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Measurement and Modeling of Respirable Suspended Particles (RSP) and Carbon Monoxide (CO) in Two Airport Smoking Lounges

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ABSTRACT

The Multiple Cigarette Exposure Model (MCEM) was derived from the fundamental mass balance equations describing mass flow through an enclosed room with an internal, multiple-cigarette source. It is based on the Sequential Cigarette Exposure Model (SCEM) for a series of cigarettes smoked in succession previously validated for a chamber and an automobile. MCEM was applied to ten studies of the time series of carbon monoxide (CO), respirable suspended particles (RSP), and number of smokers, conducted inside cigarette smoking lounges at the San Francisco Airport (SFO) and the San Jose International Airport (SJC). The studies were conducted inside glass-enclosed rooms with rows of seats and the volumes of the rooms were 747.7 and 238.2 cubic meters for SFO and SJC, respectively. The mean time series for PM-3.5 RSP was determined by averaging the readings (two-minute averages) from three TSI Model 8510 Piezobalances distributed throughout the lounge. CO was measured at eight out of the ten studies using a single Langan DataBear CO sensor with an attached voltmeter giving instantaneous concentrations each minute at the center of the room. The durations of the study visits ranged from 62 to 143 minutes. The average number of smokers ranged from 3 to about 14 smokers throughout all ten studies. After the background was subtracted, the average CO concentration over all visits ranged from 0.19 to 0.93 ppm and the average RSP concentration ranged from 60 to 177 μg/m^3. The 24-hour average concentrations ranged between 0.203 and 0.0643 ppm for CO and 3.445 and 6.676 μg/m^3 for RSP. The air exchange rate of each room was measured by waiting until all or most of the smokers had left, elevating the levels of CO by smoking 1-2 cigars, and then observing the exponential decay of the concentration. The effective RSP exchange rate -- including air exchange and other removal terms -- was determined the same way. The CO air exchange rates were 0.217 min^{-1} for SFO and 0.179 min^{-1} for SJC. The RSP effective air exchange rates were 0.263 min^{-1} for SFO and 0.213 min^{-1} for SJC. The air exchange, volume, average number of smokers, and average concentration were used to determine the average CO and RSP source strengths for each study. The average source strengths for the visits where the air exchange rate was determined were 11,135 μg/min for CO and 1,339 μg/min for RSP. MCEM was then used to calculate a predicted time series for each study visit that was compared to the observed time series using these source strengths. The visits where the air exchanges were measured had the best agreement between observed and predicted concentrations with mean differences of 5% or less and linear regressions with high R^2 values, slopes near unity and near-zero y-intercepts.

INTRODUCTION

Recently, employers have prohibited smoking in most areas of buildings, but have allowed smoking in special-purpose lounges equipped with independent ventilation systems. In the San Francisco Bay Area, the San Francisco Airport (SFO) and the San Jose International Airport (SJC) each have provided large glass-enclosed rooms that are set aside for smokers. These large smoking lounges are ideally suited for testing and validating mathematical models designed to predict pollutant concentrations created by smoking because: (1) the rooms are rectangular, facilitating calculation of their volume, (2) smokers can be observed visually, and cigarette smoking activity, *i.e.*, the number of cigarettes being smoked each minute, can be recorded with high accuracy, (3) the concentrations are relatively high and can be measured with portable monitoring instruments, (4) no other sources of carbon monoxide (CO) and respirable suspended particles (RSP) are present besides those derived from smoking, and (5) smoking activities vary greatly from hour-to-hour (and minute-to-minute) allowing "real-time" models and measurements to be compared.

This paper develops a mathematical model for predicting the time series of concentrations from multiple smokers in a room and validates the model by comparing the predicted concentrations with those actually measured in 10 field studies of RSP and CO concentrations in the smoking lounges at the San Francisco and San Jose airports. The mathematical model, which is derived from the mass balance equation, will be useful: (1) as input to exposure models, and (2) to help building planners determine the design parameters for similar smoking lounges they may build elsewhere.

DEVELOPMENT OF THE TIME SERIES MODEL

The Smoking Activity Pattern Time Series *n(t)*

A precise determination of the cigarette activity pattern *n(t)* in the smoking lounges requires an observer to record the beginning and ending times of each cigarette in the lounge. For example, the top part of Figure 1 shows the hypothetical case of 7 persons in a room, each lighting up their cigarettes at different times and smoking their cigarettes for different arbitrary time durations. Each person's cigarette, while it is actively burning, is be represented by a horizontal line. At time $t = 0$, no one is smoking. At $t = 20$ seconds, Person D ignites the first cigarette. This cigarette lasts for 7 minutes and 10 seconds, ending at $t = 7$ minutes and 30 seconds. Person A lights up a cigarette at $t = 30$ seconds, or 10 seconds after Person D's first cigarette. Person F's first cigarette begins at $t = 1$ minute and 10 seconds. Thus, there are zero cigarettes being smoked in the room from $t = 0$ to $t = 20$ seconds, one cigarette from 20 to 30 seconds (Person B), two cigarettes from $t = 30$ seconds to $t = 1$ minute and 10 seconds (Person A + Person B together), three cigarettes after $t = 1$ minute 10 seconds (Person A + Person B + Person F together), etc. The exact cigarette activity pattern *n(t)* is obtained by adding up the active cigarettes for any time *t* (Figure 1, bottom). It shows discrete integer jumps at arbitrary times is "piecewise constant over continuous time intervals."

A simpler method of determining *n(t)* -- which greatly reduces the number of observations required -- is to record instantaneous values of the cigarette activity pattern every minute. This approximation generates a piecewise-constant time series $n_1, n_2, ..., n_i$ at times $t = \delta, 2\delta, ..., i\delta$ where $\delta = 1$ minute. For the example in Figure 1, the time series between $t = 0$ and $t = 10$ minutes would give counts of 0, 2, 3, 4, 5, 5, 6, 6, 4, 2, and 2 cigarettes. The peak count of 7 cigarettes occurring between $t = 6$ and $t = 7$ minutes would be missed by this simplified minute-by-minute cigarette counting approach, because this peak lasts only 20 seconds and comes between the evenly spaced minutes, but the error is small.

