development programs are under way through sponsorship of the U.S. Department of Agriculture, National Science Foundation, Southwest Border Regional Commission, Four-Corners Regional Commission, and the state of California.

Germ plasm collections have been made from wild guayule plants in Mexico and Texas. Plantings have been established to test yields, to increase seed supplies, and to conduct plant breeding work. Test plots have been established to determine desirable planting and cultivating practices. Research is being conducted on the possibility of increasing rubber yield by treating guayule plants with plant growth regulators.

The recent development of a seed coating process to promote germination, and the development of selective herbicides, will make direct seeding in field plantations a possibility. Eliminating nursery or greenhouse propagation could produce considerable savings in production costs.

The only guayule yield figures now available are estimates developed during the ERP. During the life of the ERP the 1800 hectares that were planted yielded, per hectare, approximately 480 kg of guayule rubber per year. Kelly (*15*) obtained yields of approximately 860 kg per hectare per year from one test plot in California. Foster *et al.* (*16*) have outlined the state of the art of guayule technology and described present and projected world rubber market conditions and areas of the United States where conditions favor guayule cultivation.

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# Indoor Air Pollution, Tobacco Smoke, and Public Health

James L. Repace and Alfred H. Lowrey

Serious health effects from air pollution have led to federal standards for the regulation of outdoor exposure levels. However, Americans spend about 90 percent of their time indoors (*1*). Thus the levels of indoor air pollution are important in determining total exposure to air pollutants (*2–6*). Indeed, in a recent review article (*4*) it was concluded that indoor air pollution in public office buildings is of greater potential harm than the outdoor variety, and that these exposures may constitute a real threat to the health of many urban people. The U.S. Surgeon General asserted in his report on *Smoking and Health* that tobacco smoke can be a significant source of atmospheric pollution in enclosed areas (*7*). Some 53 million U.S. smokers consumed 615 billion cigarettes in 1978 (*8*). Thus it is apparent that indoor air pollution from tobacco smoke is pandemic.

In the presence of cigarette smoke, many normal nonsmokers experience eye and throat irritation, headache, rhinitis, and coughing; allergic persons report wheezing, sneezing, and nausea as well. Particularly acute symptoms may be found in infants, children, persons with cardiovascular or respiratory disease, and wearers of contact lenses (*7, 9*). Determining the extent of the exposure of nonsmokers to cigarette smoke is important because smoking is a cause of chronic obstructive pulmonary disease, cardiovascular disease, and lung cancer, and is associated with cancers in other parts of the body (*7*); because these diseases also occur in nonsmokers; and because the products of tobacco combustion have been detected in nonsmokers (*10*).

Although measurements of indoor carbon monoxide pollution from smoking are abundant (*7*), published reports of the exposure of the population to the particulate phase of ambient tobacco smoke are rare (*7, 11–13*). Furthermore, a comprehensive theory of the generation and removal mechanisms for tobacco particulates in naturally or mechanically ventilated habitable spaces has not been presented.

We therefore undertook a systematic study of the levels of respirable suspended particulates (RSP) in several common indoor environments in an attempt (i) to determine the relation of these levels to the aerosol from tobacco smoking, (ii) to understand the effect of ventilation on tobacco smoke concentra-


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tions, and (iii) to develop a general model for estimating the range of the public's exposure. Our goal was to provide a quantitative basis for assessing the health hazards to nonsmokers posed by repeated exposure to tobacco combustion products.

## Model Development

To relate the contribution of smoking to indoor RSP requires a model describing the behavior of the tobacco aerosol in indoor spaces. Bridge and Corn (*6*) found that a reduced form of an equation by Turk (*14*) reliably predicts carbon monoxide (CO) concentrations from tobacco smoke in ventilated spaces and so is of major value in assessing the possible hazards in occupied spaces (*11*). The equation is not valid, however, for a pollutant that is affected by physical decay due to adsorption on room surfaces. Penkala and DeOliviera (*15*) showed that decay of the tobacco aerosol in a well-mixed unventilated chamber is exponential.

We modify the Turk equation in differential form by adding a decay term to the removal rate and equating the rate of change of pollutant mass to the algebraic sum of the generation and removal rates.

Table 1. Recommended values of the mixing factor $m$, after Corn (*11*). The mixing factor is an empirical number that accounts for room-specific effects on pollutant transport. Pollutant removal is more rapid in a well-mixed atmosphere (where $m$ is large) than in a poorly mixed, stable one (where $m$ is small). Factors that affect $m$ include type and placement of ventilation grills, ventilation flow rates, inhomogeneous pollutant distribution, barriers, circulation fans, and room traffic.

| Configuration of air supply system | $m$ |
|---|---|
| Perforated ceiling* | 1/2 |
| Trunk system with anemostats | 1/3 |
| Trunk system with diffusers | 1/4 |
| Natural draft and ceiling exhaust fans | 1/6 |
| Infiltration and natural draft | 1/10 |

*This is the best standard condition.

*Summary.* An experimental and theoretical investigation is made into the range and nature of the exposure of the nonsmoking public to respirable suspended particulates from cigarette smoke. A model incorporating both physical and sociological parameters is shown to be useful in understanding particulate levels from cigarette smoke in indoor environments. Observed levels of particulates correlate with the predictions of the model. It is shown that nonsmokers are exposed to significant air pollution burdens from indoor smoking. An assessment of the public health policy implications of these burdens is presented.

The solution yields the density $A(t)$, in micrograms per cubic meter, of smoke in the room as a function of time:

$$A(t) = A_{eq}(1 - e^{-t/\tau}) \qquad (1)$$

where $A_{eq} = G\tau/V$ is the equilibrium concentration of the pollutant in the room, and where the time constant

$$\tau = \frac{\tau_a \tau_v}{m(\tau_a + \tau_v)} \qquad (2)$$

is the mean ventilation time, or the time for the smoke concentration to decrease to $1/e$ of its value (where $e$ is the base of natural logarithms); $V$ is the room volume in cubic meters; $\tau_v = V/Q$ is the ideal ventilation time, or the time required to replace a volume of air equal to the volume of the room by ventilation and infiltration; $Q$ is the volume rate of ventilation and infiltration; $\tau_a$ is the ideal decay time, a time constant associated with the removal of a pollutant from a room through adsorption on surfaces and filtration; and $m$ is the mixing factor, an empirically determined number (*16*) that modifies the ventilation time as $\tau_v/m$, where $m \leq 1$ ($m = 1$ implies ideal mixing). Corn (*11*) suggested values of $m$ for various ventilation systems (Table 1). We postulate that $m$ also modifies the ideal decay time as $\tau_a/m$. The pollution generation rate, in micrograms per minute, is given as $G = nC_0/t_b$, where $n$ is the number of cigarettes being smoked at time $t$; $C_0$ is the total particulate matter (TPM) from both sidestream and exhaled mainstream smoke; and $t_b$ is the duration of cigarette smoking.

