presented at this location at the time of sampling; Column T14 was surrounded by a large robotic resistance welding area semi-enclosed by an 8-ft high plastic sheet wall. Welding was performed most of the time during a shift. Measured particle level was constantly high. An exhaust fan was on the ceiling more than 10 m above this location without hoods to capture particles; the area around Columns P6-N6 was similar to that surrounding the Column T14. Mapping data were collected outside the plastic sheet, and particle concentrations in these enclosed areas could be higher than those measured. Although no employees worked in these enclosed areas and resistance welding is considered less hazardous compared with MIG welding, these areas as well as other similar resistance welding operations were likely to be the major contributors of particles in the facility.

The other two hot spots, P13–P14 and P03, were MIG welding areas. Local exhaust enclosures for MIG welding operations did not function equally well at all locations. The welding setups at Column P03 and P13–P14 appeared to resemble the enclosures in the suspension MIG welding area (M02–M03) and those at Columns T9–T10, which appeared effective based on particle measurements. Particle concentrations at P03 and P13 were much higher. MIG welding operations were semi-automatic in these areas. Welding was performed inside the enclosures; workers welded parts manually before putting them on the robotic welders. Welding fume leaked from the enclosures while the welding was in process and when automatic roll-down welding screens were pulled up during the parts removal. Each worker performed tasks at several welding stations during a shift. Their exposures were most likely even higher than those measured and shown on the map, since the data were collected at the designated mapping data collection locations identified by the physical columns rather than at the workstations. The facility may need to identify why the enclosures in the P03 and P13 areas were not controlling particles as effectively as they did at Column T9–T10. High concentration areas such as Columns P03 and P13 are better locations to conduct personal monitoring.

Particle Size Distributions

The OPC data showed that the GSDs for count and mass distributions differed substantially, suggesting a bimodal distribution with other sources for larger particles. Our data indicated, in the body weld department, respirable particle mass concentration was more than two times higher than the levels found in other similar automobile assembly facilities.[12] Moreover, the percentages of respirable and thoracic particles (93% and 97%) were much higher than those reported by Dasch and D'Arcy (54% and 61%).

Besides the production rate, the density of welding operations and the efficiency of the ventilation systems might explain the differences. We found that small particles distributed more uniformly than larger particles across different processing areas. A comparison of Figure 4 with Figure 6 revealed that submicrometer particle count concentration had a smaller spatial gradient compared with respirable mass concentration. This was also illustrated by the finding that the map of submicrometer particle count had smaller peak-to-mean ratios, and smaller ratios of 90th percentile to 10th percentile (Table III). These findings reflect that submicrometer particles are more readily transported by air currents and less likely to settle, and thus more uniformly distributed in a facility, as found in other studies.[9,11]

When the map of mass concentrations (Figure 4) was compared with those of count concentrations (Figures 5 and 6), the hot spot surrounding P03 split into two areas (P03 and M02) in both count concentration maps (0.30–20 μm and 0.014–1.0 μm), which implied that the local exhaust ventilation in the suspension MIG welding area functioned more effectively in capturing larger particles, while a significant fraction of small particles, especially submicrometer particles, were still emitted from the processes. This is consistent with Dasch and colleagues'[7] finding of enclosed and vented processes shifting particle size distribution to smaller particles. These findings emphasize that (1) ventilation systems should be evaluated not only by reduction on mass concentration but also on count concentration, especially for welding processes that are known to generate fine and ultrafine particles; (2) emission from less hazardous welding operations such as resistance welding should also be effectively controlled.

Those who work in areas with fewer welding activities and are predicted to have low exposures, may be exposed to fine particles at levels higher than has traditionally been thought. Therefore, removal of fine and ultrafine particles from a facility is more important than blowing them away from the emission sources. Exposures of those who do not work in close vicinity of the emission sources should also be evaluated when assessing workers' exposure to fine and ultrafine particles.

CONCLUSIONS

Aerosol mapping is a newly emerging method. Although there are not many publications on this specific topic, mapping has been used both in the practice of industrial hygienists and in exposure studies by occupational health researchers. The concept of mapping can go beyond measuring particles or aerosols. Mapping protocols need to be developed according to the study aims and the characteristics of the processes and the facility.

The following issues were considered in the process of developing the mapping protocol used in this study:

- Grid size, adjusted according to the facility layout; process density; and particle emission strength that influence the spatial variations
- Sampling locations, chosen based on accessibility but preferred to be as close to the workstations as possible
- Sampling interval at data collection locations, determined by the short-term variation and the feasibility
- Sampling time frame, selected to avoid collecting data during "resumption periods"
- Replications, determined by the magnitude of temporal variations during a shift and across shifts/days.

The particle concentrations in the body weld department had moderate over-shift temporal variation and significant spatial variations. The day-to-day variations in the spatial means were statistically significant. Following a mapping protocol developed specifically for this workplace, we found that

1. particle concentrations in the car area, especially in the car underbody area, were much higher than those in the truck area; ventilation in the car underbody area seemed insufficient even after the countermeasures;
2. local exhaust enclosures for MIG welding operations did not function equally well at all locations; the facility may need to identify the reasons and higher level of controls may be needed in some of the high concentration areas;
3. although resistance welding is considered less hazardous than MIG welding, resistance welding operations could be the major particle emitting sources if not effectively controlled;
4. submicrometer particles were more evenly distributed across the facility compared with the larger particles, and thus, workers not in the close vicinity of intensive welding operations might be exposed to fine particles at levels higher than have been traditionally thought;
5. the available data were not adequate to evaluate particle level reduction, indicating that a well-designed mapping protocol is critical in achieving the purposes of the study.

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