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# Air and Aerosol Infiltration in Homes

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ABSTRACT

This paper discusses the measurement of air infiltration rates and reports on measurements relating indoor and outdoor aerosol size distributions in the 0.01 to 1 μm size range. Measurements of air exchange rates with both the induced pressure and tracer gas techniques were performed. It is shown that airflow rates through a blower door duct can be measured to within 5% by making a simple measurement of static pressure drop between air upstream of the duct and a point within the duct. This eliminates the need for fan calibration, which is frequently done for such measurements. Also, simultaneous measurements of air exchange rates with the induced pressure and tracer gas techniques were done in two homes, and the two methods were found to agree to within estimated experimental uncertainties. Finally, indoor and outdoor aerosol size distributions were measured and compared in one home; air infiltration rates were also measured simultaneously by the tracer gas technique. It was found that for particles in the 0.01 to 1.0 μm range, the ratio of indoor to outdoor concentrations was typically between 0.2 and 0.4 and did not vary systematically with particle size.

## INTRODUCTION

It is well known that air infiltration contributes substantially to the heating and cooling loads of buildings (Tamura 1979; DOE 1981). Rising energy costs have led to a recent upsurge of interest in studies of air infiltration and ways to reduce it. However, numerous recent studies of indoor air pollution have shown that reduced air infiltration rates can lead to an undesirable buildup of indoor-generated air pollutants (NRC 1981). Since most people spend 60-90% of their time indoors (Dockery 1979), this can lead to substantial levels of exposure. In order to determine the optimum ventilation rate for a particular residence, it is necessary to know the source strengths and removal rates of all important pollutants, as well as upper limits for safe exposure.

Indoor air pollutants are varied in chemical and physical makeup and can originate from a variety of sources. It is possible, of course, for pollutants present in outdoor air to penetrate through a building envelope with infiltrating air. On the average, such pollutants will be present in concentrations that are equal to or less than ambient levels (neglecting indoor sources), and building occupants should be adequately protected by ambient air quality standards. Of greater concern are pollutants that are generated indoors. These pollutants are typically emitted by human activities (cooking, smoking, biogenic emissions, cleaning agents, aerosol sprays, etc.) or by building materials (radon, asbestos, formaldehyde), and they are often different from those of interest in ambient air. Because legislation (and hence regulatory action) has focused on ambient pollutants, relatively little research investment has been made in quantifying source strengths, indoor lifetimes, and effects of such indoor-generated pollutants.

Aerosols (airborne suspensions of particles that may be either liquid or solid in form) are one type of pollutant that may be significant in indoor air. While aerosols may contribute to

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soiling or corrosion of interior surfaces, it is likely that their most significant potential effects are associated with human health. The health effect of an aerosol depends on the chemical composition and concentration with respect to particle size. Therefore, most previous work has appropriately focused on measurements of chemical or elemental composition of respirable aerosols (Alzona et al. 1979; Halpern 1980; Moschandreas et al. 1979; Cohen and Cohen 1980; Dockery and Spengler 1981; Ju and Spengler 1981). In some of these studies total aerosol mass concentrations were also measured. A limited amount of data on indoor aerosol size distributions has been reported (Lee 1973; Lum and Graedel 1973).

The studies cited above used a variety of measuring and experimental techniques and were conducted in a variety of types of structures. There is reasonable consistency in general features of the results, however. Total mass concentrations of respirable particles in occupied buildings tend to be higher than concentrations outdoors (Dockery and Spengler 1981). Cigarette smoke, wood-burning stoves and fireplaces, and cooking have been associated with elevated particle concentrations. It is also generally agreed, however, that particles of outdoor origin tend to be present in lower concentrations within a structure. For example, Halpern (1978) found typical indoor-to-outdoor ratios of 0.03 to 0.3, depending on the element, Cohen and Cohen (1980) found the indoor-to-outdoor ratio for lead to be 0.45, and Moschandreas et al. (1979) found 0.34 ± 0.16 for lead and bromine. Dockery and Spengler (1981) used statistical techniques to distinguish between sulfates generated indoors and those entering by infiltration. They concluded that the mean infiltration rate of outdoor sulfates was approximately 70%. Much of the variability in all these results can probably be explained by season (doors and windows open or closed), type of construction, etc.