The Mass Balance Equation

Using the mass balance equation, Switzer and Ott[1] show that, if the piece-wise constant concentration time series in a well-mixed room is described only at discrete times $\delta, 2\delta, 3\delta, ..., i\delta$, then the concentration entering from outside y_i can be related instantaneously to the concentration z_i inside the room by the following recursive formula:

$$z_i \quad = \quad y_i(1 - \alpha) \quad + \quad z_{i-1}\alpha \tag{1}$$

where
$\alpha = e^{-\phi\delta}$
δ = duration of each equally spaced time interval
ϕ = air exchange rate

The air exchange rate ϕ in Equation 1 can be an "effective" (ϕ_P) or a "ventilatory" (ϕ_V) air exchange rate. Ott, Langan and Switzer[2] show that the effective air exchange rate ϕ_P consists of the ventilatory air exchange rate ϕ_V and a term ϕ_D accounting for the deposition of material onto surfaces. They also show that if, instead of assuming that y_i is a piecewise-constant source entering the room from outside through air infiltration, the source is located within the chamber, then y_i is replaced by the source strength (emissions per unit time) divided by the product of the air exchange rate, ϕ, and the mixing volume, v. As discussed above, the continuous multiple-smoker activity pattern $n(t)$ becomes a discrete time series of cigarette counts n_i, and the source strength is the product of n_i and the single mean cigarette source strength g_c. This product consists of piecewise-constant steps that are equally-spaced by the time interval δ. Thus, substituting $y_i = n_i g_c/\phi v$ into Equation 1, we obtain another recursive expression for the case in which the source is located inside the room:

$$z_i = \frac{\alpha}{\phi_E v} n_i g_c \quad + \quad (1-\alpha) z_{i-1} \tag{2}$$

where
$\alpha = e^{-\phi\delta}$
δ = duration of each equally spaced time interval [T]
ϕ = air exchange rate [1/T]
z_i = concentration at time segment i [M/L^3]
n_i = number of cigarettes being actively smoked at time segment i [Cigarettes]
g_c = average emission rate per cigarette of all cigarette brands [M/T]
v = room volume [L^3]

Lastly, Ott, Langan, and Switzer[2] show that, if the averaging time is sufficiently long, then the average concentration over the visit $\bar{z}$ is a function of the average number of cigarettes $\bar{n}$ as follows:

$$\bar{z} = \frac{g_c \bar{n}}{\phi v} \tag{3}$$

Applying the model to an actual setting requires values for the air exchange rate ϕ. Ott, Langan, and Switzer[2] show that values for both these parameters can be obtained if a large source is present but then suddenly stops, allowing the interior CO and RSP concentrations to decay at their natural rates. Since CO is not absorbed onto surfaces, the exponential decay constant of the CO concentration decay curve gives the ventilatory air exchange rate ϕ_V. Conversely, the decay constant of the RSP concentration decay curve gives the effective air exchange rate ϕ_P since particles cling to surfaces.

SMOKING LOUNGE EXPERIMENTS

To evaluate the performance of the mathematical model in realistic settings with real smokers, we located large, glass-enclosed smoking lounges that happened to be at two nearby airports: the San Francisco Airport (SFO) and the San Jose International Airport (SJC). Each lounge had its own ventilation system that maintained a slightly negative pressure relative to the airport terminals. The lounge at SFO consisted of two rectangular segments and contained 159 seats; the dimensions of the first segment were 69.4 feet by 24.3 feet, with a height of 12 feet, and the dimensions of the second segment were 69.4 feet by 11.7 feet with a height of 10 feet. The volume was 28,356 ft^3 or 747.7 m^3. The lounge at SJC contained 59 seats; its dimensions were 32.8 feet by 23.1 feet, with a height of 11.1 feet, and a volume of 8,410 ft^3 or 238.2 m^3. The seats in both lounges were in neat rows, and the unobstructed view of the visitors made it easy to count the active smokers.

The experiments consisted of one investigator looking around the room each minute and writing down the total number of people present and the number of active smokers. Besides tobacco smoke, there were no other sources of RSP or CO in either smoking lounge. Another investigator collected CO and RSP concentrations from three portable piezobalances and an electrolytic CO monitor. The piezobalances were placed at either end and in the center of each lounge, and the investigator walked in a loop inside the room to reset the piezobalances and write down the concentration readings. After every five to seven readings, the time tended to slip slightly behind the clock time, so the investigator waited one minute to synchronize the instruments with the clock. This procedure minimized the time error in the concentration time series to less than approximately 20 seconds. For the visits where CO was measured, the CO monitor was placed beside the piezobalance in the center of the room. For two of the study visits, when the number of smokers in the airport smoking lounges was at or near zero, a “cigar test” was used to measure the air exchange rates of the airport smoking lounges by smoking 1-2 cigars and measuring the exponential decay of CO and RSP concentrations.

The RSP measurements were made with a Model 8510 piezobalance (TSI, Inc. St. Paul, MN), and the CO measurements were made with the Langan L15 CO Personal Exposure Measurer (Langan Products, San Francisco, CA). The piezobalance has a 3.5 micrometer median size “cutpoint” and measures particles continuously, although in our experiments it was set to compute 2-minute averages and display them on its LED digital readout. It has a long history of use in studies of environmental tobacco smoke[3] and the Langan CO monitor has also been used in other cigarette smoke experiments.[1]

RESULTS

The time series of number of smokers and RSP concentration were recorded for five studies inside the San Francisco airport smoking lounge and for five studies inside the San Jose airport smoking lounge in the spring and early summer of 1993 between April 25th and July 15th (Table 1). In the table, “SFO 1” denotes the first visit (4/25/93) to San Francisco International Airport; similarly “SJC 1” denotes the first visit (6/2/93) to San Jose International Airport. The study visit durations ranged from 60 to 146 minutes, with an average of 108 minutes. The average number of smokers for the studies ranged from 3.1 to 13.6 with an overall mean of 7.0.

The time series for CO was recorded for each visit except the SFO 3 and SJC 1 study visits. There were three RSP concentration time series for the three different piezobalances positioned throughout each lounge, but there was only one CO time series measured in the center of the room beside one of the piezobalances for study visits when CO was measured. All studies also included measurements taken outside each lounge both before and after the experimental time series were recorded inside the lounge. The concentrations fluctuated widely when smokers entered and left the lounge after their planes arrived and/or departed. The cigar tests described above were conducted at SFO 5 and SJC 5 to determine CO air exchange rates and RSP effective air exchange rates (including all removal factors).

For both RSP and CO all averages reflect only the data collected inside the smoking lounges after the background was subtracted, but omitting data collected during the cigar test experiments. The backgrounds were obtained from the lowest concentration observed inside each smoking lounge during each episode. For the study visits where a cigar test was conducted, the lowest level occurred for when the decay curve reached its asymptote. For the other study visits the lowest level occurred when the number of smokers was very close to zero. For the SFO 4, SJC 1, SJC 2, and SJC 4 study visits, the number of smokers never approached zero and the average RSP and CO concentrations measured outside the lounge were used as the background concentration.

The average RSP concentration over all visits ranged from 46 to 156 $\mu g/m^3$ with an average of 100 $\mu g/m^3$ and the average CO concentration over all visits ranged from 0.49 to 1.2 ppm with an average of 0.75 ppm (Table 1). The overall average concentrations for both CO and RSP were higher in the San Jose airport lounge (123 $\mu g/m^3$ for RSP and 0.55 ppm for CO) than for the SFO visits (76 $\mu g/m^3$ for RSP and 0.96 ppm for CO). The 24-hour average concentrations -- calculated by weighting the average concentration by the elapsed time divided by 1440 minutes (24 hours) -- ranged from 2.7 to 14 $\mu g/m^3$ for RSP with an average of 7.6 $\mu g/m^3$ over all the visits, and 0.02 to 0.12 ppm for CO with an overall average of 0.06 ppm. The time series collected for the SJC 5 study visit are shown in Figure 2.

