### Response to Dr. James P. Lodge, Jr. "1995 Critical Review Discussion," September 1995

*Dear Editor:*

A discussant of the 1995 Critical Review takes exception to the statistical form of the NAAQS for $PM_{10}$ as follows:[1]

> "...the use of arithmetic average is a statistical abomination. Concentrations of particulate matter are not distributed normally, but lognormally. Hence, the use of arithmetic mean is wrong, actually concealing information. The sole reason for use of the arithmetic mean is that it yields bigger numbers than the geometric mean."

There are at least four reasons why the arithmetic mean (AM) is preferable to the geometric mean (GM) for the PM standards,[2] none of which is the "sole" reason cited. Simply stated, a GM standard has several major defects:

1. The health effects of PM are related to the amount of PM deposited in the lungs. For a person breathing V $m^3$ of air during a year, the product AM V is an estimate of the amount of PM inhaled. However, the product GM V has no physical significance.
2. The AM is an invariant property of the time series. The GM is a function of the averaging time. For a set of four quarterly AM values of {1, 2, 8, 1} Annual AM = 3, Annual GM = 2. If the values are combined to create two semiannual values {1.5, 4.5} the Annual AM = 3, but the Annual GM = $\sqrt{6.75}$ = 2.6.
3. The sums of lognormal variables are not lognormally distributed. If a time series of 1-hour averages of PM happened to be lognormal the time series of 24-hour averages cannot be lognormally distributed.
4. The "brute force" assumption that air quality data have a lognormal distribution *a priori*, and that it is not necessary to statistically test whether or not this assumption is valid, has been called "the Procrustean fit."[3] If the lognormal model is rejected as a good fit to the data the GM would have no meaning.

David Mage, U.S. EPA Scientist


1. Lodge, J.P., Jr. "1995 Critical Review discussion" *J. Air & Waste Manage. Assoc.* 1995, 45, 671-673.
2. Mage, D.T. "The statistical form for the ambient particulate standard: Annual arithmetic mean vs. annual geometric mean," JAPCA 1980, 30, 797-798.
3. Mage, D.T. "The Procrustean fit—A useful tool for decision making," JIR 1995, 40(1) 31-32.


*Disclaimer: The information in this letter has been funded wholly by the United States Environmental Protection Agency. It has been subjected to Agency review and approved for publication.*

**LETTERS TO THE EDITOR**

Letters to the editor are welcome in response to any information published in the *Journal*. Authors will be invited to reply in writing to letters submitted in response to their papers; author responses will be published in the same issue in which the letters are published. The *Journal* reserves the right to edit all letters for length or clarity. Correspondence should include the writer's full name, address and business telephone. Please send letters to William A. Tony, Managing Editor, *Journal of the Air & Waste Management Association*, One Gateway Center, Third Floor, Pittsburgh, PA 15222; fax (412) 232-3450; or e-mail btony@awma.org.

### AUTHOR'S RESPONSE

*Dear Editor:*

All in all, I believe my conclusion, while I cannot support it with evidence, is not unreasonable. My personal opinion is strengthened, not weakened, by the effort Dr. Mage puts forth to deny it.

Clearly it is in order to use the usual tests for goodness-of-fit to determine just how the data are distributed. I have been agreeably surprised to see just how well the vast majority of concentration data do fit the lognormal distribution. I am certainly aware that the geometric mean is not the measure of *exposure*; if you could run the sampler for a full year, it would ultimately yield a concentration value equal to the arithmetic mean of the separate hourly or daily measurements, allowing for minor measurement errors. The measure of *dose*, however, is dependent as well on the rate at which the target organism (here, man) excretes the toxicant. Nonetheless, if the data are distributed lognormally, then the distribution can be uniquely reconstructed from a knowledge of the geometric mean and geometric standard deviation, and other means and moments calculated. The same is not true of the arithmetic mean and standard deviation of a lognormally distributed variable. It is for this reason that I maintain that the use of the arithmetic mean obscures information.

I also agree with him that you cannot mix arithmetic and geometric means. I never proposed doing so. As he says, you should not take the geometric mean of quarterly or monthly or semiannual arithmetic means (reference 2). His primary argument is that, since the EPA set the other NAAQS based on the arithmetic means, this one is certainly justified in going the same way. He then argues in reference 2 that the scientists in the field are too stupid to keep the two different kinds of means straight; he cites examples to prove this. I have worked with data on concentrations of all the other "criteria" pollutants. These also are more nearly lognormally than normally distributed. Otherwise his evidence is a table derived from the Winkelstein et al. study in Buffalo, showing that stations with the same geometric mean concentrations have different arithmetic mean concentrations. In fact, the differences are in every case well within the limits of accuracy of the analytical methods involved, and far less than the resolution of the measurements of effects. The listing of a total of 21 stations and their geometric and arithmetic means, ranked in the order of increasing geometric means, shows only two inversions of order in arithmetic means.

In truth, even if the concentrations are truly lognormally distributed, their determination is subject to a series of measurement errors that are almost certainly normally distributed. Which distribution (if either) will finally manifest itself in the outcome is a matter of their relative magnitudes. Years of working with data of this kind lead me to the opinion that the dominant distribution is usually near enough to lognormal to warrant freeing these data from the "Procrustean bed" of normal statistics. The gaseous pollutants should receive the same treatment. The fact that the use of normal statistics leads to the calculation of symmetrical confidence limits is not a reason to use normal statistics if the confidence limits are in fact not symmetrical!

James P. Lodge, Consultant in Atmospheric Chemistry





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# Understanding and Reducing the Indoor Concentration of Submicron Particles at a Commercial Building in Southern California

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## ABSTRACT

Submicron particles play a major role in soiling processes and contribute to corrosion, current leakage and shorts in electronic equipment. For more than a year, optical particle counters have been used to continuously measure the concentrations of submicron particles at a telecommunications facility in Southern California. Separate instruments have simultaneously sampled at four locations: the outdoor air intake, immediately upstream of the HVAC filters, immediately downstream of the HVAC filters, and inside the office. The indoor concentrations can be explained in the context of a one-compartment mass balance model. Key parameters in the model (e.g., the air exchange rate) were monitored throughout the sampling period. In the latter part of this study, the particle counters were used as feedback elements in the HVAC system. An estimate of the concentration of indoor submicron particles, based on measurements of outdoor submicron particles, has been used as a control variable. When this variable exceeds a preset value, the outdoor air damper is partially closed, reducing the amount of outdoor air entering the building. That is, the position of the damper is based on the concentration of outdoor particles as well as the outdoor temperature. As a consequence, the average indoor concentration of submicron particles has been significantly reduced within this facility.


