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An Automatic Multi-Tracer-Gas Method for Following Interzonal Air Movement

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ABSTRACT

A new method for measuring interzonal air movement, using up to four different tracer gases simultaneously, has been developed at the Polytechnic of Central London and tested in a solar air-heated experimental house in Peterborough, UK. This paper describes the method and its application in an investigation of the transfer of air between a passively heated conservatory and the main living space of the house.

Four perfluorocarbon tracer gases are injected, and samples of tracer gas in air are collected automatically using the principle of gas adsorption on a solid adsorbent. Samples of room air are taken simultaneously at up to five points in space and up to ten points in time, leading to a profile of gas concentration with time for each gas at each sampling position.

The tracers are retrieved from the adsorbent by thermal desorption and are separated and analyzed using a gas chromatograph. The injection system, sampling system, tracer retrieval, quantitative analysis, and data collection are all controlled by a microcomputer. Airflow rates are calculated using a new matrix method of analysis.

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INTRODUCTION

The study of air movement is of fundamental importance in building design. Over the last 30 years, researchers have paid particular attention to air movement as it affects the cleanliness of special rooms such as operating theaters, the health and comfort of building occupants, and the energy efficiency of buildings in general.

Investigations show that energy losses due to air infiltration in a building may account for up to 40% of the total heating or cooling load (1,2,3,4). The need to reduce these energy losses has led workers in cold climate areas such as Scandinavia and Canada to develop highly insulated, airtight buildings (5). These building designs have been very successful in reducing heat losses but have presented problems concerning maintenance of sufficient ventilation. It is important to avoid high levels of germs and odors for health and comfort by maintaining adequate ventilation. In particular, ventilation should remove harmful substances, such as radon daughters and formaldehyde, which may be emitted from building materials (6), thus endangering the occupants (7).

So far, most of the measurements of ventilation and air infiltration have treated buildings as single zones, even though they are almost always divided up into several zones by internal walls and partitions. Such measurements cannot take into account the airflow between internal rooms, which has a profound effect on both the local air quality and internal energy transfer. By measuring interzonal airflows, valuable information may be gained concerning the exposure of building occupants to odors, airborne contaminants, and unpleasant drafts. By acting on this information, the indoor health, comfort and energy use of the occupants may be improved.

The use of a multi-tracer-gas system instead of a conventional single gas method reduces the time required to make interzonal airflow measurements (8). Using more than one tracer gas reduces the errors in the experimental determination of interzonal flow rates.

The ventilation rate of a building is defined here as the rate at which air enters from outside. Air infiltration is that part of the total ventilation due to unintentional gaps and cracks in the building envelope. Airflow rates are generally expressed either in volume flow units of $m^3 s^{-1}$ or as ventilation rate units of air changes per hour (h^{-1}). The number of air changes per hour taking place in a given zone is equal to the total volume of air entering per hour divided by the volume of the zone.

The paper is divided into three main sections. The first describes the method and apparatus. The second illustrates the development of a discrete time matrix analysis of single- and multizone data. The third gives an account of some single- and multizone experiments that have been carried out at the PCL solar heated test house at Peterborough, UK. Air infiltration and interzonal airflows are calculated from the measured data using the discrete time matrix method.

THE PCL MULTI-TRACER-GAS METHOD

The experimental method design was divided into several parts including

- --Choice of tracer gases
- --Tracer gas injection
- --Sampling system
- --Tracer gas separation and analysis

Choice of Tracer Gases

A detailed survey was carried out to find nontoxic, unreactive, odorless tracers with a zero background concentration, and which are not absorbed by room surfaces (9). A series of perfluorocarbons, similar to those used by Dietz and Cote (10), fit the requirements. The following have been used in this work:-

PP1	perfluoro-n-hexane
PP2	perfluoro-methyl-cyclohexane
PP3	perfluoro-dimethyl-cyclohexane
PP5	perfluoro-decalin

Tracer Gas Injection

In domestic spaces with volumes typically of the order of 30 m^3, about 1 ml of liquid tracer is flash evaporated by a 12 V, 55 W quartz-halogen car headlamp bulb, yielding an initial concentration of about 4 ppm. The injection system is energized by remote control using a microcomputer.