Obtaining Model Parameters

The four basic parameters in the mathematical model are the air exchange rate (ventilatory or effective), source strength, room volume, and initial concentration (Equation 2). The initial concentration is simply the concentration observed at the start of each experimental visit. Thus, the parameters left to determine are the ventilatory air exchange rate ϕ_V for CO, the effective air exchange rate ϕ_P for RSP, and the overall cigarette source strength g_c.

The raw decay data from the cigar tests conducted at the SFO 5 and SJC 5 study visits were fit to the exponential decay model in Equation 4 (background concentrations were not subtracted before the data were fit) and the parameters for the air exchange rate ϕ and initial value z_o were optimized. The background b for the model was determined from the asymptotic value measured inside the smoking lounge at the end of the decay curve and was not allowed to vary. This approach is equivalent to fitting a simple linear regression model to the data after subtracting the background from each data point and taking its logarithm.

$$z = z_o e^{-\phi t} + b \tag{4}$$

where

z = predicted pollutant concentration (RSP or CO)
z_o = initial value before decay begins
t = time (in minutes)
b = background pollutant concentration
ϕ = air exchange rate (ventilatory for CO or effective for RSP)

Although the nonlinear regression incorporated few points (7 points at SFO 5 and 10 points at SJC 5) the R^2 values are all greater than 0.95 (Table 2). The plots of the observed and predicted exponential decay (Figure 3) also appear to have no systematic residual values and the fitted curve decays asymptotically to the background level. The ventilatory air exchange rate ϕ_V determined from the decay of CO and the effective air exchange rate ϕ_P from RSP (including all removal terms) do not differ significantly for the experiments conducted at the SFO 5 and SJC 5 study visits. The difference $\phi_D = \phi_P - \phi_V$ is only about 0.05 min^{-1} for San Francisco and 0.03 min^{-1} for San Jose. Since ϕ_D is a measure of the deposition of pollutant onto surfaces, this result implies that an equivalent of 3 and 1.8 roomfuls of pollutant are deposited per hour (multiply air exchange per minute by 60 min/hr) onto surfaces in the two lounges. And the ventilatory air exchange rates determined for CO (0.217 and 0.179 min^{-1}) correspond to 13.0 and 10.7 roomfuls being removed per hour by air flow through the room. Therefore, removal of RSP from surface deposition is 23% and 17 % of the removal from air flow for the San Francisco and San Jose smoking lounges, respectively. The San Francisco smoking lounge was larger and had more seating, which may account for the larger deposition component of the removal.

The source emission rate can be obtained by solving Equation 3 for g_c:

$$g_c = \frac{\bar{z}\phi v}{\bar{n}} \tag{5}$$

where

g_c = single cigarette source strength [M/T]

ϕ = the air exchange rate (ventilatory for CO and effective for RSP) [1/T]

v = room volume [L^3]

$\bar{z}$ = average pollutant concentration [M/L]

$\bar{n}$ = average number of smokers present [cigarettes]

Here, g_c is the average cigarette source strength (measured in mass emitted per unit time) for all cigarette brands, types, and smoking styles encountered for a given visit.

After the background concentrations were subtracted from the observed RSP and CO time series (so that the source strengths reflect only the pollutants emitted from the cigarettes and not the indoor air infiltration into the lounges from outside sources), $\bar{z}$ and $\bar{n}$ were calculated for the entire episode inside each smoking lounge (except for the portion of the visits used for the air exchange rate study). Then, using the volume and the air exchange rates, the source strengths were calculated using Equation 5 for each visit even though the air exchange rates actually only apply on the days on which they were measured (Table 3). CO source strengths are reported in units of both ppm per minute and $\mu g/m^3$ per minute. The conversion factor from ppm to $\mu g/m^3$ is 1145.[1] Approximately the same RSP and CO source strength was determined for the dates where the air exchange rate was determined (SFO 5 and SJC 5). The average value of the source strength for these two visits was 1,339 $\mu g/m^3$ for RSP and 11,135 $\mu g/m^3$ for CO. It seems safe to conclude that the high variability observed in the other source strengths (6,567 to 18,257 $\mu g/m^3$ for CO and 950 to 2,199 $\mu g/m^3$ for RSP) is probably due to the error incurred by using the air exchanges from the SFO 5 and SJC 5 study visits.

Comparison of Observed and Predicted Concentration Time Series

Equation 2 from the model presented above was used with the ventilatory air exchange rates, effective air exchange rates, and source strengths determined in the last section, and the observed room volume and number of smokers time series, to calculate predicted RSP and CO concentration time series. The same CO air exchange, effective RSP air exchange, and volume were used for the predictions at each location. The source strengths used were the average of the CO and RSP source strengths determined from the SFO 5 and SJC 5 experimental data because -- since these are the only visits where an air exchange or effective air exchange was measured -- these are the most reliable estimates. The initial concentration value was set equal to the observed initial concentration for each episode.

After the predicted RSP and CO time series were calculated for each visit, they were regressed on the observed time series (Tables 4 and 5). As is to be expected, the results for visits SFO 5 and SJC 5 -- where the air exchange rates were determined precisely -- are the best for both CO and RSP with high R^2 values, slopes of approximately one, and near-zero y-intercepts. The percentage difference between observed and predicted means for the SFO 5 and SJC 5 study visits is 1-5% for both CO and RSP, whereas the percentage differences for the other study visits range between 12 and 40% for RSP and 21 to 79% for CO.

DISCUSSION

In the airport smoking lounge microenvironment, the RSP emission rates can vary according to: (1) the brand type smoked by each visitor to the lounge, (2) the smoker's rate of consuming the tobacco, (3) the degree to which the cigarette was actively smoked or allowed to smolder, or (4) the amount of smoke absorbed by the smoker's lungs. Despite the complexity of these factors, an average cigarette source strength was calculated from our data (1.34 mg/min for RSP PM-3.5 and 11.1 mg/min for CO), and it is instructive to compare these results with the source strengths reported in the literature by various investigators.

The cigarette source strengths reported in the literature are based on many different methodologies (chamber studies, measurements in microenvironments, indoor air field surveys, personal monitoring field studies, etc.).[1,4-17] The typical values of RSP emissions reported for U.S. cigarettes are 11.4, 12.7, 12.9, 14.1, 14.4, 18, and 26 mg/cigarette with a mean of 15.6 mg/cigarette. Unfortunately, instead of giving source strengths in terms of emission rates (mg/min) as we have reported in this paper, most of the studies give total emissions that assume the entire cigarette is consumed, or emission quantities based on the length or mass of tobacco consumed -- for example, mg of RSP per mg of cigarette consumed. However, we may assume a typical cigarette duration and thus make an approximate comparison to the other studies. For example, if we assume an average cigarette duration of 7 minutes we obtain 1.339 mg/minute x 7 minutes/cigarette = 9.4 mg/cigarette, and assuming 10 minutes we obtain 13.4 mg/cigarette. These results lie in the lower range of -- or possibly slightly below -- the values reported in the literature.[1,4-17] A possible reason for our low source strength would be the presence of many sidestream smokers who were holding smoldering cigarettes instead of actively smoking them. Consequently, cigarette duration would be longer than typical durations and, when multiplied by our emission rates, would give source strengths closer to the range in the literature described above. Another possible explanation of our low source strength is that the tar content of cigarettes has been declining over time[18], and the other source strength studies may have used cigarettes with higher RSP emissions than those smoked today.