While many general features about the nature of indoor aerosol are known, it is also true that a quantitative understanding of aerosol source strengths, filtration mechanisms during infiltration, and removal rates from indoor air must still be established before indoor aerosol behavior can be reliably modeled. The research reported in this paper was initiated with the aim of studying such problems. Since particle removal and formation rates tend to be functions of particle size, it was felt that measurements of aerosol size distribution over a wide range of particle sizes would contribute important information on indoor aerosol behavior. Furthermore, since particle infiltration is linked with air infiltration, it was decided to make simultaneous measurements of air infiltration rates. Similar studies for larger particles are also needed but were beyond the scope of this project.

This paper describes the first phase of this project. The objectives of the work described here were to develop and verify capabilities for measuring air exchange rates and to study the relationship between indoor and outdoor submicron aerosol size distributions and air infiltration rates. The aerosol studies were done with the objective of measuring particle infltration efficiencies over a wide range of particle sizes, not to measure occupant exposures under typical conditions. Therefore, experiments were conducted in an unoccupied house with all known indoor particle sources eliminated. Furthermore, doors and windows were kept shut in order to determine the minimum particle infiltration efficiency.

## EXPERIMENTAL

### Infiltration Measurements

The two most commonly used techniques for measuring air tightness of structures are the induced pressure (blower door) and tracer gas techniques. With the blower door technique, a positive or negative pressure difference is maintained across the building envelope with a fan and the airflow rate through the blower ducting is measured as a function of this pressure difference. Because such measurements are done with an artificially imposed pressure difference, measured exchange rates do not correspond directly to normal rates for the structure. Nevertheless, such measurements can be made with relative ease and speed by untrained personnel, and the capital cost of equipment is low. Furthermore, with this technique it is possible to determine the relative airtightness of a structure, and it is sometimes possible to locate significant sources of air leakage by detecting local air movement.

The tracer gas technique involves injecting a tracer gas and mixing it through the structure, then measuring its decay rate with an appropriate instrument (Lagus 1980). Most recent work has involved the use of sulfur hexafluoride ($SF_6$) as the tracer gas; it is measured by a gas chromatograph equipped with an electron capture detector. This technique is advantageous because infiltration rates under normal conditions can be determined. Disadvantages include the cost of purchasing and maintaining the gas chromatograph, the long-time periods (several hours) required to make measurements (during which infiltration may vary due to variation in wind and

ambient temperature), and uncertainties about uniform mixing within the structure. Furthermore, since infiltration rates depend on ambient wind speed and temperature, a single tracer gas measurement will not adequately characterize the airtightness of a structure under a variety of ambient conditions.

In the present study, air exchange rates were measured with both the blower door and the tracer gas techniques. Laboratory studies were first conducted to verify procedures for measuring airflow rates through the blower door ductwork. These measurement techniques are somewhat different from those reported previously and may be of interest to researchers who do not have ready access to airflow orifices that are usually used for blower door fan calibrations. Experiments in which air exchange rates were measured simultaneously by the blower door and tracer gas techniques were then done in two different houses. Results of these measurements are discussed. Additional details are provided by Stanbouly (1982).

## Blower Door Measurements

A schematic diagram of the blower door used in this study is shown in Figure 1. This design is similar to that described by Caffey (1979) and Harrje and Cooper (1979). An inexpensive design modification to facilitate airflow rate measurements was the fitting of a truck tire inner tube to the cylindrical duct at the flow entrance. This inner tube served to smooth the flow so as to minimize entrance losses. Also, the door panel was constructed of a single piece of plywood several inches wider and higher than most conventional door frames. This panel was sealed to the door panel with a foam rubber seal. The advantage of this design was low cost and ease of installation.

