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INDOOR–OUTDOOR RELATIONSHIPS OF RESPIRABLE SULFATES AND PARTICLES

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Abstract—Indoor and outdoor concentrations of respirable particulates and sulfates have been measured in 68 homes in six cities for at least 1 yr. A conservation of mass model was derived describing indoor concentrations in terms of outdoor concentrations, infiltration and indoor sources. The measured data were analysed to identify important building characteristics and to quantify their effect. The mean infiltration rate of outdoor fine particulates was found to be approximately 70%. Cigarette smoking was found to be the dominant indoor source of respirable particulates. Increased indoor concentrations of sulfates were found to be associated with smoking and also with gas stoves. The effect of full air conditioning of the building was to reduce infiltration of outdoor fine particulates by about one half, while preventing dilution and purging of internally generated pollutants. The model for indoor respirable particulate and sulfate levels was found to compare well with measurements.

INTRODUCTION

Exposure to respirable particulates and sulfates is largely determined by indoor air pollution levels (Dockery and Spengler, 1980). The purpose of this paper is to investigate the factors which determine indoor concentrations of respirable particulates and sulfates, to develop a model for predicting indoor concentrations. The material is presented in more detail by Dockery (1979) as part of his doctoral dissertation.

Measurements of indoor and outdoor concentrations of air pollution are being made in six cities across the country as part of a prospective epidemiological study (Ferris *et al.*, 1979) to assess the respiratory health effects of particulates and sulfur oxides. The six cities—Portage, Wisconsin; Topeka, Kansas; Kingston/Harriman, Tennessee; Watertown, Massachusetts; St. Louis, Missouri; and Steubenville, Ohio—have widely different air pollution levels. A more detailed description of air quality in these cities is presented in a preceding paper (Spengler *et al.*, 1981). A brief description suffices here. Portage and Topeka are non-industrial, Midwestern communities. Both are affected by coal-burning power plants, but ambient outdoor levels of respirable particulates and sulfates are low. Watertown and Kingston are Eastern communities with moderate outdoor respirable particulate and sulfate levels. Although Kingston is at the base of a large coal-fired power plant, the local pollution is largely transported in from other regions upwind, rather than resulting from local sources (Hanna, 1973). Watertown also is polluted principally by transport from other regions. Pollution in St. Louis and Steubenville, while affected by distant sources, is dominated by local emissions.

In each of the six cities studied, indoor and outdoor air pollution concentrations have been measured in approx. 10 homes or public facilities for at least 1 yr. Twenty-four-hour integrated samples of SO_2, NO_2 and respirable particulates are collected every sixth day. Spengler *et al.* (1979) have reported on the SO_2 and NO_2 results.

The companion paper to this (Spengler *et al.*, 1981) describes the respirable particulate and sulfate monitoring program and preliminary results. This paper describes the analysis of the respirable particulate and sulfate data.

The principal problem in an epidemiologic study of air pollution is the estimation of pollution exposure. Actual exposure of each individual is determined by his activities, coupled with the spatial and temporal distribution of pollutants. Previous studies (Dockery and Spengler, 1980) have shown that individual exposures to respirable particulates and sulfates are largely determined by the concentrations of these pollutants indoors. This paper explores the variations of respirable particulate and sulfate concentrations among homes as a function of outdoor concentrations, indoor sources, and ventilation rates. A steady state mass balance equation is derived and used as the basis of the analysis.

Home selection

The indoor–outdoor sampling network was designed around two objectives: first, to define the spatial distribution of outdoor air pollution in each of the cities being studied, and second, to define the indoor–outdoor relationships in a variety of homes. Therefore, the first criterion in the selection of homes was their location, so that a uniform geographic distribution across each city to be studied was obtained. Secondly, consideration was given to the

characterization of the household and the internal sources. No *a priori* assumptions were made on what variables were important in determining indoor levels. Rather, homes and a few public facilities were chosen in large part because of the willingness of the residents to cooperate, and secondly to attempt to draw, at least qualitatively, a sample which was representative of the range of home characteristics in that community whenever possible.

Data on the characteristics of each site were collected. For analysis, these data were reduced to eight site characteristics, which describe potential sources in the house and ventilation factors.

The indoor source variables are:

—the number of smokers in the building;
—the estimated number of cigarettes smoked each day in the building;
—the type of heating fuel used (electricity, gas, oil, wood);
—and the type of cooking fuel used (electric, gas).

The average number of cigarettes smoked in each site was estimated as the sum of the number of cigarettes smoked by each household member normally at home all day plus one half the cigarettes smoked by household members who spent part of the day away from home, at work, at school etc.

