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Characterization and Mapping of Very Fine Particles in an Engine Machining and Assembly Facility

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Very fine particle number and mass concentrations were mapped in an engine machining and assembly facility in the winter and summer. A condensation particle counter (CPC) was used to measure particle number concentrations in the 0.01 μm to 1 μm range, and an optical particle counter (OPC) was used to measure particle number concentrations in 15 channels between 0.3 μm and 20 μm . The OPC measurements were used to estimate the respirable mass concentration. Very fine particle number concentrations were estimated by subtracting the OPC particle number concentrations from 0.3 μm to 1 μm from the CPC number concentrations. At specific locations during the summer visit, an electrical low pressure impactor was used to measure particle size distribution from 0.07 μm to 10 μm in 12 channels. The geometric mean ratio of respirable mass concentration estimated from the OPC to the gravimetrically measured mass concentration was 0.66 with a geometric standard deviation of 1.5. Very fine particle number concentrations in winter were substantially greater where direct-fire natural gas heaters were operated (7.5×10^5 particles/ cm^3) than where steam was used for heat (3×10^5 particles/ cm^3). During summer when heaters were off, the very fine particle number concentrations were below 10^5 particles/ cm^3 , regardless of location. Elevated very fine particle number concentrations were associated with machining operations with poor enclosures. Whereas respirable mass concentrations did not vary noticeably with season, they were greater in areas with poorly fitting enclosures (0.12 mg/m^3) than in areas where state-of-the-art enclosures were used (0.03 mg/m^3). These differences were attributed to metalworking fluid mist that escaped from poorly fitting enclosures. Particles generated from direct-fire natural gas heater operation were very small, with a number size distribution modal diameter of less than 0.023 μm . Aerosols generated by machining operations had number size distributions modes in the 0.023 μm to 0.1 μm range. However, multiple modes in the mass size distributions estimated from OPC measurements occurred in the 2–20 μm range. Although elevated, very fine particle concentrations and respirable mass concentrations were both associated with poorly enclosed machining operations; the operation of the direct-fire natural gas heaters resulted in the greatest very fine particle concentrations without elevating the respirable mass concentration. These results suggest that respirable mass concentration may not be an adequate indicator for very fine particle exposure.

Keywords aerosol, combustion aerosol, engine plant, machining, metalworking fluid, ultra fine aerosol

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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INTRODUCTION

Workers involved in the machining of vehicle components are exposed to risk factors for a variety of occupational diseases, including dermatitis, hearing loss, musculoskeletal disorders, and respiratory problems. They have a sixfold greater incidence of occupational illness than the average American worker.⁽¹⁾

Exposure to metalworking fluid (MWF) mist has historically been associated with respiratory disease.⁽²⁾ In 1998, the National Institute for Occupational Safety and Health (NIOSH) published a recommended exposure limit for occupational exposure to MWF mist at 0.4 mg/m^3 for thoracic aerosol as a time-weighted average exposure.⁽²⁾ In response, automakers have moved toward nearly complete enclosure of machining operations to control this mist. Such enclosures move contaminated air from the point of generation to a centrally located mist collector. The collector cleans the air and then either discharges it from or recirculates it back into the plant.^(3,4) This type of ventilation, along with a shift from oil-based to water-based MWFs, has been shown to maintain MWF mist exposures below 0.2 mg/m^3 .^(5,6) These changes have also reduced the size of the aerosol mass-weighted size distribution from a mode of approximately 3 μm to 1 μm .⁽⁷⁾

Recent epidemiological and toxicological studies suggest that ultrafine particles (diameter < 0.1 μm) are associated with adverse respiratory and pulmonary health outcomes. For nonsoluble particles, these adverse outcomes correlate more strongly with particle number or surface area concentration than with particle mass concentration.^(8–10) Although machining operations are known to produce aerosols larger than 1 μm ^(11–14) they have the potential to produce submicrometer and ultrafine aerosols. Many machining operations involve “hot” processes that produce aerosols smaller than 1 μm : welding,^(15,16) heat treatment, grinding,⁽¹⁷⁾ and high speed machining.^(18,19) Semivolatile components of MWFs are subject to evaporation and condensation phenomena that may contribute to the formation of ultrafine particles during machining operations.^(20,21)

The mass of ultrafine particles is often negligible compared with the mass of micrometer-sized particles or larger. However, reduced aerosol mass concentrations may not translate necessarily into improved worker health if ultrafine particle exposures persist.⁽²²⁾ For this reason, assessment of exposure to ultrafine aerosol is both prudent and clearly needed within automotive component machining facilities.

Prior Work and Facility Description

We assessed very fine particle number concentrations in an engine machining and assembly plant during winter and spring.⁽²³⁾ This facility comprised over 100,000 m^2 of floor space and produced approximately 1000 6-L diesel engines per day while our measurements were conducted. In a previous publication, we reported on a comparison of results from winter and spring.⁽²³⁾ This work identified three distinct areas of the facility with different particulate contaminants:

1. In the block-head-rod (BHR) area, engine blocks, cylinder heads, and piston connecting rods were machined in transfer lines with state-of-the-art, near-complete ventilation enclosures that used water-based, synthetic MWFs. Seventeen air handling units, each processing 23.3 m^3/sec (50,000 cubic feet per minute), heated the air in winter with direct-fire natural gas burners or cooled the air in summer with water-cooled heat exchangers. These units had computer controlled dampers intended to control the amount of make-up air (outdoor air) and return air (recycled air) in the plant.
2. In the cam-crank (CC) area, camshafts and crankshafts were machined in transfer lines with over 20-yr-old, poorly fitting enclosures retrofitted from previous operations. In this area of the plant, straight petroleum-based oil was used as a MWF. In many locations, mist was visible in the air and had formed puddles on the floor. In addition, the blades of operator-cooling fans, which are used in the summer months, served as impaction substrates for larger mist droplets with MWF draining from fan blades and protective mesh. This area in winter was heated with forced air over steam-heated heat exchangers.
3. In the assembly area, engines were assembled from a multitude of components. There were no obvious sources of aerosol in this section of the facility.