Flow rates through the duct were determined by measuring the static pressure drop between air upstream of the duct and a point within the duct 9 in (0.23 m) downstream of the entrance. The relationship between this pressure difference, $\Delta P$, and volumetric flow rate through the duct, $Q_s$, was then determined by Bernoulli's (1977) equation (accounting for entrance loss):

$$Q_s = \left(\frac{2\Delta P}{\rho(1+C_o)}\right)^{1/2} A \qquad (1)$$

where

$\rho$ = air density

$C_o$ = entrance loss coefficient

A = cross-sectional area of duct.

The value of the entrance loss coefficient, $C_o$, depends on the shape of the entrance (ASHRAE 1977). This parameter can achieve values as large as 0.5 to 1 for a sharp-edged entrance or as small as 0.06 for a smooth, converging bell-mouthed entrance. The tubular portion of the inner tube used to construct the entrance in this apparatus was 3 in (0.076 m) radius, and the duct diameter was 18 in (0.46 m). Based on these values, $C_o$ was taken to be 0.06 (ASHRAE 1977).

The key measurement for determining volumetric flow measurements from Equation 1 is the pressure difference, $\Delta P$. In these experiments, pressure differences were measured with a manometer that was equipped with a micrometer level detector. The smallest pressure difference that can be measured with this device is 0.002 in $H_2O$ (0.5 Pa).

Experiments were done to determine the validity of Equation 1 for the measurement of airflow rates through this blower door assembly. The velocity profile along a duct radius was measured with a Pitot tube and integrated across the duct area to obtain an independent measure of volumetric flow rates. Measurements were made at 10 positions between the duct wall and the duct centerline, and flow rates, $Q_p$, were calculated with Equation 2.

$$Q_p = \sum_{i=1}^{10} u(r_i)\, 2\pi r_i\, \Delta r_i. \qquad (2)$$

In this expression, $u(r_i)$ is the airspeed measured with the Pitot tube at position $r_i$. Air flow rates, $Q_s$, were simultaneously measured by the Bernoulli equation technique (Equation 1). Airflow rates determined by these two techniques were obtained for several different fan speeds.

Results of these experiments are presented in Figure 2. Under the range of conditions tested, values of $Q_s$ and $Q_p$ (from Equations 1 and 2 respectively) agreed with within 5%; root mean square error analyses indicated that measured values of $Q_s$ and $Q_p$ should have been accurate to within 5%.

The degree of self-consistency in these results suggests that airflow rates through the blower door ducting can be measured with acceptable accuracy by using Equation 1. The advantage of this approach is that there is no need to perform a fan calibration and measurement of fan speeds is unnecessary.

Simultaneous Blower Door and Tracer Gas Measurements

In order to compare different methods for determining air exchange rates, simultaneous measurements were made using both the induced pressure and tracer gas techniques. These measurements were made in two different single family dwellings referred to here as the Minneapolis and Roseville houses. The Minneapolis house is a 60-year-old two-story home; windows in this structure had been caulked the previous fall. The Roseville house is a four year-old two-story home and was built by a public utility company. It was designed to be relatively airtight and energy efficient.

In performing these experiments, the tracer gas ($SF_6$) was first injected into the homes and allowed to mix for a period of about one hour. The forced-air circulating systems were turned on during the mixing period and throughout the experiment to facilitiate uniform mixing of the tracer gas. After the initial mixing period, the opening to the blower door duct was unsealed, and the fan was turned on to the lowest speed at which a uniform pressure difference across the building envelope could be maintained. In each house, experiments were done with windows and doors closed and at both positive and negative pressure differentials.