Equation 1 has two special cases: (i) in the case of ventilation only ($\tau = \tau_v/m$) it becomes the reduced Turk equation of Bridge and Corn (6), with $m = 1$; and (ii) in the case of adsorption only (the unventilated room), $\tau = \tau_a/m$. Then, if the generation of smoke ceases at time $t_b$, prior to equilibrium, $A$ will decay according to

$$A(t) = A_0 e^{-mt/\tau_a} \qquad (3)$$

where $A_0$ is a constant related to the equilibrium concentration by

$$A_0 = A_{eq}\,[e^{(mt_b/\tau_a)} - 1]$$

Equation 3 becomes the decay equation described by Penkala and DeOliviera (*15*) for $m = 1$.

The modified Turk equation (Eq. 1) contains only measurable quantities, and thus in principle can be used to estimate the concentration of TPM or CO from tobacco smoke (or other indoor air pollutants), as a function of time, for any room for which the pollutant generation rate, volume, and mean ventilation time are known.

## Controlled Experiments

Equation 2 shows that the mixing factor affects the time constant for decay as well as ventilation. Experiments under conditions of known ventilation were therefore necessary to assess the influence of mixing factors, decay time constants, and generation rates on the growth and decay of tobacco smoke particulates. To increase the usefulness of the experimental values determined for the mean ventilation time for the removal of tobacco smoke, we conducted these experiments in actual occupied spaces rather than in experimental chambers.

A piezobalance (TSI model 3500) (*17–19*) was used in sampling the aerosol. It collects respirable particulates (*20*) between 0.01 and 3.0 micrometers in diameter with near 100 percent efficiency (decreasing to 50 percent at 3.5 $\mu$m and to 10 percent at 4 $\mu$m). The sampling rate is 1 liter/min (*18*); the sampling time is variable. Factory-calibrated with welding smoke, the detecting crystal in the instrument used has a sensitivity of 5.74 $\mu$g/min-m$^3$ per hertz. The instrument underestimates the mass concentration of tobacco aerosol by about 15 percent compared to measurements made with low-volume filter sampling techniques. Readings can be affected by changes in humidity; the maximum expected error due to changes in relative humidity when sampling a hygroscopic aerosol (such as tobacco smoke) is given as $\pm$ 10 $\mu$g/m$^3$. The overall instrument error is about $\pm$ 10 percent compared with low-volume filter measurements of welding smoke (*19*). The aerosol from sidestream cigarette smoke (that portion emitted by the burning tip), an important component of many indoor aerosols, is log-normal, with 99 percent of the mass < 1 $\mu$m in aerodynamic diameter and with an initial mass median diameter (MMD) from 0.2 to 1.5 $\mu$m depending on dilution (*20, 21*). The relative particle sizes of fresh sidestream and mainstream smoke (the latter being that portion inhaled by the smoker) are about the same; for ex-

Table 2. Parameters for Eq. 1, as determined with experiments 1 to 3 (unventilated rooms).

| Experiment | $A_{eq}$ ($\mu$g/m³) | $A_0$ ($\mu$g/m³) | $\tau_a/m$ (min) | $m$ | $r^{2*}$ | $C_0$† (mg of TPM) | Cigarette condition |
|---|---|---|---|---|---|---|---|
| 1‡ | 530 | 503 | 10 | 1 | .98 | 12.3 | Smoldered |
| 2‡ | 5178 | 551 | 89 | 1/9 | .42 | 16.0 | Smoldered |
| 3§ | 1773 | 681 | 16.4 | < 1 | .81 | 23.0 | Smoked |

*Coefficient of determination for the decay curve. †The estimated amount of TPM liberated if the entire cigarette had been consumed, according to FTC protocol. The FTC mainstream TPM level for this cigarette is 18 mg (24). ‡$V$ = 21.9 m³. §$V$ = 29 m³.

haled mainstream smoke, particle size is estimated to be ~ 0.8 $\mu$m (MMD). Since the ambient cigarette smoke aerosol is reproducible and coagulates very slowly, it has been used as a test aerosol (21) and in evaluation of heating, air-conditioning, and ventilating systems (22). [The bulk of the ambient tobacco aerosol is probably due to cigarettes, since less than 15 percent of smokers smoke cigars or pipes (23).]

### Unventilated Growth and Decay of Tobacco Smoke

Experiments were carried out to determine the usefulness of Eq. 3, which predicts a rapid decay for good mixing and a slow decay for poor mixing; and also to discover the limits of $\tau_a/m$.

Experiments 1 and 2 were conducted in a wood-panelled den in a private residence. In the geometric center of the room (volume, 21.9 m³), a popular filter cigarette [containing 65 millimeters of tobacco and ranking 94th on the Federal Trade Commission (FTC) scale of tar and nicotine content (17 milligrams of tar and 1 milligram of nicotine) (24)] was ignited and allowed to smolder until 89 percent of its tobacco was consumed. During the first experiment, two box fans (51 centimeters in diameter) with antiparallel exhausts were used to ensure ideal mixing; each fan's exhaust, measured with a Velometer, was 55 m³/min. The growth and decay of the RSP were measured with the piezobalance. Experiment 2 was similar to experiment 1, except that the cigarette was extinguished after 75 percent of its tobacco was consumed and the circulating fans were not used, so that mixing was natural. The results of both experiments are plotted in Fig. 1, with the background levels of RSP subtracted. The data points generally represent 1-minute average values. The differences in mixing dramatically affect the slopes of the decay curves.