The ventilation variables are:

—the type of heating system, i.e. the method by which heat is delivered to the living areas (forced hot air, radiative or convective);
—whether storm windows are used;
—the type of air conditioning used (none, room units, central);
—and the type of kitchen ventilation (none, recirculating, outside).

For comparison among the cities, the percentage distribution of home characteristics by city are displayed in Table 1.

INDOOR–OUTDOOR RELATIONSHIPS

Analysis of variance has shown that there are significant differences in indoor particulate concentrations among the homes studied (Spengler *et al.*, 1981). Using the large collection of data from the indoor–outdoor monitoring program, the empirical constants in a conservation of mass model can be estimated. The resulting model can then be tested against the observations.

Conservation of mass model

Assuming uniform mixing within a building, the average concentration of pollution inside can be defined by a single conservation of mass model (Calder, 1957; Alzona *et al.*, 1979). In this model, four processes are defined which determine indoor pollution mass:

(1) Penetration of outside air into the building through windows, doors, ventilators, cracks etc. The flux of entering pollutant is defined by the product of the volume air flow rate, the outside concentration and the fraction not removed by "filtration" as it enters.

Table 1. Per cent frequency of home characteristics by city

	Portage	Topeka	Kingston	Watertown	St. Louis	Steubenville	All cities
Number of sites	11	13	10	13	12	9	68
Ventilation characteristics							
Heating system							
Forced hot air	90.9	84.6	40.0	38.5	83.3	55.6	66.2
Radiator	9.1	15.4	60.0	61.5	16.7	44.4	33.8
Air conditioning							
None	63.6	7.7	0.0	69.2	25.0	55.6	36.8
Room units	18.2	53.8	60.0	30.8	25.0	0.0	32.4
Full/central	18.2	38.5	40.0	0.0	50.0	44.4	30.9
Kitchen venting							
None	54.5	69.2	10.0	76.9	50.0	11.1	52.9
Recirculating	9.1	15.4	30.0	15.4	16.7	0.0	14.7
Outside	36.4	15.4	60.0	7.7	33.3	55.6	32.4
Storm windows	100.0	92.3	80.0	84.6	91.7	88.9	89.7
Source characteristics							
Smokers in home	9.1	38.5	50.0	31.8	50.0	55.6	38.2
Heating fuel							
Oil	36.4	0.0	0.0	61.5	16.7	11.1	22.1
Gas	54.5	100.0	30.0	38.5	83.3	77.8	64.7
Electric	9.1	0.0	70.0	0.0	0.0	11.1	13.2
Cooking fuel							
Electric/none	72.7	76.9	100.0	30.8	25.0	44.4	57.4
Gas	27.3	23.1	0.0	69.2	75.0	55.6	42.6

(2) This volume air flow into the building is balanced by an equal volume air flow out of the building which purges some of the indoor pollution. This outward flux is defined by the product of the volume flow and the indoor concentration.

(3) Pollution is removed or decays inside by physical and chemical reactions such as settling, oxidation, absorption, filtering etc. This removal is assumed to be a constant times the mass of interior pollutant.

(4) Pollution is generated inside by combustion, condensation, abrasion and resuspension.

These processes are all defined in terms of mean values for the entire building. The conservation of mass equation can then be written as:

$$dQ = (1-F)qC_o dt - qC_i dt - KQ dt + S dt, \quad (1)$$

where:

Q = mass of interior contaminant (μg),
F = fraction of pollutant filtered in the entering air,
$P = (1-F)$ = penetration of outside pollutant,
q = volume of air flow into and out of the building ($m^3 h^{-1}$),
V = interior volume of the building,
t = time (h),
K = rate of decay, settling, and removal (h^{-1}),
a = ventilation rate = $q/V(h^{-1})$ (air changes per hour ACPH),
S = interior generation rate ($\mu g\, h^{-1}$),
C_o = ambient outside concentration ($\mu g\, m^{-3}$), and
C_i = ambient inside concentration ($\mu g\, m^{-3}$).