After the fan was turned on (time 0), $SF_6$ concentrations were measured at five-minute intervals for about one hour. Samples were taken from a single probe at the entrance to the return air grille. A gas chromatograph was used for the $SF_6$ measurements. Typical data for $SF_6$ decay as a function of time are shown on a semilog plot in Figure 3. In theory, if infiltration rates are constant and mixing is uniform, the air exchange rate, I, will be given by the following expression:

$$I = -\frac{1}{t} \ln \frac{C(t)}{C(0)} \qquad (3)$$

where t is time and C(t) is $SF_6$ concentration. Note that the data shown in Figure 3 show $SF_6$ concentrations decreasing exponentially with time, in agreement with Equation 3. In determining infiltration rates from such data, the method of least squares was used to find best fit values for I and C(0). The uncertainties in I were determined by applying a root mean square error analysis, as discussed by Bevington (1969).

Results of these experiments are shown in Figure 4. Note that in all cases the two techniques agreed to within estimated experimental uncertainties. Because pressure differences between inside and outside were so small, however, (0.080 in $H_2O$ (20 Pa) [pressurization] and 0.048 in $H_2O$ (13 Pa) [depressurization] for the Roseville house and 0.010 in $H_2O$ (2.5 Pa) [pressurization] and 0.020 in $H_2O$ (5 Pa) [depressurization] for the Minneapolis house), estimated experimental uncertainties for the blower door data were relatively large. Pressure differences were kept small to minimize infiltration rates, thereby improving the likelihood of uniform mixing of the tracer gas. It is interesting to note that air exchange rates determined by the blower door were systematically higher than values based on tracer gas measurements. The reason for this systematic bias is unknown.

The observation that air exchange rates are higher for the Roseville house than for the Minneapolis house for the data shown in Figure 4 does not imply that the energy-efficient Roseville house is relatively less airtight. Instead, this discrepancy occurred because measurements in the Roseville house were done at a relatively higher pressure differential. In factor of two to three higher than rates for the Roseville house at the same inside-outside pressure differential (Stanbouly 1982).

## Aerosol Infiltration Studies

Experiments were conducted on two days at the Minneapolis house to study relationships between indoor and outdoor aerosol size distributions and air infiltration rates. In these studies, the furnace, gas stove, and electrical appliances were shut off to eliminate all known indoor particle sources, and doors and windows were kept shut to simulate winter living conditions. Air infiltration rates were measured with the tracer gas technique, as described in the previous section. The furnace air filters were removed and air was circulated continuously during the experiment to ensure uniform mixing.

Aerosol size distributions were measured with an electrical aerosol analyzer (EAA) and a single-particle optical counter (OPC). The EAA has been described by Liu et al. (1974) and the use of OPCs for such measurements by Whitby and Willeke (1979). In these studies the EAA was used for measuring aerosols between 0.01 and 0.56 μm and the OPC was used for particles in the 0.56 - 1.0 μm size range. Outdoor aerosols were measured at half-hour intervals and indoor aerosols were measured hourly. The same instrumentation with identical sample lines was used for indoor and outdoor measurements. The indoor samples were taken at the entrance to the return air grille and outdoor aerosols were sampled through a tube that protruded through an otherwise sealed window.

In normal operation, the EAA is used to measure aerosol concentrations in four equally spaced logarithmic size intervals per decade. For the data acquired in these studies, however, aerosol concentrations were very low. Therefore, the four size increments between 0.01 and 0.1 μm were combined into a single size increment to reduce statistical fluctuations, and similarly, only one increment between 0.1 and 0.56 μm is reported.

The ratios of indoor-to-outdoor aerosol concentrations in three size ranges are shown as a function of time in Figure 5. Note that this ratio typically ranged from 0.2 to 0.4 and showed no systematic dependence on particle size except during the rainfall, when small particles were apparently more significantly depleted in outdoor air than larger particles. Data acquired on the second day of measurement are qualitatively similar to those shown in Figure 5.