## INTRODUCTION

Recent studies have generated renewed interest in the health effects of submicron particles.[1-3] These same particles play a major role in soiling processes and also contribute to corrosion, current leakage and shorts in electronic equipment.[4] Our own work examining the factors that influence the indoor concentrations of fine particles has been driven by concern regarding potential damage to telecommunications equipment. In previous studies, we have collected fine and coarse airborne particles at telecommunications facilities in Wichita, KS, Lubbock, TX, Newark, NJ, and Neenah, WI.[5-7] These samples have been captured on Teflon membrane filters, with the advantage that subsequent chemical analyses could be performed on the collected material. However, long sampling periods, typically one week for indoor samples, are required to collect sufficient material for accurate gravimetric analyses. Such sampling intervals are too long to fully appreciate the dynamics of outdoor-to-indoor transport, deposition to surfaces, and changing particle-size distributions. To examine these processes in greater detail, it is necessary to monitor changes in particle concentrations that occur over much shorter time intervals. Optical particle counters are well suited to such an application.

In the current study, optical particle counters have sampled air at key locations inside and outside a commercial building in Southern California. Particle counts have been monitored, at one minute intervals, for more than a year. Not only has the resulting information improved our understanding of the factors that influence the indoor concentrations of submicron particles, but, in the latter stages of this study, the particle counters have been successfully employed as feedback elements in the HVAC system to limit the indoor concentrations of submicron particles.

**IMPLICATIONS**

In commercial buildings where there is no smoking or cooking, the major source of submicron particles is outdoor air. Since the outdoor concentration of submicron particles can vary more than an order of magnitude in several minutes, it is potentially beneficial to modulate the amount of ventilation air based, in part, on the outdoor concentration of submicron particles (analogous to current practice based on the temperature of the outdoor air). This paper demonstrates the successful application of such a control strategy.

## EXPERIMENTAL

The reported measurements were made at a telecommunications office in Burbank, CA, 15 miles northeast of downtown Los Angeles and 15 miles east of the Pacific Ocean, latitude 34.182°, longitude 118.312°. The Burbank Airport is one mile to the west, and U.S. Interstate 5 passes one-half mile northeast of the site; prevailing winds are from the west. The office is a flat-roofed building with a first floor and basement; each has an area of 930 $m^2$ and a volume of 5095 $m^3$. There is no carpeting; the interior walls are unpainted red brick; and there is little "fleecy" (high surface area) material within the building. Indoor pollutants were measured on the first floor.

From June 15 to June 16, 1992 and, again, from January 9 to January 12, 1993, air exchange rates on the first floor were measured using perfluorocarbon tracers.[8] During periods of minimum ventilation the air exchange rate (i.e., the exchange of indoor air with outdoor air) was 0.30 air changes/hour (ach or $h^{-1}$); during periods of maximum ventilation it was 1.9 ach. The "continuous" air exchange rates reported in this study were calculated using the volumetric flows of outside air and the volume of the ventilated space. The former were derived from the air velocities in the "outdoor-air" plenum. These, as well as the air velocities in the "return-air" plenum and the "mixed-air" plenum, were measured continuously using TSI Air Velocity Transmitters (anemometers; Model # 8450). On those occasions when air exchange rates were determined by perfluorocarbon tracer techniques, the measured values and those calculated using the outside air velocities agreed to within 10%.

The outdoor and indoor temperatures and relative humidities were continuously monitored using Omega Model HX93C transmitters. These devices use a thin film polymer capacitor to sense relative humidity, and a thin film permalloy resistance detector to sense temperature. The sensors are protected by a stainless steel filter.

The optical particle counters employed in this study (Met One, Model 217) use a right angle light collection system with a solid-state laser diode to sample particles. They have two channels; for the purposes of this study, channel one monitored particles with an optical diameter greater than 0.5 µm and channel two monitored particles with an optical diameter greater than 1.0 µm. The difference between these two channels provided counts for particles between 0.5 and 1.0 µm diameter—the particles that have the greatest impact on electronic equipment.[4-7] Air was sampled through isokinetic probes at 0.1 cfm; the sampling interval was every 60 s. Separate particle counters sampled air at four locations: the outdoor air intake, upstream of the HVAC filters, downstream of the HVAC filters, and within the building (on the first floor, about 1.5 meters from the floor). Throughout this report, particle counts are reported in units of "counts/$ft^3$"; 28,317 counts/$ft^3$ = 1 count/$cm^3$. During the course of these studies, we found that the particle counters frequently required cleaning and recalibration. The instruments were periodically calibrated by comparison with standards maintained by Met One; the accuracy and stability of these standards are traceable to the National Institute of Standards and Technology, or derived from acceptable values of natural physical constants.

The data logging and control system was assembled using a personal computer equipped with an Omega Model WB-FAI-16 data acquisition card. The card has 16 analog input channels and 8 digital outputs. The analog input channels were set to measure linearized 4 to 20 mA signals from the temperature/relative humidity transmitters, anemometers, and differential pressure transmitter. The particle counters were interfaced using an RS-232 serial interface. When the particle counters were serving as feedback elements in the HVAC system, digital output from the card was used to operate a relay which controlled the outside air damper. A program written in BASIC mechanized the measurement and control process; the underlying algorithm will be discussed later. This adjunct system ran continuously. At the end of every ten one-minute cycles, the particle count data and all environmental parameters were stored. Ten-minute averages were computed for each parameter and stored in a separate data file. To ensure "fail-safe" system operation, a watch-dog timer circuit was included in the adjunct system. The timer circuit disconnected the adjunct system from the main HVAC system in the event of a system malfunction such as a software lock-out. The computer that was interfaced to the particle counters also was connected to a modem. This system collected data, as described above, and at the same time was available for file transfer, initiated from a remote site.

## RESULTS AND DISCUSSION

### The Site

The building where these measurements were made is dedicated to telecommunications equipment. Its HVAC system and the resulting airflows are somewhat simpler than in buildings of comparable size, since there are fewer partitions within the space. However, in other respects, it is similar to most mechanically ventilated, one-story, flat-roofed commercial buildings. The HVAC system includes economizer operation for free air cooling. When the outdoor air temperature is greater than the return air temperature, the damper is closed; when the outdoor air temperature is less than the return air temperature, the damper is open; an adjustable throttling range is superimposed upon these criteria. There are no major sources of submicron particles within the building; there is no smoking or cooking and combustion appliances are not present.

