

The Correction for Nonuniform Mixing in Indoor Microenvironments

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Introduction

The modelling of the air pollution concentration distribution, $C(x,y,z,t)$, in an imperfectly mixed indoor setting of continuous air volume v m³ is a very complicated process [v is defined here as the total volume minus the solid volume of objects within it in cubic meters (m³)]. If the air is perfectly mixed then the concentration throughout the chamber is the same at time t and is equal to the exit concentration $C_e(t)$, or $C(x,y,z,t) = C_e(t)$ for all x, y, z . Then the mass of pollutant inside the chamber at time t is given by $v C_e(t)$. However, air velocities in rooms without forced-air flow can be quite low [1], and concentrations can vary spatially within the mixing volume.

The nonhomogeneities of concentration that exist can be influenced by the placement of fans, internal stream lines connecting a closely spaced air inlet and air return opening, internal barriers to air flow, thermal gradients in the room, etc. This paper reviews the literature on how an empirical "mixing factor" has been introduced into indoor air quality models to "correct" for lack of uniformity in concentrations and mixing in indoor settings. We contend that this mixing factor is a simplistic approximation of a complex phenomenon that may lead to invalid predictions of indoor concentration, and recent advances in monitoring of indoor environments are discussed that indicate an empirical approach that can be used to understand the

phenomenon that have been observed. Recommendations for future experimental studies are suggested that should help to clarify the prediction of the effects of nonideal mixing on measurements of exposure to pollutants in indoor settings.

The Perfectly Mixed Case

If the mixing in volume v is instantaneous and complete, the concentration throughout v will be identical to the concentration C_e leaving v in the exit flows. Figure 1 represents an idealized situation for a chamber representing a room in which inlet air containing a tracer material at concentration C_i , enters with flow rate $w(t)$ m^3/min and leaves with concentration C_e at the same flow rate $w(t)$. If there is a source in the room emitting pollutant at constant rate $g(t)$ mg/min , and sinks in the room remove the pollutant with a first-order rate constant $k(t)$ min^{-1} we can model the system using the mass balance, equation (1), by first setting the quantity entering volume v over time interval T , minus the quantity leaving and removed, equal to the change in concentration within v over the interval T , times the volume v .

$$\int_0^T (w C_i - g) dt - \int_0^T (w C_e + k v C) dt = v [C(T) - C(0)] \quad (1)$$

where w = flow rate into volume v , $[\text{M}/\text{L}^3]$

C_i = pollutant concentration in inlet flow $[\text{M}/\text{L}^3]$

C_e = pollutant concentration in exit flow $[\text{M}/\text{L}^3]$

C = pollutant concentration in volume v $[\text{M}/\text{L}^3]$

g = source strength [M/T]

k = first order rate constant for pollutant reaction [T⁻¹]

T = time since initiation of the process [T].

For the simple case where $C = 0$ at $t = 0$, $C_e = C$, and the variables C_i , w , g and k are held constant, the concentration in volume v will rise exponentially in the interval $0 < t < T$ by the equation:

$$C = (C_i + g/w) (1 - e^{-(k+w/v)t}) \quad (3)$$

Let the internal source be turned off ($g = 0, t > T$), and no tracer be allowed to enter the room in the inlet flow ($C_i = 0, T$) after achieving equilibrium [$T \gg v/(w - kv)$]. The concentration in the room, $C(T) \approx C_i + g/w$, will decay exponentially by the equation:

$$C(t) = C(T) e^{-(k + \frac{w}{v})(t-T)} \quad (3)$$

In an identical manner, the ideal system response to a 1 mg unit delta function input (a pulse with infinite amplitude and zero width, and a unit area) will also be a negative exponential decay from a maximum value of $1/v$ mg/m³ with time constant

$(k + w/v) \text{ min}^{-1}$.

Any arbitrary tracer input to a perfectly mixed indoor setting can be modelled using the principle of superposition by a combination of the responses to a set of delta functions and step functions (e.g. a source emitting 1 mg/min for 1 min can be treated as the summation of two sources, one source emitting 1 mg/min for all time $t > 0$ and a second source emitting -1 mg/min for all time $t > 1$ min).

In the literature, a mixing factor (m) where $m < 1$ often has been introduced to account for positive deviations of observed concentrations from the spatial uniformity assumed by Equation 1. Figure 2 shows the situation described in Figure 1, modified by the use of a mixing factor (m), that has been used to describe the positive deviations of observed values of C from the predictions of C by equations 2 and 3. That is the concentration being measured is higher than predicted, as if all the air that enters is not completely mixed with the entire mass of room air. Note that the fraction of inlet air that is unmixed into the room ($1 - m$) must somehow get from the inlet to the outlet intact without any mass transfer of pollutant between it and the rest of the room air. We signify this phenomenon by a streamline, represented by the continuous line to the exit, which does not allow mass transfer. Then this flow $(1 - m)w$ must recombine with the flow (mw) at the outlet, to produce an exit concentration (C_e) given by the mass balance

$$C_e = m C_i + (1 - m) C_r \quad (4)$$

Literature Review of a Mixing Factor to Describe Nonideal Mixing

The first detailed discussion of nonideal mixing of air in a room was by Lidwell and Lovelock in 1946 [2]. They stated that "If the mixing of incoming air with the air of the room is not sensibly complete (sic) the concentration of tracer substance will not, in general, decay logarithmically nor will the rate of decay be the same in various parts of the room." They state that if it is possible to fit a curve of the decay of a tracer in the room by an equation of form $C = C_0 \exp(-\Phi t)$, "the decay constant Φ may be either greater or less than the ideal air exchange rate (w/v) according to the disposition of the air circulation in the room relative to the point at which the observations were made". They further state "This 'constant' may conveniently be referred to as the equivalent ventilation at the point of measurement". Their use of 'constant' with single quotes is to emphasize that the measured value of Φ ($\Phi = m w/v$) is a function of position in the room [$\Phi(x,y,z)$] so that m is also a function of position, $m(x,y,z)$, as w and v are constant.

