Validity of the Uniform Mixing Assumption: Determining Human Exposure to Environmental Tobacco Smoke

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When using the mass balance equation to model indoor air quality, the primary assumption is that of uniform mixing. Different points in a single compartment are assumed to have the same instantaneous pollutant concentrations as all other points. Although such an assumption may be unrealistic, under certain conditions predictions (or measurements) of exposures at single points in a room are still within acceptable limits of error (e.g., 10%). In this article, three studies of the mixing of environmental tobacco smoke (ETS) pollutants are reviewed, and data from several other ETS field studies are presented. Under typical conditions for both short sources (e.g., 10 min) and the continuous sources of ETS in smoking lounges, I find that average exposure concentrations for a single point in a room represent the average exposure across all points in the room within 10% for averaging times ranging from 12 to 80 min. I present a method for determining theoretical estimates of acceptable averaging times for a continuous point source. — Environ Health Perspect 107(Suppl 2):357–363 (1999). http://ehpnet1.niehs.nih.gov/docs/1999/suppl-2/357-363klepeis/abstract.html

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For environmental tobacco smoke (ETS), as for other air contaminants, when exposure measurements are unavailable or potentially unrepresentative, exposure estimates can be made using mathematical models. As discussed in another article in this monograph (1), estimates of population exposure require both the time spent being exposed and the magnitude of exposure (e.g., the average pollutant concentration). In many studies, the mass balance equation has been the method of choice to describe indoor air pollution, and it has been repeatedly applied to the indoor pollutants present in ETS (2–5). The article by Ott in this monograph (6) presents the mass balance equation (including some historical background) and shows how it is applied to the modeling of ETS.

One of the primary assumptions made in the application of the mass balance equation is that of uniform, or ideal, mixing. All points in a room are assumed to have the same instantaneous pollutant concentration as all other points. Another common assumption (based on the assumption of uniform mixing) is that time-averaged concentrations measured at a single point in a room represent either the time-averaged concentrations at any arbitrary point in the room or the time and spatially averaged room concentration. But how accurate is this assumption when making estimates of human exposure to ETS? Can exposures be assigned to specific occupants of a space based on a single spatially localized estimate for the space?

This article reviews information relevant to these questions. Three recent articles focused on the mixing of indoor air pollutants. Mage and Ott (7) introduced a standard temporal breakdown for ETS studies, Baughman et al. (8) measured the time required for the mixing of a nearly instantaneous pollutant emission in a controlled chamber under conditions of natural convection, and Drescher et al. (9) measured mixing times for conditions of forced convection. In the present work, these papers are discussed and analyses of data from other studies are presented that give insight into the validity of using the mass balance equation to predict ETS exposures for short and temporally continuous point sources in both occupational and other settings. Finally, I present the results of original calculations that show how, given the mixing time for a nearly instantaneous source, we can estimate the required averaging time for a continuous source (under otherwise identical conditions) such that single-point exposures represent the room average within about 10%.

**Previous Studies of Uniform Mixing**

Mage and Ott (7), in discussing the mass balance equation, suggest that models using an exponential mixing factor that is less than 1 (thereby reducing the theoretical removal rate) should not be used to make estimates of human exposure to air pollutants. Instead, each location should be examined to determine the degree of nonuniform mixing, and if mixing is found to be unacceptable nonuniform, a multicompartment model should be used with a mixing factor of 1 for each compartment. In the process of examining the degree of mixing for a given location, Mage and Ott propose the delineation of three sequential time segments that can occur during the study of a single, short source: a) the time $\tau_a$ during which the source is active; b) the time $\tau_b$ during which the source is off and the room is not well mixed; and c) the time $\tau_c$ during which the source is off and the room is well mixed. The following is a representation of these three time segments:

\[ \tau_a \rightarrow \tau_b \rightarrow \tau_c \]

I use Mage and Ott’s notation in this article. The time $t = 0$ is taken to be the time at which the source begins.

