Outdoor Sources of Indoor Air Pollution

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Conservation measures that seal a building, such as storm window installation, can significantly reduce its energy requirements. These measures also protect its occupants from air pollutants having outdoor sources but amplify any harmful effects of those generated indoors. Which effect is greater?

Since it is inadequate to consider pollution levels constant, we assume that they follow daily cycles and can thus be well represented by Fourier series. We conclude that the indoor concentration of any pollutant generated solely outdoors also follows a daily cycle but its maximum lags behind and is lower than the outdoor maximum to an extent depending in an inverse manner on v, the air exchange (ventilation + infiltration) rate. A simple measure of the daily variation of pollutant concentrations and indoor production rates can be derived from their Fourier series and used to test whether these quantities can be assumed constant.

Although average daily indoor and outdoor pollutant concentrations of any pollutant are the same if there are no indoor sinks, lowering v will still protect a building's occupant if: (1) the outdoor peak or variation above its average is much greater than its average, and (2) the peak is short-lived.

Lowering v probably raises indoor average and peak pollutant concentrations from all indoor sources by at least as much as it lowers only peaks from just one outdoor source, rush hour traffic, thus increasing indoor pollutant levels.

OUTDOOR SOURCES OF INDOOR AIR POLLUTION

By designing new buildings and retrofitting existing ones to conserve energy, we can probably save 25% of the amount of fuel needed for their heating and cooling [1]. Many states are currently considering adopting regulations based on American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 90-75 [2] that set minimum levels of insulation and envelope tightness for new buildings [3]. The U.S. Department of Housing and Urban Development (HUD), with help from other agencies, is formulating energy conservation performance goals under the Energy Conservation Act of 1976 [4] that will apply to virtually all new residential and commercial buildings in the U.S.A. These goals will require increased insulation and envelope tightness but will leave the exact proportion of these and other conservation measures to the builder's discretion. We have described elsewhere [5, 6] an approach to measure the relative energy conserving effectiveness of these two methods. Both can have significant health effects on millions of people [5, 7, 8] that need to be carefully examined before widespread adoption of new building codes. Otherwise there could be a repetition of the mobile home situation, in which HUD set standards for infiltration heat loss in mobile homes [3], leading to increased indoor formaldehyde levels due to increased retention of emissions from building materials [9].

Buildings can trap pollutants released indoors by cooking, smoking, insulation and other building materials, chemicals like paint remover and insecticides, and possibly heating [8, 10 - 12]. If the air exchange rate (the air flow rate into or out of a building per unit time per unit indoor air volume = infiltration rate + ventilation rate = v) is decreased from 1 to ¼ air change/hour (ach), pollutant concentrations can be increased by as much as fourfold [5]. In addition to its beneficial energy saving effect, it could be argued that lowering

v has two beneficial health effects that compensate for increased pollutant retention: (1) less heating system operation is required for maintenance of a given indoor temperature, resulting in a lower pollution production rate. We have concluded elsewhere [5, 6] that the lower heating rate does not fully compensate for increased pollutant retention; indoor pollutant levels can still rise 2½-fold when v is reduced from 1 to ¼ ach; (2) building occupants are protected from pollutants originating outdoors. For example, indoor concentrations of total oxidants, NO, NO_2, CO, peroxyacetyl nitrate and particulates in 11 buildings in an area of southern California highly polluted during rush hour traffic were found to parallel outdoor concentrations and to rise indoors when v was increased [13].

We examine the second point in this paper and find that, in general, the harmful effects of a tight envelope retaining indoor-produced pollutants outweigh any beneficial effects of excluding those produced outdoors.

We first derive a general model relating the concentration of any pollutant to its outdoor concentration and indoor production rate and illustrate its use in two simple cases. We then approximate the outdoor concentration by a simple step function and estimate the extent of protection offered against outdoor-produced pollutants by tightening building envelopes.

THE DEPENDENCE OF INDOOR POLLUTANT CONCENTRATION ON INDOOR PRODUCTION RATE AND OUTDOOR CONCENTRATION

If the outdoor concentration of a pollutant, P, remains constant for a long time, its indoor concentration should approach its outdoor concentration. However, indoor concentrations are usually lower than those outdoors [11, 14]. There are probably two major reasons: (1) P is removed by the walls or furniture of the house, or in reactions with other pollutants, and/or (2) the outdoor concentration changes before the indoor concentration has a chance to attain a steady state concentration equal to the outdoor concentration. Thus, to adequately treat the case of outdoor sources of pollution, we cannot assume the outdoor concentration constant.