The next discussion of nonideal mixing which first coined the term "mixing factor", appears in a 1960 article by Brief [3]. Brief states "This mixing factor will depend on the vapor or gas toxicity, the uniformity of contaminant distribution within

the room, location of the fans, construction of the room, and the population therein. This factor (m) may vary from 1/3 to 1/10 and is used in conjunction with v/V to yield the effective number of air changes, $m v/V$. We note that this article referred to a specific application - determining the required number of air exchanges to take place before entry can be safely made into a contaminated space (e.g. before a worker can go into an emptied benzene storage tank for visual inspection and cleaning). Given the dangers of explosion, toxicity and asphyxiation in such circumstances, the mixing factor $m = 1/10$ is appropriately recommended as a safety factor that allows for nonideal mixing, as in the corners of the room.

In 1963, Turk [4] introduced the mixing factor (m) "to account for the fact that dilution of air is not instantaneous, and that concentration fall-off rates are actually smaller than the ideal values ... Brief [3] suggests that m commonly ranges between 1/3 and 1/10". Unfortunately, Turk's statement does not recognize that m can be greater or less than 1 depending on where in the room it is measured, and the cited usage of m in the range of 1/3 to 1/10 is for the highly specialized purpose of handling dangerous materials requiring safety factors for human activities [3].

In 1970, Constance [5] discussed the air exchange required to remove contaminants from an enclosed air space. He stated "If $m = 1$, we have the unattainable perfect mixing discussed previously. Actual mixing factor can vary from

1/3 to 1/10, depending on contaminant toxicity, uniformity of distribution in the space, location of air inlets and outlets, enclosure geometry and population". Constance [5] discussed the power cost of providing extra air flow when using too low a design value of m and the competing need to use $m < 1$ as a safety factor.

Drivas, Simmonds and Shair in 1972 [6] reported actual measurements of m and cited Constance [5] as the source of the phrase "mixing factor". They observed that the idea is identical to that first suggested by Lidwell and Lovelock [2]. They stated "Values of m are normally estimated to be from 1/3 to 1/10", which includes the "safety factor" based on toxicity that appears in Constance [5]. They measured m values in several rooms in the basement of building which were connected by a common hallway. In their study, the entire basement was ventilated by a single air supply distributed to all the rooms, and all the room air exhausted through a door into the common hallway which was then exhausted by a single air outlet. An instantaneous injection of SF_6 into the basement air intake was used as a test signal. Measurements of m were made in a room with a single inlet and outlet to the hall, and a value of $m = 0.9$ was measured while using four large fans to simulate perfect mixing. Repeating the experiment without the fans in operation, the value of m was found to be 0.68 at the same measurement point in the center of the room. In the same experiment in another room, a value of $m = 0.3$ was measured 3 ft from one

corner of that room, which they note validated the range of $1/3$ to $1/10$ for m [3-5]. Such imperfect mixing in this case may be caused by a flow streamline from the air intake in the ceiling directly to the hall through the door, which of course would reduce the air flow to the far corner of the room where m was measured to be 0.3. Simultaneous measurements made in the hallway at both ends showed variation by a factor of 2 in the concentration, and the concentration decreased with time in a manner not described by a single exponential term, as suggested by Lidwell and Lovelock [2] for nonuniformly mixed rooms.

In 1978, Esmen [7] derived the mass balance equation for a conservative pollutant in a room with $m < 1$. His paper states "Let m be defined as the portion of the [contaminant free] ventilation air flow (w) that is completely mixed with the room air. In other words, we imagine that the m fraction of the air flowing in will be totally replaced by the room air, and the remainder is totally unmixed. Under this condition the mass balance is: $v dC/dt = - m w C$ ".

This derivation is not realistic because it assumes that the 'unmixed' fraction ($1 - m$) moves through the room, from inlet to outlet, without any mixing at all as shown in Figure 2. By conservation of mass (see Lidwell and Lovelock [2]), the nonuniformity of mixing implies that there are points in the room where $m > 1$ and $m < 1$. This practical situation could occur when a streamline connects a ceiling air

inlet to a ceiling air outlet so that a portion of the inlet air bypasses the turbulent core of the room where a concentration measurement might be made. Thus Esmen's conceptual derivation [7] does not apply to real situations because the value of C in the derivation cannot be uniform throughout the room unless $m = 1$. Esmen later acknowledges this by stating that m can be a variable in the room, but claimed that it depends on the source, giving an example of a person moving away from a smoker to get away from the smell (e.g. to an area of lower concentration which is treated as an area of higher m).

In 1980, Ishizu [8] pointed out that, given the derivation of the mixing factor (m) by Brief [3] in which m is defined as the portion of the inlet air that is [apparently] completely mixed with the room air, the pollutant generation rate within the room (g) appears to be enhanced by the mixing factor as g/m if $m < 1$.

In 1981, The NAS/NRC report Indoor Pollutants [9] reviewed the literature on single-compartment models and the use of the mixing factor to account for the lower dilution than predicted by a well mixed state. They concluded that even when a compartment is not well mixed, the uncertainty of the flow patterns, and difficulty of specifying source and sink patterns "usually does not justify the development of a more sophisticated model".

In 1987, Nagda, Rector and Koontz [10] introduced the mixing factor into the mass

balance equation, but with the definition "the ratio of the actual residence time of the pollutant indoors to the residence time derived directly from the air exchange ratio". We felt that this interpretation is incorrect because, if a pollutant generated indoors does not disperse as rapidly as we might expect, its residence time indoors is greater than expected, not less than expected, which would give an m value greater than 1. However, they also give another expression for m as "the ratio of the 'exit stream' concentration to the indoor concentration" which is valid if the inlet concentration is equal to zero ($C_i = 0$) [See Equation 4]. To our knowledge no such room measurements are available in the literature as an exit stream concentration may not be measureable if there can be multiple entry and exit points for air infiltration (e.g. windows, doors, cracks, etc.).