For cigarettes, $\tau_a$, which is the length of time for which the cigarette is actually being smoked, is typically 6 to 11 min. The amount of time required for the room to become well mixed, $\tau_b$, is dependent on factors such as the presence of mechanical flow devices, air conditioning, heating equipment, sunlight, and number of active persons. The value of $\tau_b$ also depends on the location of the source(s) in the room.
and whether it (they) is (are) stationary. Each of these factors could have a large effect on \( \tau_p \). For example, turbulent airflow created by moving persons, heat input, or fans would tend to decrease \( \tau_p \). Although we cannot readily determine an exact magnitude of the effect, \( \tau_p \) can be measured for a variety of conditions in typical locations such as offices, lounges, taverns, homes, and vehicles. The third time segment (\( \tau_p \)) extends from the end of the second time segment \( \tau_p \) until such time as the room concentration \( z(t) \) decays exponentially to approximately 1% of the peak concentration. After this point, the pollutant concentration is considered undetectable.

The peak concentration is taken to occur at the end of the \( \tau_{\text{pe}} \) time period. Assuming the pollutant concentration decays exponentially after the end of the \( \tau_{\text{pe}} \) time period, the time it takes to reach 1% of the peak concentration is \( -\ln(0.01) = 4.6 \tau = 5 \tau \), where \( \tau \) is the residence time (the time it takes to reach 1/e x the original concentration). Therefore, the approximate time that elapses between the end of the \( \tau_{\text{pe}} \) period and the end of the \( \tau_p \) period is 5 \( \tau \).

A crucial quantity in assessing exposure is the time-averaged pollutant concentration. As Mage and Ott demonstrate, the overall pollutant concentration at a single point in a room \( \bar{z} \) can be broken down into a weighted average of the pollutant concentration in each of the three time periods described previously:

\[
\bar{z} = \bar{z}_{\text{pe}} \frac{T + \bar{z}_{\text{p}} \tau_p}{T + \bar{z}_{\tau}}
\]

where \( T = \tau_{\text{pe}} + \tau_p + \tau_T \) (the total study duration), \( \bar{z}_{\text{pe}} \) is the average concentration during the \( \tau_{\text{pe}} \) interval, \( \bar{z}_p \) is the average concentration during the \( \tau_p \) interval, and \( \bar{z}_T \) is the average concentration during the \( \tau_T \) interval. If the percentage of time during the transition period from the poorly mixed to the well-mixed state \( \bar{z}_p \) is small compared to the total source-off time period \( \tau_p + \tau_T \), the proportion contributed to the overall average is small for the middle term on the right side of the above equation, and \( \bar{z}_T \) is for a short source dominated by the well-mixed time period \( \tau_T \).

Baughman et al. (8) determined mixing times (\( \tau_{\text{mix}} = \tau_{\text{pe}} + \tau_p \)) in a chamber under different conditions of natural convection after the release of a pollutant from a nearly instantaneous source (\( \tau_{\text{pe}} = 6 \) min); a quiescent air (\( \tau_{\text{mix}} = 80-100 \) min); 6) the presence of a 500-W water heater (\( \tau_{\text{mix}} = 13-15 \) min); and e) the presence of incoming solar radiation (\( \tau_{\text{mix}} = 7-10 \) min). The chamber was considered to be well mixed when the relative standard deviation (standard deviation divided by the mean) over 41 points in the room was 0.10 or less. Because the air exchange rate remained at about 0.03 to 0.08 air changes per hour (ach) (\( \tau = 12.5-33.3 \) hr) for all the experiments, the well-mixed time period \( \tau_p \) as defined by Mage and Ott is very long (more than 24 hr) regardless of the value of \( \tau_p \). As a result, the proportion of time spent mixing is only 0.01 to 2.5% of the total source-off time (\( \tau_{\text{mix}} + \tau_T \)). Thus, the uniform mixing criteria of Mage and Ott are met. However, because air exchange rates in American homes are usually in the range of approximately 0.5 to 2 ach (10), a more realistic source-off time might be 25 to 10 hr. In this case, the criteria of Mage and Ott may not be met. We also must consider that Americans typically spend less than 8 hr being exposed to ETS in a given location (7).

To study the effect of shorter averaging times on errors in exposure estimates, an exposure index has been introduced by Baughman et al. (8). The exposure index is defined as the time-averaged concentration at one point divided by the time and spatially averaged room concentration. Baughman et al. (8) calculate the exposure index at each of the 41 points in the chamber for times extending from the moment the pollutant is first released. They show that for times less than or equal to \( \tau_{\text{mix}} \), the error in a single point measurement of exposure can be as much as 200 to 300% under quiescent conditions and as much as 100% when a heat source is present. However, exposure indices are only calculated for times lasting less than or equal to \( \tau_{\text{mix}} = \tau_{\text{pe}} + \tau_p \) (31 min for quiescent conditions or 7 min when heat is added to the chamber). Consequently, it is difficult to know at exactly what time the time average at each point in the room approach the 41-point time average. The time appears to be appreciably larger than \( \tau_{\text{mix}} \) but much less than \( \tau_{\text{pe}} \) (63-167 hr).

