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Automated Tracer Equipment for Air Flow Studies in Buildings

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1 Synopsis

This paper describes tracer gas methods and equipment developed to measure infiltration and inter-zone air flow rates in New Zealand houses. Air flows in houses have been studied in detail, in order to understand the role of ventilation in controlling indoor moisture, and the role of air flows through the construction cavities in transferring moisture to parts of the structure most sensitive to moisture. The main technical content of this paper, however, concerns an automated tracer gas detection and delivery system based around a gas chromatograph and an electron capture detector. Constant composition and decay modes of operation have been automated and the control loops for both modes are illustrated with a flow diagram. Favourable comparisons between air flows measured and calculated by various methods are presented. Against this background of consistency, a passive technique is shown to give plausible infiltration rates.

2 Tracer Techniques

Tracer dilution methods have been widely used to study air flows in buildings, but with manual control and data analysis methods, it can be time consuming and impractical to monitor air flows over periods of days and weeks. Automation with computers and process control technology has been employed by the Building Research Association of New Zealand (BRANZ) to make long term airflow studies practical.

The tracer gas and the detector type have an important bearing on concentration analysis and control procedures. In this case a gas chromatograph coupled to an electron capture detector (ECD) was used to detect halogenated compounds used as tracers. One advantage of an ECD is that ideal working concentrations of tracer are very dilute (parts per billion) so that transporting and applying the tracer gas are logistically easy and there are no potential air quality problems when working in occupied spaces. One disadvantage is that air samples must be analysed discretely rather than continuously and the consequent time delay can be a problem when controlling a tracer concentration to a constant level.

A computer running Basic has been used as a process controller and data analyser. This made it easy to adapt the equipment to a range of different jobs that have contributed to the air infiltration program in recent years. Early measurements of house-averaged infiltration rates[1] were made using a single tracer gas, SF_6, and the decay method with automated tracer top-up. As more sophisticated multizone air tracing tasks have emerged, the equipment has been reconfigured to analyse multiple tracers and control tracer concentrations to target constant values. Recent studies of airflows between the construction cavities and the living spaces of houses[2] have used two tracer gases in constant composition mode.

3 Gas Chromatography Hardware

The tracer gas equipment described here is fully automated and can operate in one zone in constant composition or decay mode, or it can deal with two zones simultaneously using two separate tracer gases in constant composition mode.

3.1 Hardware Configuration

The major components of the system are a computer controlled gas chromatograph with an electron capture detector (ECD). Other major pieces of hardware are shown in Figure 1. The Capricorn weather monitor can measure wind speed and direction 10 m above ground on the building site, together with temperatures inside and outside the building. Weather data, and the results of tracer investigations were written to disk and, in the case of constant composition multizone results, copied to a larger computer for analysis.