In 1991 a National Research Council (NRC) report [11] summarized the usage of the mixing factor as follows "Mixing of air within and between rooms varies spatially and temporally...so single-compartment and multicompartment mass-balance models generally incorporate a mixing factor". As explained by Lidwell and Lovelock [2] a single-compartment model is valid if and only if $m = 1$, so any single-compartment model incorporating a mixing factor violates a basic assumption. However, if a single room is modelled by multiple compartments, with air exchange between them, then that basic assumption is violated unless $m = 1$ in each compartment.

Recent investigations have considered the spatial variation of concentration in indoor settings which have incomplete mixing, and show that the concentration distribution and its modelling can be quite complex [12-20]. For example, Baughman, Gadgil and Nazaroff [20] report a study of a room in which a mixture of SF₆ and He was released as a neutrally buoyant mixture while heated to simulate the smoke from a burning cigarette. Figure 3 shows the total measurements from some of the 41 different measurement points in the room during the quiescent case ($w/v = 0.03$ to 0.08 hr^{-1}) in two duplicate test runs. Let the mean concentration in the room of dimensions a, b, c , at any time t be defined as \bar{C} ,

$$\bar{C}(t) = \frac{1}{v} \int_0^a \int_0^b \int_0^c C(x,y,z,t) dx dy dz \quad (5)$$

If a "mixing factor" were applied to these experiments, those measurements above the normalized $C/\bar{C} = 1$ line would be interpreted to have a value of $m < 1$ (C is greater than that predicted by perfect mixing) and all those values below the line would be interpreted to have a value of $m > 1$ (C is less than that predicted by perfect mixing). In fact since $C = m\bar{C}$, and the integral of $C dv$ is by definition equal to \bar{C} , the

integral of $m dv/v$ must be equal to 1. As we stated earlier, and as stated by Lidwell and Lovelock, nonuniform mixing requires that there must be points in the room where the concentrations are higher and lower than the mixed mean concentration.

Figure 4 shows the data from a similar test, but with a 500 Watt heater creating thermal eddies. The result is a reduction of time to achieve uniform mixing in the same room, from approximately 100 minutes to 15 minutes. In both experiments shown by Figures 3 and 4, more than a two order of magnitude difference in concentration spatially persisted in the room for 30 minutes and 3 minutes respectively.

DISCUSSION

Our review of the literature about the way in which the spatial variability of concentrations in indoor settings has been handled shows a rather simplistic reliance on a single parameter -- the mixing factor m -- to account for discrepancy between the concentrations predicted by the mass balance equation and those actually observed. As indicated above, use of a single factor m to characterize an indoor air pollution episode -- from emission of the pollutant until its eventual decay to negligible indoor levels -- cannot be justified, and more detailed treatment of indoor air pollution episodes is required. Toward this end, we now propose a general conceptual framework for indoor concentrations and pollutant exposures. Where possible, we draw upon recent research that promises to provide important knowledge about the spatial variability of pollutant concentrations in indoor settings. Finally, we suggest criteria for situations in which the mass balance model can provide useful predictions in indoor settings.

Concentration Field Model. Consider a rectangular volume (an empty room or a chamber) and imagine a 3-dimensional coordinate system (x,y,z) with its origin fixed in one of the lower corners of the room. Here x and y denote the horizontal distances from the corner and z denotes the vertical distance. Suppose a , b , and c

denote the length, width, and height, respectively, of the room; then $0 < x \leq a$, $0 < y \leq b$, and $0 < z \leq c$. The concentration of an air pollutant at point (x,y,z) at any instant of time t can be represented by:

$$C(x,y,z,t) \tag{6}$$

We call this the "concentration field" in the room at time t . Next we are interested in the exposure that occurs at some point $\{x(t),y(t),z(t)\}$ that is moving inside the space inside the room (for example, the exposure of a point on the person's nose inside the room as the person walks about the room), then the personal exposure $\xi(t)$ is given by substituting $x(t)$, $y(t)$, and $z(t)$ into Equation 1 to give the exposure as a function of time:

$$\xi(t) = C\{x(t),y(t),z(t)\} \tag{7}$$

The mean concentration in the room at time t will be given by the integral of the concentration field over the entire room divided by the volume of the room $v = abc$, as shown in equation 5. The variance of the concentration field at any time t can be written as

$$Var\{C|t\} = \int_0^a \int_0^b \int_0^c [C(x,y,z,t) - \overline{C(t)}]^2 dx dy dz \quad (8)$$

The variance of the concentration in the room is an indicator of the "amount of variability" of the concentration across the room at any time t . The square root of the variance is the standard deviation of the concentration across the room at any time t . Because it is useful to normalize the amount of variability by dividing it by the level of concentration present, another useful statistic is the coefficient of variation $CV(t)$, which is the square root of the variance divided by the mean at time t , or:

$$CV(t) = \frac{\sqrt{Var\{C|t\}}}{\overline{C(t)}} \quad (9)$$

Baughman, Gadgil, and Nazaroff [20] have studied the indoor concentration field by measuring the decay of an instantaneously emitted tracer gas at 41 sampling sites within a test room. For their experiments, they defined the "characteristic mixing time" as "the period required for the relative standard deviation of the tracer gas concentrations measured at the 41 points to become less than 10%." Adopting the

Baughman, Gadgil, Nazaroff-criterion, the characteristic mixing time t_γ is the time required for the coefficient of variation (also called the relative standard deviation) to be less than 0.10. That is,

$$CV(t_\gamma) < 0.1 \quad \text{for characteristic mixing}$$

After the characteristic mixing time t_γ , the pollutant is sufficiently well-mixed in the room that it makes little difference where the exposure point (for example, the person's nose) is located in the room. Thus, an important question is how much of a total indoor air pollution episode consists of this well-mixed state versus the poorly-mixed state. If a large portion of an indoor episode consists of the well-mixed state after time t_γ , then a 1-compartment mass balance model can be used to predict the average exposure of a person in the room without the use of a mixing factor, because a basic assumption of the mass balance equation -- a uniform concentration field at any time $t > t_\gamma$ -- has been met during most of this period. However, for the period $t < t_\gamma$, a multicompartment model and knowledge of a person's trajectory between compartments is necessary to describe their exposure.