The equation for the indoor concentration of P is given by [5]:

$$p' = k - v(p - p_{out}) \qquad (1)$$

where p = indoor concentration of pollutant P, $p' = dp/dt$, k = indoor rate of formation of P/unit volume of the house, v = air exchange rate (defined above), and p_{out} = outdoor concentration of P. We assume that p_{out} varies diurnally; that is, it is periodic with a period of 24 hours. It is reasonable to assume that p is also diurnal. (We also assume, as we have previously done [5], that indoor and outdoor air are uniform and that v is constant. We will not deal at all with the possibility of indoor reactions of P, that is, of sinks.)

If P is produced solely outdoors then $k = 0$. However, since many pollutants (SO_2, NO_x, CO and particulates, for example) are produced both indoors and outdoors, we shall not assume that $k = 0$ in our general treatment. In fact, with no additional difficulty, we can solve eqn. (1) when k is not even assumed to be constant, but only diurnal.

To say that p, p_{out} and k are periodic is to say that they can be represented very well by Fourier series.

We adopt the following convention: a bar over any quantity denotes its average value over time. For example, suppose f is any Fourier series:

$$f = A_0 + \sum_1^\infty A_n \cos n\theta + \sum_1^\infty B_n \sin n\theta$$

where θ is a variable, A_0, A_n and B_n are constants. Then: $\bar{f}$ = average value of f. Note the vary useful result that for any Fourier series f, $\bar{f} = A_0$.

Thus we may write:

$$p_{out} = p_0 + \sum A_n \cos n\theta + \sum B_n \sin n\theta \qquad (2)$$

$$k = \bar{k} + \sum C_n \cos n\theta + \sum D_n \sin n\theta \qquad (3)$$

$$p = \bar{p} + \sum a_n \cos n\theta + \sum b_n \sin n\theta \qquad (4)$$

where $p_0 = \overline{p_{out}}$, t = time, t_0 is some fixed time during the day.

$$\theta = 2\pi \frac{t - t_0}{24\,h} = 0.26\,(t - t_0)/h \qquad (5)$$

The coefficients A_n, B_n, C_n and D_n must be defined *empirically*.

Substituting eqns. (2), (3) and (4) into eqn. (1) we obtain:

$$\theta'(\sum nb_n \cos n\theta - \sum na_n \sin n\theta) =$$
$$[(\bar{k} - v(\bar{p} - p_0)] + \sum(\alpha_n - va_n) \cos n\theta +$$
$$\sum(\beta_n - vb_n) \sin n\theta \qquad (6)$$

where:

$$\theta' = \frac{d\theta}{dt} = \frac{\pi}{12\ h} \cong 0.26/h \tag{7}$$

$$\alpha_n = C_n + vA_n \tag{8a}$$

$$\beta_n = D_n + vB_n \tag{8b}$$

(Notice that $k + v\,p_{out} = (\bar{k} + v\bar{p}) + \Sigma\ \alpha_n \cos n\theta + \Sigma\ \beta_n \sin n\theta$ = the rate of addition of pollutant to the house while $v\ (\Sigma\ a_n \cos n\theta + \Sigma\ b_n \sin n\theta)$ = the rate of its removal and the sum of these two terms = the right side of eqn. (6).)

Equating coefficients on both sides of eqn. (6) gives us:

$$\bar{k} - v(\bar{p} - p_0) = 0$$

$$\theta' n b_n = \alpha_n - v a_n$$

$$-\theta' n a_n = \beta_n - v b_n$$

from which we get:

$$\bar{p} = p_0 + \frac{\bar{k}}{v} \tag{9}$$

and the pair, for each n, of simultaneous equations:

$$v a_n + \theta' n b_n = \alpha_n \tag{10a}$$

$$\theta' n a_n - v b_n = -\beta_n \tag{10b}$$

(Notice that the solution for $\bar{p}$ in eqn. (7) coincides with the steady-state solution for p when p_{out} and k are constant [5].)

A solution to the set of simultaneous eqns. (8) is given by:

$$a_n = \frac{\begin{vmatrix} \alpha_n & \theta'n \\ -\beta_n & -v \end{vmatrix}}{D} = \frac{v\alpha_n - \theta' n \beta_n}{v^2 + (\theta')^2 n^2} \tag{11a}$$

$$b_n = \frac{\begin{vmatrix} v & \alpha_n \\ \theta'n & -\beta_n \end{vmatrix}}{D} = \frac{\theta' n \alpha_n + v\beta_n}{v^2 + (\theta')^2 n^2} \tag{11b}$$

where:

$$D = \begin{vmatrix} v & \theta'n \\ \theta'n & -v \end{vmatrix}$$

We introduce another notational convention: for any quantity, the subscripts max and min denote its maximum and minimum values respectively. For example, $p_{out,max}$ = the maximum value of p_{out}. We are interested in p_{max} and in how much later it occurs than $p_{out,max}$.