The theoretical curves shown in Fig. 1 were generated by fitting the data points from the decay curves to Eq. 3 with a regression analysis; $A_0$ and $\tau_a/m$ were determined and used to calculate the growth curves from Eq. 1, case (ii). The ratio of the slopes of the decay curves for ideal and natural mixing yields the mixing factor for the room. Table 2 gives the values obtained for the various parameters. The value of the mixing factor obtained is in good agreement with the expected value given in Table 1 for the case of infiltration and natural draft. The growth curve for the case of natural mixing (experiment 2) shows a poor fit initially because of the effect of the warm smoke rising to the ceiling and remaining

Table 3. Field survey of indoor RSP in the absence of smoking.

| Locale | Room volume (m³) | Persons per room | Persons per 100 m³ | Indoor RSP level* ($\mu$g/m³) | Average time per RSP sample (min) | Outdoor RSP level† ($\mu$g/m³) | Comment |
|---|---|---|---|---|---|---|---|
| Crepes restaurant (Washington, D.C.) | 124 | 43 | 35 | 29 | 20 | 44 | No smoking section; aroma of frying crepes evident |
| Sandwich restaurant (Laurel, Md.) | 326 | 40 | 12 | 55 | 21 | 40 | No smoking section; near kitchen; three smokers in smoking section |
| Sandwich restaurant (Laurel, Md.) | 326 | 55 | 17 | 51 | 21 | 55 | No smoking section; near kitchen; one smoker in smoking section |
| Fast-food restaurant (Bowie, Md.) | 1,400 | 22 | 1.6 | 38 | 7 | | Aroma of hamburgers frying |
| Private residence (Seabrook, Md.) | 120 | 11 | 9 | 24 | 20 | | Cocktail party; one candle burning 6 m from RSP detector |
| Private residence (Bowie, Md.) | 124 | 1 | 0.8 | 44 | 15 | | One hour after sweeping basement floor |
| Private residence | 22 | 2 | 9 | 24 | 6 | | Natural mixing‡ |
| (Greenbelt, Md.) | 22 | 2 | 9 | 55 | 1 | | Two fans moving 110 m³ of air per minute§ |
| Private residence (Glenn Dale, Md.) | 29 | 7 | 24 | 57 | 5 | | One fan moving 55 m³ of air per minute‖ |
| Conference room (Greenbelt, Md.) | 113 | 10 | 9 | 53 | 10 | | Two fans moving 50 m³ of air per minute¶ |
| Public library meeting room (Bowie, Md.) | 1,415 | 30 | 2.1 | 29 | 30 | | During piano recital |
| Library of Congress (Washington, D.C.) | 27,000 | 130 | 0.48 | 30 | 10 | | Main reading room |
| Church (Bowie, Md.) | 4,224 | 300 | 7 | 30 | 42 | | During Sunday service |
| Bagel bakery (Yonkers, N.Y.) | 510 | 30 | 6 | 25 | 10 | 8 | Aroma of baking bagels evident |
| Private residence (Hawthorne, N.Y.) | 150 | 17 | 11 | 26 | 16 | | During dinner party |

*Mean ± standard deviation for the Washington area samples, 40 ± 13 $\mu$g/m³. †Duration of sampling, 5 minutes. ‡Experiment 2 background. §Experiment 1 background. ‖Experiment 3 background. ¶Experiment 4 background.

out of the detector's range for about 3 minutes. Experiment 3 demonstrated that Eq. 3 is valid under more general conditions, that is, when a cigarette is actually smoked.

We conclude that these experiments show that for the unventilated room, Eq. 3, the reduced form of Eq. 1, is useful in describing the growth and decay of cigarette smoke particulates.

### Ventilated Growth and Equilibrium of Tobacco Smoke

An experiment was conducted in a ventilated conference room of a modern office building to test Eq. 1 in the case of removal of uniformly generated tobacco smoke by both decay and ventilation. The experiment involved measuring the growth of cigarette-generated RSP from background levels to near equilibrium. Analysis of the RSP-versus-time curve determines $\tau$, the mean ventilation time, and $C_T$, the total RSP liberated from the combined sidestream and exhaled mainstream smoke.

The RSP detector was located in the geometric center of the 113-m$^3$ room. Two fans with antiparallel exhausts were used to establish a vigorous circulation of 100 m$^3$/min. The ideal ventilation time $\tau_v$, calculated from the volumetric flow rates of the ventilation system, was 49.2 minutes for a complete change of air. Thirty-two cigarettes were smoked in 49 minutes by a relay of seven smokers, with an average of four persons smoking at any given time. When smoking their own brands, they averaged 9.8 minutes per cigarette; when smoking cigarettes supplied to them, they averaged 5.8 minutes per cigarette. All butts were collected and the amount of tobacco consumed was measured for each cigarette. The estimated mainstream TPM ($M$) (tar plus nicotine) generated by the 32 cigarettes was determined by weighting the TPM values for each cigarette (*24*) by the fraction of tobacco consumed, and adding the results to obtain $M$ = 418 mg [TPM is emitted from cigarettes at a linear rate after the fourth puff (*25*)].

Figure 2 shows the growth against time of RSP from the cigarette smoke. The data points are corrected for background RSP levels and are 2-minute averages. A regression analysis using Eq. 1 yields $A_{eq}$ = 1947 $\mu$g/m$^3$ and $\tau$ = 14 minutes, with a coefficient of determination = .964 (from Eq. 2, $\tau_a$ = 19.5 minutes). Finally, $C_T$, or the total amount of RSP liberated in the room during the entire smoking period, 772 mg, is calculated by using Eq. 1; $C_T/M$ = 1.85. This ratio represents a weighted average for six different brands of filter cigarettes that together commanded a 23 percent share of the market in 1976 (*26*).

From the goodness of fit of the theory to the data and from the observation of predicted interactive behavior among mixing, growth, and decay processes for RSP from cigarette smoke, it appears that all the room-specific factors affecting the removal of tobacco smoke (ventilation, decay, and mixing) can be combined into a single time constant $\tau$, which can be determined for any room by regression analysis of the decay or growth-equilibrium curves, or by calculation from the equilibrium concentration if the smoke generation rate and room volume are known. The ratio of the slopes of the decay curves for ideal and natural mixing yields the mixing factor. We conclude that Eq. 1 is a useful tool for predicting the levels of tobacco smoke in both ventilated and unventilated occupied space.

