

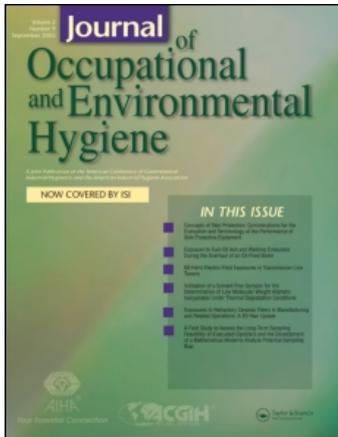
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Airborne Nanoparticle Concentrations in the Manufacturing of Polytetrafluoroethylene (PTFE) Apparel

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One form of waterproof, breathable apparel is manufactured from polytetrafluoroethylene (PTFE) membrane laminated fabric using a specific process to seal seams that have been sewn with traditional techniques. The sealing process involves applying waterproof tape to the seam by feeding the seam through two rollers while applying hot air (600°C). This study addressed the potential for exposure to particulate matter from this sealing process by characterizing airborne particles in a facility that produces more than 1000 lightweight PTFE rain jackets per day. Aerosol concentrations throughout the facility were mapped, breathing zone concentrations were measured, and hoods used to ventilate the seam sealing operation were evaluated. The geometric mean (GM) particle number concentrations were substantially greater in the sewing and sealing areas (67,000 and 188,000 particles cm⁻³) compared with that measured in the office area (12,100 particles cm⁻³). Respirable mass concentrations were negligible throughout the facility (GM = 0.002 mg m⁻³ in the sewing and sealing areas). The particles exiting the final discharge of the facility's ventilation system were dominated by nanoparticles (number median diameter = 25 nm; geometric standard deviation of 1.39). The breathing zone particle number concentrations of the workers who sealed the sewn seams were highly variable and significantly greater when sealing seams than when conducting other tasks (p < 0.0001). The sealing workers' breathing zone concentrations ranged from 147,000 particles cm⁻³ to 798,000 particles cm⁻³, and their seam responsibility significantly influenced their breathing zone concentrations (p = 0.03). The finding that particle number concentrations were approximately equal outside the hood and inside the local exhaust duct indicated poor effectiveness of the canopy hoods used to ventilate sealing operations.

Keywords aerosol mapping, apparel workers, nanoparticles, occupational exposure, polytetrafluoroethylene

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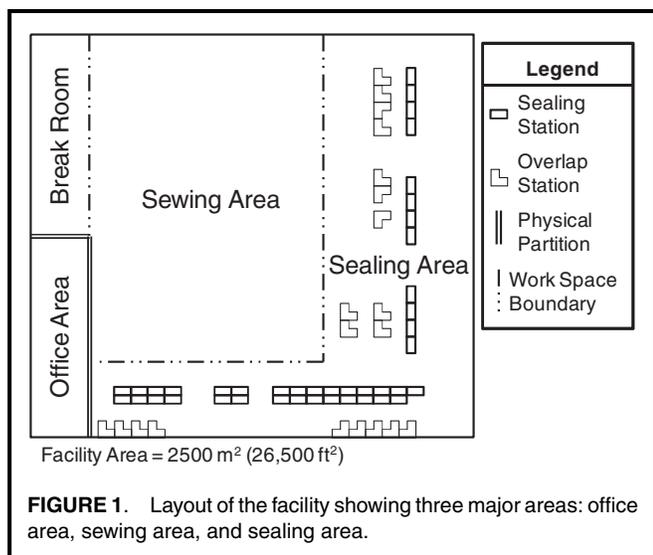
INTRODUCTION

Waterproof, breathable apparel that is impermeable to liquids but allows vapor such as perspiration to pass through⁽¹⁾ is commonly produced from polytetrafluoroethylene (PTFE) membrane laminated material.⁽²⁾ This type of apparel is used by a variety of professions, such as gowns for surgeons and nurses, foul weather survival clothing for military personnel, or protective gear for firefighters.⁽²⁾

Workers may have a wide variety of exposures (e.g., cotton dust,⁽³⁾ latex,⁽⁴⁾ formaldehyde⁽⁵⁾) depending on the fabric used to make apparel. The PTFE fabric and processes used to produce waterproof, breathable apparel may cause specific and unique particulate hazards. In the manufacturing process, pieces of fabric are joined using traditional sewing techniques. Then sealing tape, also containing PTFE, is applied to ensure that the sewn seam is waterproof.⁽⁶⁾ During the traditional sewing of the PTFE fabric there is a low potential for airborne particle production. However, during the sealing of the sewn seams, there is a possibility of exposure to incidental nanoparticles. The sealing process involves feeding the apparel through two rollers that compress the sealing tape onto the seam while hot air (600°C) is blown onto the sealing tape. Places where two seams overlap are reheated by placing the overlapping section between two heated plates to ensure they do not leak.