Indoor Air Pollution Episode. An indoor air pollution "episode" -- that is, a source emitting a pollutant inside a chamber, an automobile, or a room in the home

-- typically can be characterized by several different time periods (Figure 1). First, there is the "source-on" period -- the time period during which the pollutant source is emitting -- which in this figure lasts from time $t = 0$ until $t = t_{\alpha}$. Examples are smoking a cigarette, burning toast, using a spray can indoors. A single cigarette smoked in a room has been represented in exposure models as a continuously-emitting point source usually lasting 6-11 minutes [21]. Some sources, like freshly painted surfaces, can have very long "source-on" periods as they outgas volatile organic compounds as the material cures and harden.. Chlordane emitted into a home from the soil beneath the foundation is another example of a source with a long on-time. Other sources, like cigarettes, have relatively short source-on periods, typically about 7 minutes.

As long as the source is emitting, there will be relatively high concentrations very close to the source, and the concentration field across the room will be nonuniform. Although mechanical mixing by fans in a chamber with a burning cigarette can bring about some uniformity, concentrations always will be higher within a few centimeters above the tip of a cigarette while it is burning, and we cannot describe the concentration during this period as uniform over the entire mixing volume. Therefore, Figure 5 characterizes the source-on period, or α -phase, as a "poorly mixed" state, and concentrations will vary spatially across the room.

Furtaw [22] has found that concentrations measured in a chamber very close to the source (less than 1 meter) can be very high during the time period that the source is emitting. When close to the source, it appears that small "pockets" of high concentrations occur as a random process, causing the concentration values to be significantly higher than predicted by the mass balance equation.

At time $t > t_a$ in the conceptual model, the source stops emitting (for example, the cigarette smoking ends or toast stops being toasted), and the "source off" time period begins. In Figure 5, we characterize the source-off period as consisting of two time periods, a transition period called the β -period lasting for time duration t_β and a well-mixed phase called the γ -period lasting for time duration t_γ . The γ -period can be characterized as meeting the Baughman-Gadgil-Nazaroff criterion discussed above). That is, the spatial coefficient of variation obtained from Equation 10 for this pollutant and this source during the γ -period over the entire volume of the room is less than 0.1, or $CV \leq 0.1$.

During the poorly mixed α - and β -periods, the exact position of the receptor point $x(t), y(t), z(t)$ is important, because different points in the room experience different concentrations. During the γ -period, the position of the receptor point is not very important, because the normalized standard deviation of the exposure at any instant of time throughout the room is less than 0.10. (Problems with surface effects --

sinks that absorb and then release some pollutants near surfaces -- have been ignored to simplify our analysis.)

To compute the average concentration at any point (x,y,z) over the entire indoor air pollution episode, we form the weighted average of the three time periods:

$$\bar{C} = \frac{t_{\alpha}}{t_{\alpha} + t_{\beta} + t_{\gamma}} \bar{C}_{\alpha} + \frac{t_{\beta}}{t_{\alpha} + t_{\beta} + t_{\gamma}} \bar{C}_{\beta} + \frac{t_{\gamma}}{t_{\alpha} + t_{\beta} + t_{\gamma}} \bar{C}_{\gamma} \quad (10)$$

We shall define an indoor air pollution episode as an event lasting until the concentration becomes negligible (for example, less than 1% of the value attained at the end of the source-on period), assuming that no additional pollutant enters the room during this period. Thus, because exponential decay implies that the concentration will approach but never actually reach zero, we assume that the concentration is approximately zero at time $t \gg T$ at the end of the episode.

Recent experiments performed at Stanford University using real-time instruments operating in a home with a smoker present suggests that the α -period and β -period both are relatively brief compared with the γ -period. For a cigarette, for example, the α -period -- the time during which the cigarette is being smoked --

typically is about 7 minutes. The β -period -- the time it takes once the source has ended to reach characteristic or uniform mixing -- also is relatively brief because of the rapidity with which the air in a room disperses and mixes the pollutant by advection. As noted by Baughman, Gadgil, and Nazaroff [20] "...the transport of a pollutant over a significant distance is driven by advection since the diffusion rate is relatively small by comparison." In still air, they calculate a typical characteristic time of 450,000 seconds or more than 5 days for a pollutant to migrate 3 meters. They point out that "...from the common experience of how rapidly odors and smoke spread indoors, it is apparent that the characteristic time for contaminant dispersion is more on the order of minutes, not days." Our own experiments agree with their conclusions, and we have found that pollutant migration across a large living room, or even from a bedroom to an adjacent living room, takes only a few minutes if the door between the two adjacent rooms is open.

Baughman, Gadgil, and Nazaroff [20] have measured the concentrations of a tracer gas SF₆ at 41 points in a 31 m³ test room with a very low air exchange rate (0.03 to 0.08 ach). Thus their residence time ranged from about $\tau = 12.5$ hours to 33.3 hours. They used an instantaneous source; their experiment has virtually no source-on period (that is, $t_{\alpha} \approx 0$). They define the characteristic mixing time as the time elapsed until the relative standard deviation becomes less than 0.10, which corresponds to the

β -period in Figure 5. For two "quiescent" experiments with no internal sources in the room, they found that $t_\beta = 80$ minutes in the first experiment and $t_\beta = 100$ minutes. When a 500-w heater was added to the room, two experiments gave $t_\beta = 7$ minutes and $t_\beta = 13$ minutes. Finally, with incoming solar radiation, $t_\beta = 7$ min and $t_\beta = 10$ minutes. If we compare these value with the residence time $\tau (= 1/\phi)$ of air in their experimental chamber, we find that τ ranges from 12.5 hours to 33.3 hours, and the ratio of the transition time to the residence time, or t_β/τ , ranges from 0.05 to 0.10. Thus, once the source turns off, the period in which the pollutant is poorly mixed is only about 5-10% of the residence time. However, comparing the transition period with the residence time is not really useful, because the indoor concentration is only $1/e = 37\%$ of its starting value after τ time units have elapsed. Instead, we arbitrarily choose the endpoint of the indoor air pollution episode as the time at which the theoretical exponential decay reaches 1% of its initial value the time when the source turns off. If we set the exponential decay function equal to 0.01, we find the resulting time as:

$$\frac{C(t_\beta - t_\gamma)}{C_o} = e^{-\frac{(t_\beta - t_\gamma)}{\tau}} = 0.01, \quad \text{or } t_\beta - t_\gamma = -\ln(0.01) = 4.61\tau \quad (11)$$