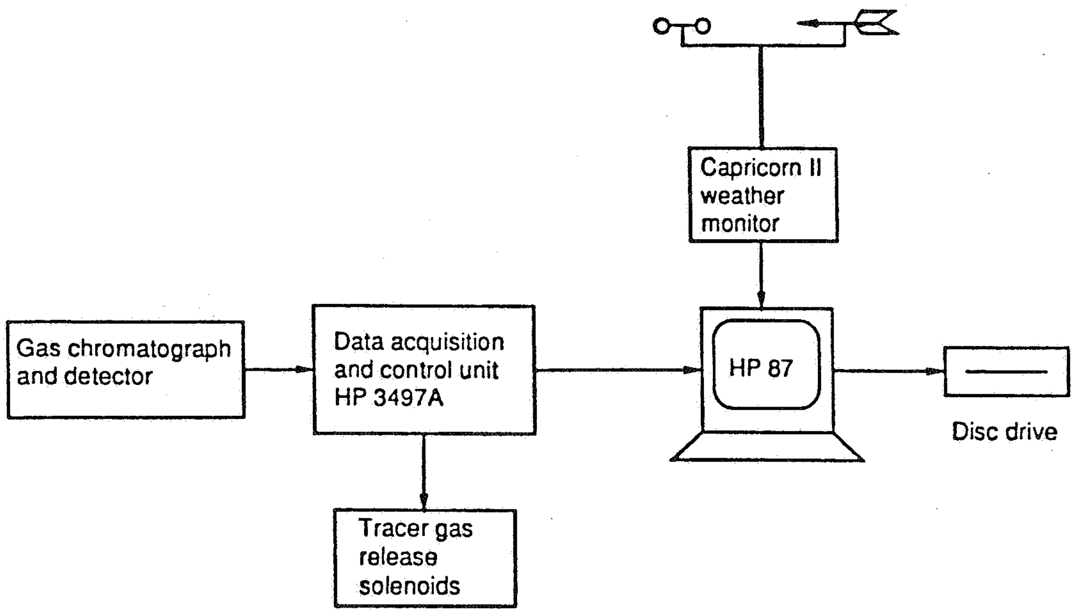

Figure 1: Schematic of automated gas chromatograph

3.2 Tracer Sampling

When working in constant concentration mode in two zones and with two gases, the GC samples air from a zone, measures both tracer concentrations, tops up the chosen zone to target concentration, and then moves on to the next zone. It repeats the process every three minutes, stepping sequentially between zones and writing tracer concentrations and injection volumes to disk.

In automated decay mode, the top-up process takes place after a sequence of 10 concentration measurements have been processed into an infiltration rate. This takes about 30 minutes and the sequence then continues until an interrupt is received from the keyboard.

Sample handling and tracer metering into the zones is achieved with a network of small bore tubes drawn schematically in Figure 2. Here the equipment is illustrated working simultaneously in two zones of a building.

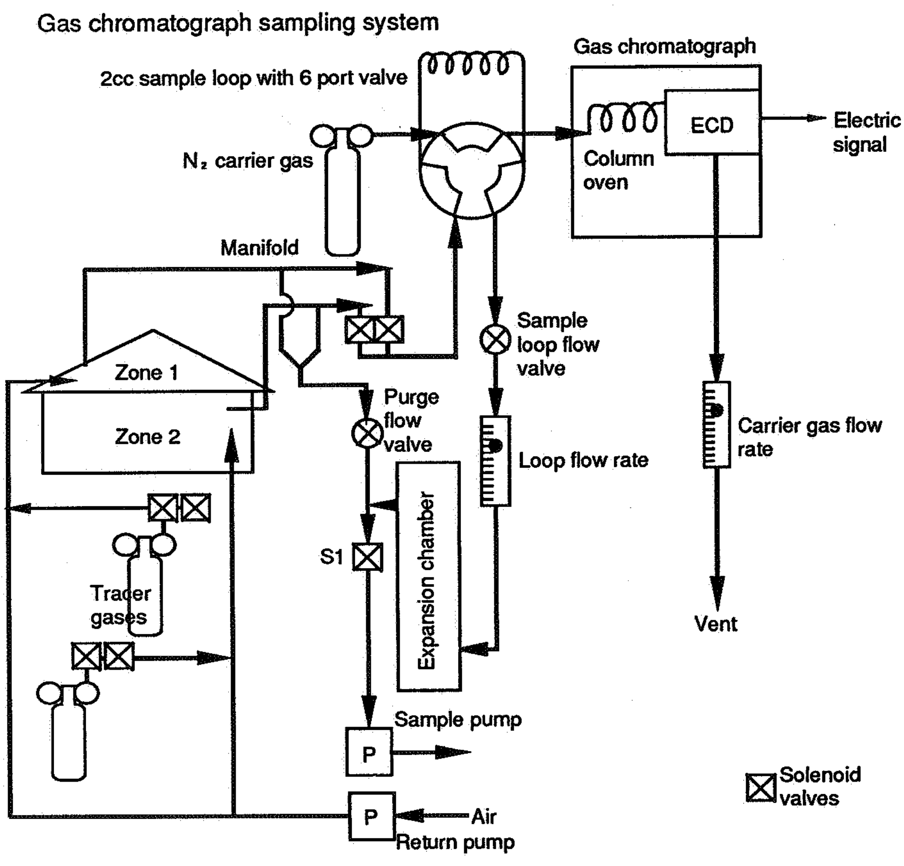

Figure 2: Tracer gas sampling and top-up network

Two air flow circuits were found necessary to ensure that transport delays in the sampling process were kept to a minimum. It would not have been possible to duct all the sample air through the sample loop because the six-port valve has too high an airflow resistance for an adequate air flow to be easily achieved. The first loop is a high air flow ($100cc/s$) circuit that maintains an up-to-date air sample at the GC and delivers top-up tracer gas back to the zone. The second, low air flow rate circuit ($1cc/s$) maintains an up-to-date sample in the sample loop. The six-port sample valve is switched to flush an up-to-date air sample through the GC.