Toxicological studies in rodents have found exposure to nanoparticles of PTFE to be toxic⁽⁷⁾ and that PTFE nanoparticles had greater pulmonary toxicity than larger particles of PTFE.⁽⁸⁾ In humans, very high exposure to PTFE nanoparticles has led to cases of polymer fume fever^(9,10) and in extreme exposure, pulmonary edema, with one case resulting in death.⁽¹¹⁾

The purpose of this work was to characterize airborne particle concentrations in a facility that makes two styles of lightweight, waterproof, breathable rain jackets made of PTFE fabric at a production rate of 1000 jackets per day. Aerosol concentrations throughout the facility were mapped, breathing zone concentrations were measured, and the hoods used to ventilate the sealing operation were evaluated. In



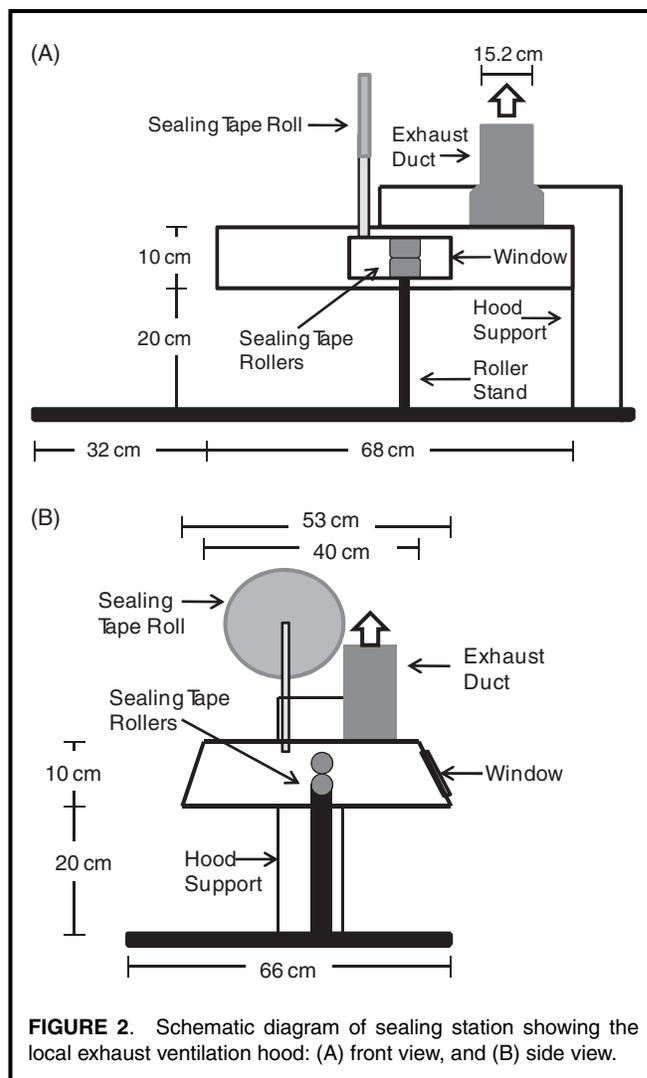
addition, worker characteristics that may have had a potential association with breathing zone concentrations were identified.

METHODS

Facility

The facility was divided into three main areas (Figure 1): office area, sewing area, and sealing area. The office area housed management, administration, and engineering staff and was physically partitioned from the other areas. Jobs performed in the sewing and sealing areas to create a rain jacket included: (1) traditional sewing of cut pieces of fabric (sewing area); (2) sealing of sewn seams (sealing area); (3) quality control (sealing area); (4) reheating overlapping seams (sealing area); and (5) bundling jackets for shipping (sewing area). In the sealing area there were 41 sealing stations (workstations to seal seams) and 20 overlap stations (workstations where overlapping sealed seams are reheated).