Sampling System

The sampling system (see Figure 1) operates on the principle of gas adsorption by a solid adsorbent. Each sampling point (see Figure 2) consists of a group of removable stainless steel tubes packed with a divinyl-benzene/styrene co-polymer adsorbent. Samples of room air are obtained by drawing a small fixed volume of air (about 100 ml) through the sample tubes, air being admitted by a solenoid valve controlled from a microcomputer. A flow constrictor in the pump side of each manifold ensures that the flow through the ten tubes sampled in turn is the same. The flows through each of the five different manifolds were not exactly the same. Their relative values were measured.

Up to four perfluorocarbon tracer gases may be injected simultaneously in different parts of a building, and the change in concentration of each gas with time is measured at up to five points in space. The solenoid valves are operated so that tubes are exposed simultaneously at each sampler and in a timed sequence from one to ten. The sample tubes are then sealed and analyzed later. Five sampling points and ten points in time have been chosen for convenience, although there is no restriction on either the number of groups or the number of tubes in each group that may be used.

To expedite experiments, a microcomputer was used to drive the gas injection and sampling system. The sampling system has been left running unattended for as long as a week.

Tracer Gas Separation and Analysis

A schematic diagram of the analysis system is shown in Figure 3. The tracer gases are desorbed from the sample tubes using an automatic thermal desorber and then separated and analyzed on a gas chromatograph fitted with a flame ionisation detector and a 4m packed glass column.

Nitrogen flows through the sample tube at 15 ml min^{-1} and an oven programed to a suitable temperature is engaged round the tube for a period of several minutes. As the gases are desorbed from the sampling tube, they are flushed into a cold trap packed with adsorbent where they are readsorbed.

The reason for using the cold trap is that by concentrating the gases into a tiny volume, band spread is reduced and column resolution is increased. When the primary desorption is complete, the cold trap is flash-heated to liberate the tracer gases. The gases are then swept directly into the separating column via a heated line. The whole process is repeated for each tube until analysis is complete.

Experiments have been carried out to examine the efficiency of the desorption process and ensure that all tracers adsorbed by the tubes are desorbed as quickly and cleanly as possible. Tests have also been carried out to ensure that under any given experimental conditions, all the tracer gas drawn into the adsorber tubes during the sampling procedure will remain on the adsorbent and that no tracer gas will break through the rear end of the tube (12).

The microcomputer was used to monitor the automatic thermal desorber and the gas chromatograph, so that peaks would only be written to disc when desorbed tracer gas samples were passed to the detector. Software allowed the screen to emulate a chart recorder, showing scalable peak heights and retention times at any point in the analysis. Very low signals activated an amplifier to avoid errors introduced by the analogue to digital convertor.

CALCULATION OF SINGLE-ZONE INFILTRATION RATES AND MULTIZONAL AIRFLOWS

A program was written to allow data from the floppy disc to be read. Each data file is loaded into computer memory, and peaks are reconstructed on the screen. As with a chart recorder plot, peaks are identified by their retention times. An average baseline may be constructed and then peak heights and integrated areas calculated.

The multizone system is modeled following Sinden (8) as a series of cells of constant and known volume, which are all connected to a cell of infinitely large volume corresponding to the outside. The net inflow and outflow from each zone are expressed by a series of equations (13) which are summarized below:

$$v_1 \dot{x}_1(t) = F_{1,1} x_1(t) + F_{2,1}x_2(t) + \ldots\ldots + F_{N,1}x_N(t)$$

$$v_2 \dot{x}_2(t) = F_{1,2} x_1(t) + F_{2,2}x_2(t) + \ldots\ldots + F_{N,2}x_N(t)$$

$$\vdots$$

$$v_N \dot{x}_N(t) = F_{1,N} x_1(t) + F_{2,N}x_2(t) + \ldots\ldots + F_{N,N}x_N(t)$$

where v_i = volume of zone i

$F_{i,j}$ = flow rate from zone i to j

The quantity $F_{i,j}$ is always positive except in the special case of i=j. Physically, $F_{i,i}$ represents minus the sum of outflows from zone i.

