

Particle Emission Characteristics of Office Printers

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In modern society, printers are widely used in the office environment. This study investigated particle number and PM_{2.5} emissions from printers using the TSI SMPS, TSI CPC 3022, and 3025A TSI P-Trak and DustTrak. The monitoring of particle characteristics in a large open-plan office showed that particles generated by printers can significantly ($p = 0.01$) affect the submicrometer particle number concentration levels in the office. An investigation of the submicrometer particle emissions produced by each of the 62 printers used in the office building was also conducted and based on the particle concentrations in the immediate vicinity of the printers, after a short printing job, the printers were divided into four classes: non-emitters, and low, medium, and high emitters. It was found that approximately 60% of the investigated printers did not emit submicrometer particles and of the 40% that did emit particles, 27% were high particle emitters. Particle emission characteristics from three different laser printers were also studied in an experimental chamber, which showed that particle emission rates are printer-type specific and are affected by toner coverage and cartridge age. While a more comprehensive study is still required, to provide a better database of printer emission rates, as well as their chemical characteristics, the results from this study imply that submicrometer particle concentration levels in an office can be reduced by a proper choice of the printers.

1. Introduction

Nowadays there is little doubt as to the importance of indoor air quality (IAQ), since modern society tends to spend the vast majority of time in various types of indoor environments. In addition to the penetration of pollutants from outdoor air, most indoor built environments contain air pollution sources that release fibers, particles, organic vapors, or inorganic gases. Many studies have reported associations between health complaints and poor IAQ (1–3), and there is mounting evidence that exposure to poor IAQ leads to excess morbidity and mortality (4).

Various types of printers are widely used in offices and homes around the world and they have become standard indoor electronic equipment. However, they are a potential source of indoor pollutants (5–7), producing volatile organic compounds (VOCs) and ozone (6–10), as well as a variety of particle emissions (6, 7, 9, 11–13). So far there have been

only a few studies on printer emissions, but it appears that there are large differences in the emission levels among different types of printers. Smola et al. (14) measured the emissions of seven different printers from leading manufacturers and recorded the emissions of particles (respirable and inhalable), ozone, and total volatile organic compounds. Among the results of the study, it was found that black-and-white laser printers did not emit toner dust in measurable amounts, and only one of the tested printers emitted low quantities of ozone. Volatile organic compounds (VOC) were emitted in varying amounts, by the lubricating oil in the printers' mechanical parts. Recently, Naoki et al. (7) investigated particle, VOC, and ozone emission from three printers and also found that the particle, VOC, and ozone emission behaviors were printer-type specific.

A small number of studies have presented a time series of submicrometer particle number concentrations measured in offices for periods of up to 48 h (15–17). The results from these studies showed that the patterns of diurnal variation of submicrometer particle concentrations in the office and outdoors were different, and that indoor activities may significantly affect submicrometer particle concentrations in the office.

In general, there is very limited information available on the emission of particles from office equipment, especially from printers. Thus it is important to develop a better understanding of the emissions from the printers in order to achieve good indoor air quality and to minimize human exposure to these pollutants.

To address this need, this study aimed to (1) simultaneously monitor submicrometer particle number concentration for 48 h, in a large open-plan office, as well as outdoors, to assess the potential impact of indoor activities on indoor particle concentrations; (2) measure concentrations of submicrometer particles in the immediate vicinity of operating printers in a multilevel office building; (3) measure particle characteristics and determine particle emission rates from three different laser printers operating in an experimental chamber; and (4) assess the potential impact of various types of printers as particle emission sources.

2. Experimental Procedures

The experimental design of this study included three steps: (1) monitoring office and outdoor submicrometer particle number concentrations for more than 48 h; (2) measuring particle number concentration levels in the vicinity of all of the printers in the office building; and (3) measuring particle concentrations and emission rates from three different printers using an experimental chamber.