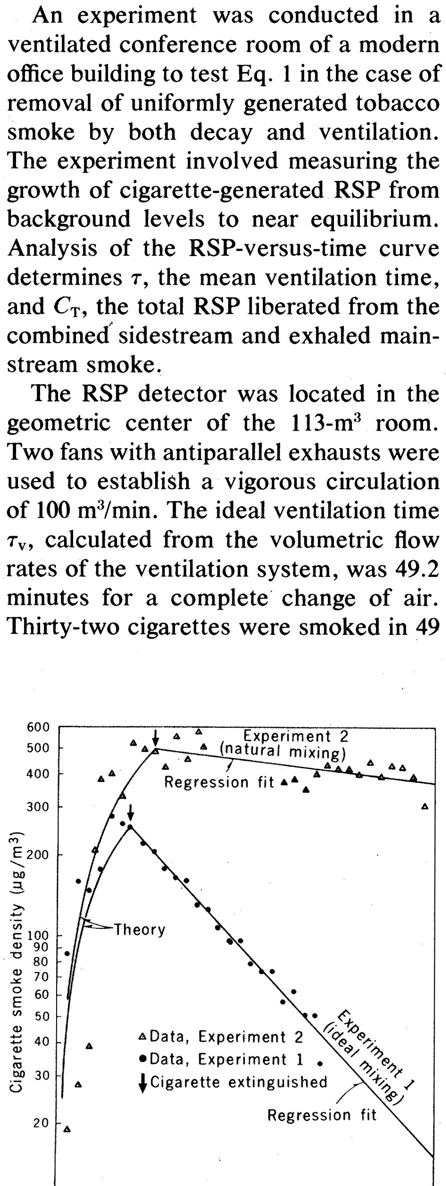


Fig. 1. Theoretical predictions versus experimental results for the growth and decay of RSP from a smoldering, average-tar cigarette in a 22-m$^3$ unventilated room. The dramatic difference in the slopes of the decay curves reflects the difference in room air turbulence (mixing) for the otherwise similar experiments.

### Field Survey of RSP

We now address the complex problem of surveying the levels of RSP indoors and determining what portion of this aerosol may be attributed to cigarette smoke by means of Eq. 1. The problem is complicated by differences in smoking rates, numbers of smokers, room volumes, effective ventilation rates, and the TPM values of various brands of cigarettes. The problem may be simplified by assuming that smoking is a random process when it occurs among large groups of people. It follows that cigarette smoke RSP values may be treated as equilibrium values; that all of the smokers may be treated as habitual smokers who smoke identical average-tar cigarettes in the same way at the same average rate, uniformly distributed over a 16-hour day. An average smoking rate $r$ of two cigarettes per hour is calculated from the 1975 figures for the number of U.S. smokers and the U.S. domestic cigarette consumption (*8*). In 1978, the sales-weighted average mainstream TPM value $M_a$ was 17.6 mg for all the cigarettes sold in the United States (*7*). The estimated emission rate $C_0$ (combined sidestream plus exhaled mainstream TPM) from a habitual smoker is given by $E = 1.85\,rM_a$ = 65 mg/hour, where 1.85, used for the ratio $C_0/M_a$, is taken from the conference room experiment. Physically observable in any field survey of smoking is $n_s$, the number of burning cigarettes (the number of "active" smokers); $n_s$ can be related to the number of habitual smokers $n_{hs}$ by considering that the average time for smoking a cigarette is 10 minutes (*2, 6*). This number and the previously calculated average smoking rate indicate that $n_{hs} = 3n_s$.

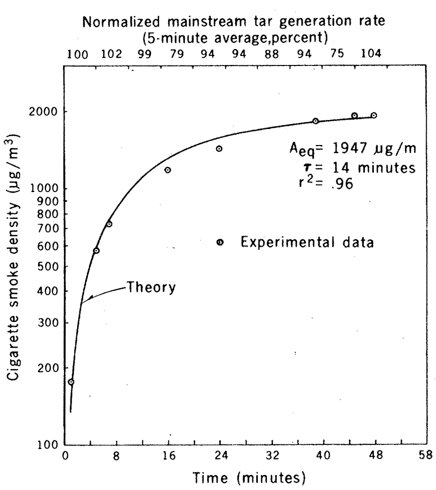


Fig. 2. Theoretical predictions versus experimental results for the attainment of equilibrium $A_{eq}$ for the combined emission of sidestream and exhaled mainstream cigarette smoke from four chain smokers in a 113-m$^3$ conference room with well-mixed ($m \sim 1$) ventilation in a modern office building. Under natural mixing conditions, about 11 habitual smokers would generate an equivalent equilibrated concentration of smoke. This many smokers would be expected in a group of 33 adults (well within the capacity of this 50-person conference room).

From the equilibrated form of Eq. 1, we determine that

$$R = A_{eq} = 650 \frac{D_s}{C_a} \quad (4)$$

where $R$ is the smoker-generated equilibrium RSP level in micrograms per cubic meter, $D_s$ is the density of active smokers (number per 100 m$^3$), and $C_a$ is the effective rate for the removal of cigarette aerosol (air changes per hour), with $C_a = 60/\tau$.

The aerosol sampling described in this article was performed from late March through early June 1978 in the Washington, D.C., metropolitan area. The MMD (seasonal average) of the outdoor urban aerosol for Washington in 1970 was 0.5 $\mu$m, with 90 percent of the aerosol mass less than 3 $\mu$m in aerodynamic diameter and lognormally distributed (*27*).

It is important to note that all of the RSP measurements we report represent time-averaged values.

Factors other than tobacco smoke may contribute to indoor RSP. These include infiltration of outdoor RSP, cooking, dust raised by indoor traffic, and industry. By restricting the sampling to nonindustrial indoor locations where tobacco smoking is absent, the effect of the remaining variables may be assessed. Table 3 gives the RSP levels for several indoor spaces in which smoking did not take place: three restaurants, four private residences, an office building conference room, two libraries, and a church during services. The mean of these measurements is 40 $\mu$g/m$^3$. In three instances, fans were mixing the air at a high rate and RSP levels were elevated, apparently because of dust entrainment. No correlation between the volumetric density of people (occupancy) and RSP is evident. Hemperly (*28*), in sampling RSP in Houston, found similar RSP levels in two schools, a library, and a museum—all nonsmoking areas.

Table 4 gives the results of RSP sampling in nonsmokers' automobiles traveling along two major commuter highways (Route 50 in Maryland and U.S. I-295 in Washington) during the rush hour. The samples were taken on different days and were measured in different vehicles. In all cases, the windows were slightly open and the ventilation fans were running. The mean of the data, 38 $\mu$g/m$^3$, is not very different from the mean of the indoor readings, 40 $\mu$g/m$^3$ (Table 3).