The important parameters $F_{o,i}$ and $F_{i,o}$ can be derived by subtraction from the other equations:

$$F_{i,o} = - F_{i,1} - F_{i,2} \ldots\ldots - F_{i,i-1} - F_{i,i+1} \ldots\ldots - F_{i,N}$$

$$F_{o,i} = - F_{1,i} - F_{2,i} \ldots\ldots - F_{i-1,i} - F_{i+1,i} \ldots\ldots - F_{N,i}$$

Using the notation $G_{i,j} = F_{i,j}/v_j$, the equations can be expressed in matrix form:

$$\underline{x}(t) = G\underline{x}(t)$$

where $\underline{x}(t) = [\ x_1(t)\ \ldots\ x_N(t)\ ]^T$

and

$$G = \begin{bmatrix} G_{1,1} & G_{2,1} & \ldots & G_{N,1} \\ G_{1,2} & G_{2,2} & \ldots & G_{N,2} \\ & & \vdots & \\ & & \vdots & \\ G_{1,N} & G_{2,N} & \ldots & G_{N,N} \end{bmatrix}$$

Single- and multizone infiltration rates are calculated from the measured data using a discrete time model. This means restricting the variable t to have only values of 1 2 ... S-1, where S is the number of samples taken in each zone. The discrete time model is written:

$$x_1(t+1) = D_{1,1}x_1(t) + D_{2,1}x_2(t)\ \ldots + D_{N,1}x_N$$

$$x_2(t+1) = D_{1,2}x_1(t) + D_{2,2}x_2(t)\ \ldots + D_{N,2}x_N$$

$$\vdots$$

$$\vdots$$

$$x_N(t+1) = D_{1,N}x_1(t) + D_{2,N}x_2(t)\ \ldots + D_{N,N}x_N$$

and in matrix form

$$\underline{x}(t+1) = D\,\underline{x}(t)$$

where

$$D = [\ D_{i,j}\ ]$$

It is well known from linear system theory that the discrete functions x_i coincide exactly with the continuous time functions above, if $D = \exp G$ where the exponential of the square matrix G is most conveniently defined by the power series:

$$\exp G = I + G + G^2/2! + G^3/3!\ \ldots$$

The system flow constants may now be obtained from a set of equations involving only the desired coefficients and the measured data.

$$\underline{x}(2) = D\,\underline{x}(1)$$

$$\vdots$$

$$\underline{x}(S) = D\,\underline{x}(S-1)$$

The solution to the equations is given by Dorny (14).

$$\underline{D}_k = (R^T R)^{-1} R^T \underline{Q}_k$$

where

$$\underline{D}_k = [\, D_{1,k}\; D_{2,k}\; \ldots\; D_{N,k} \,]^T$$

$$\underline{Q}k = [\, x_k(2),\; x_k(3)\; \ldots\; x_k(S) \,]^T$$

and

$$R = \begin{bmatrix} x_1(1) & x_2(1) \;\ldots\ldots & x_N(1) \\ x_1(2) & x_2(2) \;\ldots\ldots & x_N(2) \\ & \vdots & \\ x_1(S-1) & x_2(S-1) \;\ldots & x_N(S-1) \end{bmatrix}$$

The solution is completed by finding the logarithm of the matrix D.

SCOPE OF THE METHOD

The multi-tracer-gas method described here has shown great versatility. The infiltration rates of several very different single zones, ranging from the small and tight to large and leaky, have been measured successfully. It has also been used to measure single-zone infiltration rates and interzonal airflows in the PCL solar test house.

Measurement of Infiltration Rate in a Very Tight Enclosure

The infiltration rate of the PCL Solar Test Cells of volume 10 m^3 (15) was measured by placing four tracer liquids, three sampling units, the sampling system trolley, and the controlling computer inside the cell to be measured. The computer was programed to inject the gases after the door had been sealed from the outside. The first sample was collected ten minutes after the injection and a further nine samples were collected at ten hourly intervals.

Results. Figure 4 shows a plot of PP1 concentration against time for Sampler A. The infiltration rate implied by the data is $5.0 \times 10^{-2}\,h^{-1} \pm 0.9 \times 10^{-2}$. The error band has been calculated from the data collected for each sampler and each tracer gas.

Infiltration Rate of an Atrium.