During the prior study,⁽²³⁾ little temporal variability was observed for particle number concentrations, suggesting relatively steady-state conditions for generation and fate of very fine particles (0.01 μm to 0.3 μm). In contrast, spatial variability was great, with number concentration relatively homogeneous within but very different between the three areas of the facility. This spatial variability was attributed to the existence of multiple sources of very fine particles. The greatest particle number concentrations (>1,000,000 particle/ cm^3) were from the operation of direct-fire natural gas burners that heated the supply air in the BHR area, whereas more moderate concentrations (250,000 to 750,000 particles/ cm^3) were possibly due either to mist from metalworking operations in the CC area or dispersion of aerosol generated by the operation of the direct-fire natural gas burners. There were no barriers or walls to prevent aerosol dispersion throughout the plant. Further, mass concentrations were low (<0.2 mg/m^3) where direct-fire natural gas heaters produced the greatest very fine particle number concentration (>1,000,000 particle/ cm^3).

The purpose of the current work is to compare the spatial and temporal distribution of aerosol exposures in summer with those in winter. Additionally, we present both characterization of particle number and mass size distributions made near selected machining operations and in the air handling unit to better interpret the relationship between particle number and mass concentrations.

METHODS

Particle Concentration Mapping

Very fine particle number and respirable mass concentrations were mapped throughout the plant as previously described.⁽²³⁾ Aerosol concentrations were measured throughout the facility with real-time instruments placed on each of two mobile sampling carts. During the winter mapping in December 2004, data for the maps were collected during two sessions per day for 2 days. In winter, data were collected in three coarse sampling grids with between 59 and 102 sampling locations and in one fine sampling grid with 192 locations. During the summer, three mapping sessions involved 176 to 115 locations and one mapping session was conducted per day for 3 days.

A condensation particle counter (CPC, model 3007; TSI Inc., Shoreview, Minn.) was used to measure the number concentration of particles with diameters from 0.01 μm to 1 μm . In condensation particle counters, firstly the aerosol flows through a saturation chamber where the aerosol stream is warmed and saturated with a condensable vapor. Secondly, the aerosol flows through a condensation chamber where the vapor is condensed onto pre-existing particles, therefore increasing particle size to micrometer dimensions. The enlarged particles (droplets) subsequently flow into a sensing

volume where individual particles are of a sufficiently large size that they may be successfully detected optically and counted.^(24,25) Aerosol entering the CPC was diluted with a filter (6702–7500; Whatman Inc., Florham Park, N.J.) with a hole (diameter = 0.040 cm) drilled into its end cap. Dilution was necessary to maintain the particle number concentration below the upper concentration limit (100,000 particle/cm³) of the CPC. At higher concentrations, coincidence losses (the simultaneous presence of more than one particle in the sensing volume) causes particle counting instruments to undercount particles.⁽²⁶⁾

An optical particle counter (PDM-1108; Grimm, Ainring, Germany) was used to measure particle number concentration as a function of particle size. As particles pass through an OPC's sensing volume, each particle scatters light and the amount of scattered light is used to classify into 15 channels that ranged from 0.3 μm to 20 μm in diameter. The amount of light scattered by the particles can vary with particle physical and optical properties.⁽²⁶⁾ In past studies, dust concentrations measured with this instrument have had reasonable agreement with gravimetric results.⁽²⁷⁾ Apparently, optical particle counters are useful as a measure of relative concentration. Digital data from the real-time particle instruments were collected simultaneously and stored on a laptop computer using a software program written in Visual Basic (Microsoft Corp., Redmond, Wash.).

Respirable aerosol mass concentrations C_{resp} were computed as follows:

$$C_{\text{resp}} = \sum_{i=1}^{12} \frac{\pi}{6} \rho f_i d_i^3 C_{n,i} 10^6 \quad (1)$$

where

f_i = fraction of respirable aerosol in channel i computed per ACGIH[®] criteria⁽²⁸⁾

d_i = average of upper and lower boundaries for channel i (cm)
 $C_{n,i}$ = particle number concentration in channel i of the optical particle counter (particles/L)

ρ = assumed unit density of 1 gram/cm³ or 1000 kg/m³

In this equation, the 10⁶ factor converts grams to micrograms and the units of C_{resp} is μg/L or mg/m³. The particle number concentrations measured by the CPC were not included in the estimation of mass concentration. The CPC covers a size range of 0.01 μm to 1 μm; the size of the particles measured by the CPC was not measured during the concentration mappings. As subsequently demonstrated by ELPI number size distribution measurements, the size of aerosol particles smaller than 0.1 μm substantially changed with the operation of direct-fire natural gas heaters. In prior studies,^(7,29) less than 20% of the aerosol mass concentration was attributed to particles smaller than 0.3 μm. Thus, particles smaller than 0.3 μm were assumed to have a negligible effect on respirable aerosol mass.