Drescher et al. (9) conducted experiments similar to those by Baughman et al. (8), except under conditions of forced mixing (using fans). They find mixing times of \( \tau_{\text{mix}} = 2 \) to 15 min and, like Baughman et al. (8), find that averaging times equal to \( \tau_{\text{mix}} \) result in errors relative to the spatial room average of a factor of 2 or more. A detailed analysis showing what averaging times are sufficiently long to bring errors below 10% (or some other acceptable limit) is not provided.

**Discussion**

The proportion of the time spent mixing relative to the source-off time as described by Mage and Ott (7)—where \( \tau_p \) extends until the room concentration \( z(t) \) reaches 1% of the peak concentration—gives a reasonable indication of model accuracy. However, we require an estimate of the error associated with a given proportion. The two fundamental questions addressed in this article are a) How much can we truncate \( \tau_p \) for nearly instantaneous sources and still be confident that concentrations at a single point approximate the spatial room average over the entire study duration of \( T = \tau_{\text{pe}} + \tau_p + \tau_T \)? b) Given an acceptable \( \tau_p \) for nearly instantaneous sources, how long must the study be to give acceptable results for continuous sources? The studies considered to date address only the idealized case of nearly instantaneous sources of ETS and do not determine errors in exposure for a range of time periods, i.e., times between the values of \( \tau_{\text{mix}} \) and \( \tau_{\text{mix}} + \tau_T \). Real-life ETS exposures involve multiple ETS sources over the entire exposure duration. For example, how often do individuals remain in a room for a period of 4 hr during which time only one cigarette has been smoked for 6 min (starting at the beginning of the time period)? In realistic situations, people are present in bars, restaurants, cars, lounges, and offices in which, over the entire time period, either more than one person is smoking or one person is smoking multiple cigarettes. We should also consider realistic averaging times that represent average ETS exposure durations that people actually experience. For example, from the recent national human activity pattern study (1), we see that Americans are exposed to ETS on the order of 1 to 2 hr in vehicles and bars or restaurants, and up to 5 to 8 hr in residences and for persons working in offices and factories.

To evaluate the accuracy of the mass balance equation in estimating exposure of individuals to air pollutants, we must know the error associated with time-averaged concentrations predicted at a single point in a room over a wide range of averaging times. Specifically, we need to know the exposure duration at which the single-point, time-averaged exposure is within an acceptable error margin from the time and spatially averaged room exposure. In the next section, I present data from several studies that provide an evaluation of error in exposure estimates under realistic conditions—including continuous ETS sources.
The final section presents theoretical predictions of sufficient averaging times for continuous sources.

**Error in Single-Point Exposure Estimates: Data from a Bedroom, a Tavern, and Smoking Lounges**

How much error do we make when using a single-point concentration as a surrogate for the spatial room average? The error in a time-averaged exposure estimate or measurement in a room under conditions of nonideal mixing (i.e., most real situations) is defined in this article as the absolute difference between the time-averaged concentrations at a single point in the room and the time-averaged concentration of all points in the room. I call this error the exposure error and consider it acceptable if it is less than 10% of the room average. The relative error is the exposure error divided by the time and spatially averaged room concentration. It is acceptable if it is under 0.10, i.e., if the exposure error is less than 10% of the room average. These errors depend on the amount of time required for mixing, $t_B$, and the averaging time or exposure duration, $T$. The mean exposure error is the exposure error averaged over all monitored points. The mean relative error is the relative error averaged over all monitored points.

Different points in the room may have higher or lower exposure errors, but the mean exposure error should give a reasonable approximation of the error between a single-point measurement and the exposure a person would receive at another point in the room or when moving about the room. The goal is to determine the required exposure duration $T$ that will result in mean relative errors lower than 10% for a room with a given mixing time $t_B$. To determine the study duration that gives mean relative errors under 10% across all points in the room, the running average pollutant concentration at different points must be calculated for extended time periods.