Dividing Equation (1) by V;

$$dC_i = PaC_o dt - (a+K)C_i dt + \frac{S}{V} dt. \quad (2)$$

Defining average values over the sampling period as:

$$\overline{C}_i = \frac{1}{t_s}\int_0^{t_s} C_i dt = \text{indoor average concentration}, \quad (3a)$$

$$\overline{C}_o = \frac{1}{t_s}\int_0^{t_s} C_o dt = \text{outdoor average concentration}, \quad (3b)$$

$$\overline{S} = \frac{1}{t_s}\int_0^{t_s} S dt = \text{average emission rate}, \quad (3c)$$

then integrating Equation (2) over sampling period t_s assuming P, V, K and a remain constant

$$\frac{C_i(t_s) - C_i(0)}{t_s} = Pa\overline{C}_o - (a+K)\overline{C}_i + \overline{S}/V. \quad (4)$$

The average indoor concentration is then:

$$\overline{C}_i = \frac{Pa}{(a+K)}\overline{C}_o + \frac{\overline{S}}{V(a+K)} + \frac{C_i(0) - C_i(t_s)}{t_s(a+K)}. \quad (5)$$

Assume that the difference between the initial indoor concentration, $C_i(0)$, and the final indoor concentration, $C_i(t_s)$, is less than or equal to the mean concentration ($\overline{C}_i$). Sampling time, t_s, is 24 h for our data. Ventilation rates, a, are of the order of 1.5 ACPH, and therefore $t_s a$ is of the order of 36. Therefore:

$$\frac{C_i(0) - C_i(t_s)}{t_s(a+K)} \ll \overline{C}_i, \quad (6)$$

and can be neglected. Equation (5) can be approximated as:

$$\overline{C}_i = \frac{Pa}{(a+K)}\overline{C}_o + \frac{1}{V(a+K)}\overline{S}. \quad (7)$$

Now consider the removal rate K. For particulates, the principal mechanism in a large enclosed space is sedimentation. The sedimentation rate is proportional to particle diameter squared. For respirable particulates, the removal rate K by sedimentation in a well-mixed room is less than $0.5\, h^{-1}$ (Dockery, 1979). For particles with aerodynamic diameter less than 1 μm, the removal rate is less than $0.05\, h^{-1}$. Ventilation rates, a, as noted above, are on the order of $1.5\, h^{-1}$ (ACPH). Therefore, $(a+K) \approx a$, for fine particulates, and:

$$\overline{C}_i \approx P\overline{C}_o + \frac{1}{q}\overline{S}, \quad (8)$$

where $q = aV$, the volume flow rate.

This model states that the mean indoor concentration can be approximated by a simple linear function of the outside concentration. The constants in the equation, that is, the slope, P, and the intercept, $\overline{S}/q$, are characteristics of the house.

By linear regression of the indoor concentrations on the outdoor concentrations, P and $\overline{S}/q$ were estimated for each home. Analysis of variance was then performed to determine what home characteristics, if any, could be used to determine the unknown constants in the model. The empirical constants were then determined by multiple regression.

IDENTIFICATION OF CONTROLLING HOME CHARACTERISTICS

The important home characteristics were isolated by analysis of variance based upon hypotheses developed from the physical model, Equation (8). The estimated mean indoor concentration, $\overline{C}_i$, is determined by the known mean outdoor concentration, $\overline{C}_o$, and two empirical constants—the infiltration of outdoor pollution, P, and the indoor source term, $\overline{S}/q$. These parameters were assumed to be constants, characteristic of the house. To estimate long-term mean indoor concentration, for periods of the order of a year, day-to-day variations in these characteristics were not considered.

Infiltration

The fraction of outdoor pollution infiltrating, P, is determined by the ventilation rate and the physical

removal processes as outdoor air enters the home through windows, doors, cracks and other openings in the structure, and as make-up air enters for heating and air-conditioning systems. While not having direct measurements of ventilation, each monitoring site is characterized by four variables that may influence particle infiltration—storm windows, heating system, air conditioning and kitchen ventilation. Of these, the use of air-conditioning is expected to have the greatest influence. Use of storm windows and the type of heating system may affect the amount of make-up air entering the building principally during the heating season. The use of kitchen fans may be important and have an effect on air change rates year round. However, the largest differences are probably associated with the use of full air-conditioning of the home (either central or complete air-conditioning of the home with room units). These fully air conditioned homes will be sealed tightly all year. Without air conditioning, ventilation through open windows and doors will rapidly change the indoor air and allow free penetration of the outside pollutants during the warm seasons. It is reasonable to expect fully air conditioned homes to have much lower average ventilation rates if the conditioned air is principally recirculated air.

To determine the important characteristics, the outdoor pollution infiltration, P, of each site was determined independently for respirable particulates and sulfates by linear regression of the measured indoor concentration on the measured outdoor concentration. Infiltration is the slope in the equation. Infiltration for each site was then analysed as a function of the four home ventilation variables.