The very fine particle number concentration (N_{vfpc}), which has units of particles/cm³, was computed as follows:

$$N_{\text{vfpc}} = N_{\text{CPC}} - \sum_{i=1,5} C_{n,i}/1000 \quad (2)$$

where

N_{CPC} = number concentration of particles between 0.01 and 1 μm measured with the CPC after correction for dilution.

The particle number concentration measured by the OPC was divided by a factor of 1000 to convert the OPC number concentrations from particles/liter to particles/cm³. The lower boundary of the first OPC channel was 0.3 μm and the upper boundary of the fifth OPC channel was 1 μm. Thus, N_{vfpc} represents the number concentration of particles in the range 0.01 μm to 0.3 μm. Subsequent size distribution measurements presented in this article show that very fine particle number concentration measurements are dominated by ultrafine particles (<0.1 μm) and, therefore, the very fine particle concentration is essentially a measure of the number concentration of airborne ultrafine particles.

Filter-Based Sampling

Gravimetric samples were collected concurrently with the real-time aerosol measurements and at stationary locations with a PM-2.5 sampler (4 L/min, PM200-4-2.5; MSP, St. Paul, Minn.), and a respirable sampler (4.2 L/min, GK2.69 Respirable Cyclone; BGI, Waltham, Mass.). Battery-operated pumps (Universal Sampler pumps, model 224-PCXR4; SKC, Eighty Four, Pa.) were used to draw air through the filter-based, mass samplers at their specified flow rates. The pumps were precalibrated with a flow calibrator (tri-Cal; BGI). These pumps maintain airflow to within 5% of the set point. When the flow deviates more than 5% from the set point, the pump automatically stops and displays the sample duration. The filters in these samplers were analyzed gravimetrically using NIOSH method 0600.⁽³⁰⁾

Source Size Distribution Measurements

In summer, aerosol size distributions were measured with an electrical low pressure impactor (ELPI; Dekati Ltd., Tampere, Finland) and the OPC at selected locations to obtain information on the size distributions for selected emission sources. The ELPI is a real-time cascade impactor in which particles are first positively charged in a diffusion charger and then collected onto electrically isolated stages according to their aerodynamic diameter. The current on each stage is measured by electrometers and then converted into number concentration by particle aerodynamic diameter.⁽³¹⁾

ELPI size distributions were obtained every second in 12 channels from 0.07 μm to 10 μm. The sintered-metal impaction substrates were oiled to reduce particle bounce and re-entrainment. The number size distributions measured with the ELPI were obtained over a period of at least 5 min. Number size distributions provided by the ELPI have consistently shown comparable results with other sizing methods.^(32,33) However, there remains debate over the validity of mass size distributions derived from the ELPI due to the generation of diffusional artifacts in particle mass size distributions.^(34–37) Consequently, mass weighted size distributions were converted preferentially from number size distributions derived from the OPC.

Supply Air Sampling

In summer, the equipment on the cart was placed downstream of the chiller inside one of the air handling units that served the BHR area. The system was configured for 100% recirculation of plant air; however, visual inspection indicated that some outside air may have entered the system due to improperly functioning dampers. For the purposes of our study, the burners were cycled on and off for short durations (5–10 min at 7% of their capacity) with the chiller on. The ELPI was also used to measure aerosol number distributions upstream of the chiller.

Additional data to assess burner emissions were collected in February 2006. During this trip, the dampers were set to draw a nominal 20% of the air from the outdoors and to recycle 80% of the air from the plant. Particle concentrations were measured with the CPC and OPC inside 9 of the 17 air handling units that supplied air to the BHR and assembly areas. These measurements were made when the burners were both off and on. In addition, both number and mass concentration measurements were made near the inlets to the air handling units on the roof of the plant. Very fine particle number and respirable mass concentrations were computed from CPC and OPC data as previously described in Eqs. 1 and 2.

Statistical Analyses

Statistical analyses were conducted to determine whether season or area in the plant affected the very fine particle number or respirable mass concentration. The mapping exercise resulted in multiple concentration measurements within each area. All statistical procedures were conducted on the mean of the log-transformed concentrations within an area for each mapping session to avoid issues of spatial and temporal correlation.

Analysis of variance (Proc GLM; SAS, Cary, N.C.) was used to evaluate whether the categorical variables such as season (winter or summer), area (BHR, CC, or assembly), and their interaction affected concentration. To evaluate whether the data were lognormally distributed, the Shapiro-Wilk statistic was computed for the studentized residuals (residual divided by root mean square error) from the analysis of variance. The SAS Proc Univariate Procedure was used to compute this statistic. For each season, Tukey's HSD multiple comparison test, using the variance estimated from one-way ANOVA, was used to examine differences between the mean of the log-transformed concentrations in the different areas. This multiple comparison test controls overall error so that there is less than a 5% probability of falsely declaring one or more differences significant.^(38,39)