2.1. Office Building, Office, and Experimental Chamber.

The building investigated was a multi-floor, air-conditioned office building, with six floors, each serviced with a set of HVAC units. The building was located within the CBD of Brisbane, surrounded by roads carrying low to medium traffic flows and at a distance of approximately 120 m from a busy freeway. Printers were located in various places in the building, and smoking was prohibited in the building.

Indoor particle number concentration was measured in a large open-plan office (about 120 m²) located at the fourth floor of the building. There were 22 desks in the office, as well as several different types of printers and photocopy machines. There was also a small tea room, which was located to one side of the office.

An experimental flow-through chamber, with volume of approximately 1 m³ and equipped with a stirring fan, at the International Laboratory for Air Quality and Health (ILAQH),

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Queensland University of Technology (QUT), was also used for the study. Inlet and outlet ports were incorporated into the chamber to introduce particle-free air by HEPA filters and withdraw analytical samples for particle measurements. The air flow rate through the chamber during the experiments was 2.3 L min⁻¹.

2.2. Instrumentation. A TSI model 3022 condensation particle counter (CPC) (TSI Incorporated, St. Paul, MN) was used for continuous (more than 48 h), real-time measurements (sample time 20 s) of total number concentrations of particles in the range from 0.007 to 3 μm, in the office, and the TSI model 3025A CPC (TSI Incorporated) was used in the same way for the chamber study, except with a sample time of 10 s. A TSI model 3934 scanning mobility particle sizer (SMPS) (TSI Incorporated) was used to measure outdoor submicrometer particle number concentrations and size distributions (sample time 180 s) in the range from 0.015 to 0.737 μm, as well as the concentrations in the chamber study (in the range from 0.015 to 0.685 μm).

A TSI model 8525 P-Trak ultrafine particle counter (TSI Incorporated), which measures total particle number concentration (sample time 1 s) in the size range from 0.02 to 1 μm, was used to investigate particle emission from the printers in the building. A TSI model 8520 DustTrak aerosol monitor (TSI Incorporated) with a 2.5 μm inlet was also used to measure real-time PM_{2.5} concentrations (sample time 10 s).

2.3. Study Design. For indoor particle monitoring, the CPC 3022 was placed in the center of the office on a trolley. The nearest printer was approximately 4 m from the CPC. For outdoor particle monitoring, the SMPS was placed in the plant room on the same level of the building. The ventilation system in the building was on during the measurements.

During the investigations of printer emissions in the building, the P-Trak was placed 0.5 m above the investigated printer. The background office particle number concentration was measured when the printer was off and the measurement of the concentration was then repeated immediately after the printer had printed one page. The P-Trak was calibrated to provide one data reading per second and the duration for each test was between 2 and 3 min. The average peak values were then used to calculate the ratio between background concentrations and those measured after printing. It was considered sufficient to print only one page, as Uhde et al. (13) reported that particle concentration in the vicinity of a printer increases immediately after the printer starts operating and does not depend significantly on the number of pages printed.

Based on the results of the individual printer emission tests conducted in the office building, three printers were tested in an experimental chamber, representing the three classes of submicrometer particle emission rates: Printer A, HP LaserJet 5M (low emitter); Printer B, HP LaserJet 1020 (medium emitter); and Printer C, HP LaserJet 1320n (high emitter). There was no further testing done for “non-emitters”. During the chamber testing, the printer was placed in the middle of the flow-through chamber and the measurements were conducted in three phases: (1) background concentration measurements were taken until the particle number concentration in the chamber was lower than 500 particles cm⁻³ and PM_{2.5} concentration was lower than 0.002 mg m⁻³ (which was controlled by introduced particle free air); (2) concentration measurements were taken immediately after the print job started and continued for the duration of the print job; and (3) the measurement of decay in concentration for 30–300 min after the print jobs had finished. Print jobs of 5–100 pages were used, where all of the printers operated at normal speed and approximately 9–10 min was required to finish a print job of 100 pages. The same brand of standard quality white paper (80 g m⁻²) was used in all

tests. To assess the influence of the toner coverage on particle emissions, printers A and B were tested for two different percentages of black coverage (5% and 50%). To assess the influence of cartridge age, old and new cartridges were used in printer C.