The impact of actual ventilation practice on ambient RSP levels from smoking was investigated at eight restaurants, three cocktail lounges, two bingo games, a dinner-dance, a bowling alley, a sports arena, and a hospital emergency waiting room. For contrast, one unventilated private residence was sampled during a cocktail party. With the exception of the hospital waiting room and the hotel bar, each space sampled represented the major part of the building and was subject to ventilation requirements specified by building codes. Sampling was generally performed well after opening time to ensure that an approximately steady-state level of smoking had been reached.

Table 4. Levels of RSP in nonsmokers' cars during rush-hour traffic on a busy commuter highway in Washington, D.C., measured with the vehicles' windows slightly open and the ventilation fans running. Each car carried four persons and had a volume of 2 m$^3$, so that the occupancy was equal to 200 persons per 100 m$^3$.

| Date | Time | Sampling time (min) | RSP level ($\mu$g/m$^3$) |
|---|---|---|---|
| 23 March | a.m. | 10 | 40 |
| 23 March | p.m. | 35 | 20 |
| 24 March | a.m. | 20 | 54 |
| 28 March | a.m. | 26 | 49 |
| 31 March | a.m. | 8 | 25 |
| Mean ± standard error | | | 38 ± 15 |

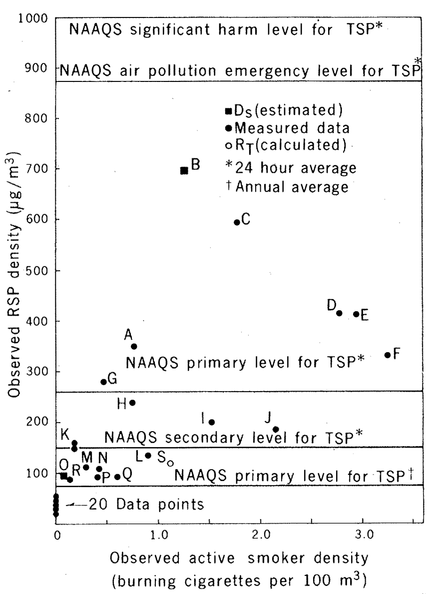


Fig. 3. Results of a field survey of short-term time-averaged levels of RSP in 38 enclosed spaces (see Tables 3, 4 and 5). Levels corresponding to federal standards for TSP are indicated for comparison only. The microenvironments include ten restaurants, three cocktail lounges, two bingo games, a dinner-dance hall, a bowling alley, a sports arena, two libraries, a church, a hospital waiting room, five vehicles, and five residences. The letters A through S correspond to those given in Table 5. The effective air change rates for microenvironments A and S are known from experiments to be $C_a$ = 1.5 and 9.2, respectively.

The piezobalance and a stopwatch were used to take tabletop-level RSP samples for periods ranging from 10 to 50 minutes (mean, 20 minutes). The piezobalance was equilibrated in advance to avoid errors due to changes in temperature or humidity.

The room dimensions were estimated and the number of active smokers was sampled periodically throughout the measurement period and averaged. It was usually not possible to sample the premises when there was no smoking; in most cases, the RSP outside the premises was sampled for comparison. Table 5 gives the results of the measurements. Figure 3 shows the average density of active smokers (defined as the number of burning cigarettes per 100 m$^3$) plotted against the total indoor RSP sampled. As a guide to whether a given datum is "high" or "low," the National Ambient Air Quality Standards (NAAQS) for total suspended particulates (TSP) are also shown. Since a specific averaging time is incorporated into these standards, violation of the standard is not demonstrated here. However, repeated exposure to such elevated levels can lead to "violation" of the annual standards, as will be shown later. Note that all the data for finite smoker density exceeded the level of the annual primary (health-related) NAAQS, whereas none of the data for zero smoker density exceeded this level. Further, the background RSP measured outside the smoking premises suggests that the source of these elevated levels was not the outdoor air. The mean and the standard deviation for the outdoor RSP are 46 ± 13 $\mu$g/m$^3$, and in every case the outdoor level is less than the indoor. In certain cases, indoor controls are available. In bingo game 2, held in the nave of a church, the active smoker density was 0.47 per 100 m$^3$, the occupancy was 3.6 persons per 100 m$^3$, and the RSP density was 279 $\mu$g/m$^3$ (Table 5). By contrast, during the tobacco smoke-free religious services, despite an occupancy of 7.0 persons per 100 m$^3$, 30 burning votive candles, and several processions, the RSP density was 30 $\mu$g/m$^3$. The elevated RSP levels in the bingo game clearly appear to be due to smoking. Similarly, measurements taken in the nonsmoking section of a sandwich restaurant showed considerably lower levels than in the smoking section, indicating that the contribution of smoking to RSP was much larger than the effect of cooking, even at the low cigarette densities shown (Table 5). Figure 3 shows that, in general, RSP levels increase with active smoker density, although there is considerable scatter in the data. The question now is whether Eq. 1 is useful in explaining this scatter.

We hypothesize that the levels of RSP for finite $D_s$ (Fig. 3) are due to near-equilibrium levels of cigarette smoke adding to much smaller background levels, and that the scatter in the RSP levels for fixed cigarette density is due primarily to differences in the mean ventilation time $\tau$. Analyzing the background corrected data given in Table 5, we use Eq. 4 to calculate a range for $C_a$ between 1.2 and 10.7 air changes per hour; $C_a$ is used instead of $\tau$ to facilitate comparison with building code–specified ventilation rates. The range determined for $C_a$ is consistent with two known values of $C_a$ derived from the cocktail party and roadside restaurant experiments (Table 5).

The $C_a$ for tobacco aerosol is affected by the rate of mechanical ventilation and infiltration, the rate of smoke adsorption, and mixing. The range of mechanical ventilation and infiltration can be calculated from tables of standards determined by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) (*29*), the authority specified by the local building code (*30*). For each premise listed in Table 5, the recommended maximum number of outdoor air changes per hour (based on the estimated floor area, maximum occupancy, and volume) was calculated from the ASHRAE tables; a two-thirds recirculation of air (the maximum permitted by ASHRAE) was assumed. This yielded a range of 0.7 to 9.4 air changes per hour. Infiltration, resulting mainly from the opening of doors, was estimated from the actual occupancy during the sampling (*29*); we assumed a 100 percent turnover of occupants per hour. This was added to the calculated mechanical ventilation rates, giving a final estimated range of $1.3 \leq C_v \leq 13.4$ air changes per hour, where $C_v = 60/\tau_v$.