(the "lag time"). Let t_m be the time at which p_{max} occurs and t'_m the time at which $p_{out,max}$ occurs. t'_m will probably be known empirically. Then the lag time is $t_m - t'_m$, and t_m can be derived simply from $\theta_m = (\pi/12\ h)\ (t_m - t_0)$ (eqn. 5). θ_m is a solution, θ, of $p' = 0$; p' is given by the left side of eqn. (6).

Unless p is given by a particularly simple Fourier series (for example, $p = \bar{p} + a \cos\theta + b \sin\theta$), it will be very difficult to solve for θ_m. For this reason, and because p can be expected to be near its maximum for only brief periods of time, we would like to have another measure of how much we may expect p to vary over a 24 hour period. Such a measure is provided by σ, the standard deviation of p about its mean; σ is particularly easy to derive for a Fourier series. In general:

$$\sigma^2 = \sigma^2(p) = \overline{p^2} - \bar{p}^2 = \frac{1}{24\ h} \int_0^{24\ h} p^2 dt - \bar{p}^2$$

Since p is a Fourier series with a period of 24 h

$$\frac{1}{24\ h} \int_0^{24\ h} p^2 dt = \bar{p}^2 + \tfrac{1}{2} \Sigma\ (a_n^2 + b_n^2)$$

so that

$$\sigma = \frac{1}{\sqrt{2}} [\Sigma\ (a_n^2 + b_n^2)]^{1/2} \tag{12}$$

(For example if $p = \bar{p} + a \cos\theta$, then $p_{max} - \bar{p} = |a|$ but σ is only $|a|/\sqrt{2}$.)

We now have a test for determining when we can assume that p_{out} and k are constant: p_{out} may be considered to be constant whenever $(1/\sqrt{2})\ (\Sigma\ A_n^2 + B_n^2)^{1/2}$ is much smaller than p_0. Similarly k_{out} may be taken as constant whenever $(1/\sqrt{2})\ (\Sigma\ C_n^2 + D_n^2)^{1/2}$ is much smaller than $\bar{k}$.

What time does t_0 represent? t_0 should be chosen to simplify p_{out} or k as much as possible. For example, if k refers to the rate of production of a pollutant due to the operation of a heating system, then:

$$k = \bar{k} - D\cos\left(2\pi\frac{t - t_0}{24\ h}\right)$$

where D is a positive constant and t_0 is chosen to be that time of the day when the outside temperature is at its maximum. (If t_0 is chosen 6 h earlier, then we can replace cos by sin.) For some pollutants it might be possible to choose t_0 so that p_{out} varies sinusoidally with $t - t_0$:

$$p_{out} = p_0 + b_1 \sin \left(2\pi \frac{t - t_0}{24\text{ h}} \right)$$

For other pollutants there might be some time during the day around which p_{out} is distributed symmetrically; for example, if p_{out} achieves peaks of comparable size and duration during the morning and afternoon rush hours, t_0 should be chosen to be either the midpoint between these peaks or 12 hours later. Figure 1 illustrates this situation and another, in which there is a single broad peak. If p_{out} is symmetric about t_0 (or equivalently about $t_0 + 12$ h) then all the $B_n = 0$ and only cosine terms appear in p_{out}.

Unfortunately, it would be wholly fortuitous if these special points in time for k and p_{out} should coincide; in general, there is no reason that they should. Thus if t_0 is chosen to simplify k, one could not expect any simplification to result in p_{out} and *vice versa*. We will assume below that p_{out} is symmetric because our results will be more clearly illustrated for this case than for the general case, and because many pollutants probably have a sym-
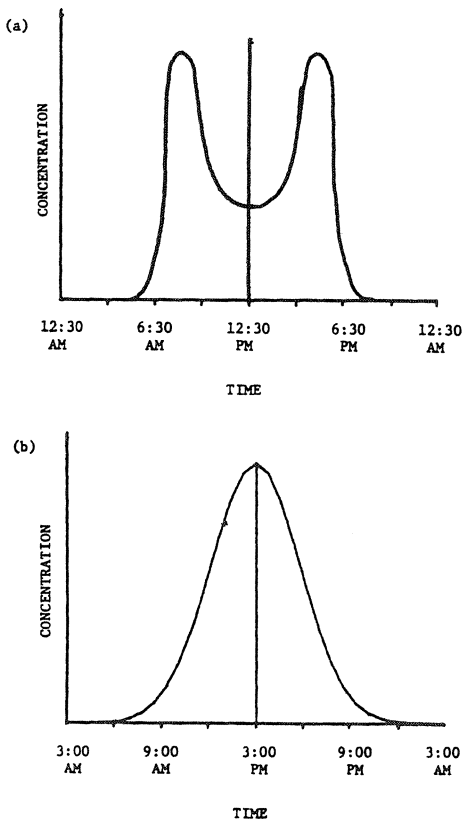
metric concentration profile (as in Fig. 1 for example).