Further notable aspects of design are:

- An expansion chamber which dampens pumping pressure fluctuations to give a steady airflow through the loop flow rate meter.
- A solenoid (S1) which isolates the sample loop from pumping pressure oscillations prior to sampling, thus ensuring the sampling loop always captures the same sample size.
- Location of as many pumps and solenoid valves as possible downstream of the loop to prevent contamination reaching the detector.
- Complete isolation of sampling and tracer dosing networks to prevent cross contamination.

3.3 Tracer Dosing and Mixing

Hardware for topping up tracer concentration in a zone is illustrated in Figure 3. In principle it is similar to the tracer discharge system described by Kumar et al[3]. It releases discrete shots of tracer gas from the small pressure vessel located between two computer controlled solenoid valves. The sequence of events leading to a shot of tracer being released is as follows:

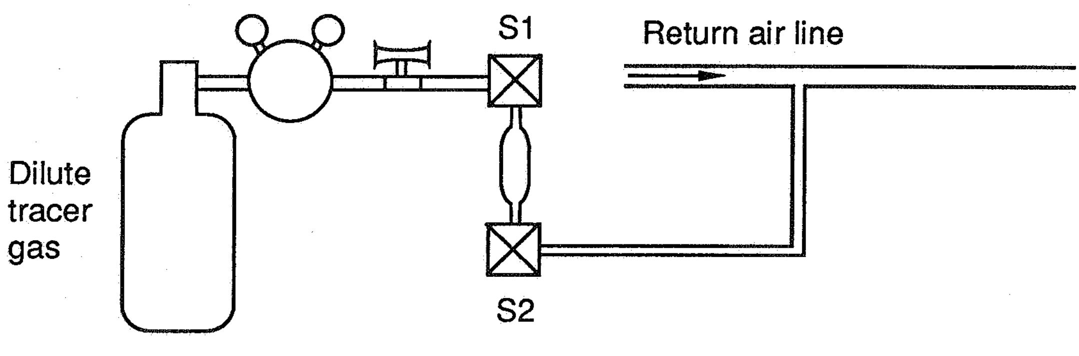

Figure 3: Tracer gas metering system

1. Solenoid valve S1 on low pressure side of regulator opened.
2. Pressure of tracer gas in pressure vessel equalises to regulator setting.
3. Solenoid valve S1 on low pressure side of regulator closed after 200 ms.
4. Solenoid valve S2 on pump side opened.
5. Tracer gas pressure relaxes to atmospheric pressure and excess volume carried to zone by return air hoses.
6. Solenoid valve S2 on pump side closed after 500 ms.
7. Wait 100 ms and return to 1.

Shot sizes were measured for a range of regulator settings and the required number of shots was calculated by a control function within the main program. Working concentrations of tracer gases and shot sizes found convenient in houses are shown in Table 1. The working concentration and amount of SF_6 were chosen to avoid air quality problems in an overspill. In the case of freon-12 (CCl_2F_2) the concentration was chosen to avoid liquifaction.

Tracer type	Concentration	Delivery pressure	Shot size
SF_6	5%	100 kPa	$1cc$
$freon - 12$	1%	100 kPa	$50cc$

Table 1: Details of working tracer gases

Tracer gas delivered to the zone in the return air leg of the tracer dosing circuit was released in front of 400 mm portable fans running at slow speed. This mixing process has been found to minimise tracer concentration differences in the living spaces of houses. In subfloor and roof space construction cavities mixing fans have been shown to give homogeneous gas concentrations, at the same time not causing pressure differences that alter the natural infiltration driving forces. This has been confirmed by showing that major changes in the location and number of mixing fans have not changed the infiltration characteristics of the space.