Air infiltration rates during these experiments were generally quite low. For the data shown in Figure 5, the measured infiltration rate between noon and 2100 was 0.1 air changes per hour, while for the remainder of the day, the average rate was only 0.02 air changes per hour. These rates are lower than would normally be expected for this type of structure and can probably be explained in part by the relatively low wind speeds and lack of a significant indoor/outdoor temperature difference (typically only 2 to 3 F [1 to 2°C]) during the measurements. Temperature differences were insignificant because the furnace was turned off during the week in which experiments were conducted in order to eliminate the possibility of aerosol formation by the combustor. Outdoor temperatures typically ranged between 50 F (10°C) and 65 F (18°C) during the experiments.

## DISCUSSION

The amount of data acquired to date is not sufficient to make conclusive statements about mechanisms that contribute to the depletion of particles in indoor air relative to outdoor air. Some general observations, however, can be made.

Ratios of indoor-to-outdoor concentrations are similar in magnitude to values reported by other investigators using other measuring techniques. This supports the argument that exposure to particles of outdoor origin is reduced by remaining indoors. Under conditions of this study, the indoor-to-outdoor ratios typically varied from 0.2 to 0.4 and did not vary systematically with particle size for particles in the 0.01 to 1.0 μm size range. It seems likely that the extent of protection would depend upon the type and integrity of the structure, the extent to which windows and doors were kept opened, and infiltration rates. Additional experimentation is necessary to quantify the significance of these parameters.

For particles smaller than about 0.4 μm, removal of particles from an enclosed space is likely to be dominated by diffusional deposition and not by gravitational sedimentation. This is because sedimentation rates become vanishingly small for such particles, while particle diffusivity becomes significant. The key to calculating diffusional loss rates is an accurate characterization of the air motion due to natural or forced convection. Convective currents tend to transport particles close to surfaces, enabling them to diffuse through the concentration boundary layer to the surface. Once deposited, such small particles are unlikely to be reentrained since they are held tightly to the surface by molecular forces (Fuchs 1964). It

is possible for larger dust particles to be resuspended, and submicron particles may become attached to dust particles and resuspended in that way. Such resuspension would not have interfered with these measurements because resuspended particles are likely to be much larger than 1 μm, the largest size reported in these experiments.

Therefore, it is likely that the two mechanisms contributing to particle depletion of very small (particle size $\leq$ 0.5 μm) aerosol particles in inside air are removal during infiltration and deposition by convective diffusion from the air within the enclosure. It is well known that convective deposition rates depend on particle diffusivity, which in turn is a strong function of particle size (Crump and Seinfeld 1981). Therefore, if deposition by convective diffusion were important, a size dependence in indoor-to-outdoor ratios would have been expected for the data shown in Figure 5. This was not observed. Furthermore, it would seem likely for diffusional deposition to be relatively more important at low infiltration rates when residence times for particles within the structure are longer. Again, this was not observed. Although infiltration rates decreased from 0.1 to 0.02 air changes per hour after 2100 for the data shown in Figure 5, no significant trend in indoor-to-outdoor ratios was observed. This also suggests that diffusional deposition was not important.

These data, then, support the hypothesis that particle removal during infiltration is the primary mechanism leading to depletion of indoor aerosol concentrations. The observation that concentration ratios did not systematically depend on particle size is still difficult to explain, however. Removal of particles by filtration is also size dependent, so a simple filtration model is not consistent with observations. Indeed, the absence of a size dependence is surprising, and additional work is necessary to determine the reasons for this observation.

## SUMMARY AND CONCLUSIONS

This paper deals with the methodology for measurement of air exchange rates and application of such measurements to studies of outdoor aerosol infiltration. It is shown that airflow rates through a blower door duct can be made by measuring the static pressure drop between points upstream of the duct and within the duct. This technique gives results accurate to within 5% and does not require a fan calibration, which is usually necessary.

Measurements of air exchange rates were done simultaneously with the blower door and tracer gas techniques. The results of such measurements in two different houses showed that the two techniques agreed to within estimated experimental uncertainties, although the uncertainties in the blower door data were relatively large due to the small indoor-outdoor pressure differential that was maintained during the measurements. The air exchange rates measured with the blower door assembly in these experiments were systematically higher than the tracer gas results. The reason for this discrepancy is unknown.