As depicted in Figure 2, each sealing station was fitted with a local exhaust ventilation hood intended to remove contaminants that were generated by the sealing process. The hood consisted of a transparent canopy (the hood manufacturer requested to remain anonymous) with a design airflow of 11.3 m³ min⁻¹ (400 ft³ min⁻¹). The hood had sloping front and back sides and a flat top (Figure 2B). The hood was positioned approximately 20 cm over the worktable and was held by a support on the right side. The sealing workers viewed their work through a window on the front of the hood. The hood was connected to a ventilation duct (diameter = 15.2 cm; 6 in.) on the right front corner. The duct opening was positioned away from the sealing tape rollers to avoid cooling of the hot air required to produce a high-quality seal. The hood contained gaps where the sealing tape holder extended up through the hood top. The hood (68 cm by 53 cm) covered only a portion of the entire worktable (100 cm by 66 cm).



Aerosol Mapping

On a morning when 15 workers were actively sealing seams, particle number and respirable mass concentrations were mapped at multiple locations in the sewing and sealing areas and at one location in the office area. As described by Peters et al.,⁽¹²⁾ two real-time aerosol instruments were placed on a mobile sampling cart—condensation particle counter (CPC) (Model 3007; TSI Incorporated, Shoreview, Minn.) and an optical particle counter (OPC, PDM-1108; Grimm, Ainring, Germany)—and measurements were taken at 34 locations throughout the sewing and sealing areas. At each location over a period of 1 min, the CPC was used to measure the number concentration of particles between 10 nm to 1 μm in diameter, and the OPC was used to measure the number concentrations of particles between 0.3 μm to 20 μm in diameter in 15 size channels. These data were then used to estimate nanoparticle number and respirable mass concentrations.⁽¹²⁾

Initial number concentrations measured with the CPC were found to exceed the maximum concentration range for the instrument. Therefore, to dilute the particle concentration, a filter (6702-7500; Whatman Inc., Kent, U.K.) with a 0.16 cm

hole drilled into its end cap was connected to the inlet of the CPC as described by Peters et al.⁽¹²⁾ In the office area, 1-min mean particle number concentrations were measured using the CPC with (W) the filter present and without (WO) the filter present in the following configuration: WO-W-WO-W-WO-W. The dilution factor was then estimated by dividing the mean number concentration measured without the filter by that measured with the filter. Mapping software (Surfer; Golden Software, Golden, Colo.) was used to perform kriging—a geostatistical method that produces regularly spaced data from irregularly spaced data—of the particle number concentrations measured at the 34 locations. The regularly spaced data was then used to construct a map of the facility with contours of equal particle number concentration. Respirable mass concentrations were summarized in tabular format.

Breathing Zone Concentrations

Particle number concentrations were measured in the breathing zone of nine sealing workers. A 0.64 cm inner diameter electrically conductive tube was used to transport air from outside the exhaust hood, directly above the window, to a CPC (Model 3007; TSI) that was set up to log concentrations once per second. The inlet of the transport tube was positioned in the breathing zone of the sealing workers when they were sealing seams.⁽¹³⁾ Although a representation of personal exposure, this measurement is not a true personal sample because the inlet of the transport tube was affixed to the window of the canopy hood on the workstation instead of on the sealing worker. Aerosol entering the CPC was diluted as described above for the aerosol mapping.

Measurement duration for each worker varied from 9 to 26 min to cover all the tasks that composed the job of sealing seams. Sealing seams involved four tasks. First, the sealing worker collected a bundle of jackets from a storage shelf in the sewing area and brought it back to their sealing station. The sealing worker then filled out paperwork associated with the bundle. Next, the worker sealed a number of seams on each jacket. Each jacket required the sealing of over 20 seams, but each worker was assigned only a specific set up seams to seal on the jacket. Multiple workers had similar seam responsibilities. When finished, the jackets were rebundled and placed on a different shelf in the sewing area for the next sealing worker to collect. One jacket from every third bundle was taken to a quality control station by the sealing worker.

Sealing worker tasks and characteristics were video recorded to allow identification and coding of tasks and characteristics that may have influenced breathing zone concentrations. The task information from the video included the specific time when a worker was sealing seams and when they conducted other tasks (e.g., paperwork). Percent time sealing seams versus conducting other tasks was calculated, and each worker was placed in one of three groups: greater than 70% time, 61 to 69% time, and less than 60% time. The characteristic information from the video included the worker's seam responsibility, jacket style, and worker movement while feeding material into the rollers. Worker movement (determined by

personal preference) was categorized as either a smooth, fluid motion or a choppy motion, quickly and repeatedly moving the material slightly up and down.

The video was also used to place sealing workers into one of four seam responsibility groups, based on seam length, position, and number of seams. The groups were:

- *long*—two long seams (the length of the jacket) with or without two additional short seams (less than one-quarter the length of the jacket)
- *middle*—10 or more long (at least one-half the length of the jacket) and short (less than one-quarter the length of the jacket) seams located in the middle of the jacket
- *short*—four or fewer short seams (less than one-quarter the length of the jacket)
- *mixture*—five long (length of the jacket) and short (less than one-quarter the length of the jacket) seams throughout the jacket.