RESULTS

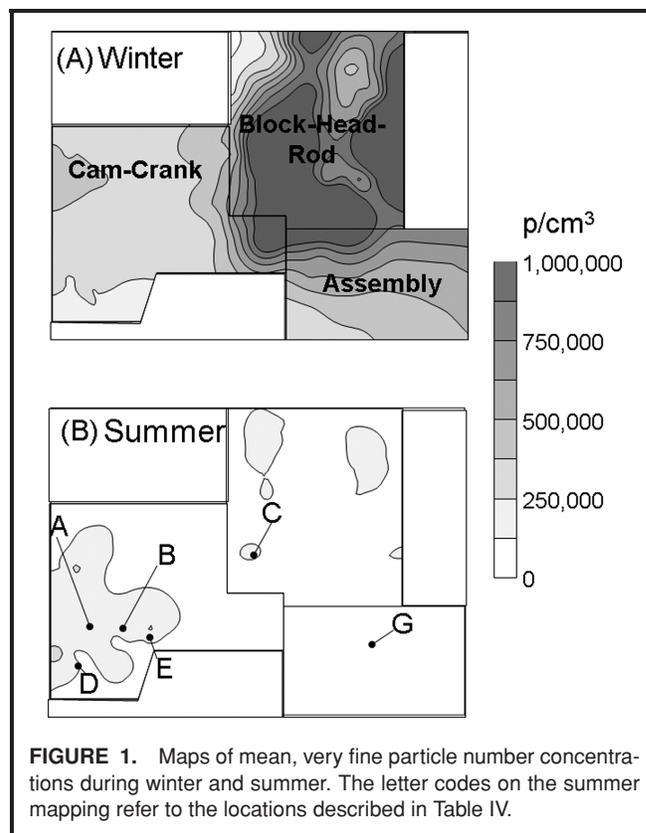
Comparison of Instrumental and Gravimetric Mass Concentration

As shown in Table I, the mass concentrations estimated with the OPC were consistently lower than those measured gravimetrically. The ratio of the OPC to the gravimetric

TABLE I. Summary Statistics for Ratio of Mass Concentration Estimated with OPC to Mass Concentration Measured Gravimetrically per NIOSH Method 0600

Statistic	Respirable	PM _{2.5}
Geometric mean ratio	0.66	0.62
Geometric standard deviation	1.52	1.35
Number (n)	11	10
Upper 95% confidence limit on geometric mean ratio	0.93	0.80
Lower 95% confidence limit on geometric mean ratio	0.47	0.48
Probability of larger deviation from normality (Shapiro- Wilk)	0.51	0.81

sampler had a geometric mean of 0.66 and 0.62 for respirable and PM_{2.5} aerosol mass concentrations, respectively. The confidence intervals on these geometric means suggest that respirable mass estimated with the OPC is predictive of the mass measured with the filter to within a factor of two. The Shapiro-Wilk test, performed using the SAS Univariate



Procedure, does not indicate noticeable deviations from the assumed log-normal distribution, since the probability of larger deviations was larger than 0.05. These results are not surprising because the response of OPCs are known to vary with the particle's size and optical properties.^(26,40) Furthermore, the OPC does not detect particles smaller than 0.3 μm , which may contribute slightly to the overall respirable mass concentration.

Concentration Variation with Season and Area

Figure 1 presents very fine particle number concentration maps in winter and summer. Very fine particle concentrations were elevated in the BHR area during winter as compared with other areas of the plant. In summer, the very fine particle concentrations were lower and more evenly distributed throughout the plant compared with those measured in winter. Very fine particle number concentration was affected by season ($P = 0.0001$), sampling area ($P = 0.003$) and the interaction between area and season ($P = 0.04$). The Shapiro-Wilk statistic indicated that the deviations from a log-normal distribution were insignificant ($P > 0.3$).

Table II presents the results of Tukey's multiple comparison test for very fine particle number concentrations measured during the winter and summer sampling sessions. Although the very fine particle number concentration did not vary significantly with sampling area in summer ($P = 0.13$), it was substantially and significantly greater in the BHR area than in the other two areas in winter ($P = 0.0005$). As reported earlier, this difference was attributed to operation of direct-fire natural gas heaters.⁽²³⁾

Figure 2 presents maps of the respirable mass concentrations in winter and summer. The respirable aerosol mass concentrations were apparently elevated in the CC area of the plant as compared with other areas of the plant. Unlike the very fine particle number concentration maps (Figure 1), the distribution of respirable mass concentration was similar in winter and summer. ANOVA showed that the respirable aerosol mass concentration was affected by sampling area ($P = 0.0001$), season ($P = 0.03$), and the interaction of season and sampling area ($P = 0.04$). The Shapiro-Wilk statistic indicated that the deviations from a log-normal distribution were insignificant ($P > 0.3$).

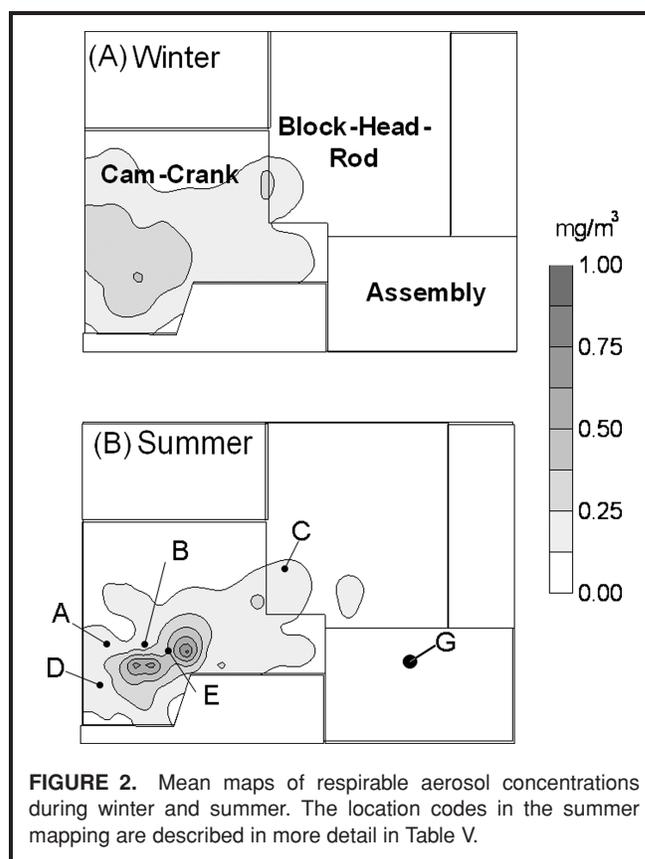


FIGURE 2. Mean maps of respirable aerosol concentrations during winter and summer. The location codes in the summer mapping are described in more detail in Table V.