### Typical Results

Data were collected at the Burbank site, with only brief interruptions, from June 1992 to September 1994. During this period, the outdoor concentration of 0.5 µm to 1.0 µm diameter particles ranged from about 10,000 to 3,500,000 counts/$ft^3$ and the indoor concentration ranged from about 1,000 to 1,000,000 counts/$ft^3$. Outdoor and indoor ozone, nitrogen dioxide, and nitric oxide concentrations were measured at this same location during the same time interval. These results have been presented elsewhere.[9]

Figure 1a shows outdoor and indoor concentrations, in counts/$ft^3$, of 0.5 µm to 1.0 µm particles during the week of March 14, 1994. In many respects, this data is typical of data collected for more than a year at the Burbank site. Close to noon, on March 17, the outdoor count reached a value of 1,500,000 counts/$ft^3$. On the other extreme, just before noon on March 14 and at 1:00 am on March 19, the outdoor count was as low as 30,000 counts/$ft^3$. The outdoor concentration can change dramatically over relatively short time intervals. On March 15, in a period of an hour, it rose from 200,000 to 1,000,000 counts/$ft^3$ and then fell just as fast. A strong local source such as an idling truck can cause an even faster change in particle concentrations (such an event was not represented in the week of March 14).

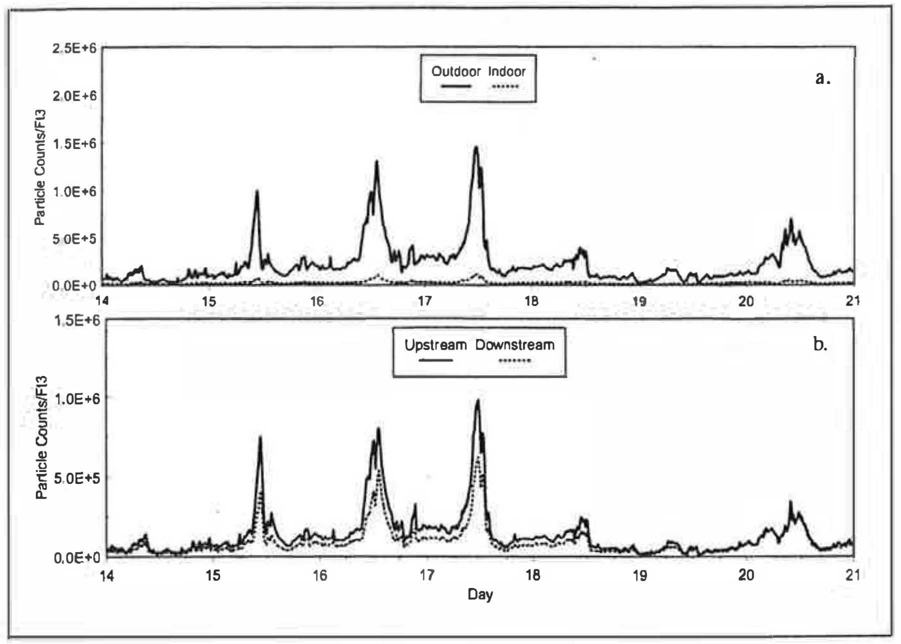


**Figure 1.** Concentrations (particle counts/$ft^3$) of 0.5 to 1.0 µm diameter particles measured during the week of March 14, 1994; a) outdoors and indoors; b) upstream and downstream of the HVAC filters.

The indoor concentrations for the week of March 14 fall between 1,000 and 12,000 counts/$ft^3$. The indoor concentration tracked the outdoor concentration, but *the ratio of the indoor values to the outdoor values was not constant*.

Figure 1b shows particle counts measured just before (upstream) and after (downstream) the filters in the HVAC system. These filters have a nominal ASHRAE dust spot rating of 40%. The downstream concentrations are less than the upstream concentrations, although the ratio of the downstream to upstream concentration varies throughout the week. This variation is due to changes in the size distribution of 0.5 µm to 1.0 µm particles (see Efficiency of the Particulate Filters, below). It is also interesting to compare the indoor concentrations in Figure 1a with the downstream concentrations in Figure 1b. The former are much smaller than the latter (note the different y-axis scales in the two figures). This reflects loss of fine particles from the point of measurement downstream of the filters to the point of measurement within the office. Particulate deposition occurs to a variety of surfaces: the ductwork, floors, walls, ceilings, equipment, and furnishings within the office. The total area available for deposition is quite large. Indeed, the number of 0.5 µm to 1.0 µm particles removed by surfaces is roughly one to two times greater than the number removed by the filters in the HVAC system (see Mass-Balance Model, below).

### Earthquake

On January 17, 1994, an atypical event occurred at the sampling location—an earthquake. A brief examination of data collected during this event provides an indication of the detail that can be captured by particle sensors that respond with a relatively short time constant. Figures 2a and 2b show outdoor and indoor particle counts during the first 11.5 hours of January 17. Figure 2a focuses on the 0.5 to 1.0 µm diameter particles. At the time of the earthquake, 4:27 am, there was a slight increase in the outdoor concentration of 0.5 to 1.0 µm particles, followed a short time later by an increase in the indoor concentration. Both increases were relatively brief in duration; within 20 minutes the concentration of 0.5 to 1.0 µm particles had returned to pre-earthquake levels. A second, much larger increase in 0.5 to 1.0 µm particle counts began about 6:15 am. This correlated with smoke, from fires caused by the earthquake, passing over the Burbank site. The outdoor particle concentration reached a value of 3,000,000 counts/$ft^3$ and stayed at this level for almost 45 minutes. During this same interval, the indoor concentration reached 250,000 counts/$ft^3$. Note that the indoor concentration again peaks later than the outdoor concentration, consistent with the time lag expected for outdoor-to-indoor transport.

Figure 2b shows the counts for particles greater than 1.0 µm diameter ("larger" particles) on January 17. At 4:27 am, both the outdoor and indoor concentrations of these larger particles increased *simultaneously*; the relative increases were much greater than the corresponding increases of 0.5 to 1.0 µm particles. The outdoor counts climbed from 10,000 to 40,000 counts/$ft^3$ in less than 15 minutes while the indoor concentrations climbed from less than 100 to 70,000 counts/$ft^3$ in a comparable time period. The simultaneous increases of the indoor and outdoor counts were caused by the direct effects of the earthquake (i.e., the increase in larger particles indoors was not due to outdoor-to-indoor transport, since there was no time lag between outdoor and indoor increases). Earthquake-related occurrences that generated larger particles within the office included vibration of the interior brick surfaces, falling ceiling tiles, dislodged books, and scattered papers. These disturbances had little effect on the indoor concentration of 0.5 to 1.0 µm particles. About 6:15 am, when the smoke began to reach the Burbank site, the outdoor concentration of larger particles increased even more than at the time of the earthquake; the value peaked at roughly 110,000 counts/ft$^3$. This increase in the level of larger particles outdoors had very little effect on the indoor concentration of larger particles. The building filters were capable of removing the majority of these larger particles, and there was very little infiltration through openings in the building shell (i.e., cracks around doorways, etc.).