Evaluation of Hood Used to Capture Particles at Sealing Stations

The effectiveness of the hood used to capture particles was evaluated at three sealing stations. At each station, the airflow was measured 80 cm downstream of the hood-duct connection by pitot tube traverse using a Series 400 Air Velocity Meter (Dwyer Instruments, Inc., Michigan City, Ind.).

Particle number concentrations were measured simultaneously in the breathing zone of the sealing worker and inside the exhaust duct immediately downstream of the hoods. Breathing zone concentrations were measured with one CPC as described above, and a second CPC was used to measure in-duct concentrations. A 0.64 cm conductive tube, with the opening placed in the center of the duct, was used to transport aerosol to the second CPC. The aerosols entering both instruments were diluted as described above. Both CPCs were set up to record concentrations once per second, and the measurement duration for each station varied from 28 to 38 min. Hood concentration reduction factor was estimated as the geometric mean (GM) number concentration measured in the duct divided by the sum of that measured in the duct and in the breathing zone times 100%.

The number concentration by size of the airborne particles was measured at the final discharge of the facility's local exhaust ventilation system. An electrically conductive tube with a 0.64 cm inner diameter was used to transport the aerosol to a 20-L holding chamber from the final discharge duct. A scanning mobility particle sizer (SMPS, SMPS+C model 5.4; Grimm) was used to measure the particle size distribution of aerosol in the holding chamber. The holding chamber dampened fluctuations in aerosol concentration that would otherwise have rendered the size distribution measured with the SMPS invalid.

Statistical Analyses

The particle number concentrations measured in the workers' breathing zones and in the local exhaust ducts were

log-transformed. Repeated measurements obtained on the same individual typically exhibit a positive correlation that must be accounted for. Linear mixed-effects models account for the correlation of the repeated measures on a person by fitting a correlation structure with few parameters while distinguishing between-subject and within-subject sources of variation.⁽¹⁴⁾

To address correlation associated with repeated measures, a linear mixed-effects model was used to analyze the repeated 1-sec measurements taken on each sealing worker. A linear mixed-effects model was fit to determine if there was a statistically significant difference in the breathing zone concentrations when the sealing workers sealed seams compared with when they conducted other tasks (e.g., paperwork) and to determine if the sealing workers' breathing zone concentrations were equal across workers to test if the sealing workers were a homogenous exposure group. Many variance/covariance structures were tested to specify the within-subject correlation in the model, and compound symmetry was chosen because it had the lowest Akaike information criterion (AIC) value. A post hoc Tukey-Kramer multiple comparison test identified which workers' breathing zone concentrations were statistically different. The GM and geometric standard deviation (GSD) of the particle number concentrations for each worker was determined.

The GM particle number concentration for each worker was calculated from his or her repeated 1-sec measurements. These GM values were used to represent the sealing workers' breathing zone concentrations when determining which worker characteristics of seam responsibility, movement, and jacket style significantly influenced breathing zone concentrations. One-way analysis of variance (ANOVA) was used to test whether breathing zone concentrations were equal across the four seam responsibility groups with a post hoc Duncan's multiple comparisons test to identify which groups had different concentrations.

Independent sample t-tests were used to determine if worker movement or jacket style was associated with breathing zone concentrations. A one-way ANOVA was used to determine if GM breathing zone number concentration was equal across the three groups of percent time sealing seams vs. conducting

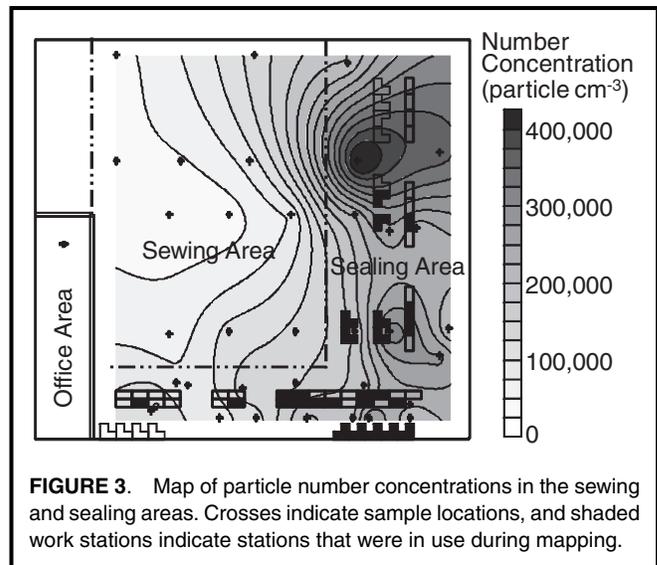


FIGURE 3. Map of particle number concentrations in the sewing and sealing areas. Crosses indicate sample locations, and shaded work stations indicate stations that were in use during mapping.

other tasks. Statistical significance for all tests was evaluated at the 95% confidence level. Analyses were carried out using the statistical software SAS version 9.2 (SAS Institute, Cary, N.C.)