Table III presents the results of Tukey's multiple comparison tests. The CC area had greater respirable mass concentrations than the other two areas, and the overall rank ordering of these results is the same in summer and winter. Although the respirable mass concentration was greater in summer (geometric mean = 0.06 mg/m^3) than in winter (geometric mean = 0.04 mg/m^3), this difference was of little practical importance.

Direct-Fire Natural Gas Heaters

In summer 2005, the CPC was used to measure particle number concentration on the roof of the plant at the supply-air intake and downstream of the burners in a single air handling

TABLE II. Geometric Mean Very Fine Particle Number Concentration

Area of Plant	Winter		Summer	
	Geometric Mean (GSD) Particles/cm ³	Grouping Code	Geometric Mean (GSD) Particles/cm ³	Grouping Code
CC	3.0×10^5 (1.56)	B	0.84×10^5 (1.95)	A
BHR	7.5×10^5 (1.23)	A	0.78×10^5 (2.16)	A
Assembly	4.4×10^5 (1.24)	B	0.29×10^5 (1.92)	A

Note: Separate multiple comparison tests were conducted for each season. Within seasons, geometric means with different grouping codes differ significantly at an overall level of confidence of 95%. These geometric means were computed from geometric means obtained from four mapping sessions in the winter and three mapping sessions in the summer.

TABLE III. Geometric Mean Respirable Mass Concentrations

Area of Plant	Winter		Summer	
	Geometric Mean (GSD) mg/m ³	Grouping Code	Geometric Mean (GSD) mg/m ³	Grouping Code
CC	0.15 (1.33)	A	0.12 (1.61)	A
BHR	0.04 (1.13)	B	0.05 (1.12)	B
Assembly	0.02 (1.66)	C	0.04 (1.07)	B

Note: Separate multiple comparison tests were conducted for each season. Within seasons, geometric means with different grouping codes differ significantly at an overall level of confidence of 95%. These geometric means were computed from the geometric means obtained from four mapping sessions in the winter and three mapping sessions in the summer.

unit. The mean very fine particle number concentration on the roof of the plant was 5.4×10^4 particles/cm³. Inside the air-handling unit, the mean very fine particle number concentrations were 8.8×10^4 particles/cm³ with the burners off and 2×10^6 particles/cm³ with the burners on. Figure 3 presents particle number distributions measured with the ELPI in the air handling unit upstream and downstream of the chiller when the burners were on. Both locations were downstream of the burner. The particle number-size distributions were dominated by particles smaller than 0.07 μm. The particle number concentrations downstream of the chiller were roughly one-half of that measured upstream of the chiller. A combination of particle losses to the chiller and better mixing (dilution) of the burner plume probably accounts for this difference.

Table IV presents a summary of follow-up measurements on 9 of the 17 air-handling units conducted in February 2006. The burners were intermittently being used because the outside

temperature was relatively warm, ranging from 5°C to 12°C. When the burners were on, the geometric mean very fine particle number concentration was 3.1×10^6 particles/cm³ with a geometric standard deviation of 1.47. In contrast, the geometric mean very fine particle number concentration was substantially and significantly ($P < 0.0001$) lower (1.3×10^5 particles/cm³ with a geometric standard deviation of 2.23) when the burners were cycled off. Although the operation of the burners substantially elevated the very fine particle number concentration, it did not statistically ($P = 0.2$) alter the respirable mass concentration of particles in the air supplied to the plant.

Aerosol Size Distributions

Figures 4 and 5 present the number-weighted and mass-weighted size distributions measured with the ELPI and the OPC at various locations in the plant in summer. Table V provides mean concentrations and descriptive information about each location. The map location codes, listed in the first column of Table V, identify the location of the measurement in the legend of the size distributions (Figures 4 and 5) and on the summer maps (Figures 1B and 2B).

Figure 4 presents particle size distributions measured on the roof of the plant at the supply-air intake and downstream of the burners in an air handling unit when the burners were off. The particle number concentrations with the burners off (Figure 4) were a factor of 20 to 100 less than the number concentrations when the burners were on (Figure 3). However, the aerosol on the roof of the plant was composed of larger particles (Figure 4; number mode diameter between 0.03 μm and 0.04 μm) when compared with that generated by the natural gas burners (Figure 3; the apparent number mode diameter captured on the electrical filter stage in the ELPI 0.007 μm to 0.023 μm).