The largest space (3000 m^3) measured during this programe of work was the uncluttered atrium of a new school (16). The weather was warm and still. Two gases were injected, PP1 (10 ml) and PP3 (10 ml), from four injection heaters placed in different positions about the space. Two gases and two sampling units were used so that an estimate could be made of the measurement error, and the four injection points were used to help distribute the tracer gases evenly throughout the atrium. A pair of mixing fans and two people walking about waving newspapers promoted further mixing of the tracer gas with the room air. Ten minutes after injecting the tracer gas, the first sample was taken and a further nine samples were taken at ten minute intervals. The similarity of results from the two sampling positions which were widely separated, suggested that ten minutes was an adequate mixing time.

Results. The measured data implys an infiltration rate of 1.0 h^{-1} ± 0.2, which is lower than had been expected. The low rate may be due to the absence of either wind or a significant temperature difference between indoors and outside. The error band has been calculated from all the data collected.

Infiltration Rate of the Conservatory of the PCL Solar House.

Four sampling units were set up side by side in the conservatory of volume 35 m^3, and tracer gases PP1 (0.5 ml), PP2 (0.5 ml), PP3 (0.5 ml) and PP5 (0.5 ml) were flash-evaporated simultaneously from a single injection heater. After a pause of ten minutes to allow the tracer gases to mix with the air in the conservatory, the first sample was collected. A further nine samples were collected at ten minute intervals. The conservatory was left as it would normally be used in winter, with all the doors and windows shut and with no special sealing measures. No artificial mixing was used. The tracer gas was left to mix naturally with the surrounding air. The weather was cold and still.

Results. Figure 5 shows a plot of concentration against time for PP2 collected at sampler B. The calculated infiltration rate was 1.4 h^{-1} ± 0.5. The error band has been calculated from all the data collected for each sampler and each gas.

Interzonal Airflows in the PCL Solar House

Several experiments have been carried out to investigate the airflow between the south-facing conservatory and the living room of the house (17). The one described here illustrates the exchange that took place between the living room and conservatory on 12/7/84. Sampler B was placed in the living room and sampler C in the conservatory. The weather was warm and sunny and the following temperatures were observed:-

Outside .... 22.2°C

Conservatory .... 30.6°C

Living room .... 24.7°C

Hall .... 23.2°C

1.0 ml PP1 was injected in the living room and 1.0 ml PP3 in the conservatory. A total of nine minutes was allowed for the injection and mixing of the gases in their respective zones, before ten gas samples were collected at ten minute intervals. During the entire experiment all internal and external doors remained closed. No artificial mixing was used.

Results. Figure 6 shows a plot of gas concentration in the living room (Sampler B), and Figure 7 shows concentrations in the conservatory (Sampler C). Figure 8 shows a schematic of the interzonal flows calculated from the gas concentration data. The overall direction of flow is predominantly from the house to the conservatory and to the outside. A calculation of the energy balance from the measured temperature difference and calculated flows indicates for the conservatory a net loss of 0.9 kW; for the living room, a net gain of 0.1 kW; for the outside, a net gain of 0.8 kW; and for the hall, a net gain of 0.0 kW.

CONCLUSION

A new automated multi-tracer gas method has been successfully developed and has been used to measure interzonal airflows in a solar heated test house. In addition to this, single zone air infiltration rates have been measured in a wide variety of building types. A novel discrete time matrix method of analysis has also been developed and demonstrated using measured data.