### Mass-Balance Model

*Parameters of Interest.* The influence of the various HVAC operating parameters on the steady-state concentrations of indoor airborne particles (or other pollutants) can be evaluated using a one compartment mass-balance model developed for telephone switching offices.[10-12] For example, the steady-state indoor concentration (counts/ft$^3$) of 0.5 to 1.0 µm particles in the indoor air, $C_{ia}$, is given by:

$$C_{ia}=(x)\frac{R_i+v_1(1-F_1)C_{oa}+v_{sa}(1-F_p)(1-F_s)fC_{oa}}{v_dA_d+v_{sa}F_s(1-f)+v_1+v_{sa}f} + (1-x)\frac{R_i+v_1'(1-F_1)C_{oa}}{v_dA_d+v_1'} \qquad (1)$$

where $C_{oa}$ = concentration of 0.5 to 1.0 µm particles (counts/ft$^3$) in the outdoor air, continuously measured at the Burbank site; x = fraction of time building fans are on (0 - 1), 1 at the Burbank site; f = fraction of circulation made up with outside air (0 - 1), 0.08 to 0.43 at the Burbank site; $R_i$ = internal generation rate of 0.5 to 1.0 µm particles (counts/ft$^3$), set to 0 for the Burbank site since smoking was not permitted and no combustion appliances were present; $v_1'$ = volume of air leaking into or out of the building when the building fans are on (m$^3$/min), set to zero for the Burbank site; $v_1'$ = volume of air leaking into or out of the building when the building fans are off (m$^3$/min), not applicable at the Burbank site; $v_{sa}$ = air flow in the supply air duct, equivalent to total air flow in the air-handling system, 12,070 ft$^3$/min (342 m$^3$/min) at the Burbank site; $F_1$ = fractional equivalent filter efficiency of leakage paths (0 - 1), not applicable at the Burbank site; $F_p$ = the fraction of 0.5 to 1.0 µm particles removed by the outdoor air filters located upstream of the mixing box (0 - 1), not applicable at the Burbank site; $F_s$ = the fraction of 0.5 to 1.0 µm particles removed by the supply air filters located downstream of the mixing box (0 - 1), continuously measured at the Burbank site and referred to as the "effective filtration efficiency" in this document (see section titled Efficiency of the Particulate Filters for further discussion of this parameter); $v_d$ = deposition velocity of the species to indoor surfaces, 0.02 ft/min (0.01 cm/s) for 0.5 - 1.0 µm particles, based on measurements at other telecommunications offices;[5-7] $A_d$ = area of indoor surfaces available for deposition, 154,000 ft$^2$ (14,300 m$^2$); estimated from the interior dimensions of the office, plus the surfaces of equipment and furnishings within the office, plus the interior surfaces of the ductwork.

Hence, at the Burbank site, Equation 1 simplifies to:

$$C_{ia}=\frac{v_{sa}(1-F_s)fC_{oa}}{v_dA_d+v_{sa}F_s(1-f)+v_{sa}f} \qquad (2)$$

*Fraction of Circulation Made Up with Outside Air.* Figure 3a shows the pressure difference, ΔP, across the building shell measured during the week of March 24, 1993. These values provide a graphic indicator of the position of the outdoor air (OA) damper. A ΔP of 0.04 inches of water corresponds to the minimum setting of the OA damper. At this setting, the fraction of circulation made up with outside air, f, was 0.08, and the indoor air was replaced with outdoor air at 0.3 ach. A ΔP of 0.23 inches of water corresponds to the maximum setting of the OA damper; at this setting, f was 0.43 and the indoor air was replaced with outdoor air at 1.9 ach.

*Efficiency of the Particulate Filters.* The particulate filters at Burbank were located downstream of the mixing box. Their effective filtration efficiency, $F_s$, was calculated as:

$$F_s=(1-\frac{C_{da}}{C_{ua}}) \qquad (3)$$

where

$C_{da}$ = concentration of 0.5 to 1.0 µm particles (counts/ft$^3$) in the air immediately downstream of the building filters, continuously measured at the Burbank site;

$C_{ua}$ = concentration of 0.5 to 1.0 µm particles (counts/ft$^3$) in the air immediately upstream of the building filters, continuously measured at the Burbank site.

In other words, $F_s$ is simply the fraction of 0.5 to 1.0 µm particles captured by the filters. Figure 3b shows the value of $F_s$ during the week of March 24, 1993. During this period, the effective filtration efficiency varied from a low of 10% on March 25 to a high of 48% on March 30. This should not be misconstrued. The probability that the filter captured a particle of a given size did not change. Instead, the size-distribution of particles within the range of 0.5 to 1.0 µm diameter changed.

There are two major influences on the size-distribution of 0.5 to 1.0 µm particles that pass through the particulate filters. The first is the size-distribution of the outdoor aerosol; the second is the fraction of recirculated air. It is often difficult to separate the contribution of these two factors. However, there are periods when one factor is relatively constant, providing an opportunity to examine the influence of variations in the other factor. Consider the period from 12:01 am on March 24 to approximately 8:00 am on March 25. During this time the fraction of recirculated air is roughly constant (0.89, see Figure 3a for an indication of the damper position). Nonetheless, the effective filtration efficiency for 0.5 to 1.0 µm particles varies from 19% to 35% (see Figure 3b). This reflects changes in the size distribution of the outdoor 0.5 to 1.0 µm particles. Among the factors that influence this distribution is the age of the aerosol.[13] When the aerosol is relatively fresh, the distribution is shifted towards the finer particles and the effective filtration efficiency for 0.5 to 1.0 µm particles decreases. When the aerosol is relatively aged, the distribution is shifted towards the larger particles and the effective filtration efficiency for 0.5 to 1.0 µm particles increases. A second example of a period dominated by changes in the size distribution of the outdoor aerosol occurs from 10:00 pm on March 26 to noon on March 28. During this interval the fraction of recirculated air again is roughly constant (0.57, see Figure 3a for damper position), but lower than in our earlier example. The effective filtration efficiency for this period varies from approximately 15% to 30% (see Figure 3b).