Infiltration was analysed separately for respirable particles and sulfates. However, inasmuch as the sulfate mass is a portion of the respirable particulate mass, it is reasonable to expect, for first approximation, that the transport and removal processes will be similar for both pollutants. It was therefore required that the infiltration relationships should be the same for both respirable particulates and sulfates.

Mean infiltration and standard errors for values of each of the four ventilation variables are displayed in Fig. 1. Only the presence of complete air conditioning in the home appears to produce a significant decrease in infiltration rates for both respirable particulates and sulfates. Analysis of variance of infiltration by the ventilation variables confirmed this (Dockery, 1979). Air conditioning was found to have a weak effect on respirable particulate infiltration ($p < 0.20$) and also on sulfate infiltration ($p < 0.05$).

Kitchen ventilation showed a weak effect in the analysis of variance on respirable particulate infiltration only. The pattern was not consistent for sulfates, however (Fig. 1). Similarly, the use of storm windows showed an effect on sulfate infiltration in the analysis of variance. As seen in Fig. 1, the use of storm windows had higher infiltration rates. The pattern was reversed for respirable particulate infiltration and was not statistically significant.

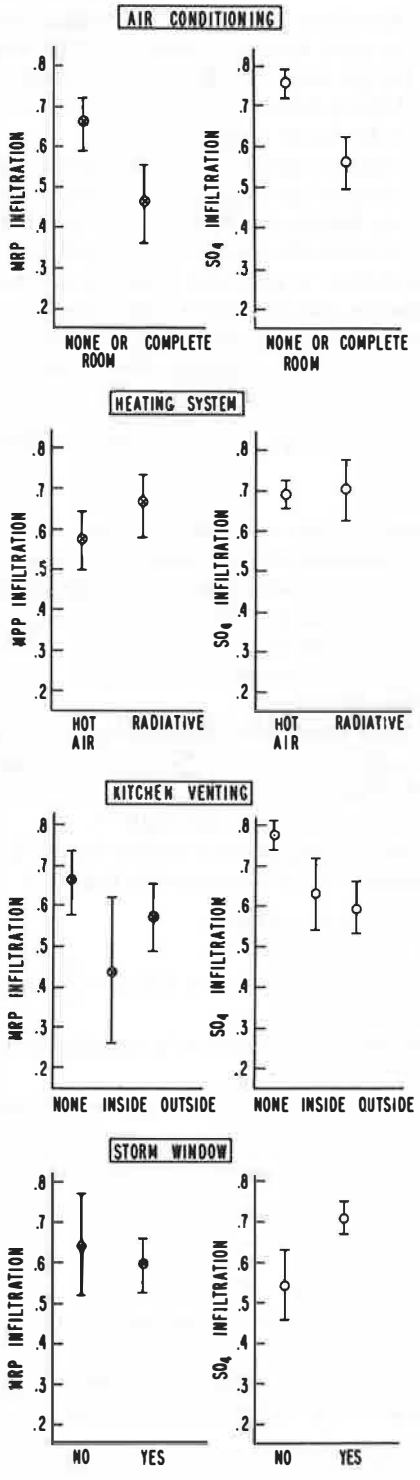

Fig. 1. Mean infiltration (plus and minus one standard error) from indoor/outdoor regressions for respirable particulates (MRP) and respirable sulfates (SO_4).

The presence of full air conditioning in the house was therefore used as the only variable characterizing infiltration for both pollutants. The magnitude of this effect will be determined in the following sections.

Indoor sources

The source term, $\overline{S}/q$, for each site was also determined independently for respirable particulates and sulfates by linear regression. The source term is simply the intercept of the linear regression on outdoor levels. The indoor source contribution will be determined by the mean indoor source strength, $\overline{S}$, and the mean volume air flow rate, q. The source strength, $\overline{S}$, will potentially be a function of the source variables—smoking, heating fuel and cooking fuel. The volume flow rate, q, will be a function of ventilation variables.

As with infiltration, the source terms were analysed independently for respirable particulates and sulfates. However, since these pollutants may have different sources, consistency was not required as with the infiltration variables.

Each of the ventilation variables was considered for its direct effect on the intercept terms and for interaction with the source variable. Only air conditioning was found to have a significant interaction effect. Therefore only air conditioning analysis is presented. Mean intercept values (Fig. 2) indicate higher intercept values in fully air conditioned homes. Analysis of variance showed the interaction of the source variables and full air conditioning to be statistically significant $P < 0.001$).