In several previous studies, three monitors were placed at widely separated points in a residential bedroom (11), a tavern (4), and smoking lounges (5,12). These studies provide an opportunity to study real locations with progressively longer source-on times $t_C$: a cigarette was smoked for 6.5 min in the bedroom; four cigarettes were smoked for 11 min in the tavern; and smokers were constantly present in the lounges (i.e., they provided a continuous ETS source).

| Table 1. Summary of results from experiments involving three widely spaced monitors. |
|-----------------------------------------------|
| Experiment description | $\phi, \text{ ach}$ | $t, \text{ min}$ | $t_A$ | $t_B$ | $t_{10\%}$ |
|-------------------------|-----------------|----------------|-------|-------|-------------|
| Residential bedroom$^b$ (CO: 1 cigarette) | 1.2 | 50 | 6.5 min | ~ 30 min | ~ 15 min |
| Tavern$^b$ (CO: 4 cigars) | 7.2 | 8 | 11 min | ~ 5 min | ~ 12 min |
| Public smoking lounge$^b$ (RSP; multiple smokers) | 13 | 4–5 | Continuous | ~ 80 min |
| Company smoking lounge$^b$ (Nicotine; multiple smokers) | 13 | 4–5 | Continuous | ~ 8 hr |

$\phi$ is the pollutant decay rate (ach), $t$ is the pollutant residence time (1/\(\phi\)), $t_A$ is the source-on unmixed time period, $t_B$ is the source-off well-mixed time period, and $t_{10\%}$ is the time it takes after the tobacco source was ignited for the mean relative error of the three monitors to drop below approximately 10% of the three-monitor mean. $^b$Raw data are from Ott et al. (11). $^c$Raw data are from Ott et al. (4). $^d$Raw data are from Klepeis et al. (5). $^e$Raw data are from Hammond (12). For sources of short duration, the time spent mixing ($t_B$) was estimated to be the time that elapsed from the end of the source to when concentrations measured at the three monitors began to converge.

Data from three monitors do not provide enough data to fully analyze the distribution of exposures in the room at different times, but an estimate of the extreme exposures that could occur in each room can be provided by calculating the relative error for each point. These calculations have been performed and are reported here. By using running means (over time), I estimate the exposure duration required for the mean relative error to fall below 10% (Table 1). This time ($t_{10\%}$) is defined as the necessary exposure duration (starting just after the source becomes active) for measurements taken at one location to have an average error margin of less than 10% relative to the spatial room mean. In other words, after $t_{10\%}$ has passed, the exposure a person would experience at a given point in the room is, on average, only 10% different from the average room concentration.

**Residential Bedroom**

During a bedroom experiment (11), the 25.7-m$^3$ room had an air exchange rate of $\phi = 1.2$ hr, which corresponds to a residence time of $t = 50$ min. Carbon monoxide (CO) was measured at three points in the room: a corner 5 inches from the floor, the center of the room 36 inches from the floor, and near the ceiling 95 inches from the floor. After being smoked from $t = 0$ min to $t = 6.5$ min, a cigarette was extinguished and the CO levels decayed to background levels 7 to 8 hr later. The time spent mixing ($t_B$) was estimated at approximately 30 min. The mean relative error fell steadily for 5 min after the source started and dropped below 10% at approximately $t = 15$ min (Figure 1).

**Tavern**

In a tavern experiment (4), the 521-m$^3$ room had an air exchange rate of about 7.2 ach, with a residence time of approximately 8 min. As in the bedroom, CO was measured at three widely spaced points in the room: a central table, a booth facing the southwest corner of the tavern, and a booth in the northwest corner of the tavern. After four cigars were smoked two-at-a-time from $t = 0$ to $t = 11$ min, it took 40 to 45 min for the CO levels to decay to their background level. The time segment $t_B$ was estimated at about 5 min. The mean relative error began a fairly steady decline starting at $t = 12$ min where it was 3%; it remained less than 5% thereafter (Figure 2).

**Smoking Lounges**

Up to this point, I have considered single, relatively short point sources of air pollution: one or more cigarettes or cigars smoked over a 10-min time period at a single location in a room. A very different situation arises in smoking lounges, where cigarettes are continually smoked over extended time periods (a number of hours) and at multiple points throughout a room. Because it is difficult to obtain detailed information on the time and spatial coordinates of each cigarette smoked, investigators have treated multiple, overlapping cigarette sources as a single, continuous source whose pollutant emission rate changes in time as the number of smokers present in the lounge changes (5). Although it may be convenient at times (and even necessary) to equate a series of short sources with a single continuous source (see section "Exposure to Continuous Sources"), multiple point sources with an unknown spatial distribution can have an unpredictable effect on the mean relative error in exposure (see discussion that follows).