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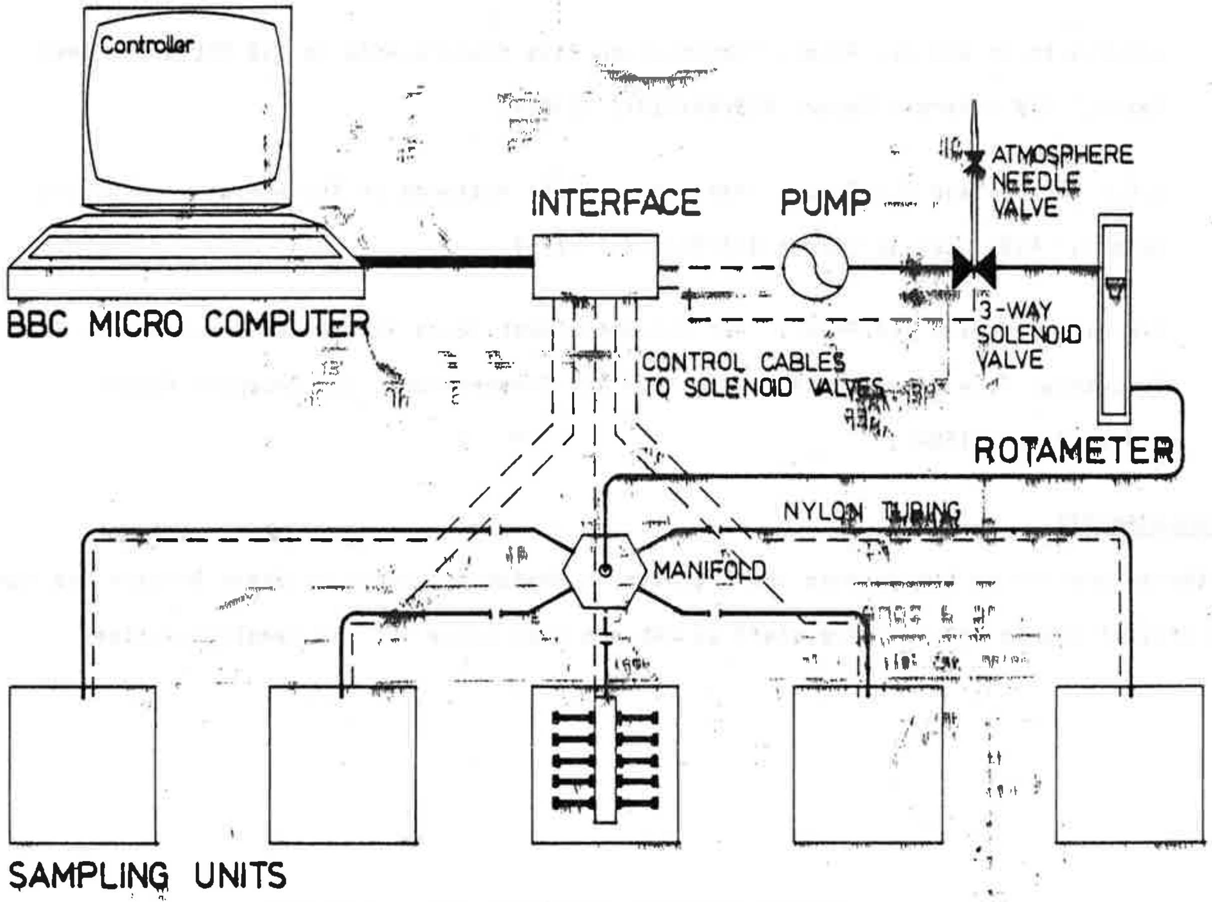