2.4. Particle Emission Rates. The principal factors governing particle concentration levels in a chamber are the contributions from the sources in the chamber and from the outside air, the deposition rate of particles on surfaces of the chamber, the air exchange rate, and coagulation (although in this case, the particle coagulation rate is significantly lower than the emission rate and is therefore insignificant). A formula for the calculation of particle concentration in the chamber, taking into consideration these factors, can be written as follows (18, 19):

$$\frac{dC_{in}}{dt} = P\alpha C_{out} + \frac{Q_s}{V} - \lambda C_{in} \quad (1)$$

where C_{in} and C_{out} are particle concentrations inside and outside the chamber; P is the penetration efficiency; α is the air exchange rate; λ is the total removal rate which includes air exchange rate, deposition rate, and coagulation rate; Q_s is particle generation rate in chamber; t is time; and V is the volume of the chamber. In general, all of the factors in this equation, with the exception of the volume of the chamber, are functions of other factors and can vary with time (for example, penetration efficiency is a function of particle size). Since the air introduced into the chamber in this study was particle-free air, C_{out} was considered to be zero. Thus, eq 1 can be rewritten as follows:

$$\frac{dC_{in}}{dt} = \frac{Q_s}{V} - \lambda C_{in} \quad (2)$$

Further, the air exchange rate, α , was constant, and assuming the emission rate, Q_s , was also constant (not dependent on time), the time-averaged solution to eq 2 is as follows (18):

$$Q_s = V \left[\frac{C_{int} - C_{in0}}{\Delta t} + \lambda \overline{C_{in}} \right] \quad (3)$$

where C_{int} and C_{in0} are the peak and initial background particle concentrations in the chamber; $\overline{C_{in}}$ is the average value of particle concentrations between the initial background and peak; λ is the total removal rate; and Δt is time difference between initial background and peak concentration. Equation 3 can be used for both particle mass and number concentration, as well as emission calculations (mass balance equation).

Similarly, based on eq 2, after the printer had finished printing, $Q_s = 0$, and the time-dependent solution to eq 2 becomes

$$\ln(C_{inT}/C_{in0}) = -\lambda t \quad (4)$$

Using the average decay rate of particle concentration in the chamber after the printer had finished printing, the total removal rate (λ) can be obtained by fitting a line to a plot of $\log(C_{inT}/C_{in0})$ versus time, where C_{inT} is particle concentration in the chamber after the printer finished printing.

Thus, eqs 3 and 4 can be employed to determine particle emission rates, based on the calculated total removal rate, and measured peak and background concentrations. This method is similar to the methods used to calculate indoor particle sources emission rates and particle deposition rates in residential houses in previous studies (20, 21).

2.5. Data Processing and Analysis. Since the DustTrak operates on the principle of light scattering, it does not measure gravimetric mass and its response is dependent on