SYMMETRIC p_{out}

Since we are focusing our attention on outdoor sources of indoor pollution, we may assume that there are no indoor sources, or $k = 0$. Then, according to eqns. (4), (9) and (11), p is given by:

$$p = p_0 + v\Sigma \frac{A_n}{v^2 + (\theta')^2 n^2} (v \cos n\theta + \theta' n \sin n\theta) \tag{13}$$

and by eqn. (12), σ is given by:

$$\sigma = \frac{v}{\sqrt{2}} \left[\Sigma \frac{A_n^2}{v^2 + (\theta')^2 n^2} \right]^{1/2} \tag{14}$$

Notice that although p_{out} is symmetric, p is not. This is due to the terms of the form $b_n \sin n\theta$, each of which modifies the phase of the corresponding cos term. The total phase difference resulting from $\Sigma b_n \sin n\theta$ is what we previously called the "lag time". As we might have expected, p increasingly resembles p_{out} in both magnitude and phase as v becomes large (*i.e.* $\lim_{v \to \infty} p = p_{out}$). We are more interested, however, in the behavior of p when v is small.

As v becomes small compared to $\theta' = 0.26/\text{h}$, $v \cos n\theta$ becomes negligible compared to $\theta' n \sin n\theta$, and v^2 becomes negligible in the denominator terms of eqns. (13) and (14): $v^2 + (\theta')^2 n^2$. Thus for $v \ll 0.26$ ach:

$$p \cong p_0 + v \Sigma \frac{A_n}{\theta' n} \sin n\theta \to p_0 \text{ as } v \to 0 \tag{15}$$

$$\sigma \cong \frac{1}{\sqrt{2}} \frac{v}{\theta'} \left(\Sigma \frac{A_n^2}{n^2} \right)^{1/2} \to 0 \text{ as } v \to 0 \tag{16}$$

This shows that as v decreases below $\frac{1}{4}$ ach: (1) p becomes increasingly out of phase with p_{out} (the cos terms of p become increasingly insignificant so that p is effectively left with sin terms while p_{out} has only cos terms), (2) the oscillations about p_0 become smaller, and (3) $\bar{p} = p_0$ is unaffected; that is, p becomes more nearly constant. This is shown in Fig. 2, where p is plotted for several values of v and compared with the specific p_{out} given in the next section.

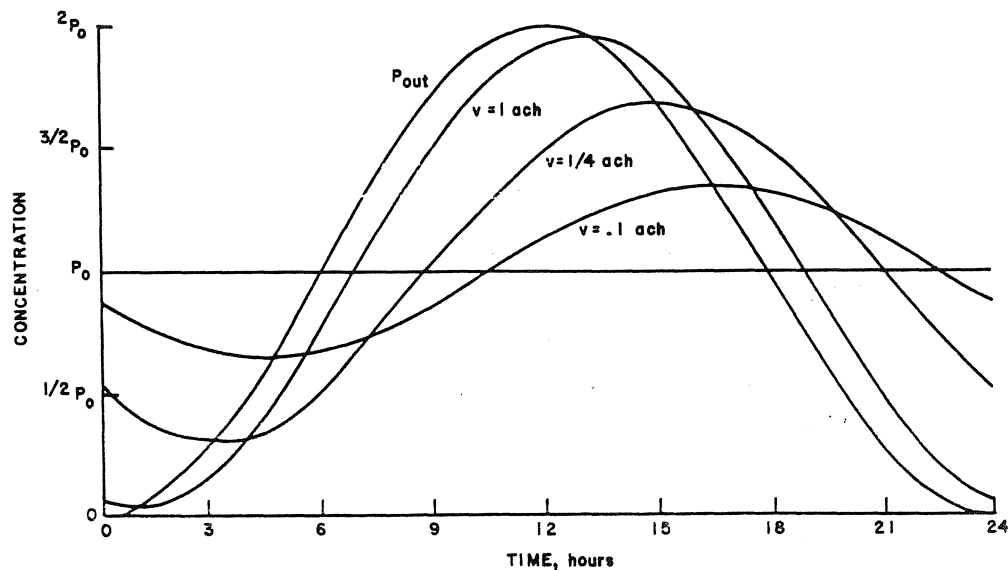In Fig. 3 we show an actual profile of the CO concentration inside a house in Hartford,

(a)

CONCENTRATION

12:30 AM   6:30 AM   12:30 PM   6:30 PM   12:30 AM

TIME

(b)

CONCENTRATION

3:00 AM   9:00 AM   3:00 PM   9:00 PM   3:00 AM

TIME

Fig. 1. Symmetric pollutant concentration profiles: (a) rush hour-like; (b) single broad peak.