Using this equation, we see that the β -period in the experiments of Baughman,

Gadgil, and Nazaroff [20] gives a β -period time of t_β that typically is less than 5% of the total source-off time, as can be seen from Table 1. The minimum and maximum values in this table are obtained by substituting the minimum and maximum air residence times (τ ranging from 12.5 to 33.3 hours) into the above equation. When viewed from this perspective, the portion of the source-off period in which the room is poorly mixed ranges between 0.1% and 2.9% of the total source-off time. The proportion is greatest (0.9% to 2.9%) when the room is in its quiescent condition and relatively free of mechanical or thermal agitation.

Table 1. Ratio of Transition Time (t_β) to Residence Time (τ) and to Source-Off Time ($t_\beta + t_s$) Expressed as a Percentage, Based on the Experiments by Baughman, Gadgil, and Nazaroff [20]						
No.	Experiment Type	Transition Time t_β (hours)	Transition ÷ Residence, t_β/τ_{\max} (minimum) (%)	Transition ÷ Residence, t_β/τ_{\min} (maximum) (%)	Transition ÷ Source-Off $t_\beta/(t_\beta + t_s)$ (minimum) (%)	Transition ÷ Source-Off $t_\beta/(t_\beta + t_s)$ (maximum) (%)
1	Quiescent	1.67	13	5	2.9	1.1
2	Quiescent	1.33	11	4	2.3	0.9
3	500-W Heater	0.25	2	1	0.4	0.2
4	500-W Heater	0.22	2	1	0.4	0.1
5	Solar Radiation	0.12	1	0.4	0.2	0.2
6	Solar Radiation	0.17	1	1	0.3	0.1

As soon as a heater or solar radiation is added, the poorly mixed period t_{β} becomes almost negligible (0.1-0.4%) of the overall source-off period. Thus, if the average human exposure is computed for the entire indoor air episode using Equation 10, then the proportion contributed to this average when the pollutant is poorly mixed in the source-off period is likely to be very small or negligible, based on these experiments. In other experiments that we have performed with a cigarette smoked in a real home, t_{β} has been so small that we were unable to see it, relative to the duration of episode. The reason for the relatively small poorly mixed period appears to be the rapidness with which the pollutant mixes through the room of a home -- typically a few minutes -- combined with the relatively low air exchange rates of homes, typically about 1 ach (see, for example, Pandian, et al., [23]). Thus, the experiments suggest that the pollutant exposures to some sources -- such as the cigarette -- can be modeled well using the well-mixed assumption in the mass balance equation, since the source-on time (t_{α}) is relatively small (about 7 minutes), the poorly mixed source-off time period (t_{β}) is only a few percent of the total source-off period, which can last for several hours until the episode ends. Of course, this hypothesis needs more testing in future experiments in real homes, but the evidence now suggest that modeling environmental tobacco

tobacco smoke (ETS) exposures in the home will be reasonably accurate if the mixing factor m is eliminated entirely from the equation. This elimination of the mixing factor is equivalent to setting $m = 1$. This approach was found to work well in experiments on cigarette smoking activity and exposures in a moving automobile and a chamber [21].

However, as we have shown in this paper, use of a uniformly mixed assumption is valid only if the α -period and β -period are small relative to the γ -period. This result may not be valid for some other common indoor sources of air pollution, such as a carpet that continuously emits a pollutant and therefore has a large α -period relative to the indoor air residence period. The concepts presented in this paper show the need for more research on events occurring in the α -period during which the source is on and for experiments conducted in realistic settings in which people actually experience exposures from indoor sources.

Summary and Conclusion

Our analysis of the literature concerning the correction for nonuniform mixing by use of a mixing factor, $m < 1$, shows that this concept is not appropriate on theoretical grounds. It was derived originally as a safety factor to account for the existence of poorly ventilated compartments in a multicompartment setting.

However, if such deviations from uniform mixing occur then a multicompartment model with $m = 1$ in each compartment could be used. Certainly, if a nonventilated compartment, such as a hold of a ship, is to be entered by a worker, a safety factor is warranted to estimate how long to wait before entering, but it could not be used to estimate that worker's exposure.

Development of our framework eliminates the perceived need for the use of a "mixing factor m ", and indeed, we have found it desirable to discard this concept altogether. We show that in many cases, where air exchange is typical of that in homes and offices, the concentration between multicompartments equilibrates quickly to meet the criterion suggested by Baughman et al. [20]. Even in the first phase during the source on period, the concentrations fluctuate rapidly about the mean or expected value of uniform mixing. Therefore a person moving about the room may experience these fluctuations, and the average exposure during this brief interval might even be represented by the expected exposure with $m = 1$.

- Thus, we hope that indoor and exposure modelling research of the future will look more precisely at the processes that occur in mixing volumes, using our proposed framework, and will attempt to account for differences between observed and predicted concentrations without using a gross single parameter such as m . As we have argued, uniform mixing requires $m = 1$; all other cases require that m vary across the volume being modelled by mass balance considerations. If there is a significant concentration gradient, then a multicompartment model with $m = 1$ in each compartment should be used. Therefore, we do not feel that a single parameter m unequal to 1 is useful for indoor air and exposure modelling applications when mixing is not uniform.