The practical range of physical decay from adsorption for cigarette aerosol can be computed from our experiments and the literature. Most establishments possess simple filters that are relatively ineffective at removing tobacco smoke (*22*). The shortest ideal decay time measured (in experiment 1) was equivalent to six air changes per hour (Table 2). By contrast, Penkala and DeOliviera (*15*) measured a mean life for tobacco smoke, under uniform mixing in a chamber with unreactive walls, equivalent to one air change per hour. These two extremes given an estimated range of $1 \leq C_d \leq 6$ air changes per hour for RSP from tobacco smoke, where $C_d = 60/\tau_a$.

The range of mixing $m$ appropriate for the spaces listed in Table 5 is $1/4 \leq m \leq 1/2$, as determined from Table 1. By using Eq. 2, a theoretical range of mean air change rates, $1/2 \leq C_{aTh} \leq 10$ air changes per hour, is calculated from the estimated ranges for $C_v$, $C_d$, and $m$. This is consistent with the 1 to 11 air changes per hour determined with our model from the experimental results. In other words, the variations in the observed RSP density for fixed cigarette density can be phenomenologically ac-

Table 5. Field survey of indoor RSP sampled in the presence of smoking. Where the standard deviation is given, the value is an average of 2-minute samples; where it is not given, the sampling time is the averaging time.

| Locale | Estimated volume ($m^3$) | Average number of smokers | Indoor sampling time (min) | Average occupancy (persons) | Active smoker density per 100 $m^3$ | Indoor RSP ($\mu g/m^3$) | Outdoor RSP ($\mu g/m^3$) | Outdoor sampling time (min) | Occupants smoking (%) | Date | Time |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A. Cocktail party* | 268 | 2 | 15 | 14 | 0.75 | 351 ± 38 | | | 14 | 8 April | 9:00 p.m. |
| B. Lodge hall | 3,168 | 40† | 50 | 350 | 1.26 | 697 ± 28 | 60 | 6 | 11† | 31 March | 11:00 p.m. |
| C. Bar and grill | 507 | 9 | 18 | 75 | 1.78 | 589 ± 28 | 63 | 6 | 12 | 21 March | 8:00 p.m. |
| D. Firehouse bingo | 541 | 10.5 | 16 | 125 | 2.77 | 417 ± 63 | 51 | 15 | 8.4 | 27 March | 10:00 p.m. |
| E. Pizzeria | 170 | 5 | 32 | 50 | 2.94 | 414 ± 58 | 40 | 5 | 10 | 14 April | 8:00 p.m. |
| F. Bar/cocktail lounge | 216 | 7 | 26 | 55 | 3.24 | 334 ± 120 | 50 | 5 | 13 | 25 March | 10:00 p.m. |
| G. Church | | | | | | | | | | | |
| Bingo game | 4,224 | 20 | 8 | 150 | 0.47 | 279 ± 18 | | | 13 | 31 March | 10:00 p.m. |
| Sunday service | 4,224 | 0 | 31 | 300 | 0 | 30 | | | 0 | 13 May | 11:00 a.m. |
| H. Inn | 338 | 2.5 | 12 | 70 | 0.74 | 239 ± 9 | 22 | 10 | 3.5 | 23 March | 1:00 p.m. |
| I. Bowling alley | 918 | 14 | 20 | 128 | 1.53 | 202 ± 19 | 49 | 5 | 11 | 25 March | 8:00 p.m. |
| J. Hospital waiting room | 93 | 2 | 12 | 19 | 2.15 | 187 ± 52 | 58 | 6 | 11 | 28 March | 10:30 p.m. |
| K. Shopping plaza restaurant | | | | | | | | | | | |
| Sample 1 | 1,369 | 2.5 | 18 | 95 | 0.18 | 153 ± 8 | 59 | 5 | 2.6 | 24 March | 7:30 p.m. |
| Sample 2 | 1,369 | 2.5 | 18 | 50 | 0.18 | 163 ± 4 | 36 | 10 | 5 | 24 March | 9:30 p.m. |
| L. Barbeque restaurant | 225 | 2 | 10 | 25 | 0.89 | 136 ± 17 | | | 8 | 24 March | 9:00 p.m. |
| M. Sandwich restaurant A | | | | | | | | | | | |
| Smoking section | 781 | 2.25 | 20 | 30 | 0.29 | 110 ± 36 | 40 | 5 | 7.5 | 25 March | 8:00 p.m. |
| Nonsmoking section | 326 | 0 | 20 | 40 | 0 | 55 ± 5 | 40 | 5 | 0 | 25 March | 7:30 p.m. |
| N. Fast-food restaurant | | | | | | | | | | | |
| Sample 1 | 360 | 1.5 | 40 | 30 | 0.42 | 109 ± 38 | | | 5 | 26 March | 2:00 p.m. |
| Sample 2 | 360 | 0 | 7 | 30 | 0 | 30 | | | 0 | 26 March | 1:30 p.m. |
| O. Sports arena | 823,000 | 759† | 12 | 6,700‡ | 0.09 | 94 ± 13 | 24 | 5 | 11† | 29 March | 10:00 p.m. |
| P. Neighborhood restaurant/bar | 250 | 1 | 12 | 35 | 0.40 | 93 ± 17 | | | 2.9 | 25 March | 8:30 p.m. |
| Q. Hotel bar | 169 | 1 | 12 | 25 | 0.59 | 93 ± 2 | | | 8 | | 2:30 p.m. |
| R. Sandwich restaurant B | | | | | | | | | | | |
| Smoking section | 781 | 1 | 8 | 30 | 0.13 | 86 ± 7 | 55 | 5 | 3.3 | 14 April | 11:00 a.m. |
| Nonsmoking section | 326 | 0 | 21 | 50 | 0 | 51 | 55 | 5 | 0 | 14 April | 1:30 p.m. |
| S. Roadside restaurant | | | | | | | | | | | |
| Sample 1 | 90 | 1 | 18 | 5 | 1.12 | 107§ | | | 20 | 29 March | 3:00 p.m. |
| Sample 2 | 90 | 0 | 2 | 3 | 0 | 30 | | | 0 | 29 March | 3:00 p.m. |

*Only the cocktail party microenvironment was unventilated. †Estimated. See (*31*). ‡Paid attendance. §Calculated, equilibrium value.

counted for by ventilation, recirculation, infiltration, decay, mixing, and average smoking behavior. We conclude that the finite $D_s$ RSP levels shown in Fig. 3 are indeed generated primarily by cigarette smoke and that this is consistent with the predictions of our model.