Fig. 2. $p_{out} = p_0 \, (1 - \cos \theta)$ and $p = p_0 \, (1 - \{v/(v^2 + (\theta')^2)\} \times (v \cos \theta + \theta' \sin \theta))$ for several different v. ($\theta' = \pi/12$ h and $\theta = \theta' t$).
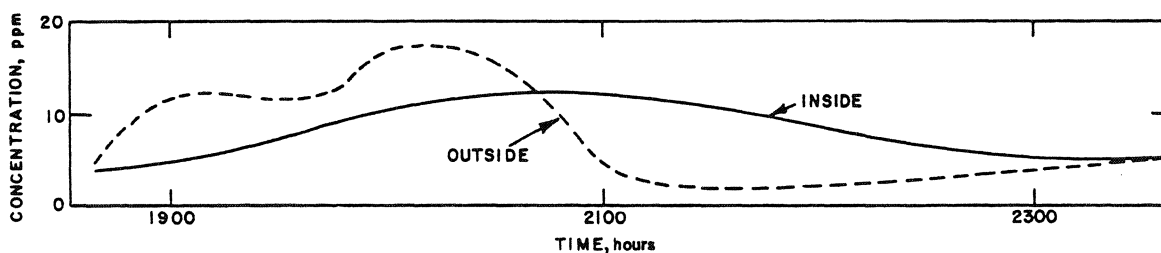

Fig. 3. Carbon monoxide concentrations for house in Hartford, Connecticut; September 22, 1969 [15]. (Reproduced from ref. 14.)

Conn. [14,15]. As the model presented above predicts, $p < p_{out}$ when p_{out} is near $p_{out,max}$ and $p > p_{out}$ when p_{out} is near $p_{out,min}$. A similar result is reported for SO_2 [16]. Often, however, this behavior is only approximated; while p continues to be smaller than p_{out} for CO, SO_2, NO_x and suspended particulate matter when p_{out} is large, p is either approximately equal to or a little smaller than p_{out} when p_{out} is small and $\bar{p} < p_{out}$ [11, 17]. Some possible explanations for this are that v is not constant throughout the day and neither indoor nor outdoor air is completely uniform, as we have assumed. Instead, there is a pollution gradient between the ultimate pollution source and the interior of the house. Unless measurements are taken just inside and outside an air channel of the house, the average concentration outside would be expected to be greater than the average concentration inside. Another complication is that the house contains sinks for some pollutants like SO_2 and particulates [11]. (If

these sinks are located in the cracks of the house, as they may be for particulates, sealing up these cracks may actually remove sinks.)

Thus, at best, lowering v may have some protective value in reducing peaks of concentrations of externally generated pollutants. This will only occur when p_{max} or σ is very large compared to p_0, and as we shall see below, only when the pollution peak is transient. By contrast, lowering v raises the average concentration of internally generated pollutants [5] no matter what their particular profiles.

In the next section we obtain some quantitative estimates of the reduction in p due to lowering v; we then derive conditions for when lowering v has a maximal beneficial effect.

p_{out} IS SINUSOIDAL

Actually, it will be more convenient to represent p_{out} as:

$$p_{\text{out}} = p_0 - A \cos \theta, A > 0 \qquad (17)$$

than as $p_0 + A \sin \theta$; the only difference in these profiles is a phase difference of 6 h; all the important parameters such as the lag time, $p_{\max}$ and σ are identical.

We choose A as large as possible compared to p_0, so that lowering v will have the greatest possible effect. Since $p_{\text{out}} \geq p_{\text{out,min}} = p_0 - A \geq 0$, A must be no greater than p_0. We will take $A = p_0$. Equation (17) now becomes:

$$p_{\text{out}} = p_0 (1 - \cos \theta) \qquad (18)$$

and the solution (13) is given by:

$$p = p_0 - p_0 \frac{v}{v^2 + (\theta')^2} (v \cos \theta + \theta' \sin \theta) \quad (19)$$

We plot p_{out}/p_0 and p/p_0 for several values of v, in Fig. 3. We also have, from eqn. (14):

$$\sigma = \frac{p_0 v}{\sqrt{2}(v^2 + (\theta')^2)^{1/2}} \qquad (20)$$

We can now calculate $p_{\max}$ and the lag time. Let $t_0 = 0$. Then $p_{\text{out,max}}$ occurs at:

$$t_m' = 12 \text{ h}$$

We need p':

$$p' = \frac{p_0 v \theta'}{v^2 + (\theta')^2} (v \sin \theta - \theta' \cos \theta)$$