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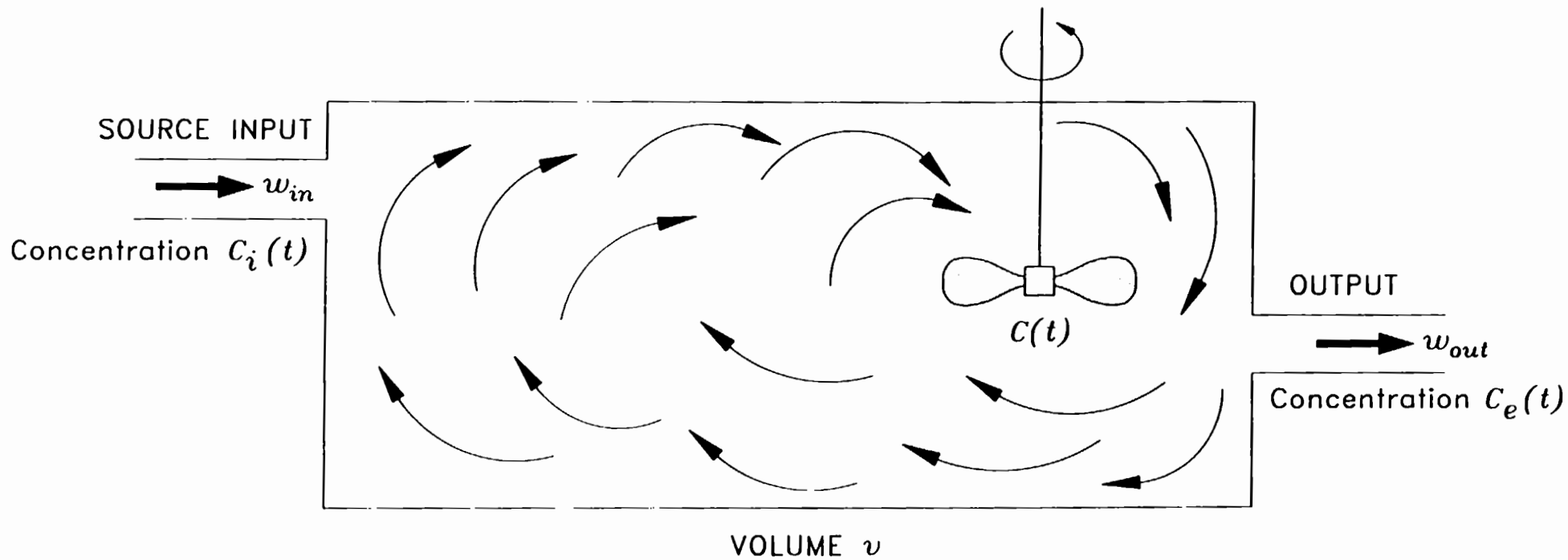


Figure 1. Air mixing chamber with source input port flow rate w_{in} at concentration $C_i(t)$ and output port with flow rate w_{out} at concentration $C_e(t)$.

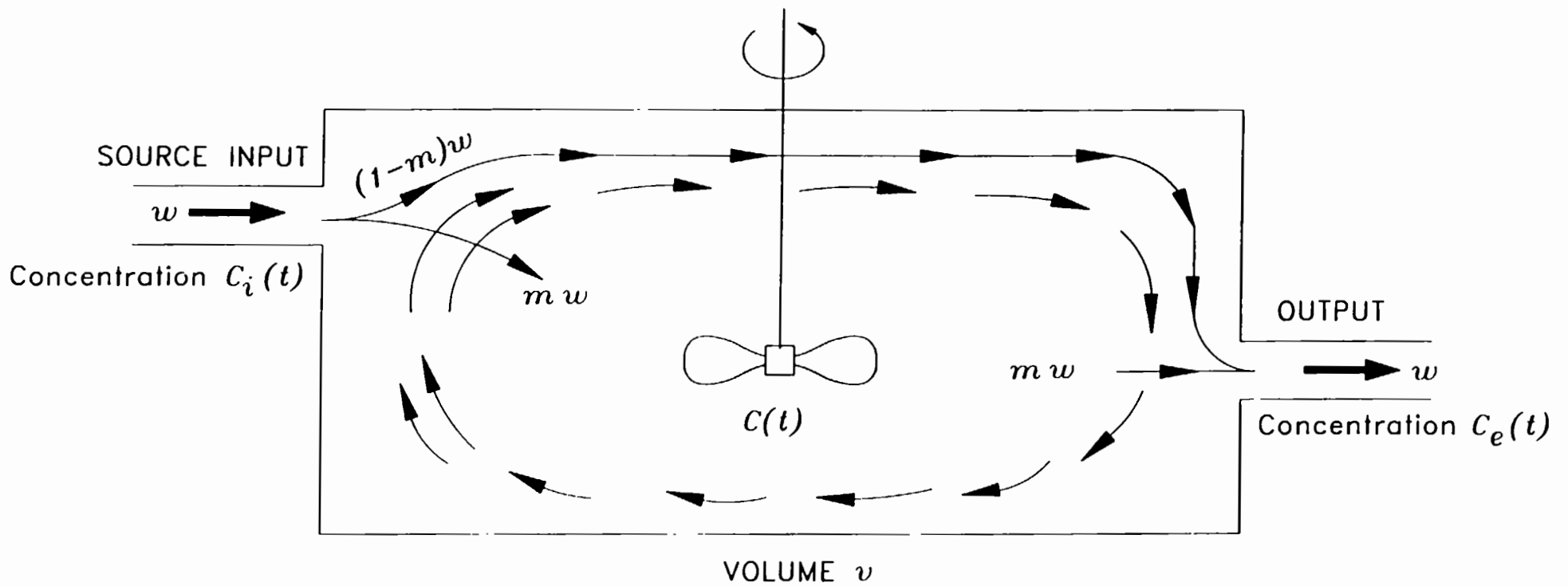


Figure 2. Air mixing chamber with source input flow rate w at concentration $C_i(t)$ and output port with flow rate w at concentration $C_e(t) = mC(t) + (1-m)C_i(t)$. Usage of the mixing factor m implies that a fraction $(1-m)$ bypasses the chamber without mixing in it.