### The Range of Public Exposure

We can now model the full range of exposure of the nonsmoking public to cigarette smoke. Equation 4 may be rewritten as

$$R = 25.6 \frac{P_a}{C_a} \qquad (5)$$

where $P_a$ is the occupancy (persons per 1000 square feet). (The volumetric measure is implicit, assuming a 10-foot ceiling.) The $P_a$ is three times the density of habitual smokers $D_{hs}$ and nine times the density of active smokers $D_s$ (*31*). A family of RSP curves is generated from Eq. 5 by varying $C_a$ and $P_a$ over their ranges. Representative samples of this family are plotted in Fig. 4. A lower limit for $C_a$ of about one-half to one mean air change per hour has been determined experimentally and theoretically for removal of cigarette aerosol from private dwellings ventilated by infiltration and from commercial establishments whose mechanical ventilation is poor. A realistic upper bound for $C_a$ may be obtained from the well-ventilated environment of the commercial airliner. A mechanical (design) ventilation rate of 15 to 20 air changes per hour with no recirculation is typical of the Boeing 707 (*32*). The best ideal decay rate measured in the experiments was six air changes per hour. Assuming a mixing factor of unity, we calculate an upper limit for $C_a$ of 26 air changes per hour. The practical range for $P_a$ is obtained from the ASHRAE (*29*), which specifies mechanical ventilation rates for typical average occupancies in various structures. For commercial structures, these densities (in persons per 1000 square feet) range from 10 for general office space to 70 for dining rooms to 150 for such places as stand-up bars, auditoriums, arenas, and commercial aircraft. The design ventilation rate $C_v$ is typically determined from both the design occupancy and the intended use of the structure. For example, 15 to 25 cubic feet per minute per occupant is specified for general office space, 10 to 20 for dining rooms, and 30 to 40 for cocktail lounges. In 1975, *ASHRAE Standard 90-75*, "Energy conservation in new building design," decreased these rates by factors of one-half to one-third. *ASHRAE Standard 62-73* is currently being revised to specify higher rates of ventilation for premises in which smoking is permitted. How effective would increases in $C_v$ be in lowering the levels of RSP from tobacco smoke? Equation 5 shows that such levels decrease only exponentially with increasing $C_a$. Furthermore, as Kalika *et al.* (*33*) observed, "the current practice of recirculation or reuse of air is largely dictated by the economics of heating and cooling, with little regard for changes in indoor air quality." That is, ventilation may be subject to arbitrary reduction by building management or by legislative or bureaucratic fiat; in many nonurbanized areas, it may not even be regulated by building codes (*34*).

Figure 4 illustrates the estimated range

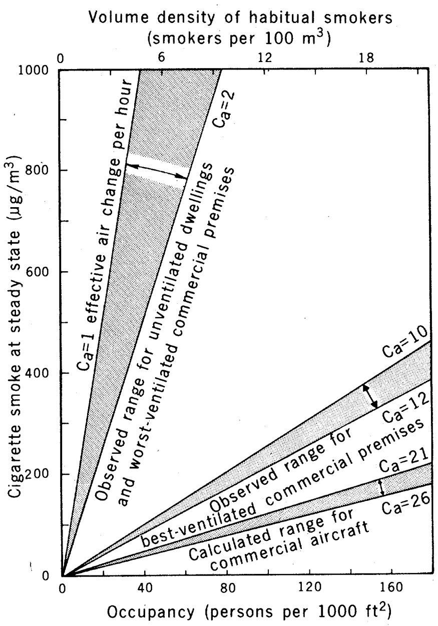


Fig. 4. Theoretical steady-state density of respirable particulates from environmental cigarette smoke in habitable indoor spaces, as related to the design occupancy $P_a$. On the average, one-third of adults are habitual smokers; for every three such smokers, we calculate that an average of one cigarette burns constantly throughout a 16-hour day. According to standard engineering criteria (*29*), occupancy and the type of microenvironment determine the design rate of mechanical ventilation $C_v$. The effective air change rate ($C_a$) for the removal of tobacco aerosol from room interiors is determined by $C_v$, by mixing, and by the rate of adsorption of tobacco particles on room surfaces. Generally $C_v$ and hence $C_a$ increase with $P_a$. [Typical $P_a$ (in persons per 1000 square feet) ranges from 10 for office buildings to 70 for restaurants to 150 for bars, sports arenas, and aircraft (*29, 32*).] We estimate the practical range of $C_a$ to be from 1 to 12 air changes per hour. It appears that over the combined practical ranges of $P_a$ and $C_a$, repeated exposure to tobacco smoke can lead to annual RSP burdens that violate the primary annual NAAQS.

of exposure of the nonsmoking public to RSP from cigarette smoke. The actual dose of RSP is clearly a function of personal activity patterns; differences in respiration rate also affect the dose. Many different scenarios can be imagined. In the following, we express a range of RSP burdens from the cigarette aerosol relative to a typical RSP ambient background level. For an air shed (air quality control region) that is in compliance with the annual secondary (public welfare) NAAQS for TSP of 60 $\mu g/m^3$, the RSP fraction of the ambient aerosol is conservatively estimated at 50 $\mu g/m^3$ and is likely to be composed largely of combustion-produced sulfates (*35*). Since the particle size distributions of this fraction and the cigarette aerosol are both in the respirable range, we first compare them on a mass basis, without regard for differences in the chemical composition of each.

Let A, B, C, and D be nonsmokers who dwell in the same air shed and who breathe at the average rate of 20 $m^3$/day. All have different occupations and lifestyles that lead, as we shall see, to dramatically different RSP burdens.

Nonsmoker A is a mailman who walks a regular route and is able to live in a completely tobacco smoke-free environment. He is exposed only to the background ambient and therefore inhales 365 mg of RSP annually.

Nonsmoker B is an office worker who works a 40-hour week 50 weeks per year in a 40-$m^3$ office with two other persons, one of whom is a habitual smoker. Replacing $D_s$ in Eq. 4 with $D_{hs}/3$, we find that B's mass RSP exposure is more than three times that of A (we calculate an expected $C_a$ of 1.1 for office buildings).

Nonsmoker C is a musician who entertains in a popular, poorly ventilated nightclub 8 hours nightly, 5 nights per week, 50 weeks per year. The average $P_a$ in the club is 100 persons per 1000 square feet (about 33 smokers). Further, C shares a 100-$m^3$ apartment with a roommate who is a chain smoker. C is exposed to the roommate's smoke 5 hours per day, 7 days per week, annually. By using Eqs. 4 and 5 and a $C_a$ of one air change per hour, we find that C's mass RSP burden is more than 15 times that of A.