Figure 4 presents a single day, February 11, 1994, during which the size distribution

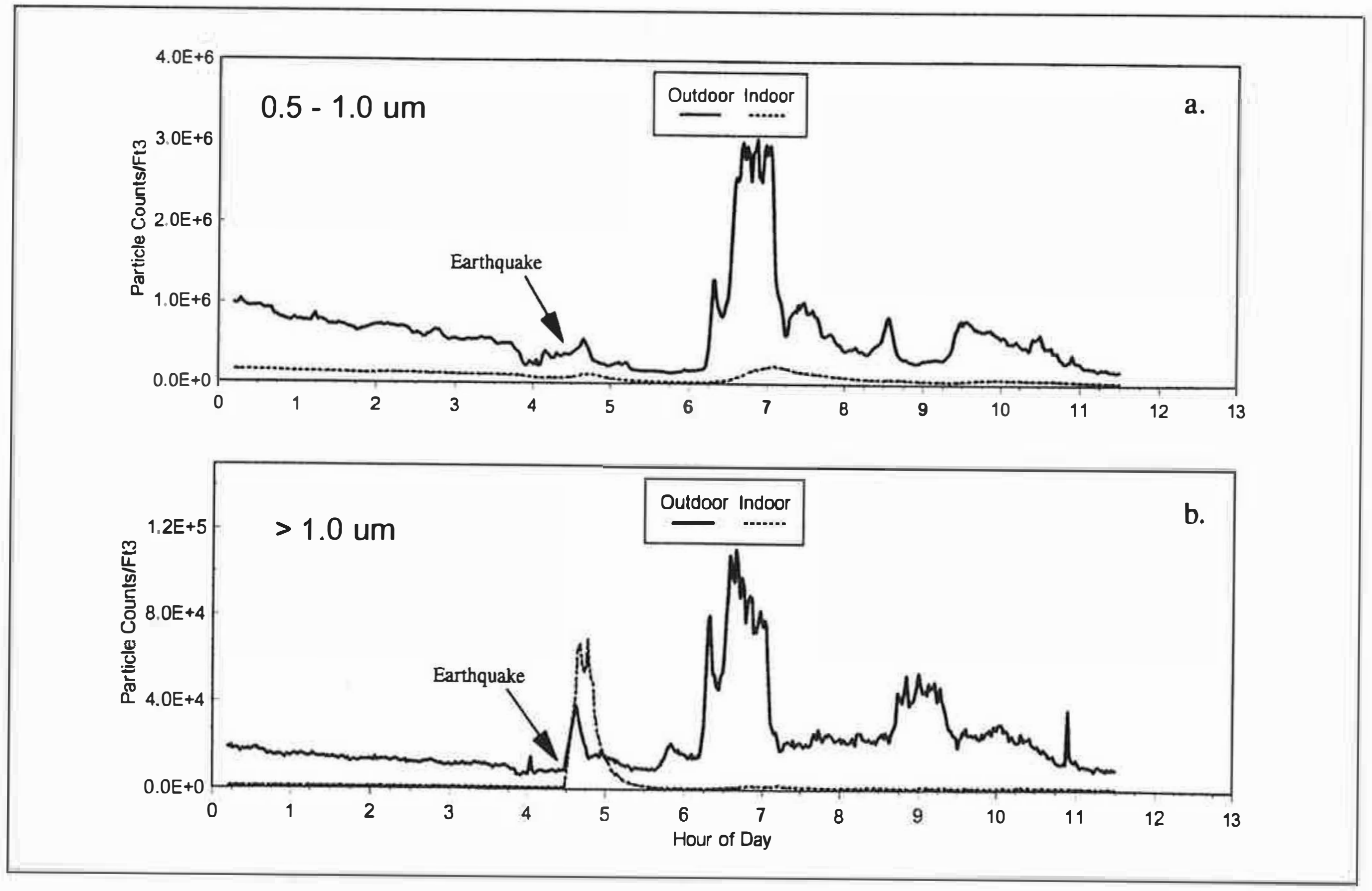


**Figure 2.** Concentrations (particle counts/ft$^3$) of particles measured during the first 11.5 hours of January 17, 1994; a) 0.5 to 1.0 µm diameter particles; b) greater than 1.0 µm diameter particles. Earthquake occurred at 4:27 am PST.

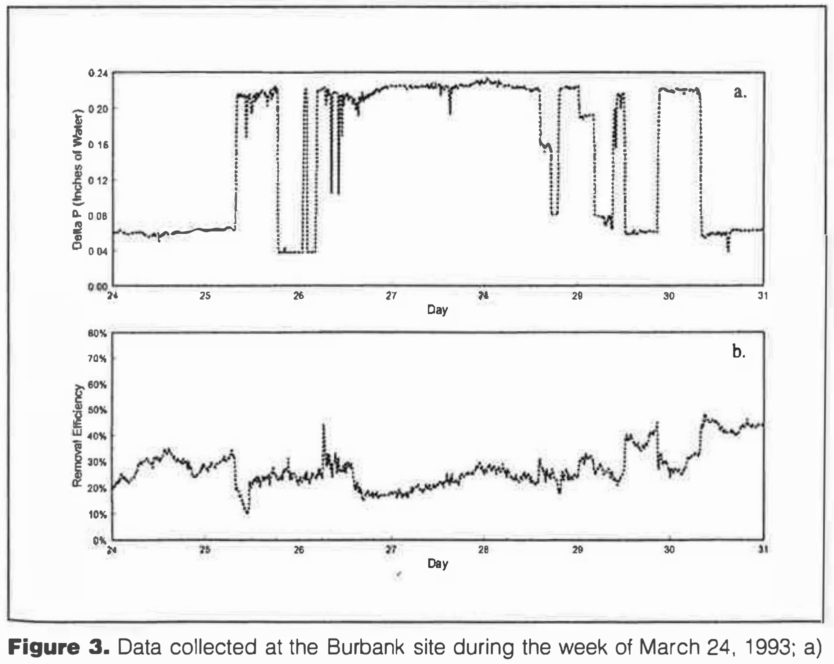


**Figure 3.** Data collected at the Burbank site during the week of March 24, 1993; a) pressure difference (inches of water) across the building shell; b) percentage of 0.5 to 1.0 µm diameter particles removed by building filters.

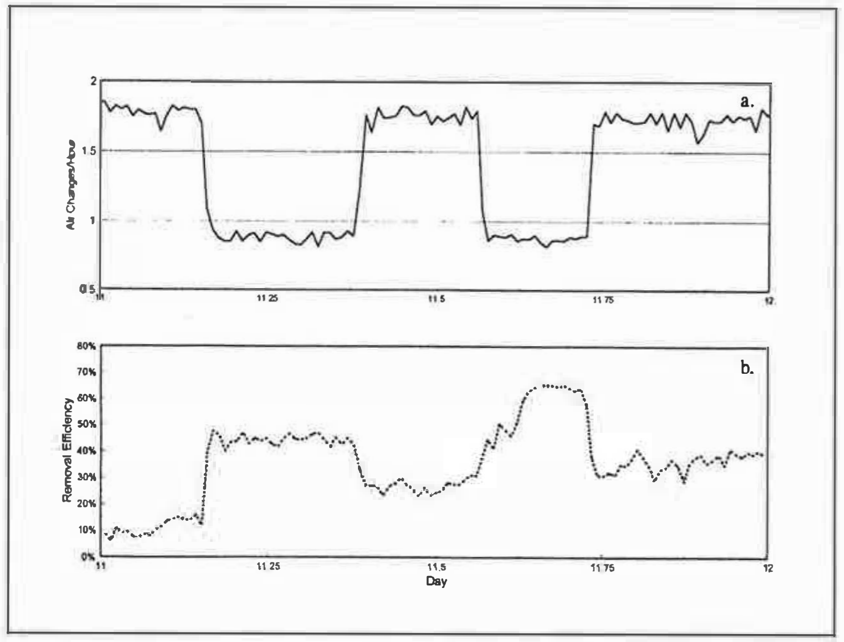


**Figure 4.** Data collected at the Burbank site on February 11, 1994; a) air changes (with outdoor air) per hour; b) percentage of 0.5 to 1.0 μm diameter particles removed by building filters.