Smoking showed the largest impact. Figure 2 indicates that the mean intercept value vs number of smokers in the home, increase with smoking for both respirable particles and sulfates. This was confirmed in the analysis of variance analysis. (For respirable particulates, $p < 0.001$; for sulfates, $p < 0.05$.)

It is interesting that cigarette smoking has a strong association with indoor sulfate levels. Previous studies (Dockery, 1979) have shown that sulfates are produced by matches, but not significantly by cigarettes themselves. Smoking is therefore serving as a rough estimator of the use of matches. A more direct measure of match use would undoubtedly give a better estimate of indoor sulfate sources. Hollowell *et al.* (1977) also report that sulfates are produced by gas ovens. As seen in Fig. 2 and also the analysis of variance, there is weak evidence ($p < 0.20$) for a difference in the indoor sulfate source term based on cooking fuel. No relationship was found with heating fuel.

In summary, the model for the long-term mean indoor respirable particulate source contribution is then a linear combination of the amount of smoking in the home, air conditioning and the interaction of these two variables. The model for long-term mean indoor sulfate levels will include the smoking and air conditioning terms and their interactions, plus the cooking fuel and its interaction with air conditioning. The magnitudes of each of these terms were estimated by regression analysis.

Determination of empirical constants

It was stated earlier [Equation (8)] that the average

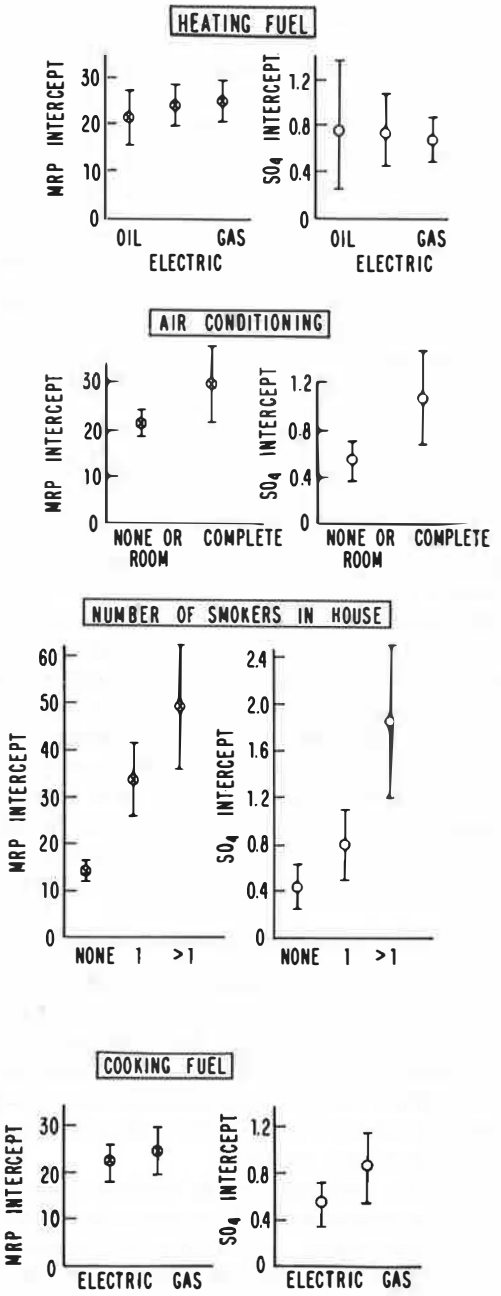

Fig. 2. Mean intercepts ($\mu g\ m^{-3}$) from indoor/outdoor regressions for respirable particulates and sulfates.

indoor particulate levels can be approximated by:

$$\overline{C}_i = P\overline{C}_o + \frac{1}{q}\overline{S}.$$

We will assume that infiltration, P, is a simple linear function of air conditioning, that is,

$$P = B_1 + B_2(A) \tag{9}$$

where A is an indicator variable for fully air conditioned sites, and the Bs are empirical constants to be determined.

The source term, $\overline{S}/q$, is a function of source strength and the volume flow rate of air through the building. The amount of smoking in the building and the air flow characterized by air conditioning are important variables for both pollutants. The cooking fuel used is also a potential source of sulfates.

The model for respirable particulate sources then has the form:

$$\overline{S}/q = B_3(N_{cig}) + B_4(AN_{cig}) + B_5(A) + B_6, \quad (10)$$

where N_{cig} is the estimated number of cigarettes smoked per day and the Bs are empirical constants to be determined.

The sulfate source model is of the form:

$$\overline{S}/q = B_3(N_{cig}) + B_4(AN_{cig}) + B_5(G) + B_6(AG) + B_7(A) + B_8, \quad (11)$$

where G is an indicator variable for cooking fuel (1 for gas and 0 otherwise).