Figure 1. The automatic sampling system

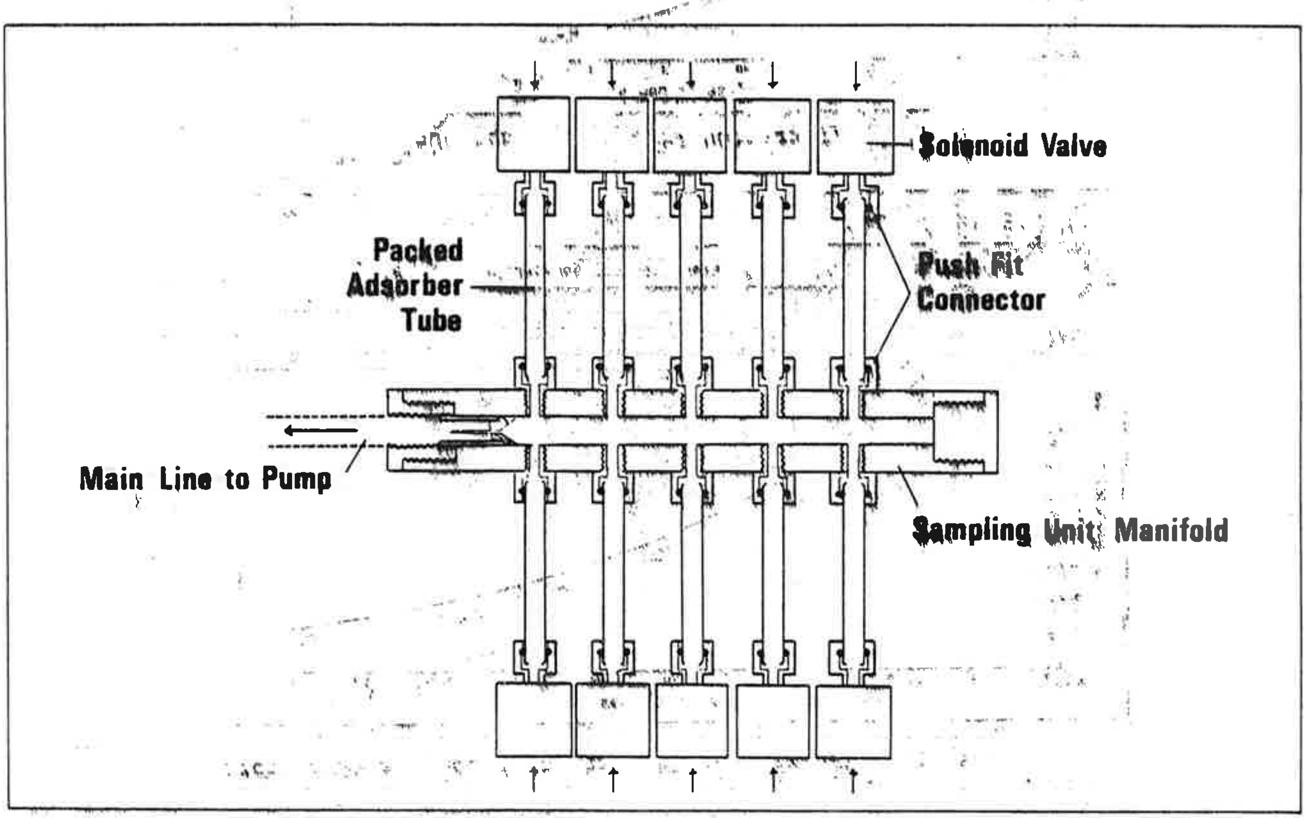


Figure 2. A single sampling unit

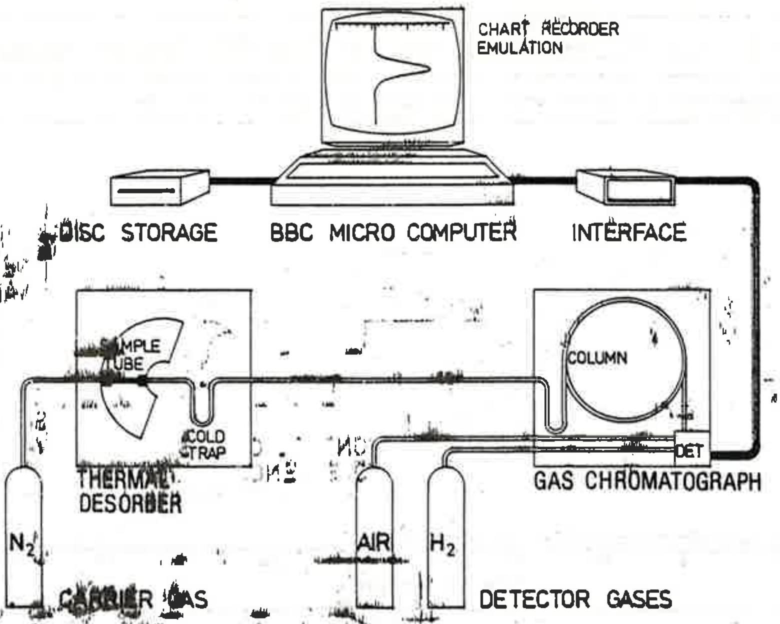


Figure 3. Analysis and data handling

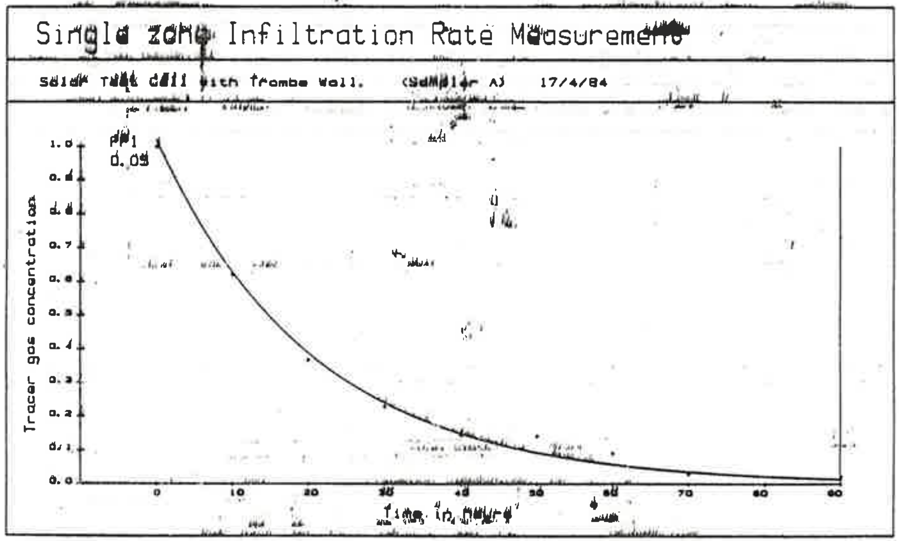