of the *outdoor* particles between 0.5 to 1.0 μm diameter was relatively constant. This fact is inferred from the ratio of "outdoor particle counts for 0.5-1.0 μm dia particles" to "outdoor particle counts for particles larger than 1.0 μm dia" throughout the day. Despite the relatively constant size distribution among the outdoor 0.5 to 1.0 μm particles, the effective filtration efficiency of 0.5 to 1.0 μm particles varied dramatically on this day, and the variations correlated with changes in the fraction of recirculated air. This is apparent from Figures 4a and 4b; Figure 4a shows the air exchange rate, which is directly related to the fraction of recirculated air; Figure 4b shows the efficiency with which the building filters remove particles between 0.5 and 1.0 μm diameter. When the air exchange rate is high and the fraction of recirculated air is low (e.g., 12:01 am to 4:00 am in Figure 4a), the effective filtration efficiency tends to be low (see 12:01 am to 4:00 am in Figure 4b); when the air exchange rate is low and the fraction of recirculated air is high (e.g., 4:00 am to 9:00 am in Figure 4a), the effective filtration efficiency tends to be high (see 4:00 am to 9:00 am in Figure 4b). In general, when the amount of recirculated air increases, the distribution is shifted towards the larger particles. This reflects the fact that kinematic coagulation is a significant process for submicron particles contained in air flowing through ductwork. In such a situation, collisions among the particles are enhanced due to centrifugal effects, shear effects and turbulence.[14] The larger the fraction of recirculated air, the larger the fraction of time that the air has flowed through ducts, and the more the size distribution within the 0.5 to 1.0 μm range is shifted towards larger particles. The net result is that the effective filtration efficiency increases with increasing recirculation. The converse is also true.

*Iterating Equation 2 for Dynamic Conditions.* Equation 2 has been derived for steady-state conditions, but, as is apparent in Figures 1a and 2a, the outdoor and indoor concentrations are changing over time intervals that are significantly smaller than the time required for air exchange within the structure. Such a situation is optimally addressed with a dynamic model.[15] However, a simple alternative that is less computationally intensive and has proven satisfactory, is to iterate Equation 2 over a series of previous time steps to predict $C_{ia}$ for the current time interval. Using a time step of 12 minutes, we have found that an iteration of Equation 2 over the six preceding intervals yields a calculated indoor value that is in reasonable agreement with the measured indoor value. Figure 5 presents a comparison between values calculated using such an approach and measured values for the week of March 24, 1993. This particular week is demanding to model for several reasons: 1) $C_{oa}$ varied over a wide range and, occasionally, changed quite rapidly; 2) there were frequent changes in f, as evidenced by the change in the pressure difference across the building shell (see Figure 3a); and 3) there were large fluctuations in $F_s$ (see Figure 3b). Despite the challenges presented by the data set, the agreement between calculated and measured values is remarkably good. The largest mismatch occurs on March 25, about 10:00 am, when the calculated value exceeds the measured value. Just prior to this point the outdoor air damper had opened (Figure 3a), and the effective filtration efficiency, $F_s$, had decreased sharply from 34% to 10% (Figure 3b), reflecting a shift in particle-size distribution towards smaller particles as expected with a decrease in the fraction of recirculated air. The calculation quickly incorporates this change, whereas the actual system gradually transitions between the two states. The second largest mismatch occurs about 2:00 am on March 29, when the measured value exceeds the calculated value; just prior to this point, the outdoor damper had closed and the filtration efficiency increased. Once again, the calculation reflects this change too quickly. There are other instances during the week of March 24 when a change in the position of the outdoor air damper results in a change in the effective filtration efficiency of the building filters. However, these other instances do not produce a large mismatch. Apparently a large mismatch results when a rapid change in the outdoor concentration occurs at the same time that the position of the outdoor air damper changes. Regardless, the salient point is that values calculated using an iterated





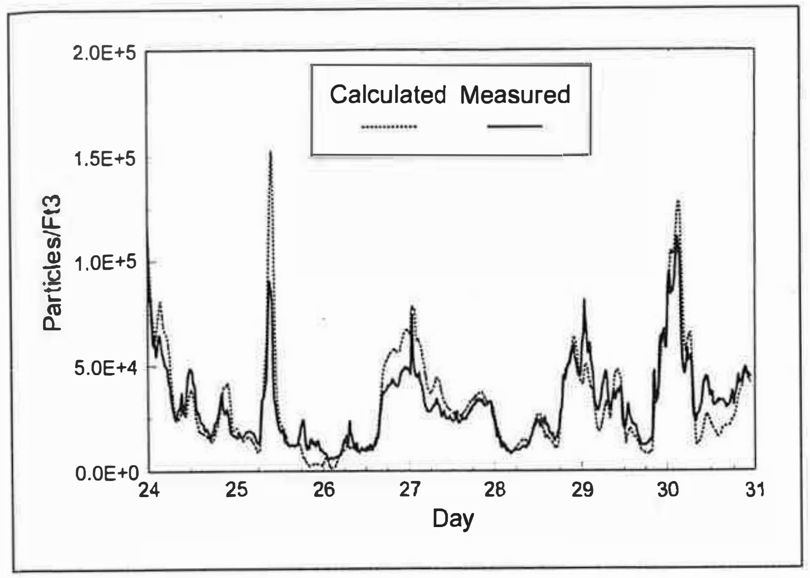


**Figure 5.** Measured and calculated indoor concentrations (particle counts/ft³) of 0.5 - 1.0 μm diameter particles for the week of March 24, 1993.

version of Equation 2 match the measured values reasonably well, with only a few exceptions.

## Particle Counters as Feedback Elements in the HVAC System

Towards the conclusion of this study, the algorithm that described the operation and data logging of the particle counters was modified so that the particle counters became feedback elements in the HVAC system. In this mode, the position of the outdoor air (OA) damper is determined by the concentrations of 0.5 to 1.0 μm particles as well as the outdoor air temperature.