The empirical constants were determined by multiple regression (Nie *et al.*, 1975) of the measured indoor concentrations on the measured outdoor concentrations and the home characteristics which were found to be important. A total of 2822 observations were included in the respirable particulate regression and 2725 in the sulfate regression. The empirical constants were estimated independently for the two pollutants. A summary of the results and a discussion of the meaning of the estimated constants follows.

Indoor respirable particulate model

The indoor respirable particulate model had an overall multiple correlation of 0.68. The model variance ratio ($F_{5,2816} = 471.8$) was very significant ($p < 0.0001$). The regression coefficients are summarized in Table 2 along with the standard error of each coefficient and the F ratio for the explained variance attributable to each variable.

The direct infiltration of the outdoor respirable particulates represented by B_1, is seen to be 0.70, that is, in the main, approx. 70% of the outdoor respirable particulates penetrate indoors. The effect of full air conditioning represented by B_2, is to reduce this penetration by 0.39, which implies net infiltration of only 31%. Air conditioning appears to have an important impact on the penetration of particulates into the house. These regression coefficients have small standard errors and large F ratios, so that both are statistically significant.

The F ratios for the two smoking terms indicate that this is a very significant source. The direct impact of smoking, B_3, implies that indoor mean respirable particulate concentrations increase by 0.88 $\mu g\,m^{-3}$ for every cigarette smoked in the house. A one-pack-a-day smoker will raise mean indoor respirable particulate levels 17.6 $\mu g\,m^{-3}$. The effect of air conditioning, B_4, is to increase this impact of each cigarette by 1.23 $\mu g\,m^{-3}$ to a total of 2.11 $\mu g\,m^{-3}$ per cigarette in fully air-conditioned homes. Apparently any filtration of particulates by the air conditioning is not nearly as important as the reduced dilution of the cigarette smoke as the interior air is recirculated.

The influence of indoor sources in homes without full air conditioning and with no smokers, represented by the constant B_6, is 15.02 $\mu g\,m^{-3}$. This represents the influence of all the activities we have not characterized, including cooking, vacuuming and dusting. In fully airconditioned homes, the impact of these sources, represented by B_5, is reduced by 2.39 $\mu g\,m^{-3}$. This may reflect some removal of particulates in the air recirculating through the air conditioner. The effect is rather tenuous, however, since the large standard error and small F value indicate that we cannot say with confidence that this effect is different from zero.

Indoor sulfate model

The indoor sulfate concentration model had an overall multiple correlation of 0.79 and a very significant variance ratio ($F_{7,2717} = 623.57$, $p < 0.0001$). The regression coefficients along with their standard error and F values are summarized in Table 3.

The impact of the outdoor sulfate concentration, B_1, is seen to be 0.75. In fully air conditioned homes, this is reduced by 0.47 to a penetration of only 0.28. These values are both statistically very significant. We hypothesized earlier that the processes removing particles as they enter the building would be similar for the respirable particulates and their sulfate fraction. This is supported by the fact that the regression coefficients for the penetration, B_1 and B_2, while being determined

Table 2. Respirable particulate regression analysis results

Parameter	Variable	Regression coefficient	Standard error of coefficient	F-value
B_1	$\overline{C}_{out}$	0.70	0.035	387.55*
B_2	$A \cdot \overline{C}_{out}$	−0.39	0.047	69.17*
B_3	N_{cig}	0.88	0.057	242.96*
B_4	$A \cdot N_{cig}$	1.23	0.079	243.79*
B_5	A	−2.39	1.835	1.70
B_6	Constant	15.02	0.882	—

*Probability of $F < 0.001$.

Table 3. Respirable sulfate regression analysis results

Parameter	Variable	Regression coefficient	Standard error of coefficient	F-value
B_1	$\overline{C}_{out}$	0.75	0.012	3839.69*
B_2	$A \cdot \overline{C}_{out}$	−0.47	0.019	613.81*
B_3	N_{cig}	0.006	0.007	0.82
B_4	$A \cdot N_{cig}$	0.046	0.011	16.52*
B_5	G	1.08	0.142	58.62*
B_6	$A \cdot G$	−0.97	0.282	11.78*
B_7	A	1.73	0.212	66.63*
B_8	Constant	0.04	0.092	—

*Probability of $F < 0.001$.

independently for the two pollutants, have overlapping confidence intervals. That is, the infiltration of outdoor pollutants is the same for respirable particulates and sulfates according to our data. Moreover, the impact of full air conditioning on penetration is also the same for particles and sulfates.