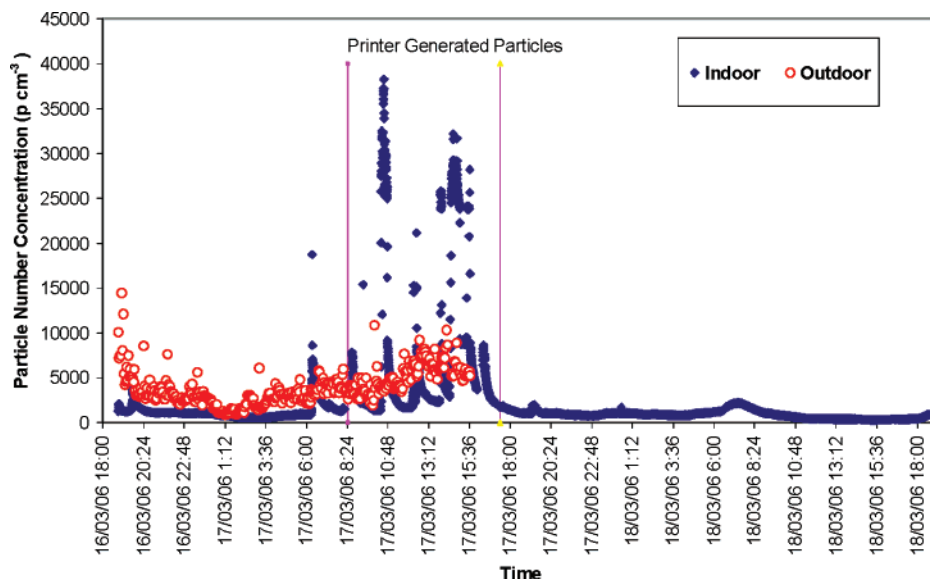


FIGURE 1. Indoor and outdoor particle number concentration (particle cm^{-3}) variation during Friday – Saturday March 17 and 18, 2006.

the size distribution and refractive index of the sampled aerosol. In order to obtain values closer to true $\text{PM}_{2.5}$, all of the $\text{PM}_{2.5}$ data collected by the DustTrak in this study was corrected using a calibration equation obtained from a previous study, where the DustTrak was set to operate side by side with a TEOM, in an environment dominated by the presence of submicrometer particles (22).

All statistical analyses (correlation, regression, *t*-test, One-Way ANOVA) were conducted using a statistical analysis software package: SPSS for Windows version 10 (SPSS Inc.). A level of significance of $p = 0.05$ was used for all statistical procedures. When the distribution of the data was not a normal distribution, robust analysis (trimming off the maximum and minimum) was employed.

3. Results and Discussion

3.1. Particle Number Concentration Diurnal Variation in the Office. Figure 1 presents a time series of particle number concentration in the office, conducted from 18:54 Thursday (March 16, 2006) to 18:51 Saturday (March 18, 2006). The outdoor time series of particle number concentration (particle cm^{-3}) was conducted from 18:54 Thursday (March 16, 2006) to 15:38 Friday (March 17, 2006) and is also presented in Figure 1. Analysis of the indoor concentrations showed clear diurnal variation (one-way ANOVA, $p < 0.005$), with an average concentration of $6.5 (\pm 8.2) \times 10^3$ particle cm^{-3} for working time (8:30 to 17:30), $1.2 (\pm 0.9) \times 10^3$ particle cm^{-3} for nonworking time and $0.86 (\pm 0.4) \times 10^3$ particle cm^{-3} for the weekend. This means that average particle number concentration in this office during working time was about 5 times higher than that during nonworking time. However, average outdoor particle number concentration during working time was also about 1 time higher than during nonworking time, for the same measurement time period. A comparison of indoor to outdoor particle number concentration showed that the average indoor concentration was lower ($p < 0.01$) than that of the outdoors during nonworking time, but significantly higher ($p < 0.01$) than that of the outdoors during working time. The highest indoor particle number concentration measured was 38.2×10^3 particle cm^{-3} , which is clearly higher than the outdoor concentration of 10.9×10^3 particle cm^{-3} .

Preliminary investigations of the indoor sources contributing to these concentrations showed that although there was a microwave oven in a tea room, which was located approximately 10 meters from the CPC, it was a weak particle

source. As shown in Figure 1, it was some of the printers (not photocopiers) in this office, which were the main particle sources and the cause of large increases in particle number concentrations in the office. This result indicates that office printers could be the main submicrometer particle source in large mechanically ventilated office buildings, where tobacco smoking is prohibited.

3.2. Printer Emission Investigation. Following the above findings, an investigation into printer emissions in the building was conducted. Based on the ratio of particle concentrations measured immediately after the printer printed one page, compared to the background office concentrations, the investigated printers were catalogued into four different classes, in terms of their particle emission levels, including: non-emitters (ratio ≤ 1); low emitters (ratio > 1 and ≤ 5), medium emitters (ratio > 5 and ≤ 10); and high emitters (ratio > 10).