RESULTS

Aerosol Mapping

Particle number concentrations were greater in the sealing area than in the sewing area (Figure 3; Table I). The GM of the particle number concentrations in the sewing area (67,000 particles cm^{-3}) was over three times greater than that in the office area (12,100 particles cm^{-3}). The GM of the particle number concentrations in the sealing area (188,000 particles cm^{-3}) was more than a magnitude greater than the office area. Respirable mass concentrations in the sewing and sealing areas ranged from 0.001–0.007 mg m^{-3} with the GM concentration (0.002 mg m^{-3}) in the sealing area slightly greater than that in the sewing area (0.001 mg m^{-3}).

TABLE I. Particle Concentrations Found During Aerosol Mapping

| Particle Number Concentrations | | | | |
|--------------------------------|----|----------------------------------|-------------------------------------|------|
| Area | n | GM (particles cm^{-3}) | Range (particles cm^{-3}) | GSD |
| Office | 1 | 12,100 | 11,600–12,500 | 1.02 |
| Sewing | 11 | 67,000 | 39,000–136,000 | 1.63 |
| Sealing | 23 | 188,000 | 78,000–445,000 | 1.59 |
| Respirable Mass Concentrations | | | | |
| Area | n | GM (mg m^{-3}) | Range (mg m^{-3}) | GSD |
| Sewing | 11 | 0.001 | 0.001–0.002 | 1.36 |
| Sealing | 23 | 0.002 | 0.001–0.007 | 1.5 |

TABLE II. Breathing Zone Concentrations by Worker

| Worker | Number of 1-Sec Measurements | GM (particles cm ⁻³) | GSD | Tukey-Kramer Grouping Levels ^A |
|--------|------------------------------|----------------------------------|------|---|
| 1 | 1312 | 240,000 | 1.79 | A |
| 2 | 1464 | 248,000 | 1.16 | B |
| 3 | 1275 | 250,000 | 1.21 | B |
| 4 | 1211 | 291,000 | 1.48 | C |
| 5 | 1316 | 321,000 | 1.96 | C |
| 6 | 1599 | 798,000 | 2.27 | D |
| 7 | 865 | 591,000 | 1.75 | D |
| 8 | 485 | 147,000 | 1.75 | E |
| 9 | 592 | 603,000 | 2.10 | D |

Note: The workers were not a homogenous exposure group but made up five statistically significantly different groups.

^AMeans with the same letter are not statistically different.

Breathing Zone Concentrations

The GM of 1-sec particle number concentrations measured in the breathing zone of the sealing workers ranged from 147,000 particles cm⁻³ to 798,000 particles cm⁻³ (Table II). The concentrations were highly variable with GSDs ranging from 1.16 to 2.27. The GM concentrations were not equal across workers ($p < 0.0001$). Thus, the sealing workers were not a homogeneous exposure group with respect to breathing zone number concentration. Five breathing zone concentration groups were found to be statistically significantly different. Breathing zone number concentrations were significantly different ($p < 0.0001$) when the workers were sealing seams (GM = 394,000 particles cm⁻³, GSD = 2.18) compared with when they were conducting other tasks (GM = 266,000 particles cm⁻³, GSD = 1.77).

Results from the analysis of tasks and characteristics using each worker's calculated GM particle number concentrations are summarized in Tables III and IV. The GM number concentrations of the four seam responsibility groups ranged from 192,000 particles cm⁻³ ("short" group) to 688,000 particles cm⁻³ ("middle" group), and the GM concentrations were not equal across seam responsibility groups ($p = 0.03$; Table III). The GM concentration of the "middle" group was significantly greater than that of the "short" and "mixture" groups. The GM concentration of the "long" group was not statistically different from that of any other group. The GM concentrations of the three percentage time sealing seams vs. conducting other task groups were also not statistically different ($p = 0.22$;

Table IV). The GM concentrations were not statistically significantly different for workers using different movements ($p = 0.82$) or sealing seams on different jacket styles ($p = 0.36$).