SUMMARY AND CONCLUSIONS

The development of the Multiple Cigarette Exposure Model (MCEM) and the experimental verification of its real-time predictions at 10 visits to smoking lounges both offer a validated approach for determining exposure from multiple indoor sources of tobacco smoke in the smoking lounge microenvironment. For the two study visits in which air exchange rates were measured, the minute-by-minute CO and RSP time series predicted by the model agreed well with the observed concentration time series. Errors in overall average RSP and CO concentrations for the two visits were only 1-5 %.

Although the model was used only for RSP and CO, the techniques introduced in this paper should work equally well for other pollutants emitted by cigarettes and for other microenvironments. In applying the model to the smoking lounge microenvironment we: (1) collected the cigarette count and pollutant concentration time series, (2) determined the room volume and air exchange rate (including removal of the pollutant from absorption onto surfaces), and (3) calculated the overall cigarette source strength. The measurement of the time series was accomplished with two investigators, and the air exchange rate was determined by the controlled release of a strong source such as a cigar.

The usefulness of MCEM lies in its predictive capabilities. Given any arbitrary room volume, effective air exchange rate, overall cigarette source strength, and cigarette count time series or average cigarette count, the model can be used to predict the time series of pollutant concentration or the long term average concentration. It can be used by planners and engineers in the design of new smoking lounges or incorporated in probabilistic population exposure models such as NEM,[19] REHEX,[20] SHAPE,[21,22,23] BEAM,[24] and THEM.[25]

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Table 1. Summary of the RSP and CO Average Concentrations for Each Study Visit.

							RSP				CO			
Study Visit	Study Visit Date	Starting Time	Ending Time	Elapsed Time	Average No. of Smokers	No. Smk. Meas	Average RSP Concentration ($\mu g/m^3$)	No. RSP Meas	24-hour RSP Concentration ($\mu g/m^3$)	Average RSP Background Concentration[e]	CO Concentration (ppm)	No. CO Meas	24-hour CO Concentration (ppm)	Background CO Concentration
SFO 1[a]	4/25/93	5:28 PM	7:11 PM	103	5.23	30	58.52	60	4.19	5	0.49	42	0.035	0.83
SFO 2	5/4/93	3:27 PM	4:45 PM	78	6.85	72	63.22	37	3.42	10	0.67	49	0.036	1.3
SFO 3	5/14/93	5:08 PM	6:56 PM	108	10.48	109	88.10	50	6.61	23				
SFO 4	6/23/93	11:07 AM	12:53 PM	106	13.55	107	123.84	47	9.12	19	0.61	47	0.045	1.35
SFO 5[b]	7/15/93	7:25 PM	9:51 PM	146	6.80	149	46.27	68	4.69	20	0.41	64	0.042	0.8
SJC 1	5/23/93	4:30 PM	6:00 PM	90	5.53	91	128.92	40	8.06	6				
SJC 2	6/2/93	11:59 AM	1:58 PM	119	6.76	119	126.72	53	10.47	10	0.91	57	0.075	0.91
SJC 3[c]	6/9/93	12:52 PM	1:52 PM	60	3.05	61	64.81	27	2.70	6.7	0.54	31	0.025	0.81
SJC 4	6/21/93	11:37 AM	1:40 PM	123	6.69	123	155.64	55	13.29	21	1.19	55	0.102	0.9
SJC 5[d]	7/1/93	12:37 PM	3:00 PM	143	5.28	143	139.47	62	13.85	13	1.19	56	0.118	0.74
AVERAGE SFO				108.2	8.58		75.99		5.60		0.55		0.040	
STD. DEV. SFO					3.38		30.77		2.29		0.12		0.0045	
AVERAGE SJC				107	5.46		123.11		9.67		0.96		0.079	
STD. DEV. SJC					1.51		34.54		4.54		0.31		0.042	
AVERAGE OVERALL				107.6	7.02		99.55		7.64		0.75		0.059	
STD. DEV. OVERALL					2.96		39.59		4.01		0.31		0.035	

[a] The number of smokers was measured more often during the second part of this session. This fact was not considered in calculations of averages, standard deviations and source strength.

[b] Air exchange rate determined by “cigar test”. The averages reflect the period before the test was begun.

[c] A controlled release of >20 cigarettes was performed during this visit. The averages reflect the period before the release was initiated.

[d] Air exchange rate determined by “cigar test”. The averages reflect the period before the test was begun.

[e] Background concentrations averaged from each of the three piezobalance instruments based on measurements made outside the lounges before and after each visit.

The “cigar test” consists of the smoking of several cigars and observation of the decay.

Air exchange rates were determined by fitting a nonlinear model (Z Exp(-P X) + B) to measurements of RSP decay in each location

No averages include data that was collected outside the smoking lounges

Averages are determined by averaging measurements from each instrument after the background has been subtracted.

Background concentrations were determined for each instrument from the end of the decay curve INSIDE the lounge for study visits involving “Cigar Tests” OR the lowest measurement INSIDE when the number of smokers became low OR the number OUTSIDE if the number of smokers were never low (SFO 4, SJC 1, 2, 4).

Negative concentrations obtained after the background was subtracted were omitted in all calculations

Table 2. Regression Results for the Cigar Test Studies to Determine CO (Ventilatory) and RSP (Effective) Air Exchange Rates at the SFO 5 and SJC 5 Airport Smoking Lounge Study Visits.

Visit	***SFO 5***		***SJC 5***	
Pollutant	**CO**	**RSP**	**CO**	**RSP**
[a]ϕ	0.217	0.263	0.179	0.213
[b]z_o	1.86	291	3.23	476
[c]b	0.8	20	0.74	13.33
[d]N	7	7	10	10
R^2	0.98301	0.97890	0.96392	0.98789

[a] air exchange rate [1/minute]

[b] initial concentration [$\mu g/m^3$ for RSP; ppm for CO]

[c] background concentration [$\mu g/m^3$ for RSP; ppm for CO]

[d] sample size

Table 3. Determination of the Source Strengths for RSP and CO.