Setting $p' = 0$ we obtain θ_m :

$$v \sin \theta_m = \theta' \cos \theta_m$$

$$\tan \theta_m = \frac{\theta'}{v}$$

$$\theta_m = \theta' t_m = \text{arc tan} \frac{\theta'}{v} \qquad (21)$$

There are two solutions to eqn. (21); t_m is the greater of these; the other solution, occuring 12 hours earlier, is the time when $p = p_{\min}$. Choosing the correct solution of eqn. (21), we get:

$$\text{"lag time"} = t_m - 12 \text{ h} = \frac{1}{\theta'} \text{ arc tan} \left(\frac{\theta'}{v} \right) -$$

$$12 \text{ h} \qquad (22)$$

Substituting eqn. (21) into eqn. (19) we obtain:

$$p_{\max} = p_0 + p_0 \frac{v}{(v^2 + (\theta')^2)^{1/2}} \qquad (23)$$

Comparing eqns. (20) and (23) we see that:

$$\sigma = \frac{1}{\sqrt{2}} (p_{\max} - p_0) \cong 0.7 (p_{\max} - p_0) \qquad (24)$$

As an approximation, since $p > p_0$ about as often as $p < p_0$, we may consider that p has an effective concentration of $p_0 + \sigma$, for half of each day and of $p_0 - \sigma$ for the other half. In Table 1 we calculate lag times, p/p_0, and σ/p_0 for various values of v; we include the extreme cases $v = 0$ and $v = \infty$. As expected, all the parameters approach their values for these extreme cases as v becomes very small or large, respectively. Note that for $v = \frac{1}{4}$ ach, which is very close to θ', the lag time is midway between its two extreme values; this is also as expected from the discussion in the last section.

TABLE 1

The effects of v on outdoor generated indoor air pollution when $p_{\text{out}} = p_0 (1 - \cos \theta)$

v (ach)	lag time (h)	$\dfrac{p_{\max}}{p_0}$	$\dfrac{\sigma}{p_0}$
0 (limit)	6	1	0
0.1	5:54	1.36	0.25
¼	3:05	1.69	0.49
½	1:51	1.89	0.63
1	0:59	1.97	0.68
2	0:30	1.99	0.70
∞ (limit)	0	2	0.707

What are the effects of lowering v from 1 to ¼ ach, for example? For $v = 1$ ach, $p = p_{\max}$ 1 h later than $p_{\text{out}} = p_{\text{out,max}}$, and $p_{\max} = 1.97 p_0$. For the half of the day we are interested in (i.e., when $p > p_0$), $p \cong 1.68 p_0$. For $v = \frac{1}{4}$ ach, $p = p_{\max}$ 3 h later than $p_{\text{out}} = p_{\text{out,max}}$, $p_{\max} = 1.69 p_0$ and for the interesting half of the day $p \cong 1.49 p_0$. Thus, $p_{\max}$ is reduced 14%, and for half of each day, the effective concentration is reduced by 12%. $\bar{p}$, of course, remains unchanged at p_0. In contrast, if P were produced exclusively indoors at a rate independent of v [5], then for the same reduction of v, its average concentration would increase 300%! (150% if heating systems produce P because they operate less if v is reduced [5].)

We don't wish to give the impression that this result is a general one. The shape of p_{out} is much more important for an analysis of p than the shape of k. The reason for this is that

since $\bar{p}$ changes when it is due to k, but not when it is due to p_{out}, any oscillations about average values are more important in the latter case. For example, in the profile we analyzed in detail above, an examination of Table 1 will reveal that the orders of magnitude of p_0, $p_{out,max}$ and σ are similar. Figure 2 shows that the breadth of the peak in p_{out} (the time it takes for p_{out} to rise from ½ of its peak height above average, 3/2 p_0, through its peak, 2 p_0, and back down to 3/2 p_0) is 8 h. We will show in the next section that if we increase $p_{out,max}$ relative to p_0 and decrease the breadth of the peak sufficiently, then lowering v may be beneficial in protecting against high outdoor pollution levels.

HEALTH BENEFITS OF LOWERING v

In order to achieve a significant reduction in p_{max} when v is lowered, $p_{out,max} - p_0$ must be much larger than p_0; otherwise even the complete elimination of the peak at t_m will have little effect on p_{max}. (Since $p_0 \leqslant p_{max} \leqslant p_{out,max}$, p_{max} will be close to p_0 if $p_{out,max}$ is.) In addition, the breadth of the peak at t_m must be small. We can see this as follows.

If there are no indoor sources of P, then the essential features of p can be derived from eqn. (1): (1) p increases ($p' > 0$) whenever $p < p_{out}$, (2) p reaches its maximum when $p = p_{out}$, and (3) p decreases ($p' < 0$) whenever $p > p_{out}$.