An electrical aerosol analyzer and optical particle counter were used to measure size distributions of aerosols in the 0.01 to 1.0 μm size range inside and outside of one unoccupied house. All windows and doors were kept tightly shut during these measurements to simulate winter living conditions, and all known indoor particle sources were eliminated to ensure that measured particles were of outdoor origin. Air infiltration rates were measured simultaneously by the tracer gas technique and were quite low during these experiments (0.02 to 0.1 ACPH). It was found that under these conditions indoor-to-outdoor ratios for particle concentrations ranged from 0.2 to 0.4 and did not vary systematically with particle size. Insufficent data are available to make definitive conclusions about mechanisms that led to depletion of indoor particle concentrations.

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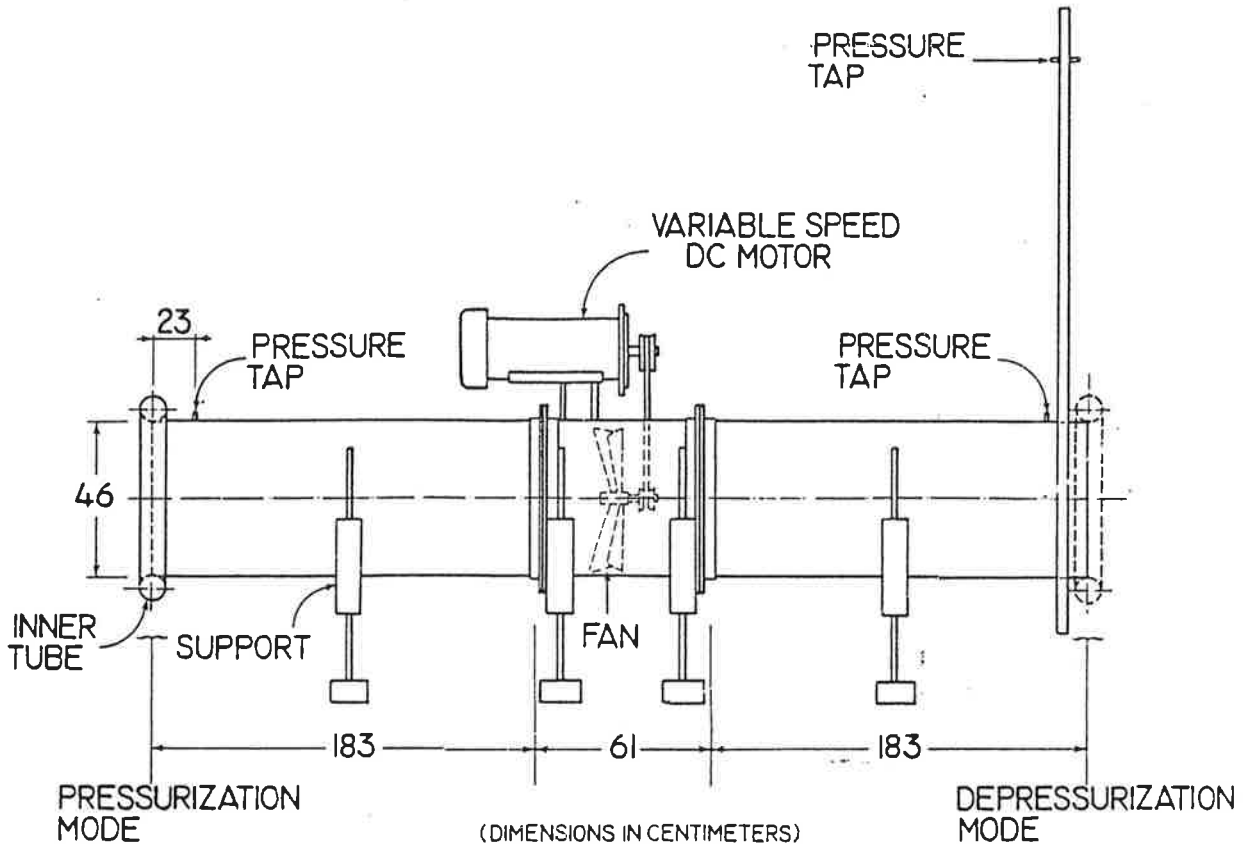