Figure 4 shows breathing zone particle number concentrations as a worker transitioned from lunch break to the beginning of the afternoon shift. Breathing zone concentrations were relatively low and constant during the end of the lunch break (GM = 117,000 particles cm⁻³, GSD = 1.21) but increased dramatically and became more variable when the afternoon shift began (GM = 240,000 particles cm⁻³, GSD = 1.79). Breathing zone concentrations during lunch break did not reach levels of the office area due to other sealing workers working through the lunch break.

Evaluation of Hood Used to Capture Particles at Sealing Stations

Particle number concentrations measured in the breathing zone and inside the exhaust ducts of the local exhaust ventilation system are shown in Table V. Although some of the particles were captured, the concentration reduction factor of the hood was 56% or less. Airflow through the local exhaust ventilation system ranged from 11.5–12.3 m³ min⁻¹ (405–436 ft³ min⁻¹) and met vendor specifications.

The particle number concentration by size of the aerosol captured by the local exhaust ventilation, measured at the final discharge of the system (Figure 5), was composed almost entirely of nanoparticles. The size distribution had a number median diameter of 25 nm with GSD of 1.39.

TABLE III. Breathing Zone Concentrations by Seam Responsibility

| Group | Worker ID | Number of Workers in Group | GM (particles cm ⁻³) | GSD | Duncan Grouping Levels ^A |
|---------|-----------|----------------------------|----------------------------------|------|-------------------------------------|
| Long | 4, 5, 9 | 3 | 383,000 | 1.48 | A, B |
| Middle | 6, 7 | 2 | 688,000 | 1.24 | A |
| Short | 2, 8 | 2 | 192,000 | 1.44 | B |
| Mixture | 1, 3 | 2 | 245,000 | 1.03 | B |

Note: Seam responsibility was a statistically significant characteristic associated with sealing sewn seams.

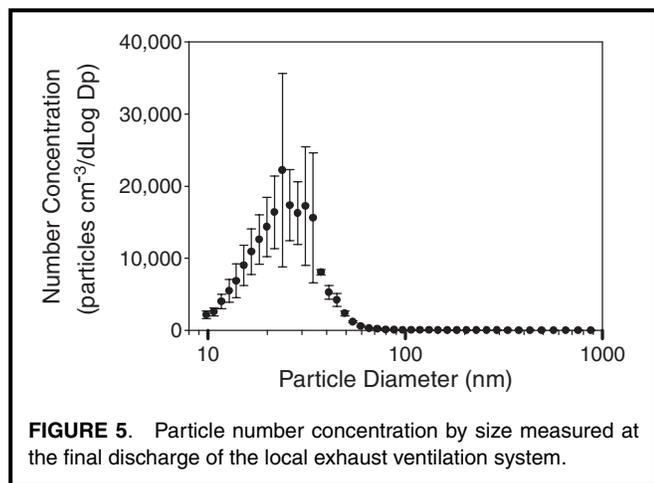
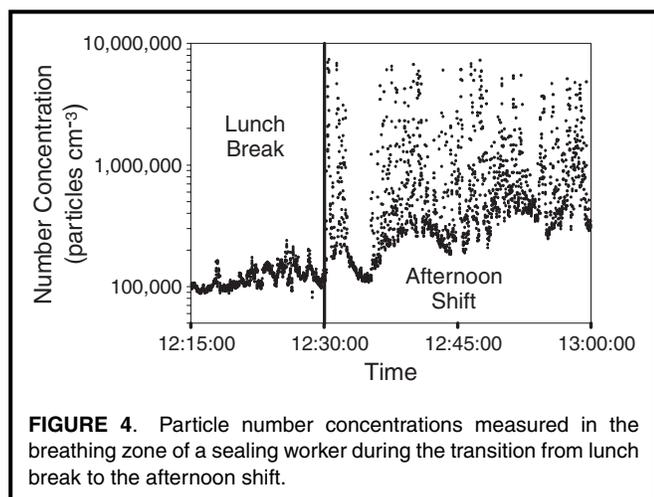
^AMeans with the same letter are not statistically different.

TABLE IV. Breathing Zone Concentrations by Percent Time Sealing Seams

| Group | Worker ID | Number of Workers in Group | GM (particles cm ⁻³) | GSD | Duncan Grouping Levels ^A |
|------------------|-----------|----------------------------|----------------------------------|------|-------------------------------------|
| Greater than 70% | 1, 6, 7 | 3 | 484,000 | 1.87 | A |
| 61% to 69% | 3, 5, 9 | 3 | 364,000 | 1.57 | A |
| Less than 60% | 4, 2, 8 | 3 | 220,000 | 1.42 | A |

Note: Percent time sealing seams vs. conducting other tasks was not a statistically significant characteristic associated with sealing sewn seams.