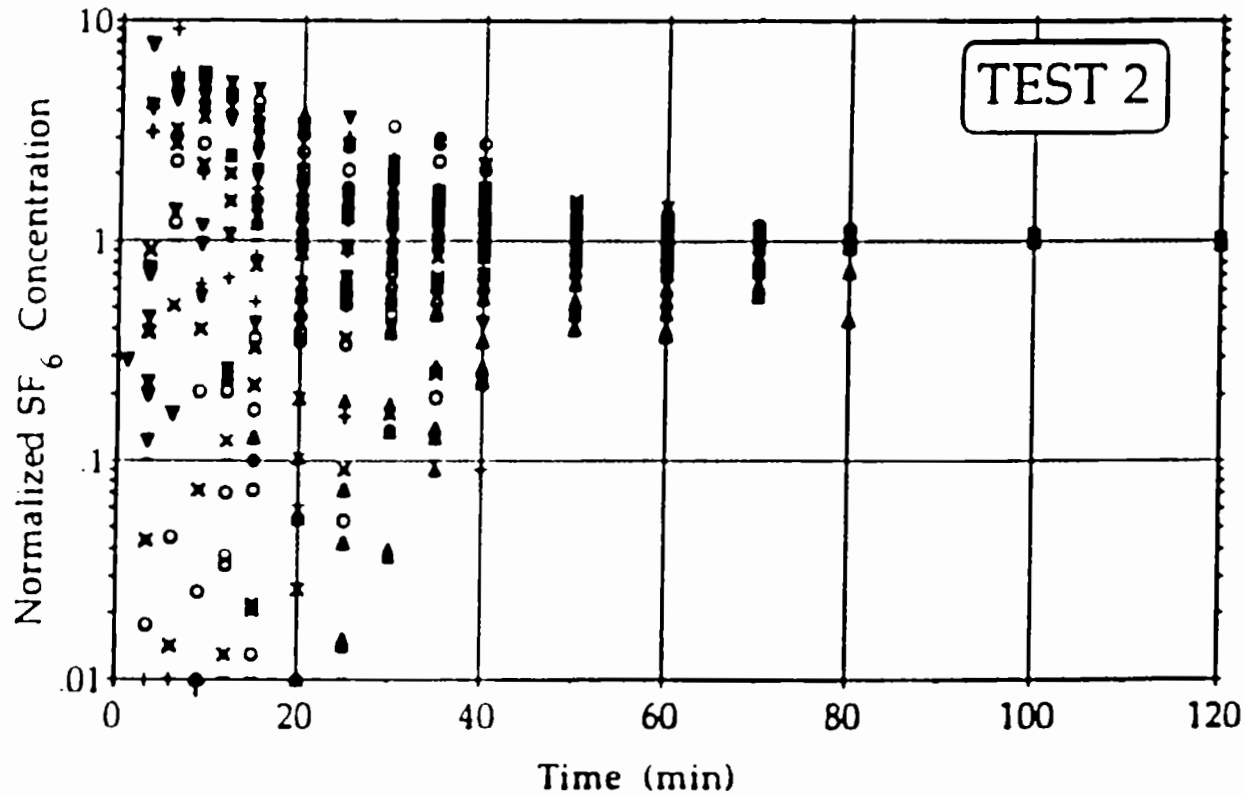


Fig. 3. Scattergram of normalized tracer gas concentration versus time under nearly isothermal conditions. The tracer gas was released at time = 0 minutes. The symbols represent different sampling zones: Δ \Rightarrow core at 76 cm height; \circ \Rightarrow core at 160 cm height; ∇ \Rightarrow core at 206 cm height; \times \Rightarrow corners; and $+$ \Rightarrow surfaces.