There is a suggestion, however, that sulfate particulates may enter slightly more efficiently than the respirable particulates, possibly because of their smaller size. They also may be removed more efficiently by air conditioning, possibly because of their high solubility in the water condensing on the cooling coils.

The source terms in the indoor sulfate model are not nearly as important as they were in the respirable particulate model. In fact together they add only 3.6% to the total explained variance (r^2), above that explained by the infiltration terms alone. Nevertheless, some of the terms are statistically significant and physically interesting.

The impact of cigarette smoking in the house is estimated by the linear regression to be small. The direct effect, represented by B_3, is only 0.006 $\mu g\ m^{-3}$ of sulfate per cigarette. Statistically this is not significant and cannot be said to be different from zero. The interaction of smoking and air conditioning, B_4, is significant with a value of 0.046 $\mu g\ m^{-3}$ of sulfate per cigarette in fully air-conditioned homes. Thus the impact of smoking a pack of cigarettes in a fully air-conditioned home would add approx. 1.0 $\mu g\ m^{-3}$ sulfate to the indoor concentration.

Filters collected from homes with smokers often have a yellow color. This presents the potential for overestimating sulfate concentrations by a positive interference of cigarette smoke in the turbimetric measurements (Wolfson, 1980). Filters with this potential interference are separated, and analyzed with blank corrections to compensate for the cigarette smoke interference.

Recalling that the source of these sulfates is matches and not the cigarettes, and that smoking is only a crude surrogate for the number of matches used, the relationship between indoor sulfates and matches is probably much stronger than indicated by this regression analysis.

The regression coefficients for the impact of gas stoves, B_5, and its interaction with air conditioning, B_6, are both statistically significant. The regression analysis implies that the use of a gas stove adds 1.08 $\mu g\ m^{-3}$ sulfate to the indoor levels, supporting Hollowell's (1977) observations. Full air conditioning reduces this impact to essentially zero. This is contrary to the increased impact of smoking noted with air conditioning. The explanation for this difference is not apparent.

We have included smoking and cooking with gas as important source variables. The remaining potential sources are included in the constant B_8, which is not significantly different from zero. The air-conditioning term, B_7, represents the interaction of these unspecified sources and air conditioning. It has a value of 1.73 $\mu g\ m^{-3}$ in air conditioned homes. This is not only statistically significant, but very large considering that the mean indoor levels range from 4 to 13 $\mu g\ m^{-3}$ across all six cities. This term probably reflects in part our inability to characterize the match and gas stove impacts adequately. Detailed sampling in more homes is needed to define this ventilation effect which we have attempted to characterize by air conditioning.

Model validation

Having developed a model for indoor particulate and sulfate concentrations, and determined the empirical constants, the mean estimated indoor concentrations were estimated for each site. Scatter plots of predicted vs observed are presented for respirable particulates in Fig. 3 and for sulfates in Fig. 4. Mean values across all the monitoring sites in each city (Table 8) show a tendency to overpredict indoor respirable particulate levels and a slight tendency to underpredict indoor sulfate levels. The correlations between predicted and observed values (Table 4) are high across the total sample. Of course this correlation across all six cities spans a wide range of values. The values in each city have a limited range, so that the correlation for the monitors within each city, especially Topeka, is not high. Analysis of covariance indicates that the differences in the residuals between cities are not significant.

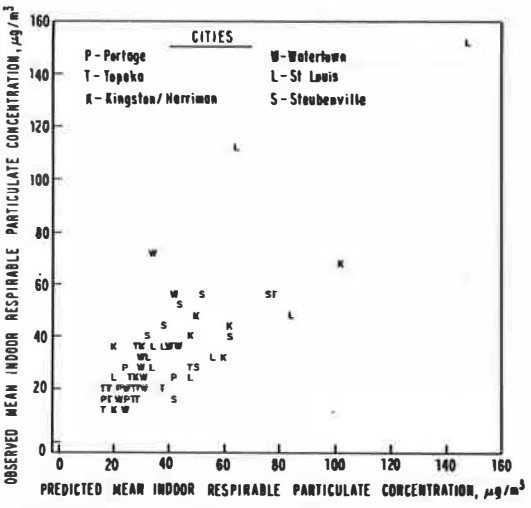

Fig. 3. Comparison of predicted vs measured mean indoor respirable particulate concentrations for each home. Twelve observations are hidden.