The actual CO profile in Fig. 3 displays these features, as do the profiles in Figs. 2 and 4.

Now suppose that p_{out} has a sharp peak at time t_m (Fig. 4). If v is small, p will not increase very much before it intersects p_{out} during the descent of the latter from its maximum, after which p must also decrease. (Figure 4 illustrates the behavior of p for relatively small and large v.)

How small must the breadth of the peak be in order for the outdoor concentration of pollutant to be significantly reduced?

Let us approximate any peak of breadth w and height h by the step function (shown in Fig. 5):

$$p_{out} = h \text{ for } 0 \leqslant t \leqslant w$$

$$p_{out} = 0 \text{ elsewhere}$$

Let us further assume that $p = 0$ at time $t = 0$. Then, we know [1] that p_v (we write p_v for p to emphasize its dependence on v) achieves its maximum at time w and that:

$$p_{v,max} = h(1 - e^{-vw}) \tag{25}$$

In Table 2 we show how large w can be so that p remains smaller than certain multiples of h, for $v = ¼$ ach. For example, if we don't want p to exceed ¼ h, then p_{out} must not remain equal to h for longer than 1.09 h (the breadth of any peak in p_{out} should be smaller than about 1 h).
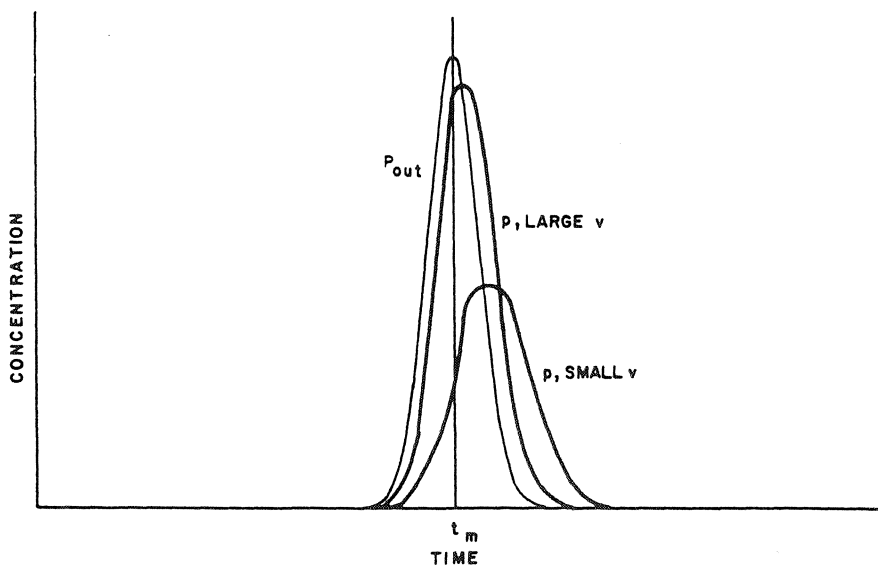

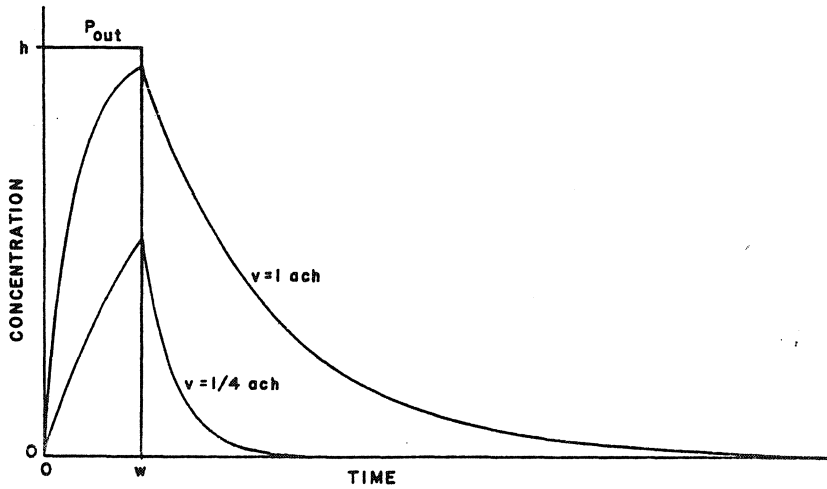Fig. 4. Pollutant concentration profile with a single sharp peak at time t_m.

Fig. 5. Approximation of a pollutant concentration profile with a single sharp peak by the step function, p_{out}. $p_{out} = h$ for $0 \leqslant t \leqslant w$, $= 0$ elsewhere. p is given for $v = \frac{1}{4}$ and 1 ach.