Figure 5 presents the particle number and mass distributions obtained at various locations in the plant. Some operations (e.g., heat treating) elevated very fine particle number concentrations substantially above background levels. Although all of the number-weighted size distributions had modes between 0.02–0.04 μm and had similar shape, perhaps due in part to their persistence and the ease in which they move with air currents, the mass-weighted size distributions (Figure 5B) were

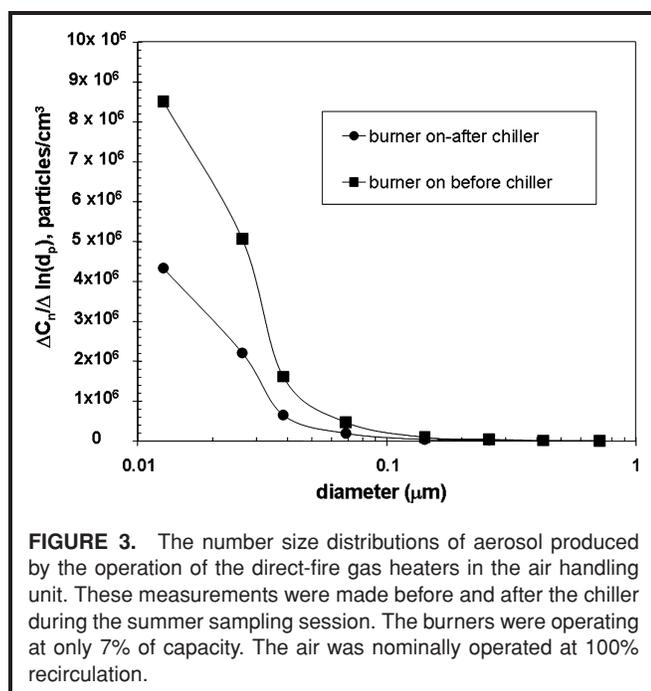


FIGURE 3. The number size distributions of aerosol produced by the operation of the direct-fire gas heaters in the air handling unit. These measurements were made before and after the chiller during the summer sampling session. The burners were operating at only 7% of capacity. The air was nominally operated at 100% recirculation.

TABLE IV. Summary of Measurements Made Inside Air Handling Units (February 2006)

Measurement Condition	Very Fine Particle Concentration			Respirable Mass Concentration		
	Geometric Mean (particles/cm ³)	Geometric Standard Deviation	n	Geometric Mean (mg/m ³)	Geometric Standard Deviation	N
Burners on, upstream of chillers	3.1×10^6	1.47	9	0.033	1.75	9
Burners off	1.3×10^5	2.23	9	0.047	1.75	9
Background outside plant on roof at air intakes	6.4×10^4	1.53	13	0.006	2.20	13

visually different for different operations. Some of the mass-weighted distributions appeared to have two or three modes in the 2–20 μm range. These particle size distributions may not be attributed to a single source because the aerosol from adjacent sources was mixed by the worker-cooling fans. However, as shown in Figures 4 and 5, the mass distributions measured

near machining operations were visually quite different from those measured on the roof of the plant, in the air handling unit, and in the assembly area.

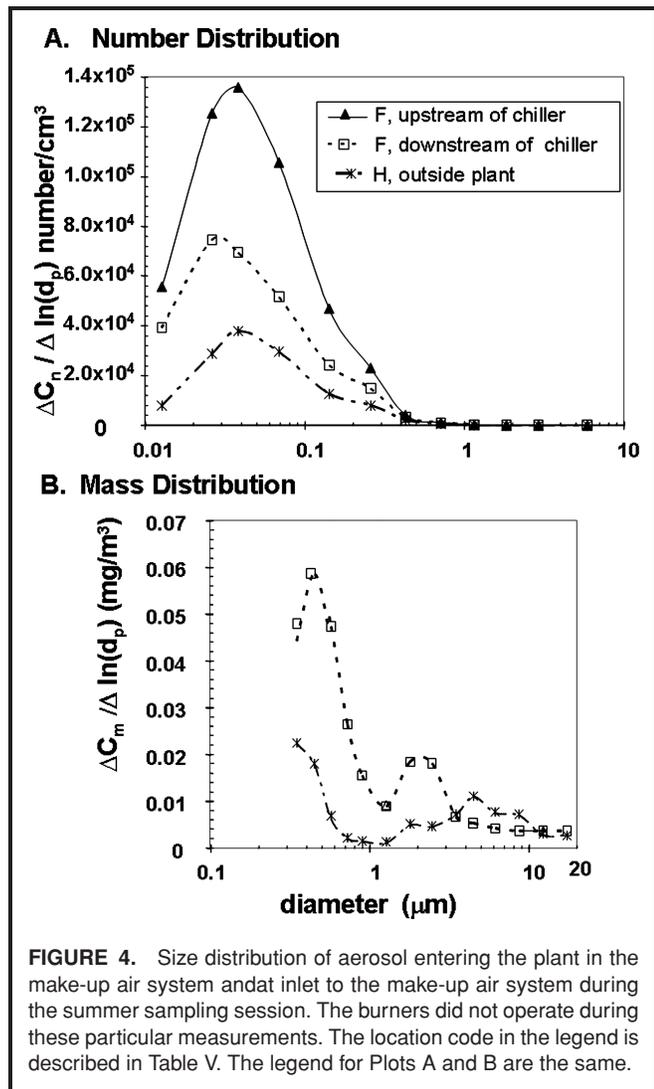
Inspection of Figures 3–5 shows that the particle number concentration is dominated by particles smaller than 0.1 μm; thus, the very fine particle number concentration is essentially a measure of the number concentration of ultrafine particles.