A total of 62 different printers were investigated, including various models from CANON, HP COLOR LaserJet, HP LaserJet, RICOH, and TOSHIBA. Table 1 presents a summary of the results of the printer emission investigations, including printer brand and name, and the class of emissions. It can be seen that 37 of the printers were non-emitters, 6 were low, 2 were medium, and 17 were high emitters. Overall, 60% of the investigated printers were non-emitters and of the 40% that were emitters, 27% were classed as high submicrometer particle emitters. It can also be seen that the same model of a printer (in this case the HP LaserJet 5) can act as either a non-emitter or a high emitter, and further investigation should be conducted for this phenomena.

3.3. Chamber Testing Printer Emissions. **3.3.1. Particle Emission Characteristics.** In summary, the chamber measurements confirmed that particle emissions start immediately after the printer starts operating, and they showed that in general, size distributions of the particles generated by the printer are monodisperse. They also showed that particle number and size distributions vary among the three printers, at peak concentrations. Figure 2 presents a comparison of the total average particle size distributions emitted by the three printers. Ultrafine particles represented about 73% of total submicrometer particles emitted by printer A, while for printer B and C, this value was about 98–99%.

The mean particle count median diameter (CMD) was the largest for printer A (76 ± 11 nm) and the smallest for printers B (46 ± 9 nm) and C (40 ± 4 nm), although it is interesting to note that printer A had a lower emission rate

TABLE 1. Summary of Results for Printer Emission Investigations, Based on the Ratio of Submicrometer Particle Number Concentration Peak Value Emitted by the Printer to the Background Value (measured by P-Trak)

non-emitter (ratio ≤ 1)	low level emitter (ratio < 1.1–5)	middle level emitter (ratio < 5.1–10)	high level emitter (ratio > 10)
HP Color LaserJet 4550DN (1)	Canon IRC6800 (1)	HP LaserJet 1020 (1)	HP Color LaserJet 4650dn (1)
HP Color LaserJet 8500DN (1)	HP LaserJet 5M (3)	HP LaserJet 4200dtn (1)	HP Color LaserJet 5550dtn (1)
HP LaserJet 2200DN (1)	HP LaserJet 9000dn (1)		HP Color LaserJet 8550N (1)
HP LaserJet 2300dtn (1)	RICOH CL3000DN (1)		HP LaserJet 1320N (1)
HP LaserJet 4 plus (1)			HP LaserJet 1320n (1)
HP LaserJet 4000N (1)			HP LaserJet 2420dn (1)
HP LaserJet 4000TN (1)			HP LaserJet 4200dtn ^a (1)
HP LaserJet 4050N (2)			HP LaserJet 4250n (old) (1)
HP LaserJet 4050TN (6)			HP LaserJet 4250n (new) (1)
HP LaserJet 4si (1)			HP LaserJet 5(a) (1)
HP LaserJet 5(b) (1)			HP LaserJet 8000DN ^a (1)
HP LaserJet 5000n (1)			HP LaserJet 8150N (1)
HP LaserJet 5100tn (2)			TOSHIBA Studio 450 (1)
HP LaserJet 5N (2)			
HP LaserJet 5si (1)			
HP LaserJet 5si/NX (1)			
HP LaserJet 8000DN (2)			
HP LaserJet 8150DN (3)			
Mita DC 4060 (photo copy) (1)			
RICOH Aficio 2022 (1)			
RICOH Aficio 3045 (1)			
RICOH Aficio 3245C (3)			
RICOH Aficio CC3000DN (1)			
TOSHIBA Studio 350 (1)			

^a Possible high emitter.