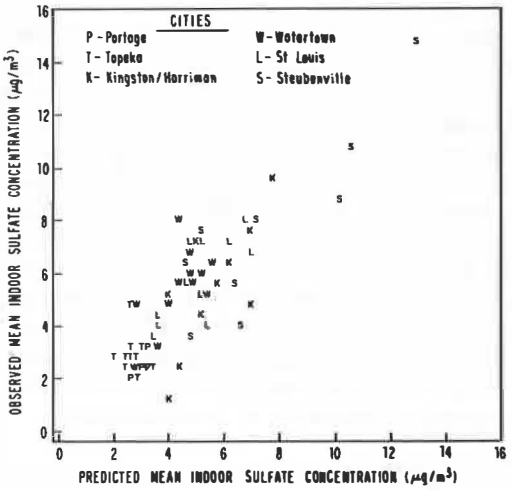

Fig. 4. Comparison of predicted vs measured mean indoor respirable sulfate concentrations for each home. Twelve observations are hidden.

SUMMARY AND FUTURE RESEARCH

Extensive long-term measurements of indoor and outdoor respirable particulates and sulfates have been taken as part of a prospective epidemiological study. In a preceding paper (Spengler *et al.*, 1981), the outdoor respirable particulate and sulfate concentrations were found to be significantly different between the six cities. The outdoor respirable particulates and sulfates were found to have a uniform distribution across each of the cities, except Steubenville, where topography and industrial siting set up large gradients. This would indicate that the sample population in each city, except as noted in Steubenville, has approximately the same exposure to *outdoor* particulates. However, there are significant differences in the *indoor* mean concentrations measured at our sampling sites in each of the cities. Thus actual personal exposure, which is determined in large part by the indoor environment, will vary significantly among people in the sample population in each city.

A simple linear model for indoor concentrations was proposed based on conservation of mass. Analysis of the indoor–outdoor data indicated that indoor levels of respirable particulates and sulfates are determined by the infiltration of outside air plus the impact of indoor sources. Long-term mean infiltration is approx. 70%. This is reduced to approx. 30% in fully air-conditioned buildings and homes.

Smoking is an important source of indoor particulates. The mean impact of smoking a pack of cigarettes inside is to raise the respirable particulate levels by approx. 18 $\mu g\ m^{-3}$. In fully air-conditioned buildings, the recirculation of the interior air increases this impact to approx. 42 $\mu g\ m^{-3}$. Other sources in the home add approx. 15 $\mu g\ m^{-3}$ to the indoor respirable particulate concentrations.

Potentially important sources of sulfate were found associated with smoking and gas stoves. The impact of smoking was not significantly different from zero. Cigarettes serve as a surrogate for matches, the real source of the sulfate emissions. The mean impact of gas stoves was to raise indoor sulfate concentrations approx. 1 $\mu g\ m^{-3}$. The model showed good correlation with the observed indoor respirable particulate and sulfate concentrations.

Table 4. Comparison of measured and predicted indoor concentrations and their correlation by city

		Respirable particulates			Sulfate		
	Number of sites	Mean measured	Mean predicted	Correlation	Mean measured	Mean predicted	Correlation
Portage	11	19.6	24.0	0.46	2.82	2.98	0.75
Topeka	13	23.3	30.1	0.84	2.86	2.68	0.02
Kingston	10	36.3	44.5	0.84	5.41	5.65	0.76
Watertown	13	31.2	31.0	0.66	5.17	4.25	0.72
St. Louis	12	46.7	49.7	0.87	5.72	5.02	0.77
Steubenville	9	39.0	46.7	0.53	7.68	7.61	0.87
Total	68	32.4	37.1	0.81	4.81	4.53	0.87

Significant variations in indoor particle and sulfate concentrations have been demonstrated in all six cities. The variability in indoor concentrations may represent an important proportion of the variability in population exposures. Developing a predictive model for indoor concentrations is important to air pollution epidemiologic studies. Eliciting descriptions of home characteristics from study populations can provide the basis for categorizing exposures to respirable particles and sulfates within a community.

The analysis presented in this paper is on the aggregated samples collected in a number of homes over periods of up to 2 yr. Home air exchange rates and indoor sources are variable. Ventilation rates for homes change seasonally, daily, and even hourly depending on meteorology and home characteristics. The fraction of outdoor air pollution infiltrating inside and the impact of indoor generated pollutants will also vary in response to changes in air exchange rates.

Future research will examine the seasonal and daily variations. A predictive model for indoor air pollution is an essential component for predicting personal exposures. Improving our estimates of actual individual exposures is essential for air pollution epidemiology.

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