Hammond (12) conducted a number of experiments in company smoking lounges in
1987 using three time-integrated nicotine samplers distributed throughout the lounge. The time period for three of the studies was 8 hr. The mean relative error for the three studies ranged from 0.5 to 2.5%. The averaging time for which the mean relative error was 10% was most likely less than 8 hr, although we cannot pinpoint it exactly.

In 1 of 10 different experiments in airport smoking lounges (5), a 238-m³ room had an air exchange rate of about 13 ach, corresponding to a residence time of 4 to 5 min. Respirable suspended particles (RSP) were measured in a chair at the center of the room and in chairs at two opposite corners of the room starting at \( t = 0 \) min. There was an average of approximately five smokers present for the duration of the experiment and at least one smoker was present during each minute. The time spent mixing (\( \tau_b \)) at this smoking lounge was probably similar to that in the tavern (about 5 min), as there were many people present who provided heat energy and a forced-air ventilation system was in operation. The mean relative error began to fall steadily at about \( t = 60 \) min and became 10% at about \( t = 80 \) min (Figure 3).

Over all 10 smoking lounge experiments in which RSP was measured at three room locations, the mean relative error averaged 12%—from 5 to 22%. The study time periods ranged from 60 to 146 min. Regression results of model concentrations versus predicted concentrations were excellent for most of the study visits. The model prediction of the time-averaged room concentration matches the observed room average closely for all ten visits to smoking lounges.

As a caveat to the above calculations, note that mean relative error calculations based on only three monitoring positions...
are biased. In general, for both short and continuous sources, the relative error calculated can depend on the flow of air in the room, the direction of smoke emissions, the location of the smoker(s), and the emission rates of the different cigarettes. Without highly resolved spatial monitoring, it is possible for error calculations to misrepresent the actual extent of mixing. For example, the range of relative error in smoking lounge studies may be a result of the location of smokers in each room. If smokers were fairly spread out in each lounge, or at least equal distances from each monitor, the monitor concentrations could be fairly close to each other and to the room mean regardless of the rapidity of mixing.

**Mobile Exposures**

Because a person might move about in different locations of a room suggests that he/she could experience exposure close to the average room concentration. Thus, it is possible that the true error in exposure for this person is smaller than that predicted for a single point in the room by the mean relative error. For example, if we find that after a time \( T \), the mean relative error in pollutant concentration across all points in the room is 9%, the true error in relative exposure for a person moving about the room could be somewhat lower than 9%. It is impractical to consider occupant motion in exposure models, but we should keep in mind that the calculated mean exposure error could overestimate the true error under certain conditions. On the other hand, if a person spends too much time close to the source, the calculated mean exposure error could underestimate the true exposure. When dealing with the special case of continuous sources, Furtwag et al. (13) found that concentrations should be measured or estimated at distances of more than 0.4 to 0.8 m from a source to minimize large positive errors.

**Exposure to Continuous Sources**

Mage and Ott (7), Baughman et al. (8), and Drescher et al. (9) consider sources of very short duration (\( t_\text{a} = 20 \text{ sec} - 11 \text{ min} \)) compared to the entire exposure duration (\( T = t_\text{a} + t_\text{b} + t_\text{c} > 1 - 2 \text{ hr} \)). For a single short source, after the source stops and the room has become well mixed, the time series at the monitored locations have converged. This event occurs at the beginning of the \( t_\text{r} \) time period. The mean relative error falls within an acceptable error margin (arbitrarily chosen as 10%) beginning at time \( t_{10\%} \) after the source has started.