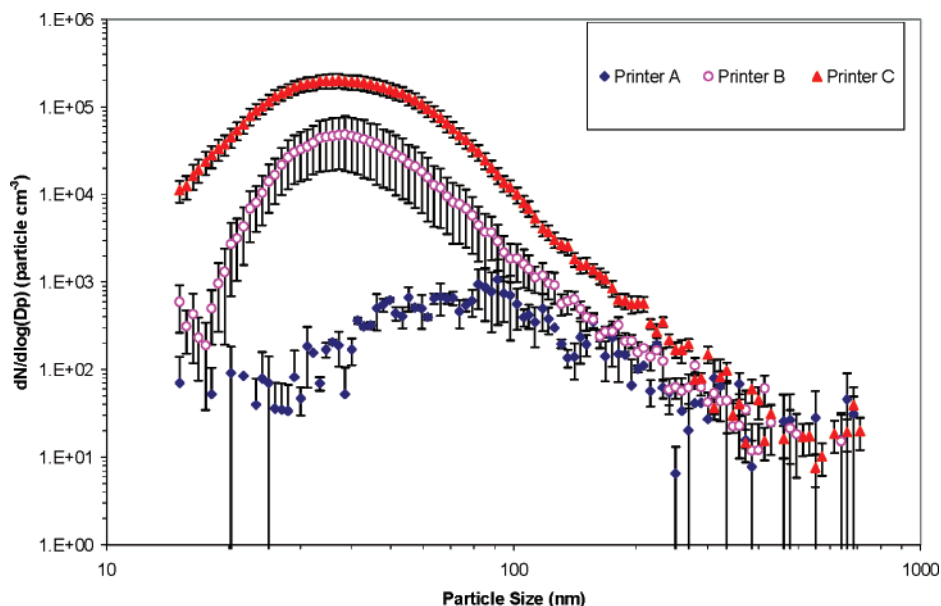


FIGURE 2. Average particle size distributions of the particles generated by the three different printers. Error bars are standard errors.

than printers B and C. The difference in CMDs was statistically significant ($p < 0.05$) between printers A and B, as well as between A and C, but was not statistically significant ($p > 0.05$) between printers B and C.

A comparison of the average particle size distributions for 5% and 50% of toner coverage conditions for printer B operating with old cartridges and printer C operating with old and new cartridges, found a clear difference in particle size distributions between 50% and 5% toner coverage conditions for both printers operating with old cartridges. For printer C, when operating with a new cartridge, the difference in particle size distribution for different toner coverage conditions was not clear, however when operating with an old versus a new cartridge, it was found that while the old cartridge generated a lower total number of particles

than the new cartridge, it generated a greater number of smaller particles, below 25 nm in diameter.

Further analysis conducted with the application of the K-S test showed that for particles with sizes ranging from 15 to 710 nm, there were statistically significant differences ($p = 0.01$) between printers, as well as between printing conditions (e.g., toner coverage and cartridge age). These results indicate that the particle emission characteristics are printer-type specific and are affected by printing conditions, such as toner coverage and cartridge age.

3.3.2. Particle Emission Rates. Table 2 presents a summary of the average particle number and $PM_{2.5}$ emission rates of the three different printers investigated. It can be seen that the differences in particle number emissions between the “low emitter” (printer A) and “medium emitter” (printer B)

TABLE 2. Summary of the Estimated Particle Emission Rates from Chamber Tests for Three Different Printers (Particle Numbers Concentration Measured by the Condensation Particle Counter 3025A, PM_{2.5} Measured by DustTrak)

printer ID ^a	cartridge	toner coverage	testing number	emission rate (particle min ⁻¹ × 10 ⁹)		PM _{2.5} emission rate (μg min ⁻¹)	
				average	S.D.	average	S.D.
A	new	5%	3	0.04	0.01	0.29	0.07
B	old	5%	2	4.21	3.66	NE ^b	
B	old	50%	2	9.54	8.23		
C	old	5%	3	41.1	12.0	NE ^b	
C	old	50%	2	92.8	0.99		
C	new	5%	2	76.3	18.8		
C	new	50%	1	159			

^a Printer ID: A = HP LaserJet 5M, B = HP LaserJet 1020, C = HP LaserJet 1320n. ^b NE: no emission rate.

are approximately 2 orders of magnitude, and the difference between the “medium emitter” and “high emitter” (printer C), is approximately 1 order of magnitude.