Figure 4. Infiltration rate of a tight enclosure

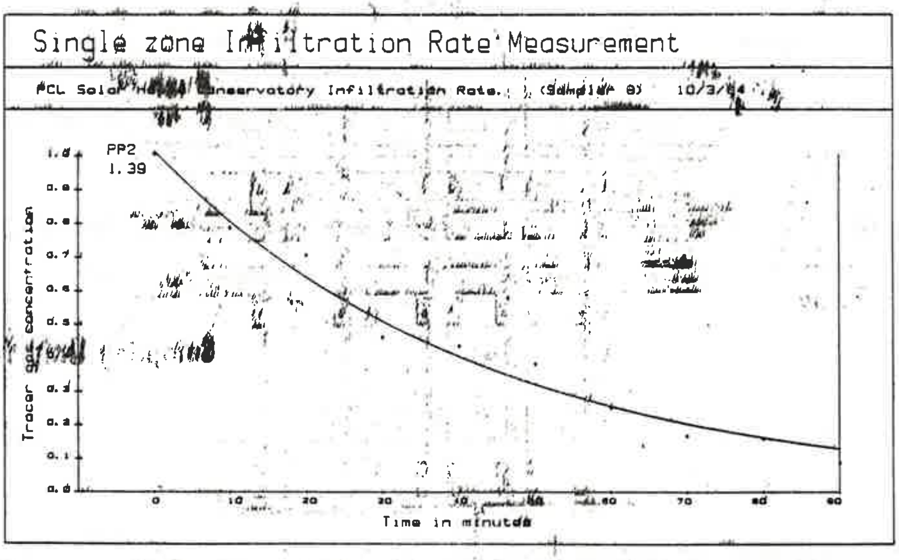


Figure 5. Infiltration rate of the PCL solar house conservatory

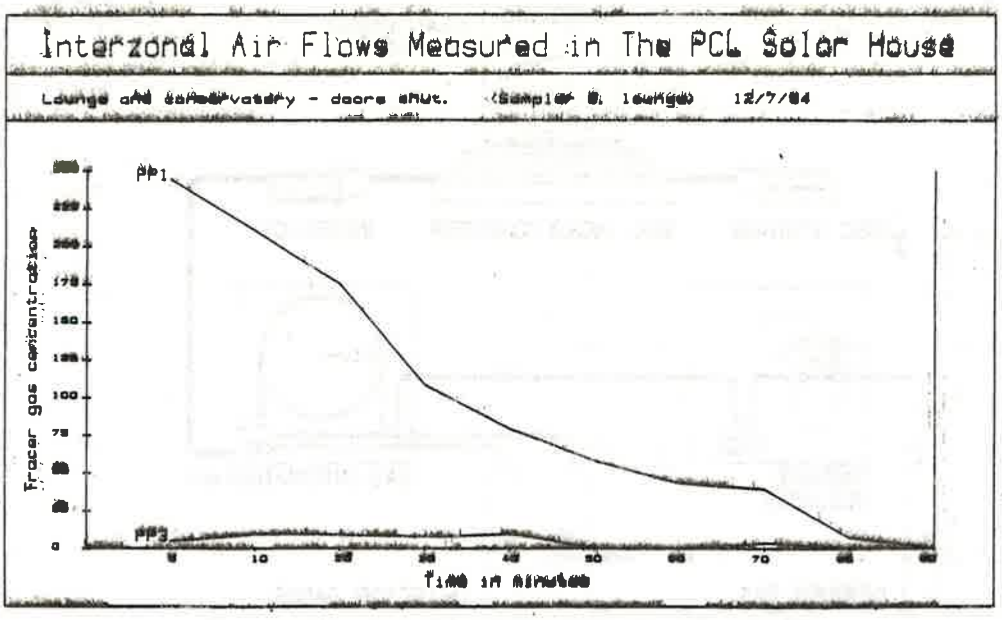


Figure 6: Gas concentration in the lounge