*The Algorithm.* The algorithm that was used to operate the system in either monitoring mode or control mode is shown in Figure 6. In the monitoring mode, only measurements of the selected parameters were made, and no control actions based on particle measurements were performed. In the control mode, the position of the outside air damper was based on the measured values of particle counts, as well as the outdoor temperature. The selection of the operating mode was made by setting a variable, *ctrl*, to 0 or 1 in the input file, which was read by the program at midnight of each day. The input file also included the variables *pc_hi*, *pc_lo*, and *t_ref*, where *pc_hi* and *pc_lo* defined upper and lower set points for the particle concentrations in indoor air and, *t_ref* defined the minimum time required for the OA damper to remain closed before it could again be opened.

As noted earlier, particle counts were measured every minute at the following locations: the outdoor air intake ($C_{oa}$), indoors ($C_{ia}$), upstream of building filters in the mixing chamber ($C_{ua}$), and downstream of the filters ($C_{da}$). Running averages, "boxcar," of the previous 10 measurements were calculated for each sampling location ($AVG_{Coa}$, $AVG_{Cia}$, $AVG_{Cua}$, and $AVG_{Cda}$ for particle counts $C_{oa}$, $C_{ia}$, $C_{ua}$, and $C_{da}$, respectively). If the running average of the indoor air concentration ($AVG_{Cia}$) exceeded the upper setpoint (*pc_hi*), the outdoor air damper was closed. The damper was then kept closed for at least 30 minutes (*t_ref*). If $AVG_{Cia}$ decreased below the lower setpoint (*pc_lo*), the outside air damper was made available for control by other parameters such as temperature.

The decision process just described is based on measurements from just one instrument—the indoor particle counter. To take advantage of the other particle counters and anticipate increases in the indoor concentration resulting from increases in the outdoor concentration, the control of the OA damper was also based on a "modified" running average of the indoor concentration, $MOD_{Cia}$, that incorporated running averages measured by the particle counters at the other three sampling locations:

$$MOD_{Cia}=AVG_{Cia}\left(\frac{(AVG_{Coa})v_{oa}+(AVG_{Cra})v_{ra}}{(AVG_{Cua})v_{sa}}\right) \tag{4}$$

where

$v_{oa}$ = air flow in the outdoor air duct;

$v_{ra}$ = air flow in the return air duct;

$v_{sa}$ = air flow in the supply air duct, equivalent to total air flow in the air-handling system;

$AVG_{Cra}$ = running average of the previous 10 measurements for particle counts measured in the return air duct (just before the mixing box).

There was no particle counter in the return air duct, and hence no direct measurement of $AVG_{Cra}$. Instead, the concentration of 0.5 - 1.0 μm particles in the return air duct was estimated using the approximation:

$$C_{ra}=C_{ia}\left(\frac{C_{ia}}{C_{da}}\right) \tag{5}$$

This approximation assumes that the relative reduction in particle concentration that occurs as the air passes from the supply air duct (immediately downstream of the filters) to the indoor measuring point is equivalent to the reduction in particle concentration that occurs as the air passes from the indoor measuring location to the return air duct (just before the mixing box). Equation 5 is only a crude estimate of $C_{ra}$ and, in turn, $AVG_{Cra}$. However, for the purposes of the control algorithm, the approximation has proven satisfactory.

(Note: With the benefit of hindsight, we recognize that alternatives exist for Equation 4 that are better suited to the control algorithm outlined in Figure 6. For example, for the purpose of estimating the indoor concentration at the

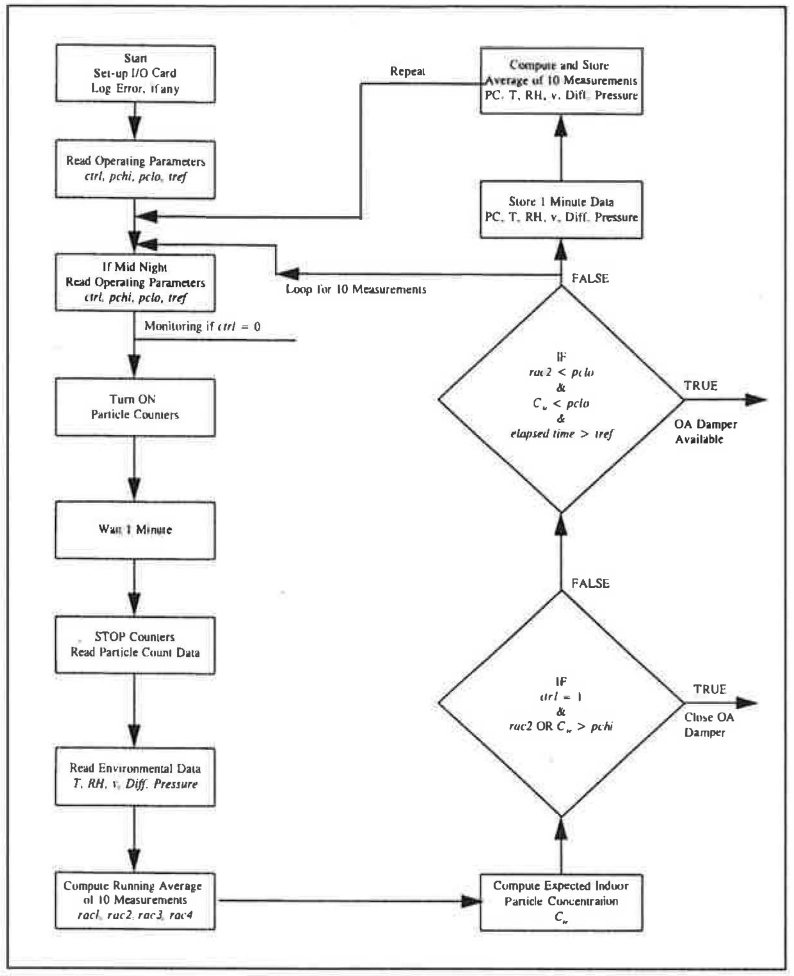


**Figure 6.** Measurement and control algorithm.

next time step from measurements at preceding time steps, a numerical solution to the mass-balance model obtained using Euler's method might be used.[16])