It can also be seen from Table 2 that particle number emission rates are higher for 50% toner coverage than for 5% toner coverage, for both printers B and C. However, statistical analysis showed that the difference was only significant for printer C ($p < 0.05$). Printer C, when operating with a new cartridge, emitted more particles than when operating with

an old cartridge, under both toner coverage conditions, but statistical analysis showed that the differences were not significant, although this may have been the result of there being not enough test data for statistical analysis. Thus it can be concluded that toner coverage and cartridge age could be the most significant factors affecting the emission rates of a particular printer, however more study on the effect of these factors on printer particle emissions is needed.

PM_{2.5} concentrations, generated by printers B and C in the chamber, were very low and not significantly higher than the background level, therefore the PM_{2.5} emission rate was only calculated for printer A, as shown in Table 2.

Figure 3 presents examples of particle concentrations combined with the printer activity information for printers A and C. By comparing the graphs it can be seen that PM_{2.5} concentration increased clearly after printer A had started printing, however this did not happen for printers B or C (data not shown). This result raises a question in relation to particle number emissions, for the printers classified as “non-emitters”, which were not investigated in the chamber study. Such printers could still be emitters of larger particles, thus contributing to PM_{2.5} concentrations, and therefore should be further investigated in the future studies.

The results from this study provide the first database on submicrometer particle number emission rates of office printers. These data are important not only to improve knowledge on particle emissions, but are also necessary for indoor air exposure assessment and for considerations of