		RSP		**CO**		
Study Visit	Average Number of Smokers	Average RSP Concentration ($\mu g/m^3$)	Calc. RSP Source Strength (μg/min)	Average CO Concentration (ppm)	Calc. CO Source Strength (ppm/min)	Calc. CO Source Strength (μg/min)
SFO 1	5.23	58.52	2198.89	0.49	15.23	17436.69
SFO 2	6.85	63.22	1814.66	0.67	15.95	18259.64
SFO3	10.48	88.10	1653.47			
SFO 4	13.55	123.84	1797.01	0.61	7.28	8333.37
SFO 5	6.80	46.27	1338.06	0.41	9.84	11265.31
SJC 1	5.53	128.92	1183.32			
SJC 2	6.76	126.72	950.39	0.91	5.74	6567.39
SJC 3	3.05	64.81	1078.48	0.54	7.60	8704.62
SJC 4	6.69	155.64	1180.21	1.19	7.58	8684.38
SJC 5	5.28	139.47	1338.97	1.19	9.61	11004.98
AVERAGE SFO			1760.42			13823.75
AVERAGE SJC			1146.28			8740.34
AVERAGE OVERALL			1453.35			11282.05

Shaded areas denote study visits where air exchange rates were measured

1 ppm/min = 1145 $\mu g/m^3$/minute

Table 4. Summary of Regression Results for the RSP Predicted Average Concentration ($\mu g/m^3$) vs. the Observed RSP Concentration Using a Source Strength of 1.34 mg/min and the Air Exchange Rates Measured at SFO 5 and SJC 5 Study Visits.

Study Visit	Elapsed Time (minutes)	Initial RSP Value	Sample Size	MCEM RSP Mean	MCEM RSP STDEV	Observed RSP Mean	Observed RSP STD	Absolute RSP Difference	Percent Difference	Test Statistic of t-test	**Regression**		
											R^2	Slope	Y-int
SFO 1	103	40	30	38.4	19.5	49.33	40.7	10.93	27	-2.5	0.86	1.9	-25
SFO 2	78	60	36	46.2	28.2	62.7	49.7	16.50	26	-3.7	0.84	1.6	-12
SFO 3	108	10	49	71.6	34.6	88.1	55.2	16.50	19	-4.7	0.91	1.5	-21
SFO 4	106	154.7	47	93.1	22	127	35.3	33.90	27	-7.9	0.29	0.87	46
SFO 5	146	43.33	65	47.3	19.9	46.2	30.4	1.10	2	0.5	0.67	1.3	-13
SJC 1	90	114	40	145	66.1	129	82.1	16.00	12	3	0.83	1.1	-36
SJC 2	119	123	53	177	93	126	83	51.00	40	12.62	0.9	0.85	-24
SJC 3	60	130	28	79.4	41.4	63.9	36.9	15.50	24	3.9	0.74	0.77	2.8
SJC 4	123	118.7	55	176	73.3	155	82.2	21.00	14	4.33	0.81	1	-23
SJC 5	143	300	62	145	82.1	144	89	1.00	1	0.19	0.92	1	-6
AVERAGE					101.9		99.12	18.3					
STD. DEV.					54.23		41.50	14.9					

From Table 2, the SFO 5 RSP effective air exchange rate was 0.263 min^{-1} and the RSP SJC 5 effective air exchange rate was 0.213 min^{-1}

From Table 3, the average calculated RSP source strength from the SFO 5 and SJC 5 study visits was 1,339 $\mu g/m^3$

Table 5. Summary of Regression Results for the CO Predicted Average Concentration ($\mu g/m^3$) vs. the Observed CO Concentration Using a Source Strength of 11.1 mg/min and the Air Exchange Rates Measured at SFO 5 and SJC 5 Study Visits.

Location	Elapsed Time (minutes)	Initial CO Value	Sample Size	MCEM CO Mean	MCEM CO STDEV	Observed CO Mean	Observed CO STD	Absolute Difference	Percent Difference	Test Statistic of t-test	**Regression**		
											R^2	Slope	Y-int
SFO 1	103	80.5	15	313	152	396	365	83.00	21	-1.43	0.89	2.3	-310
SFO 2	78	1294	46	424	321	759	607	335.00	44	-5.71	0.65	1.5	113
SFO 3	108												
SFO 4	106	939	47	912	189	696	259	216.00	31	6.97	0.35	0.81	-45
SFO 5	146	573	64	477	187	472	276	5.00	1	0.22	0.59	1.1	-69
SJC 1	90												
SJC 2	119	1122	55	1754	865	982	822	772.00	79	14.5	0.79	0.85	-505
SJC 3	60	1523	30	767	425	622	423	145.00	23	5.23	0.88	0.93	-92
SJC 4	123	1008	55	1740	700	1363	663	377.00	28	12.15	0.89	0.89	-193
SJC 5	143	3309	55	1449	876	1384	968	65.00	5	2.6	0.94	1.1	-190
AVERAGE				979.5		834.25		249.8					
STD. DEV.				592.05		377.35		247.9					

From Table 2, the SFO 5 CO air exchange rate was 0.217 min^{-1} and the SJC 5 CO air exchange rate was 0.179 min^{-1}.

From Table 3, the average calculated CO source strength from the SFO 5 and SJC 5 study visits was 11,135 $\mu g/m^3$