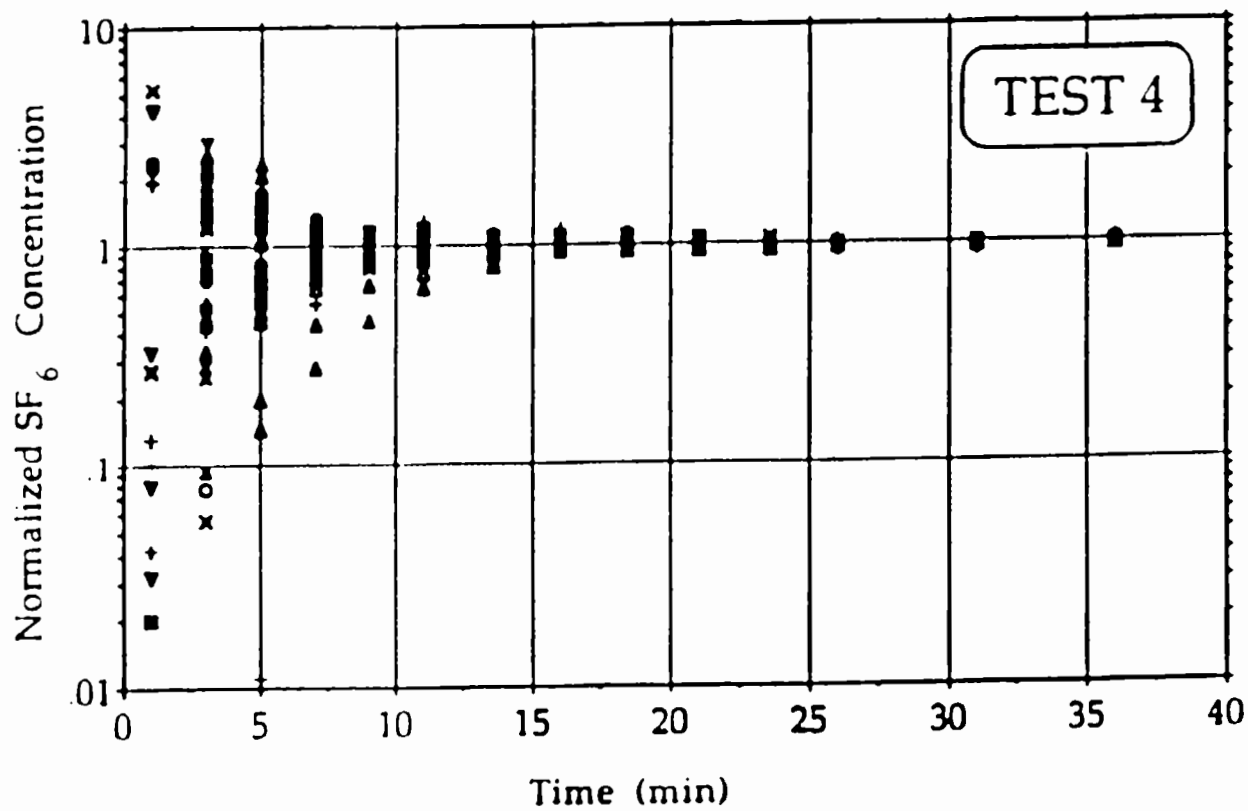
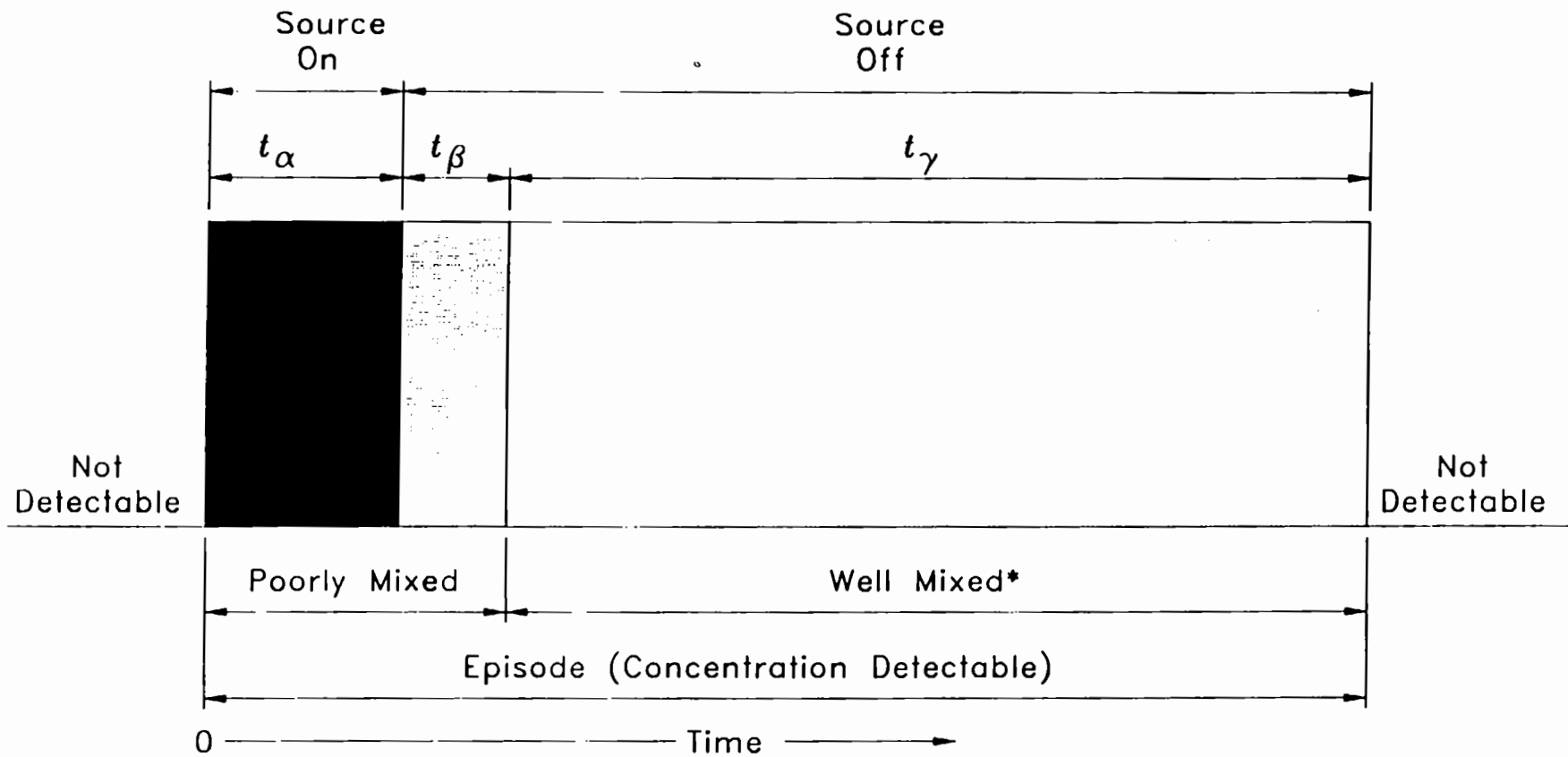


Fig. 4 Scattergram of normalized tracer gas concentration versus time with 500-W heater operating. See caption to Fig. 3 for symbol legend.



* Baughman-Gadgil-Nazaroff criterion

Figure 5. Schematic representation of three concentration phases of a pollutant emitted into a room. Concentration is not detectable after t_γ .

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16. ABSTRACT <p>The modelling of the indoor concentration distribution produced by sources and sinks of pollutants is complicated by nonuniform mixing within the indoor settings. Two common approaches to predicting the concentration distribution are to either treat the indoor volume as containing multiple compartments with uniform mixing within each, or to treat the entire indoor volume as a single uniformly mixed compartment with an empirical mixing factor m that is introduced to correct for nonuniform mixing. We review the literature on m and show that this empirical approach violates a basic principle of conservation of mass.</p> <p>We propose a new conceptual model for the case of a source of pollution in an indoor setting by defining the source operating conditions within three periods, t_0, t_1, and t_2, where t_0 is the time while the source is emitting, t_1 is the time after the source stops emitting, but while the concentration distribution is nonuniform in the indoor setting, and t_2 is the time from the point where the indoor concentration becomes uniform until it becomes nondetectable above the background value. We define the state of uniform concentration as when the coefficient of variation of concentration (standard deviation/mean) throughout the volume becomes less than 0.1. We show, that with this definition, the assumption of uniform mixing for the entire volume will not lead to serious errors in predictions of exposures if a subject is moving about in the indoor setting and $t_2 \gg t_0 + t_1$.</p>					
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