3.4 Tracer Detection

The gas chromatograph is a Shimadsu GC-Mini 2 fitted with an electron capture detector but without the temperature programming option. Important aspects of configuration and operation, when used to detect SF_6 and freon-12, are as follows:

The hardware specification for the gas chromatograph is as follows:

Sample loop volume	2cc
Electron capture detector source	Ni^{63}
Operating temperature of ECD	140 C
Chromatograph column packing	Molecular sieve
Column operating temperature	100 C

The operational characteristics can be summarised as follows:

Retention time for SF_6	75 s
Working concentration range	1 - 60 ppb
Retention time for freon-12	100 s
Working concentration range	200 - 1500 ppb
Retention time for oxygen	120 s

Working concentration ranges of 1-60 ppb for SF_6 and 200-1500 ppb for freon-12 were found to be consistent with simple linear relationships between integrated output from the ECD and tracer gas concentration.

For SF_6 the relationship was:

$$\text{concentration } SF_6 \text{ ppb} = 1.29 + 60.6 \text{ (area in volt.sec)}$$

and for freon-12:

$$\text{concentration freon-12 ppb} = 5.1 + 1004.4 \text{ (area in volt.sec)}$$

4 Analysis and Control Functions

A control program was written to operate the 6 port sampling valve, analyse the chromatogram into tracer concentrations and run the tracer metering solenoids to top-up tracer concentrations. All of these functions, together with copying weather data and infiltration records to disk, were accommodated within one program. The program structure is illustrated in Figure 4.