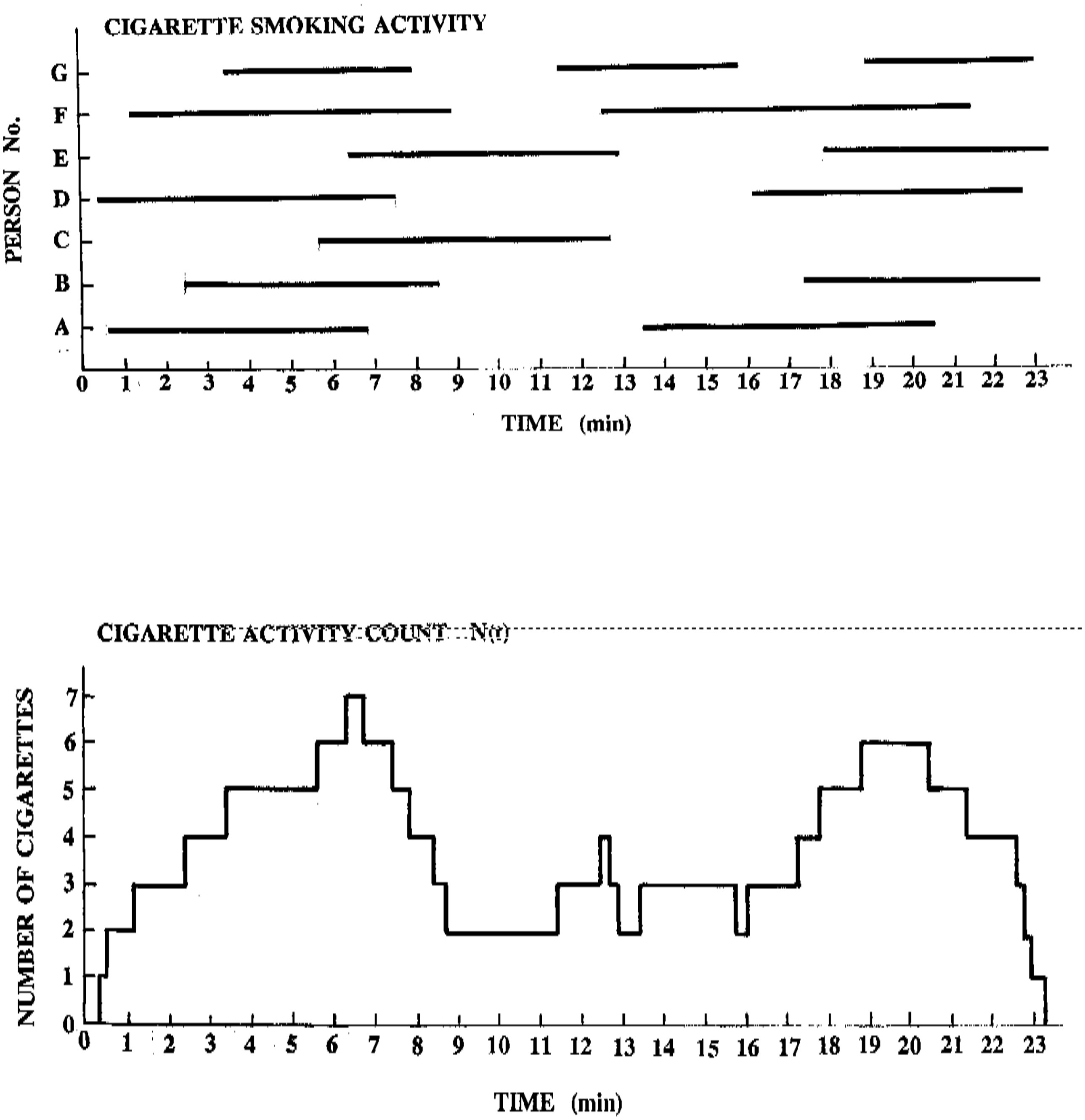
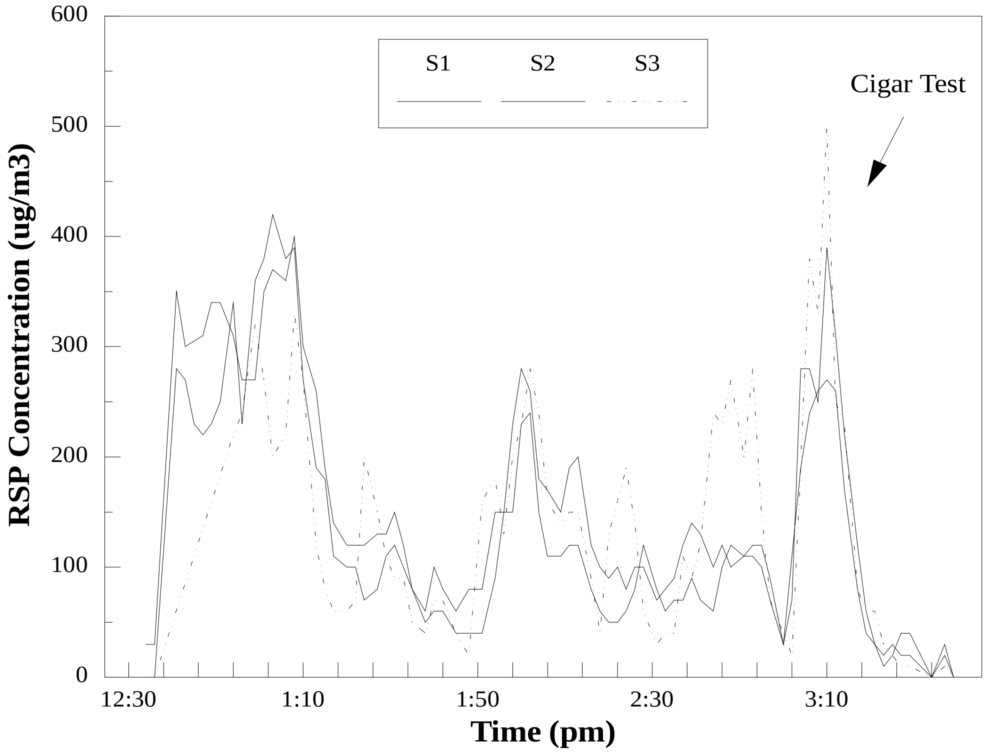


Figure 1. Top: A hypothetical smoking activity pattern with 7 smokers (A through G). Horizontal lines show the time for which a smoker is active with gaps showing the time the person is not smoking. Each smoker has a unique smoking frequency and duration. Bottom: The instantaneous cigarette activity count time series *n(t)* yielded from the number of active smokers at time *t* in the multiple-smoker activity pattern shown on top. Notice the piecewise constant nature of the cigarette count *n(t)*.



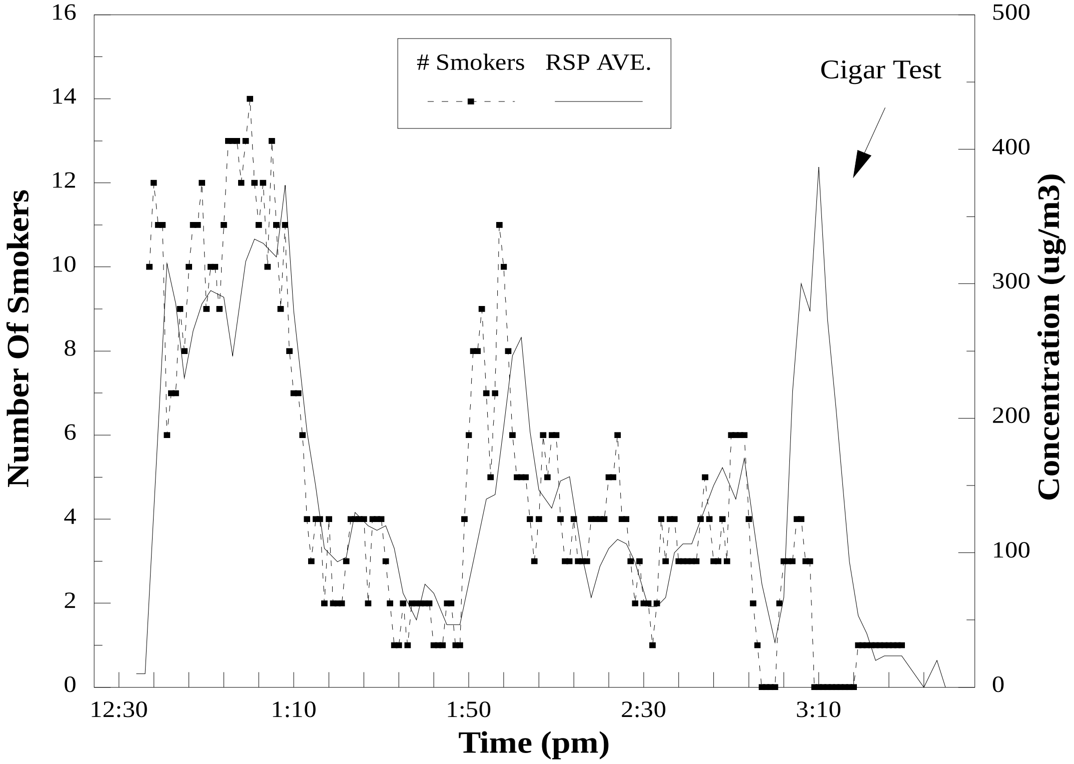


Figure 2. Top: RSP concentration time series measured by three piezobalances distributed evenly throughout the smoking lounge at the SJC 5 study visit. The large decay curve at the end of the trace is for the cigar test conducted to determine the air exchange rate after all the smokers had left. Bottom: The cigarette count time series and the mean RSP concentration time series from the three piezobalances at the SJC 5 study visit.