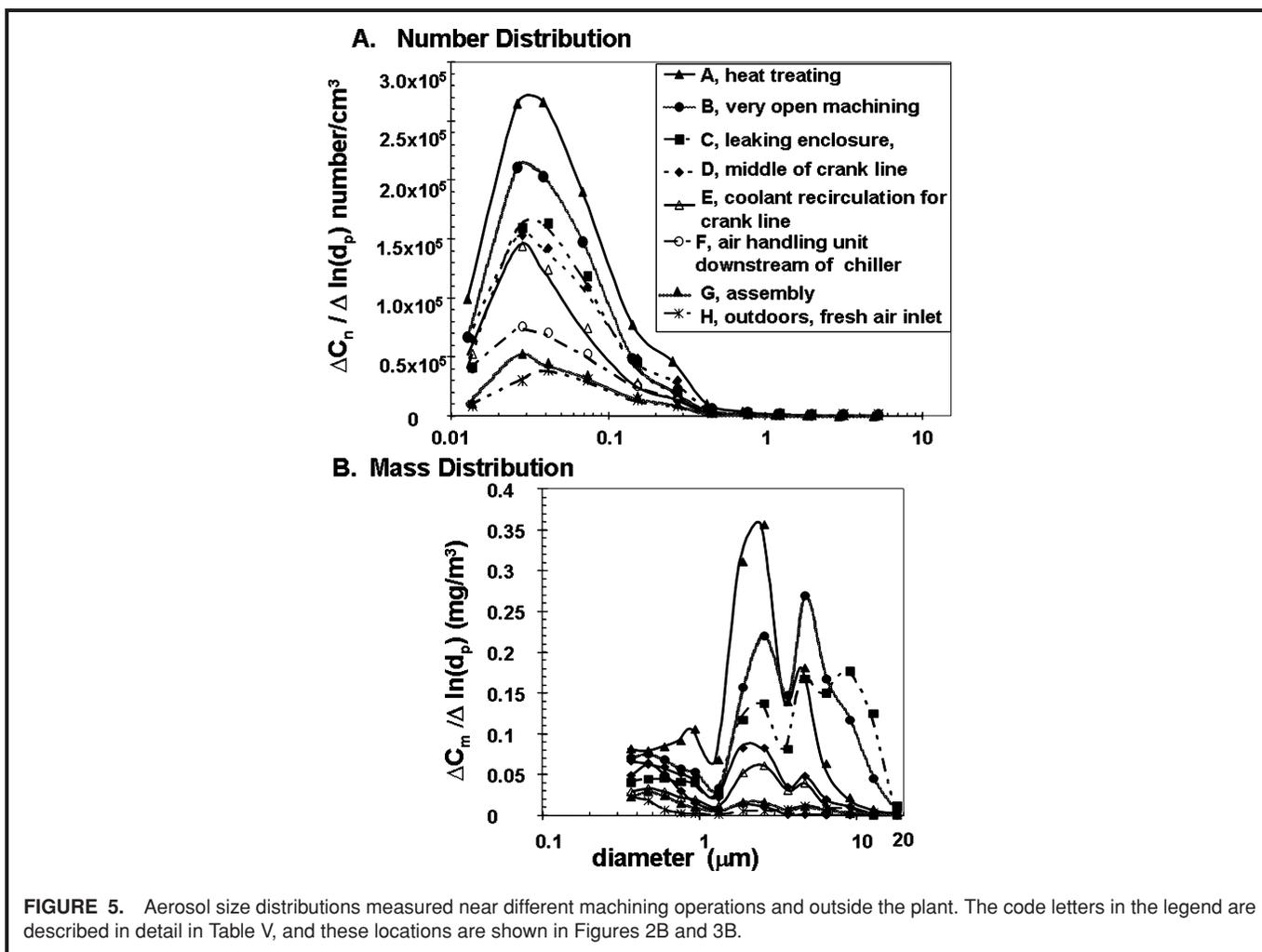
DISCUSSION

As summarized in Table II and graphically displayed in Figure 1, the very fine particle number concentrations were lower by a factor of between 5 to 15 in summer when compared with concentrations in winter. The direct-fire natural gas burners contributed to a concentration of 3×10^6 particles/cm³ (Table IV) in the heated air supplied to this facility during winter. As shown in Figure 3, these burners produced an aerosol dominated by very fine particles smaller than 0.03 μm. Perhaps, these very fine particles were easily dispersed throughout large sections of the plant because there were no physical barriers or extensive walls separating areas of the plant. During the winter mapping exercises, the high particle number concentrations generated by the burners tended to obscure particle sources by machining operations, particularly in the BHR area where these burners were used to heat the air.

In summer, the very fine particles present in the outdoor air may have substantially contributed to very fine particle number concentration observed inside the plant. The very fine particle number concentration measured in the air handling unit (88,000 particles/cm³ for Location F in Table V) and inside the plant during the summer (geometric means between 29,000 and 84,000 particles/cm³ for summer conditions in Table II) was close to that measured on the roof of the plant (a geometric mean of 64,000 particles/cm³ in Table IV and 54,000 particles/cm³ in Table V for Location H).

Furthermore, there were few elevated peaks in very fine particle number concentration in the BHR and assembly areas (Figure 1B), which suggests the absence of substantial very fine particle emission sources. There were, however, some concentration peaks present in the CC area (Figure 1B), suggesting very fine particle sources were present there. In addition, the number-weighted size distribution of the aerosol





outside plant (Figure 4) had roughly the same shape as the aerosol from the different machining operations (Figure 5) and that of the aerosol upstream and downstream of the chiller with the burners off (Figure 4). This observation further supports the notion that particles from outdoor air contributed to very fine particle number concentrations found in the plant during summer.

As shown in Figure 2 and Table III, the respirable mass concentration did not change noticeably with season. However, the respirable mass concentration was higher in the CC area (Table III) than in the other areas of the plant. In this area, the enclosures were poorly fitting and allowed visible mist to escape into the workplace. These fugitive emissions likely explained most of the elevated respirable mass concentration.

Respirable mass concentration does not appear to be a useful surrogate for very fine particle number concentration. For example, in winter, the BHR area had the greatest fine particle number concentrations while having substantially less respirable mass concentrations than the CC area. As documented in Table IV, the operation of the direct-fire natural gas heaters did not affect the respirable mass concentration.