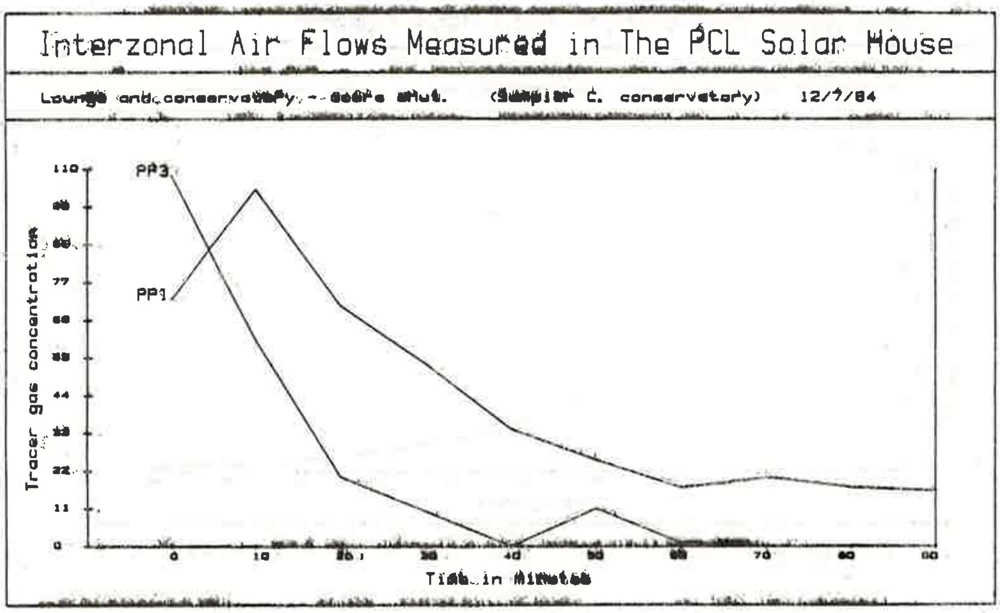
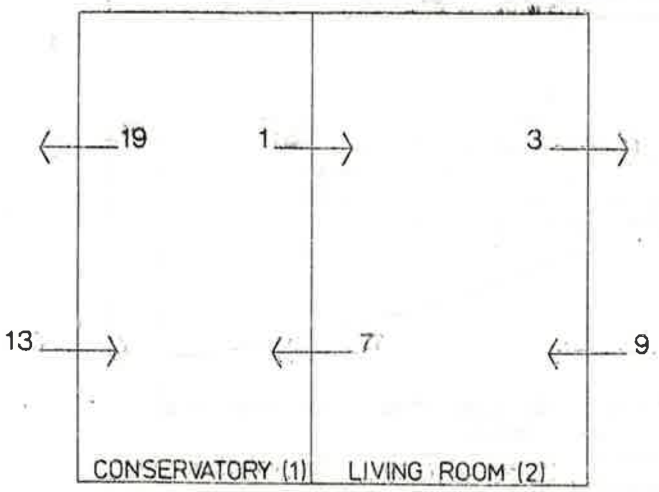


Figure 7. Gas concentration in the conservatory



FLOWS ARE IN $m^3/10mins$

AIR CHANGE RATES

ZONE	h^{-1}
(1)	3.5
(2)	1.3

Figure 8. Diagram showing airflow between two zones.