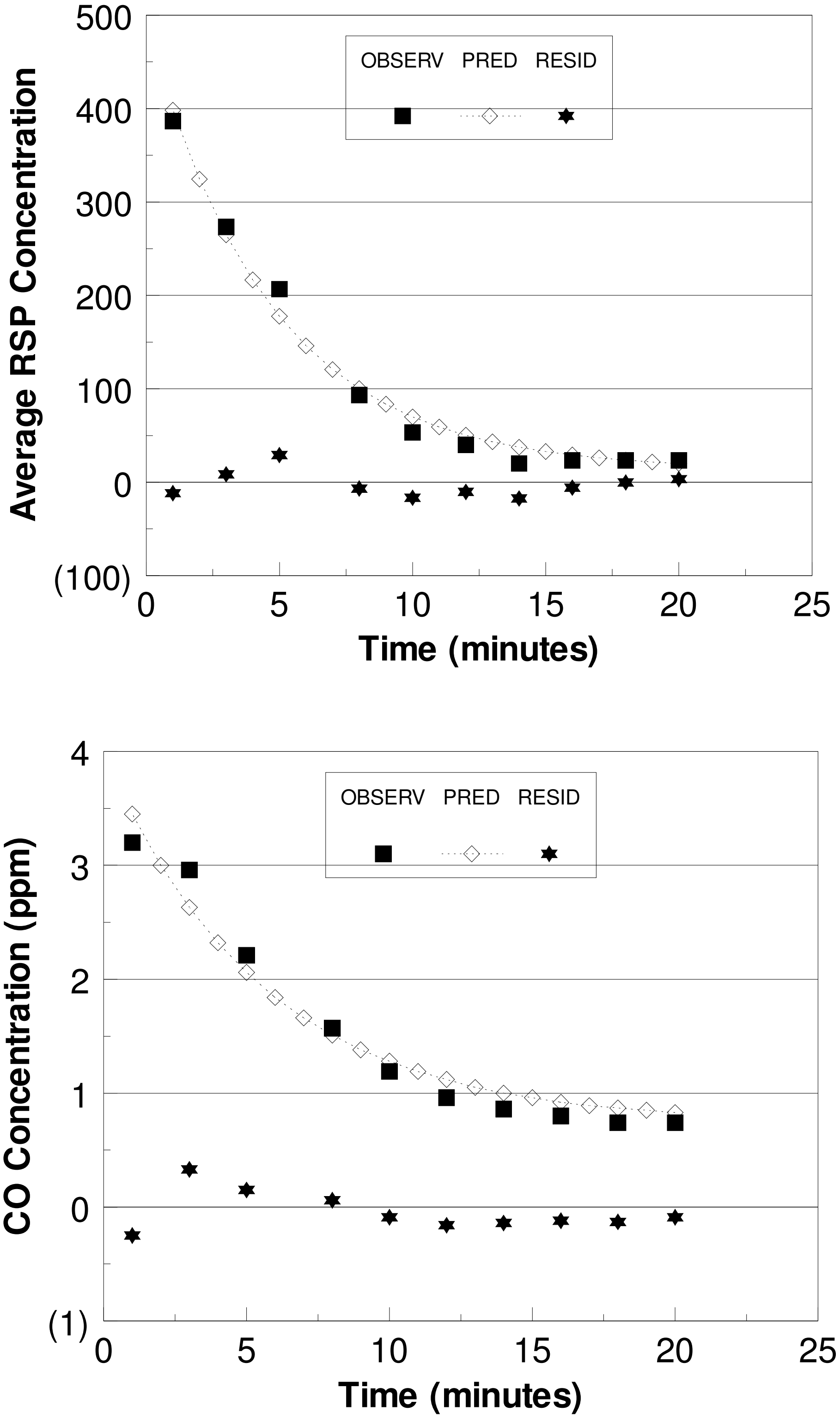
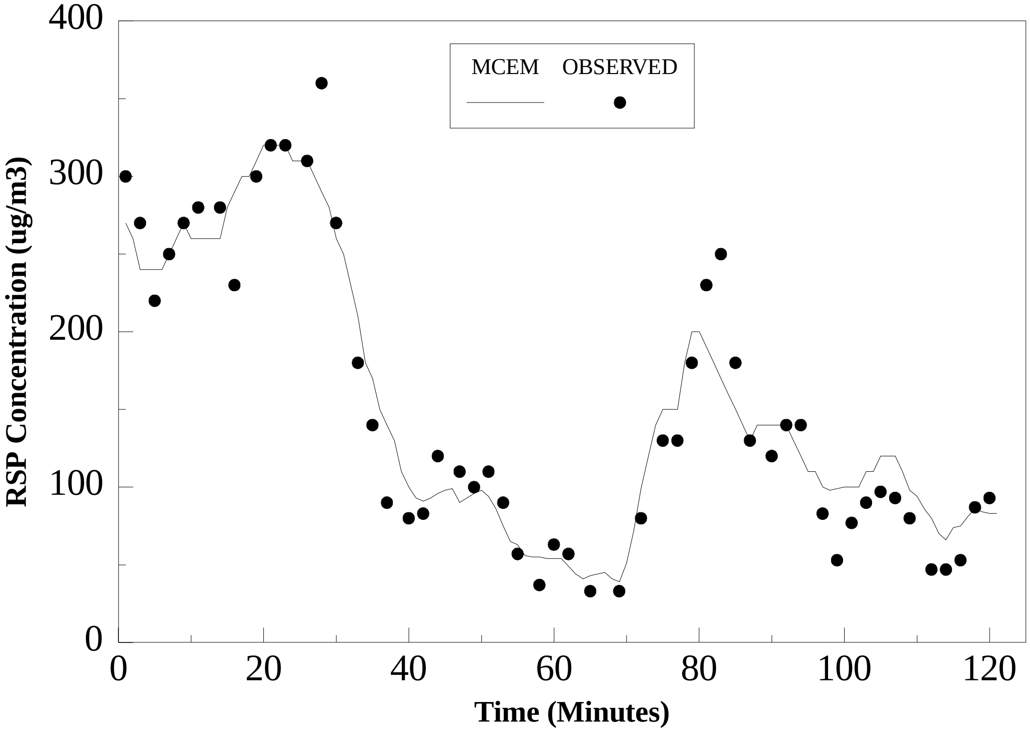


Figure 3. Plots of concentrations predicted by the exponential decay model (smooth curve) along with observations measured in the smoking lounge at San Jose International Airport (Visit SJC 5) for RSP (top) and CO (bottom). The residual values are shown at the bottom of each graph, and the air exchange rates given in Table 2 (ventilatory for CO and effective for RSP) are determined from the exponential decay constant in (see Equation 4).