However, the operation of the gas burners increased the concentration of the very fine particles from 1.3×10^5 to 3.1×10^6 particles/cm³ (Table IV) in the air supplied to the plant. The number-weighted size distributions of the aerosol generated by the burners (Figure 3) were substantially different in shape than those measured in other locations of the plant (Figures 4 and 5). Specifically, the aerosol generated by the burners (Figure 3; number mode diameter $<0.023 \mu\text{m}$) was substantially smaller than that observed in other locations of the plant (Figure 4 and Figure 5; number mode diameter between $0.03\text{--}0.04 \mu\text{m}$). In this plant, the operation of the direct-fire natural gas heaters appeared to be the major source for the number concentration of very fine particles. The respirable mass concentration was apparently generated by machining operations and the movement of metal working fluid.

During summer, some machining operations appeared to generate very fine particles that elevate particle number concentrations above outdoor background levels. As shown in Figure 5, the number-weighted distributions measured near machining operations in the CC area (identified as A, B, D, and E) and near the leaking enclosure in the BHR area (identified

TABLE V. Very Fine Particle Number Concentration and Respirable Mass Concentration

Map Location Code ^A	Area	Location Description	Very Fine Particle Number Concentration (particles/cm ³)	Respirable Aerosol Mass Concentration (mg/m ³)
A	CC	Heat treating. Hot parts were mechanically transferred from an induction hardening process to the next operation.	2.8×10^5	0.36
B	CC	A very open and ineffectively ventilated machining operation. Concentrations were measured when machining operations were not performed. Aerosol generation appeared to result from fluid moving in flumes.	2.2×10^5	0.26
C	BHR	Leaking enclosure. This nearly complete tunnel enclosure appeared to have inadequate air movement.	1.2×10^5	0.17
D	CC	Middle of the crank-line. The enclosures partially enclosed the process. Measurements at this location probably reflect a blend of adjacent aerosol sources.	1.6×10^5	0.16
E	CC	Near coolant system for the crank-line. Machining fluid is recovered at this location, filtered, and returned to the machining operations.	1.4×10^5	0.24
F		Inside the air handling unit and downstream of the chiller at 100% recirculation. This is typical of the air returned to the plant in the BHR area. One hundred percent recirculation was used to maximize cooling efficiency of air chillers in the plant during summer months.	0.88×10^5	0.06
G	Assembly	This area appeared to be devoid of noticeable aerosol generation sources.	0.58×10^5	0.04
H		Outdoors at the inlet to an air handling unit on the roof.	0.54×10^5	0.02

^ALocation identified by letter code in Figures 1B and 2B.

as C) were elevated when compared with the aerosol outside the plant (identified as H), in the air-handling unit without the burners on (identified as F), and in the assembly area (identified as G). In Figures 4 and 5, the number-weighted size distributions all appear to have the same shape for particles smaller than 0.1 μm .

The mechanism of very fine particle generation during machining operations is unclear and several different mechanisms are possible. Perhaps a very fine aerosol may result when MWF, present on the surfaces of components, thermally degrades during induction-hardening (heat-treatment) operations. Very fine aerosol may also be released or volatilized at the interface between the tools and the components during grinding or

cutting operations and this has been reported for other grinding operations.⁽¹⁷⁾ Aerosol generation by atomization is known to generate primary droplets and smaller "satellite" droplets, formed by the separation of the primary droplet from the bulk fluid.⁽¹⁴⁾ Perhaps these satellite droplets contribute to concentration of very fine particles.

Evaporation/condensation phenomena may contribute to the generation of particles smaller than 0.1 μm . The temperature of the fluid and that of the air probably affects how semivolatile substances such as MWFs partition between the gas/vapor state and the particulate phases.^(3,20) MWF components reportedly have sufficient volatility such that temperature can affect the partitioning between aerosol and

vapor phases.^(41–44) Thus, further data collection is needed to evaluate the contributions of these different mechanisms to the formation of very fine aerosol.

Most of the measured respirable mass concentration was associated with particles in the 2–20 μm range (Figure 5). These mass-weighted size distributions appear to have distinct shapes with multiple modes that may correspond to different mechanisms of aerosol generation.

However, differences in aerosol mass-size distribution shape cannot be attributed entirely to specific machining operations because adjacent operations were not physically separated. The mass distributions measured in the CC area of the plant contained particles that were larger than 10 μm and corresponded with visual observation of mist emanating from poorly fitting enclosures. This mist probably explains the slippery floors and the observation that MFW dripped from the blades of the worker-cooling fans in this area. Mist generation appeared to be caused by fluid flow in flumes and fluid flow over rotating parts. Fluid flow in flumes has caused noticeable mist concentrations.⁽⁵⁾ Because these operations are sequential operations on transfer lines, the observed distributions are a blend of adjacent operations and one cannot attribute specific size distributions to specific operations.

CONCLUSIONS

In this engine machining and assembly facility, direct-fire natural gas heaters were a primary source of very fine particles. However, some machining operations generated particles smaller than 0.3 μm . The area of the plant observed with the greatest very fine particle number concentration possessed the smallest respirable mass concentration. The source of particles leading to the greatest very fine particle concentrations was different from that leading to the greatest respirable mass concentrations. Some machining operations, however, were found to substantially elevate both very fine particle number concentration and respirable mass concentration. These results indicate that respirable mass concentration may not be a useful indicator for very fine particle exposure because particles may be formed by markedly different sources.

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