^AMeans with the same letter are not statistically different.



DISCUSSION

Nanoparticle number concentrations were elevated in a facility that produces apparel made of PTFE fabric. The airborne particles were dominated by nanoparticles (NMD = 25 nm, GSD = 1.39), with the greatest concentrations observed in the breathing zone of sealing workers (GM ranged from 147,000 to 798,000 particles cm⁻³). Particle number concentrations in both sealing and sewing areas were very high compared with those found in the office area.

There are no regulatory standards for particle number concentration. However, particle number concentrations found at this facility were similar to or greater than those observed in heavy industrial settings, such as an automotive foundry⁽¹⁵⁾ and plants where smelting and grinding occurred.⁽¹⁶⁾ Actual breathing zone concentrations may in fact be greater than measured because even with the filter to dilute the particle number concentrations, the CPC readings were at times above the upper limit of the CPC (100,000 particles cm⁻³). At concentrations above the upper limit, coincidence may cause the CPC to underestimate the particle concentration.⁽¹⁷⁾

In contrast, particle mass concentrations were low throughout the facility (GM < 0.020 mg m⁻³). These values are substantially lower than the OSHA permissible exposure limit for particles not otherwise regulated with a time-weighted average exposure limit of 5 mg m⁻³ for respirable mass concentration. This finding is expected given that the aerosol was composed almost entirely of nanoparticles that contribute little to mass concentration despite their high particle number concentrations.

The source of the nanoparticles is attributed to the hot process of sealing seams. Breathing zone number concentrations were significantly greater when the sealing workers were

TABLE V. Results From Hood Evaluation

| Station | Number of Measurements | Airflow (m ³ min ⁻¹) | Breathing Zone | | In-Duct | | Concentration Reduction Factor (%) |
|---------|------------------------|---|----------------------------------|------|----------------------------------|------|------------------------------------|
| | | | GM (particles cm ⁻³) | GSD | GM (particles cm ⁻³) | GSD | |
| 1 | 2440 | 12.3 | 6.03 × 10 ⁵ | 2.60 | 7.75 × 10 ⁵ | 2.57 | 56 |
| 2 | 1761 | 11.5 | 2.57 × 10 ⁶ | 2.44 | 1.45 × 10 ⁶ | 1.90 | 36 |
| 3 | 2318 | 12.3 | 3.77 × 10 ⁵ | 1.41 | 2.31 × 10 ⁵ | 3.30 | 38 |

sealing seams compared with when they were conducting other tasks. They also increased dramatically at the start of a work shift (Figure 4). The single mode observed in the particle size distribution (Figure 5) is typical of a single aerosol source, and the aerosol mapping provided further evidence that the source was located within the sewing and sealing areas. And finally, the fact that breathing zone particle number concentrations were substantially greater than those observed during aerosol mapping was consistent with the heated sealing process being the dominant aerosol source.

The canopy hoods of the local exhaust ventilation system do not adequately capture the nanoparticles generated by the sealing process. Breathing zone concentrations were very high for all sealing workers. The concentration reduction factor was poor and ranged from 36% to 56%.

Certain characteristics of canopy hoods, combined with their application for sealing, may explain the poor capture efficiencies. First, canopy hoods function best when they are used to control hot contaminants that have thermal buoyancy to aid in their collection.⁽¹⁸⁾ Although sealing involves high heat, nanoparticles may have been created and then trapped underneath the jacket during sealing. Those particles would then tend to mix with cool air and would no longer be carried by thermal buoyancy up into the hood. Second, canopy hoods are known to produce a limited capture zone even with a high exhaust airflow rate.⁽¹⁸⁾ When removing the jacket from underneath the hood, the worker may have released the nanoparticles that were trapped under the jacket outside the canopy hood's capture zone. Capture efficiency of a canopy hood is diminished by objects located below the hood,⁽¹⁹⁾ and sealing required the workers' arms and the jacket to be below the hood.