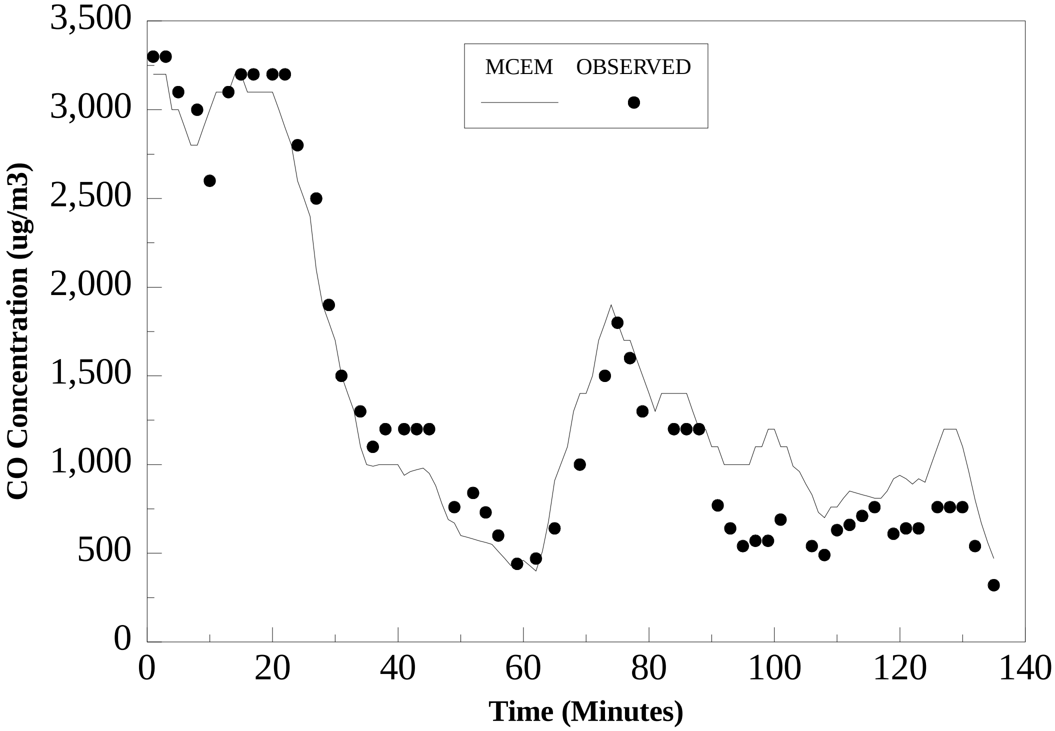


Figure 4. Time series of concentrations predicted by the model and concentrations observed in the smoking lounge at San Jose International Airport for RSP (top) and CO (bottom) on 9/1/93 (Visit SJC 5).

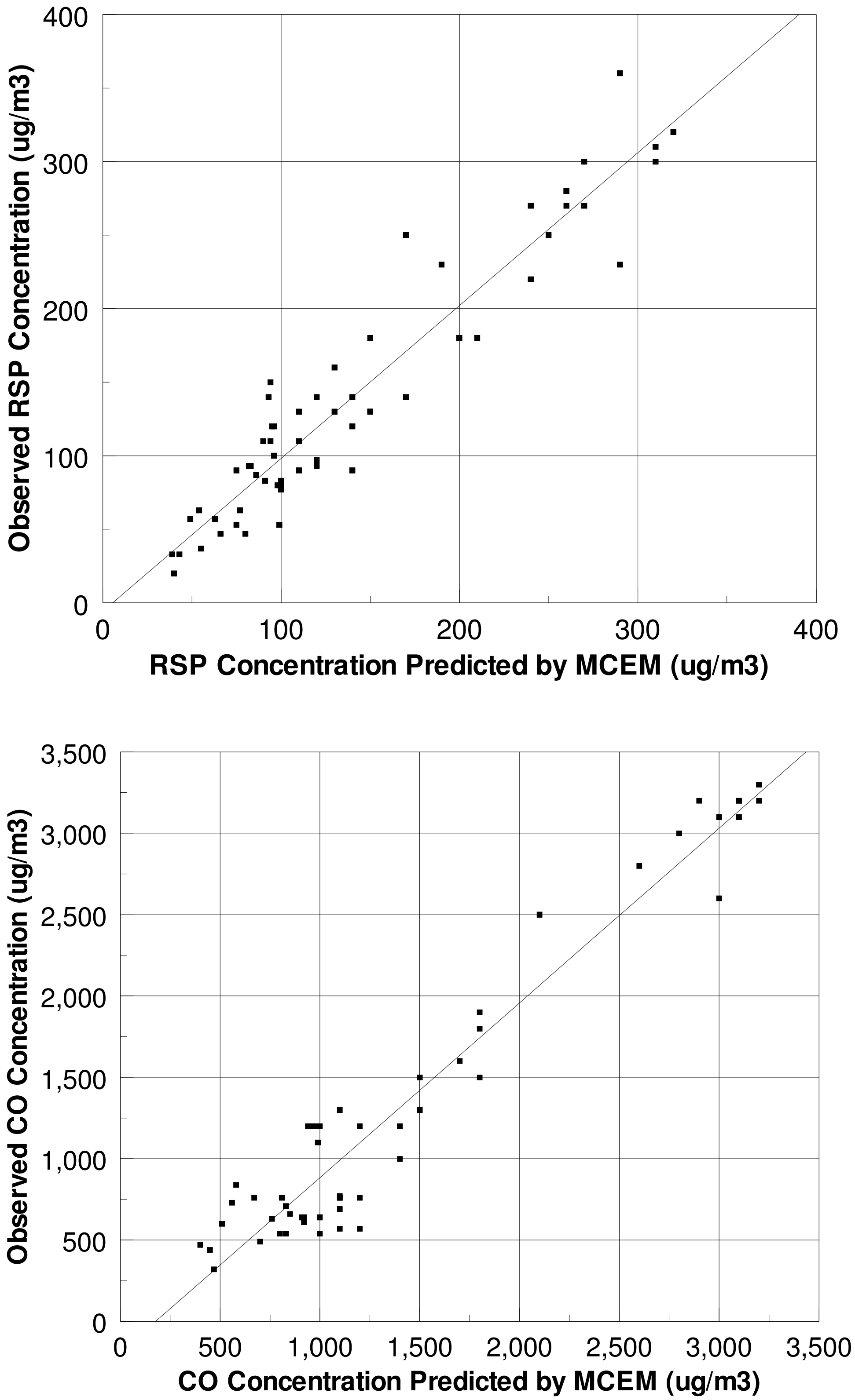


Figure 5. Scatterplots of the model vs. observed RSP (top) and CO concentrations (bottom) for the SJC 5 study visit (regression results for RSP and CO at all study visits are given in Tables 4 and 5).