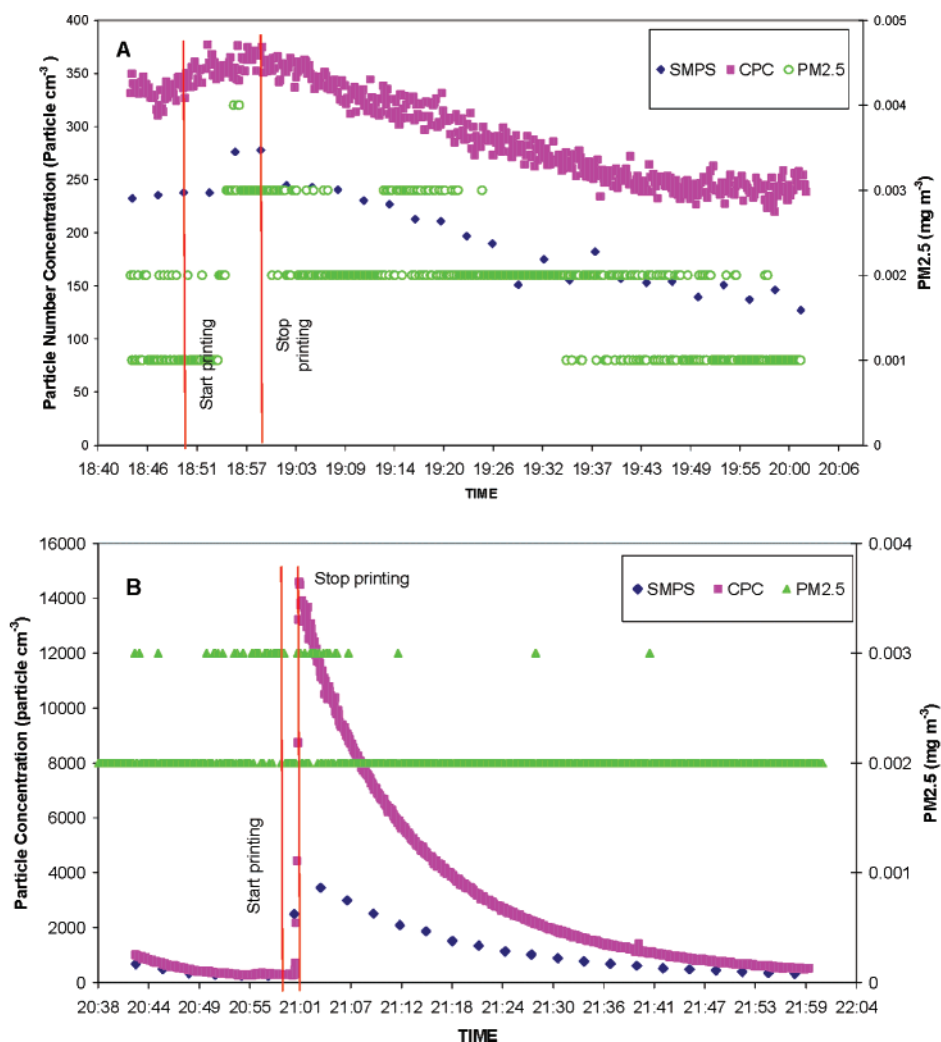


FIGURE 3. Two examples of real-time particle concentration data, combined with printer activity information, for Printer A (A) and Printer C (B).

indoor air improvements, as well as for future indoor air modeling studies.

3.4. Discussion. There is little literature data available to compare particle number concentrations measured in the office environment. Koponen et al. (16) studied wintertime indoor and outdoor particle size distributions in a mechanically ventilated office building and found that indoor particle number concentrations (particle size 7–500 nm) varied in the range from 500 to 10^4 particles/cm³, with a significant relationship to outdoor concentrations. This range is comparable to the range found in this study, of 350 to 3.8 10^4 particles/cm³, despite differences in the equipment used in the two studies. Luoma and Batterman (15) found that while occupants' activities, such as walking past or visiting the monitoring site in the office, explained 24–55% of the variation of 1–25 μ m diameter particle number concentrations, number concentrations of particles smaller than 1 μ m had little correlation with indoor activities, other than cigarette smoking, and were highly correlated with outdoor concentrations. Matson (23) also reported on indoor and outdoor particle number concentrations (0.01 to greater than 1 μ m) measured under different conditions (location, type of building, smoking, or nonsmoking). For measurements which were conducted in nonsmoking, mechanically ventilated urban office buildings, the average indoor particle number concentration (3.9×10^3 (particle cm⁻³)) was comparable to the value observed this study (3.85×10^3 (particle cm⁻³)). An analysis of temporal variation of indoor and outdoor particle number concentrations also showed that there were strong particle sources in the office, however none of the three studies mentioned above provide any information about printer use during the measurements.

Jungnickel et al. (24) reported benzene emissions from 65 laser printers and photocopiers, however no information was provided regarding particle emissions or the types of printers investigated, therefore no comparison can be conducted with the particle number emissions found in this study.

Recent studies by Uhde et al. (13) and Wensing et al. (12) investigated the characteristics of ultrafine particle number emissions from a laser printer and from a hardcopy device (laser printers and multi-function devices, respectively). Uhde et al. (13) found that small particles were detected during the first few minutes following the commencement of a printing job: the mean size of released particles was in the range from 90 to 120 nm, and the dependence of particle emissions on page coverage and the number of pages printed was weak. The results from this study found that the mean size of released particles was smaller, in the range from 35 to 94 nm, and that there was a dependence of particle emission rate on toner coverage. Again, these differences imply that particle emissions are printer-type specific, however there is no further literature data available for comparison of the particle number emission rates of printers.

The highest printer particle number emission rate found in the chamber study was 1.6×10^{11} particle min⁻¹, which is close to the median value of submicrometer particle number emission rates for activities, such as cigarette smoking (1.91×10^{11} particle min⁻¹), occurring in residential houses (20).

Particle mass (referred to as dust) emissions from 20 different laser printers were reported by Eggert et al. (11). The average mass emission rates were found to be 61 μ g min⁻¹. This value is nearly 100 times higher than the results found in this study ($PM_{2.5}$ 0.75 (± 0.18) μ g min⁻¹), however they referred to printers of a different generation than those currently used. Lee et al. (9) found that emissions of PM_{10} from two laser printers were nearly twice as high as those from two ink-jet printers, however there are no particle number data available from this study.

The high standard deviation of the average emission rates estimated in this study also indicates that the particle emission process and the behavior of individual printers are complex and that they are still far from being completely understood. Many factors, such as printer model, printer age, cartridge model, and cartridge age may affect the particle emission process and all of these factors require further study.

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