As we have seen in the previous section, the time \( t = t_{10\%} \) can occur either before or after the beginning of \( t_\text{r} \). By completing measurements shortly after \( t = t_{10\%} \) or at some later time, we are assured that the mean relative error will be less than 10%. However, many instances of human exposure to ETS can involve the presence of multiple smokers where smoke is constantly emitted into the room. In this case, multiple, overlapping smokers can be treated as a single continuous source. From results in smoking lounges (see previous section), it appears to take a much longer time for the mean concentrations at the three points to converge on the room mean (80 min in the smoking lounge vs 5 min for similar conditions in the tavern). Smoke emitted during any given short time interval may take only 5 min to become well mixed, but an additional 5 min is needed for smoke emitted in each successive time interval to become well mixed. For continuous sources, the time series are constantly diverging, since smoke is continually emitted. How does the mean relative error ever reach an acceptable level?

Because our single-compartment mass balance equation is linear, it is possible to treat the time series arising from a single source as a superposition of a number of shorter sources (Figure 4). I refer to these shorter sources as subources. For example, the pollutant time series of a 60-min source with a constant emission rate of 10 mg/min can be broken down into six identical subources lasting 10 min each and each having a constant emission rate of 10 mg/min (Figure 4A). The subources can be considered to exist by themselves in separate rooms, with their starting points staggered by 10 min. The total time series is obtained by adding together all the time series in each room. For a source that has a varying emission rate or, equivalently, if there are different numbers of identical subources present...
in each time interval (as in a smoking lounge where each cigarette is considered to have the same emission rate), the total pollutant time series can be treated as a number of staggered subsources with different emission rates. For example, the complicated pollutant time series of a 2-hr source can be broken down into 12 subsources lasting 10 min each with emission rates between 20 and 90 mg/min (Figure 4B).

The subsources are assigned subdurations (τα*) that are very short compared to the total exposure duration, T. A convenient value is δ, the time interval between measurements (e.g., δ = 1 or δ = 10 min for real-time monitoring). If each successive subsource existed in the room by itself, it would have characteristic times τp* and τ10%. The time when the subsource time period ends is taken to be T* = τ10%, which is the ending time for the subsource's well-mixed time period τα* unless τ10% < τp* + τα*.

Because the subsources are staggered in time, a number of the T* values must be truncated so they will fit into the given total exposure duration T (Figure 5). As T increases from zero, more and more of the subsource time period's T* fit into T. When a large proportion of the T* values fit into T (e.g., 90%), then we can be confident that the mean relative error of different monitors in the room will be close to 10%. For example, Figure 6 contains box plots for the distribution of truncated T* values over increasing values of the total study duration T. When the untruncated value for T* is 10 min, it takes a total exposure duration of about T = 100 min before 90% of the untruncated T* values fit (Figure 6A). This value of T is close to the value of 80 min that was reported for the smoking lounge experiment previously described. When the untruncated value for T* is 30, about T = 5 hr is required before 90% of the untruncated T* values fit (Figure 6B). This case corresponds to rooms with very long τp values, such as under quiescent conditions.

Summary

In the preceding section, I provided a rough determination of the required averaging time for exposure studies involving continuous pollutant sources. A more thorough treatment might involve characterizing the movement of individual air parcels in a room, i.e., using computational fluid dynamics (14). My method begins with the following relatively simple concept: If the mean relative exposure error associated with an arbitrarily short source is under 10% after some elapsed time, then the mean relative error for a series of these short sources is under 10% after a somewhat longer time. The short sources are staggered in time, with one beginning immediately after another has ended so that their collective emissions are equivalent to the
emissions from a single continuous source. We note that the mean relative error for continuous-source emissions only becomes acceptable after the mean relative errors for the bulk of the short sources are acceptable. This approach predicts that the time required for the mean relative error associated with the continuous source to fall below 10% is about 10 times the time required for a single short source.

Conclusions

How much error do we make when we use predictions or measurements of concentration at single points in a room as surrogates for an average room concentration? The exposure indices reported from two chamber studies indicate that times less than 7 to 31 min for natural convection and 2 to 15 min for forced convection are generally not long enough for the time-averaged room concentration at different points to approximate the time and spatially averaged room concentration. In contrast, results in a bedroom and a tavern suggest that under realistic conditions, averaging times on the order of 12 to 15 min may be long enough so that the exposure error is less than 10%. For a continuous source, the averaging time must be considerably longer. For conditions in an actual smoking lounge, an 80-min averaging time was required before the mean exposure error was less than 10%. From theoretical considerations, given adequate averaging times of 10 and 30 min for a nearly instantaneous source, adequate averaging times for a continuous source (under the same room conditions) are approximately 10 times larger at 100 min and 5 hr, respectively.

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