TABLE 2

Maximum breadth of peak in order that $p \leqslant \alpha h$ when $v = \frac{1}{4}$ ach

α	maximum w (h)
0.1	0:25
0.25	1:09
0.5	2:46

How much protection can we get by lowering v from 1 to $\frac{1}{4}$ ach? We take the ratios, R, of $p_{1,max}$ to $p_{1/4,max}$:

$$R = \frac{p_{1,max}}{p_{\frac{1}{4},max}} = \frac{1 - e^{-wh}}{1 - e^{-w/4h}} \qquad (26)$$

Now for $0 < w \leqslant 0:50$ h, $3 \leqslant R < 4$,

for $0:50$ h $< w \leqslant 2:26$ h, $2 \leqslant R < 3$,

and for $2:26$ h $< w < 24$ h, $1 < R < 2$.

If v is only reduced to $\frac{1}{2}$ from 1 ach, then R is always <2.

Thus we see that as long as the peak height is less than $2\frac{1}{2}$ h, there will be at least a two-fold reduction of p caused by lowering v from 1 to $\frac{1}{4}$ ach. Pollutants that are most likely to exhibit this kind of transient behavior, that is, attain short-lived peaks that are enormous relative to their average concentration, are automobile emissions during rush hour traffic.

DISCUSSION AND CONCLUSIONS

We have developed a model relating indoor air pollutant concentrations to outdoor concentrations and to v, the air exchange rate, that is consistent with reported behavior of NO, NO_2 [13], CO [15, 18], SO_2 [11, 19] and O_3 [20]. The model predicts that indoor concentrations follow outdoor concentrations but maxima and minima lag behind and are not as pronounced as their outdoor counterparts. Reducing v decreases even further the influence of outdoor peaks on indoor levels and increases the lag time but has no effect on average indoor values.

One would like to use the model to compare any reduction in levels of outdoor-generated pollutants resulting from lowering v with increases of those originating indoors. Relative effects depend on distance from a highway, meteorological conditions and the nature of indoor pollutant sources. Unfortunately the necessary data are either non-existent or too inadequate for a complete analysis. While the relative importance of the two effects undoubtedly varies among buildings, we believe indoor sources are usually more important.

Lowering v may significantly reduce indoor pollutant concentrations due to only one source, rush hour traffic, since it alone among common outdoor sources produces pollutants at a relatively high rate for a short time. By contrast, pollutant levels from all indoor sources would be raised.

At present, v is estimated to be about 0.7 - 1 ach [5]. With extensive retrofitting of existing buildings and extremely good construction of new ones, v could be reduced to about 0.2 - 0.25 ach [21], but it is much more likely to be reduced only to about 0.4 - 0.5 ach. Indoor concentrations from rush hour traffic lasting about 2½ h would then be reduced by about 25%.

Concentrations due to all indoor sources would increase by at least this much even if they are produced for only a short time (for example, gas range cooking) and could double if they are produced for a long time (for example, pilot lights, long oven use, frequent smoking or release by building materials) [5, 8]. (To accurately compare absolute changes, we require better data than now exist.)

More people are likely to be affected by increased indoor-generated pollutant retention than by increased exclusion of outdoor pollutants. More people are home during dinner and at night than during rush hours. Furnaces, which may be sources of indoor pollutants [10, 22] are most heavily used at night when it is coldest. Furthermore, pollution from rush hour traffic declines with distance from major roads (meteorological conditions being equal) [18], further reducing the size of the affected population.

Thus the predominant health effects of lowering v are negative. Yet at the same time state and federal governments are encouraging tightening of building envelopes to conserve energy. We should investigate these practices to determine how to implement as safely as possible. For example, there are probably parameters v_1 and v_c defined as follows (for each class of buildings like hospitals, factories and residences): v_c = the lowest safe v when buildings are constructed and furnished according to current practice; v_1 = the lowest safe v when buildings are constructed and furnished to minimize indoor pollutant emissions. Clearly $v_1 < v_c$. We can safely reduce v to v_c (which we speculate to be around ½ ach for residences). Mitigating measures would have to be taken between v_1 (which we speculate to be around 0.2 ach for residences) and v_c. Pilot lights would have to be eliminated (as they should be in any case since they waste natural gas), gas cooking appliances would have to be well ventilated or replaced with electric ones, and certain building materials

that emit fumes would have to be avoided. Further investigation is required to determine the extent to which heating furnaces pollute indoor air and how to mitigate any pollution they cause.

It might be desirable to construct buildings with infiltration rates lower than v_1 in areas with cold climates, but they would then have to be equipped with forced air ventilation systems (possibly with heat pumps to retain heat) to raise v above v_1.

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