*Typical Results with the Particle Counters as Feedback Elements.* Although not shown in the figures, there have been occasions in the course of this study *when the algorithm presented in Figure 6 was in monitoring mode* and the indoor concentration of 0.5 to 1.0 µm particles approached 2,000,000 counts/ft³. In contrast, Figure 7 shows typical data from the week of April 1 *when the algorithm was in control mode* (i.e., the particle counters were being used as feedback elements in the HVAC system to control the position of the outdoor air damper). From April 1 to 6:00 pm on April 3, the outdoor concentration of 0.5 - 1.0 µm particles was quite high, reaching a value of 3,500,000 counts/ft³ on April 2, and generally staying above 1,000,000 counts/ft³ (see Figure 7a). From 6:00 pm on April 3 to the end of the week on April 7, the outdoor concentration of 0.5 to 1.0 µm particles remained much lower than in the preceding 2.75 days. Figure 7b shows the air exchange rate, the rate at which indoor air was replaced with outdoor air, during this same period. When the air exchange rate was 0.75 air changes/hour (ach), the outdoor air damper was near its minimum position (as the system was configured at the time of these measurements). When the air exchange rate was about 1.8 ach, the outdoor air damper was near its maximum position. It is apparent from Figure 7b that from April 1 to April 3 at 6:00 pm, the outdoor air damper remained at its minimum setting. From April 3 at 6:00 pm until the end of the week on April 7, the outdoor air damper opened and closed in a manner consistent with changes in the outdoor air temperature (see Figure 7c). Figure 7c shows that the diurnal variation in the outdoor air temperature for the period from April 1 to April 3 was not significantly different from that for the period from April 4 to April 7. Taken together, Figures 7a - 7c indicate that on April 1, 2 and 3, there were periods when the outdoor air damper would have been open (namely, periods when the outdoor air temperature was less than 63 °F) under the standard operating procedure; however, since the particle counters, as well as temperature, were being used to control the position of the outdoor air damper, it remained closed. As a consequence, the indoor concentration of 0.5 to 1.0 µm particles stayed below 550,000 counts/ft³ during a period such as 6:00 am to 2:00 pm on April 2, when according to Equation 2 and previous experience, they might otherwise have risen to more than 1,800,000 counts/ft³. (Note that the minimum setting of the outdoor air damper during the period shown in Figure 7 was 0.75 ach. If the minimum setting had been lower, for example 0.25 ach, the maximum indoor concentration of 0.5 to 1.0 µm particles would have been even lower.)

## CONCLUSIONS

The data collected for more than a year at the Burbank location show that the indoor concentration of 0.5 to 1.0 µm particles closely tracks the outdoor concentration, and that most of the 0.5 to 1.0 µm particles found indoors have originated outdoors. This is consistent with the absence of indoor sources at the site. The outdoor concentration of 0.5 to 1.0 µm particles can vary by large amounts over time intervals as short as an hour. Consequently, there exists the opportunity to reduce the indoor concentration of submicron particles by limiting the amount of outdoor air during periods when the outdoor concentration of submicron particles is elevated. Particle counters can be used as feedback elements in the HVAC system to accomplish this task. The present study demonstrates the successful use of particle counters in this manner. However, these devices must become less expensive, more reliable and require less frequent calibration before such an approach becomes cost effective.





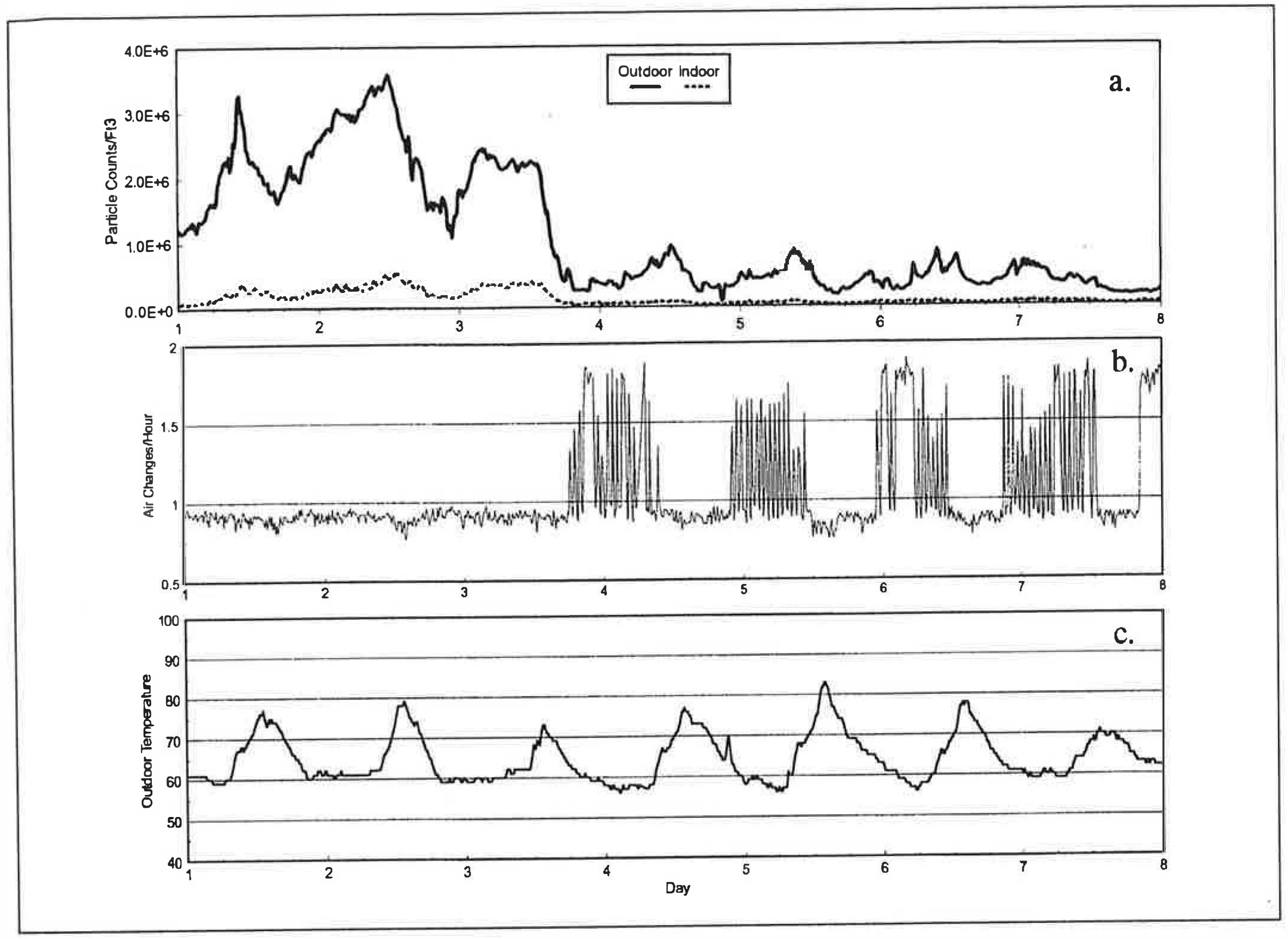


**Figure 7.** Data collected at the Burbank site during the week of April 1, 1994; a) outdoor and indoor concentrations (particle counts/ft³) of 0.5 to 1.0 µm diameter particles; b) air changes (with outdoor air) per hour; c) outdoor temperature in degrees Fahrenheit.


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