The importance of the combination of canopy hood characteristics is illustrated by the association among seam responsibilities and breathing zone concentrations. The breathing zone concentrations for the "short" or "mixture" groups were lower than those in the "middle" group (Table III). Workers in "short" or "mixture" groups had at least one seam that ended at a jacket edge, so they lifted the jacket when it was still underneath the hood before starting another seam. With this lifting action, nanoparticles would have a fair likelihood of capture. In contrast, the "middle" group was responsible for a combination of more than 10 long and short seams located in the middle of the jacket. The location of those seams required the worker to slide and drape the jacket over the worktable as they moved from seam to seam. Sliding the jacket may have drawn the nanoparticles outside the canopy hood's capture zone.

A redesigned hood may improve nanoparticle capture and reduce the number concentrations in the breathing zone. However, a new design must balance the need to provide sufficient workspace to access all seams of a jacket, maintain the temperature at the seam to create a high-quality seal, and adequately capture the nanoparticles. Although providing adequate workspace and proper sealing temperature, the current design does not have an appropriate concentration reduction factor. A hood with a partial enclosure may address

these competing issues more effectively than a canopy hood but may also reduce the workspace to an unacceptable size. Further work under controlled laboratory conditions is needed to evaluate the effectiveness of different hood designs.

There are several issues that may limit the applicability of our findings. The measurements for this study were taken at one facility and may not be representative of other facilities that seal sewn seams. Aerosol mapping was conducted during one morning only and, consequently, may not be representative of different days or times of day. The particle size distribution measured in the exhaust air was assumed to represent the particulate inside the facility. This assumption enabled measurement despite constraints of sampling with the SMPS (requires stable aerosol concentrations over ~6 min sampling time) near aerosol sources with highly fluctuating generation rates (i.e., sealing sewn seams). It is possible that larger particles within the facility were not captured or conveyed through the ductwork, thereby biasing the measured distribution to smaller sizes. However, the results of aerosol mapping (Table I; high number concentrations and low mass concentrations) are consistent with the fact that the aerosol burden within the facility is dominated by nanoparticles and with the particle size distribution measured in the exhaust air.

Breathing zone concentrations were not measured when workers were away from their workstation conducting tasks other than sealing because the tube was affixed to the canopy hood. However, these tasks (picking up and dropping off bundles of jackets) took the worker away from the measurement location for a short time (<10%) compared with the tasks that were conducted at the workstation (filling out paperwork and sealing sewn seams). Particle mapping results suggest that these tasks were conducted in areas of the facility where particle number concentrations were likely to be substantially lower than at the workstation. Thus, particle number concentrations for these tasks were likely overestimated. Despite this fact, breathing zone concentrations during sealing sewn seams were found to be significantly and substantially greater than those observed during other tasks. Sampling was conducted in this way because of the limitation that there were no direct-read instruments to measure personal exposure to nanoparticles at the time of this work.

Some seemingly conflicting results arose from our inability to apply linear mixed-effects models throughout the statistical analysis. The use of a mixed model enabled us to determine that the nine workers studied were not part of a single homogenous exposure group, although the differences among the GM of workers were sometimes small (Table II; Group A is different from Group B). The ability of the mixed model to take advantage of the numerous 1-sec measurements on each worker ($n > 485$) allowed these differences to be detected.

The limited number of subjects prevented our use of mixed-effects models to investigate the influence of characteristics on breathing zone concentrations. Instead, we used ANOVA and t-tests to determine whether characteristics were associated with breathing zone concentrations. These analyses require that measurements are independent. The GM of 1-sec

measurements for each worker (n = 9) were used to avoid the issue that 1-sec measurements were highly correlated temporally.

The low number of samples limited our ability to detect differences between groups. Consequently, the characteristics of time sealing seams, movement of sealing worker, and style of jacket sealed were not found to be statistically significant, although there were sometimes substantial differences in the group GMs (Table IV) compared with those observed in Table II. The characteristics may be significant when tested with a larger sample size.

CONCLUSIONS

Nanoparticle number concentrations were identified to be very high in a facility that produces apparel made of PTFE fabric. The greatest concentrations were found in the breathing zone of workers responsible for sealing sewn seams. These nanoparticles were identified to be incidental to the hot process of sealing seams. Canopy hoods used to ventilate the sealing workstations were found to have poor concentration reduction factor. Several limitations of canopy hoods when applied to this particular application may explain this poor concentration reduction factor.

RECOMMENDATIONS

Determination of the composition of the particles in the facility was outside the scope of this work. However, it is an important subject of future work.

A redesigned hood is likely to improve nanoparticle capture and reduce the number concentrations in the breathing zone. A hood with a partial enclosure may reconcile the need to provide sufficient work space, obtain high concentration reduction factor, and maintain adequate temperature of sealing. Further work under controlled laboratory conditions is needed to develop different hood designs and evaluate their effectiveness.

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