*Figure 1. A schematic diagram of the blower door assembly. Note the location of the truck tire inner tube, which was used to reduce pressure losses at the duct entrance*

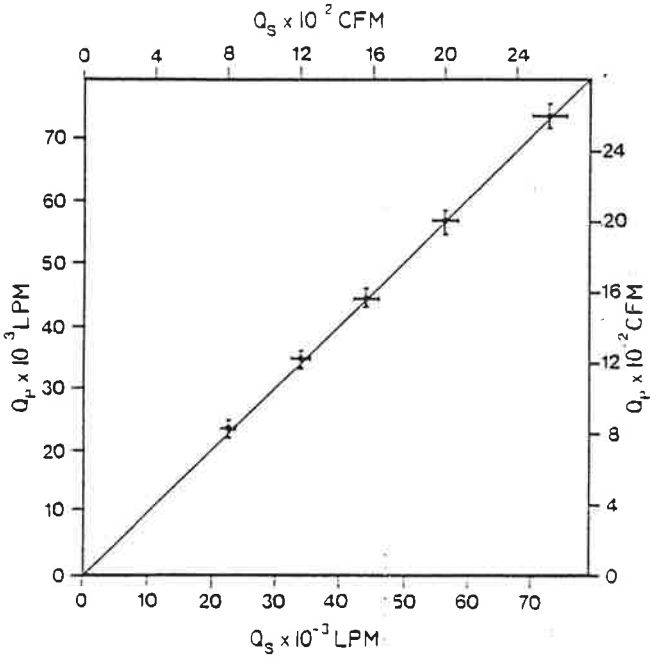


*Figure 2. Comparison of air volumetric flow rates determined by measurements of static pressure drop ($Q_s$) and by a integration of flow speed over the duct area ($Q_p$) Note that these independent measurement techniques agreed to within estimated experimental uncertainties*

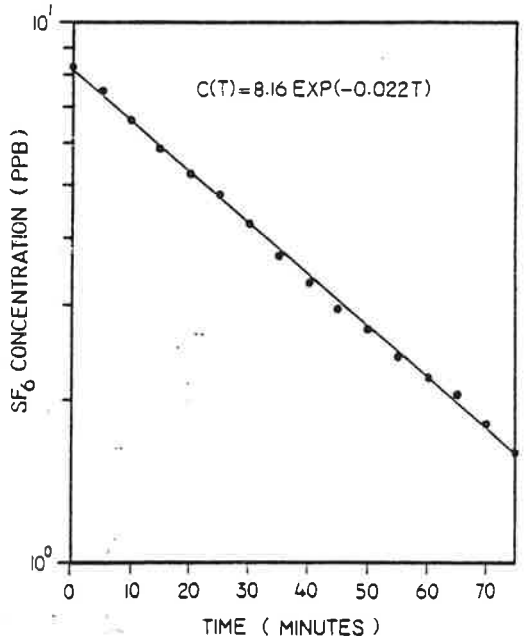


*Figure 3. Typical data showing $SF_6$ concentrations as a function of time when applying the tracer dilution method in a house. Air infiltration rates can be determined from the slope of this line, as shown in Equation 3*