An alternative way of approaching the excess RSP exposure is in terms of cigarette equivalents. The cigarette with the least tar in the May 1978 FTC scale has 0.55 mg of TPM. In these terms, B's excess RSP burden is equivalent to 5 cigarettes per day and C's burden to 27 cigarettes per day. However, this may underestimate the true impact, since many nonsmokers have greater sensitivity to smoke than smokers (*7*).

Nonsmoker D is a flight attendant who spends 40 hours per week, 50 weeks per year on board a commercial airliner with a $C_a$ of 23 air changes per hour. The average $P_a$ on the plane is 150 persons per 1000 square feet. D's RSP burden is nearly twice that of A. Even with one of the best ventilation systems in use, the high density of smokers causes a substantial increase in mass RSP inhaled by D.

The following three considerations may help to place these scenarios into perspective. First, an annual exposure 1.5 times that of A is sufficient to exceed the primary annual NAAQS; the exposure of D, B, and C to RSP all violate the standard by factors of 1.2, 2, and 10, respectively. Second, pulmonary clearance studies show that the half-life of inert respirable particles (2.8 $\mu$m in MMD) in the lungs of nonsmokers is ~ 70 days (*36*): residence of RSP in the lungs is prolonged. Third, in a series of pulmonary lavage studies on 400 nonrandomly selected volunteers (250 nonsmokers and 150 smokers) (*37*), two of the nonsmokers had tarry lavage fluids with pigmented pulmonary alveolar macrophages strikingly similar to those found in smokers. In these two volunteers, the levels of aryl hydrocarbon hydroxylase, an inducible carcinogen-detoxifying pulmonary enzyme, were intermediate in value between the levels found in smokers and most nonsmokers. These findings were attributed to the effects of exposure to tobacco smoke (*38*).

## Health Policy Implications

There is good toxicologic evidence that elevated levels of particulates in outdoor air, perhaps in combination with other pollutants, cause illness and death during air pollution episodes (particulate levels in excess of 1000 $\mu$g/m$^3$ per 24 hours). There is much epidemiologic evidence, some of it conflicting, that lower levels of particulates, perhaps in combination with other pollutants, affect respiratory health adversely when exposure to them is sustained (*39*). (This evidence has been used to establish the thresholds for harm on which the primary annual NAAQS for TSP is based.) There is excellent toxicologic evidence that mainstream cigarette smoke causes chronic obstructive pulmonary disease (*7, 40*). Epidemiological evidence, some of it conflicting, indicates that exposure to tobacco smoke in the home affects respiratory health adversely (*7, 41*). Finally, there is excellent evidence that mainstream cigarette smoke causes cancer in many organs (*7*). Sidestream smoke is chemically identical to mainstream smoke, and typically is more concentrated (*2*). Coke-oven emissions, which chemically are similar to tobacco smoke, are associated with increased rates of many forms of cancer in coke-oven workers (*42*). Animal studies demonstrate that the particulate phase of tobacco smoke contains numerous potent carcinogens and tumor promoters, initiators, and accelerators (*7*). One of these, benzo[*a*]pyrene, was detected at a concentration of 40 parts per million in ambient tobacco smoke (*13*). Strong evidence supports a correlation between the magnitude of long-term exposure to carcinogens and the incidence of cancer (*43*). Therefore, given the efforts by public health authorities to eliminate involuntary public exposure to saccharin and the fire retardant Tris—which have, respectively, one fifty-thousandth and one-tenth the experimental carcinogenic potency of benzo[*a*]pyrene alone (*44, 45*)—similar efforts to prevent involuntary exposure to ambient tobacco smoke (*46*) appear justified.

## Conclusions

We have defined the probable range of exposure of the nonsmoking public to a common pathological aerosol, cigarette smoke. We showed, both experimentally and theoretically, that under the practical range of ventilation conditions and building occupation densities, the RSP levels generated by smokers overwhelm the effects of ventilation and inflict significant air pollution burdens on the public. Our observations show that levels of RSP in places where tobacco is smoked greatly exceed levels found in smoke-free environments, outdoors, and vehicles on busy commuter highways. Our experimental results are consistent with the large differences in 24-hour average RSP levels reported for smoking and nonsmoking homes in the Harvard Six-City Study (*47*), with a survey of short-term RSP levels in commercial and public buildings in Houston (*28*), and with other studies of tobacco-generated TSP (*7, 11-13*).

Attempts to reduce RSP levels from smoking by increasing the rate of mechanical ventilation or the efficiency of filtration yield exponentially diminishing returns for linear increases in ventilation energy (and cost). Moreover, efforts to conserve energy in buildings will decrease ventilation rates (*48*). Therefore, increased ventilation does not appear to be a solution to the problem. Indoor air is a resource whose quality should be maintained at a high level. Smoking indoors may be incompatible with this goal (*33, 49*).

Further research is necessary to define the integrated particulate exposure of various segments of the population; compliance with the NAAQS, as indicated by the establishment of outdoor TSP sampling stations, does not imply protection of the public from excessive RSP burdens. Repeated exposure to ambient cigarette smoke imposes air pollution burdens on nonsmokers that exceed the primary annual NAAQS. It appears that the RSP burdens from ambient tobacco smoke are so large that they must be incorporated explicitly in future epidemiological assessments (*50, 51*) of the relation between particulate levels and morbidity or mortality.

The Clean Air Act of 1970 and its amendments mandate the control of public exposure to outdoor TSP. However, little legislative attention has been devoted to the quality of indoor air—other than the passage of the Public Health Service Act of 1978, which provides for an ongoing study of the health costs of indoor air pollution. Clearly, indoor air pollution from tobacco smoke presents a serious risk to the health of nonsmokers. Since this risk is involuntary, it deserves as much attention as outdoor air pollution.

*Note added in proof*: A very recent epidemiological study concluded that long-term exposure to tobacco smoke, limited to the work environment only, is deleterious to the nonsmoker and significantly reduces small-airway function to the same extent as smoking one to ten cigarettes per day. This is consistent with scenario B (*52*). *ASHRAE Standard 62-73R*, a proposed standard for ventilation required for minimum acceptable indoor air quality, has been published (see *29*). Using data supplied in the standard, we calculate a $C_a$ of $\leq$ 1.28 for office buildings where smoking is permitted.

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