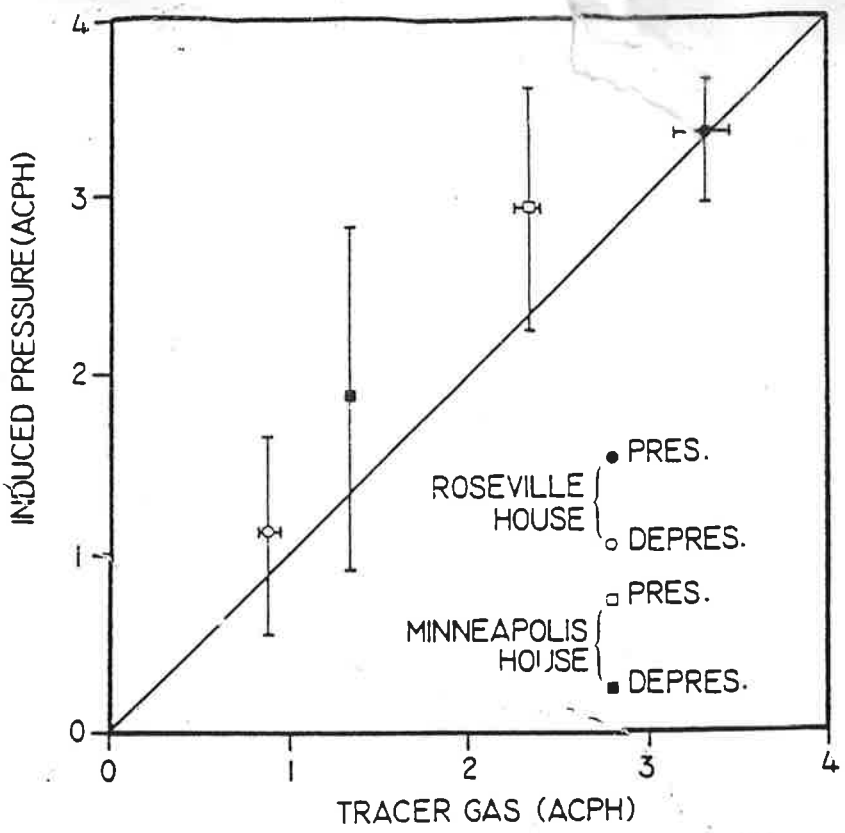


*Figure 4. A comparison of air exchange rates measured simultaneously by the induced pressure and tracer gas techniques. Experiments were done in two houses, and for each house data were obtained at both positive and negative pressure differentials. Units are air changes per hour (ACPH)*

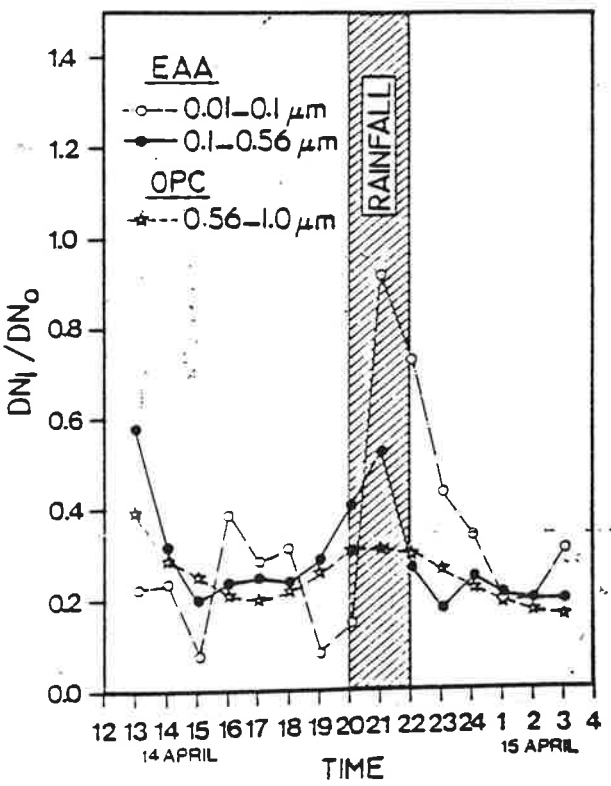


*Figure 5. Ratio of indoor-to-outdoor aerosol concentrations as a function of time. Data for particles in three different size ranges are shown. Note that the ratio does not appear to vary systematically with particle size (except during rainfall) for the range of particle sizes which was investigated*