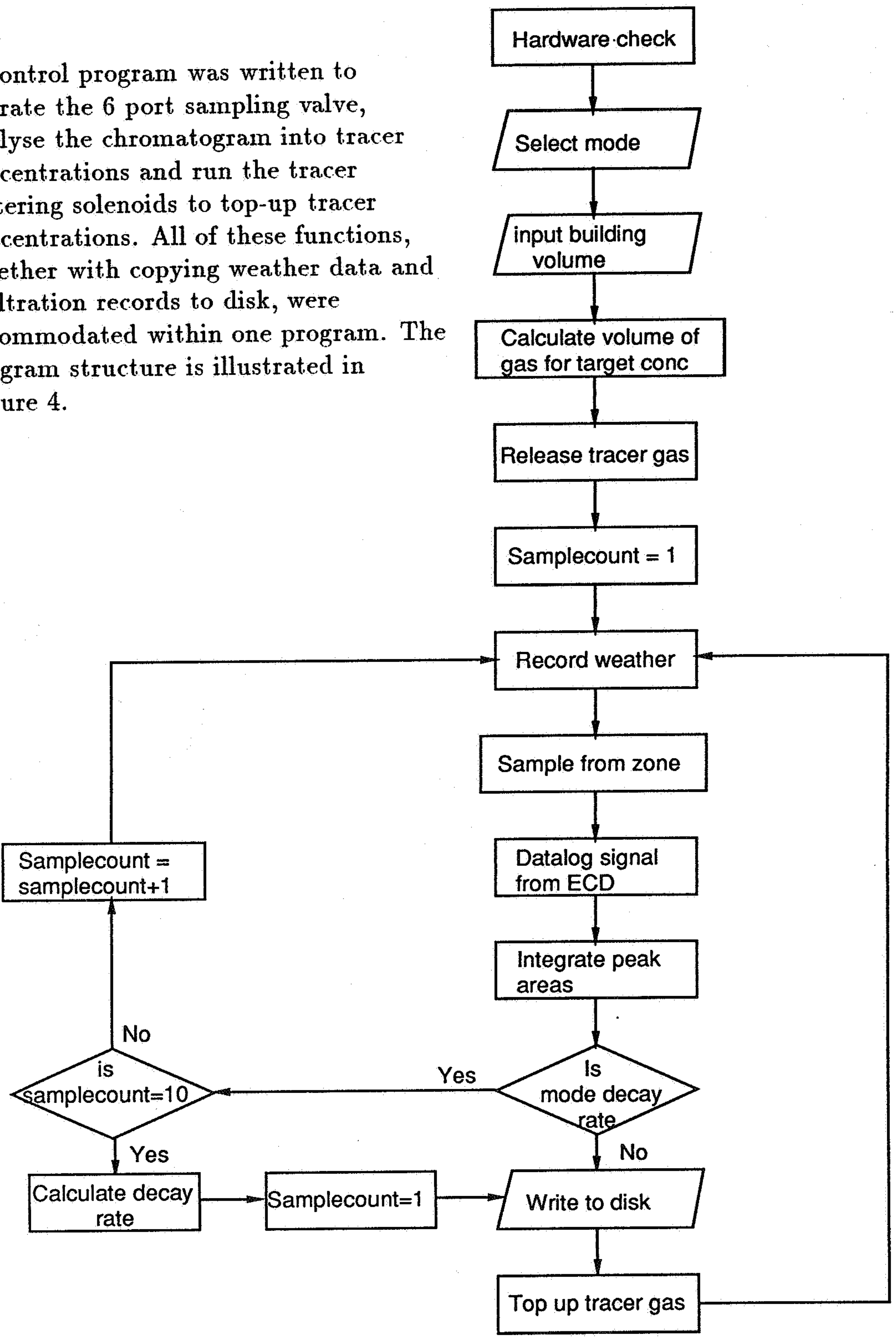

Figure 4: Flow diagram of control and analysis program

4.1 Analysis of Tracer Concentrations

Tracer concentrations were determined from integrated chromatograph peak areas rather then the peak height. This added complexity was considered necessary to allow columns to be swapped without having to have alter calibration constants resident in the program. This turned out to be too simplistic a view, however, as both column changes and variations in carrier gas pressure were shown to influence the calibration constants. As a consequence, it was always necessary to adjust the carrier gas pressure to ensure tracer gas retention times were at standard values. In these circumstances, peak height is an equally satisfactory variable to use in calculating tracer concentrations. Figure 5 gives peak area and peak height for SF_6 over the working range of concentration and both variables are shown to be a linear function of concentration.

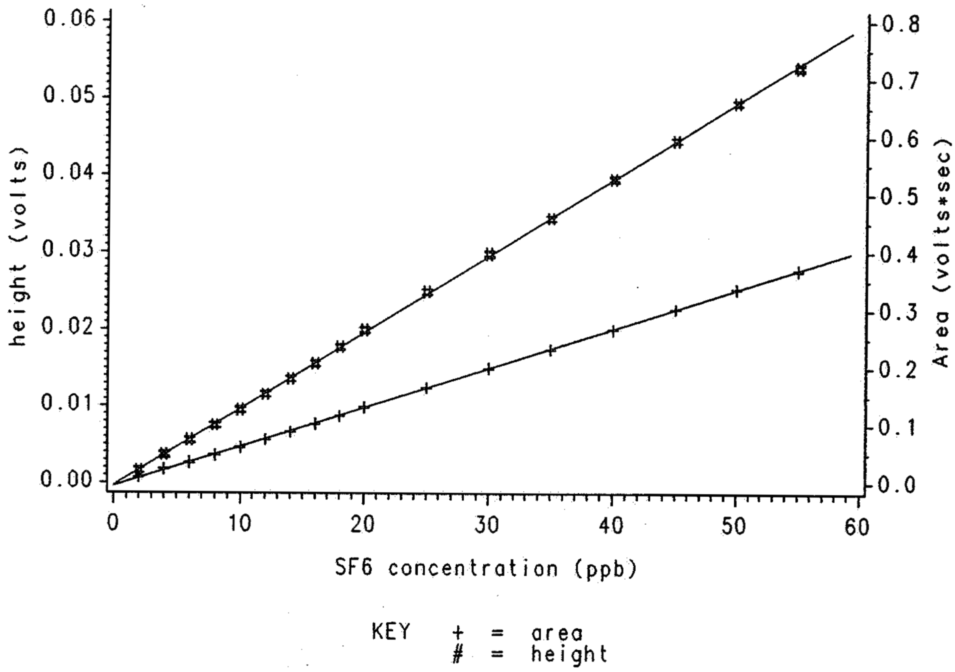

Figure 5: Peak area and height relationship with concentration of SF_6

The accuracy achieved in freon-12 and SF_6 concentration measurement is considered to be around 5% in the calibrated range.

An integration procedure found to be a reasonable compromise between speed and noise rejection is illustrated below. First the analog signal from the electron capture detector was digitised and logged to memory at the rate of 7.69Hz. Then, to eliminate an interference problem with AC pick-up, adjacent data values were averaged to give a new filtered data set. Peak identification, integration and concentration determination were then carried out as follows. Figure 6 is an example of a chromatograph peak and the associated text illustrates how the beginning and end of a peak were identified, with the help of intermediate decision points.

The slope at data point n, Dat(n) is defined as :Dat (n + 4) - Dat (n)

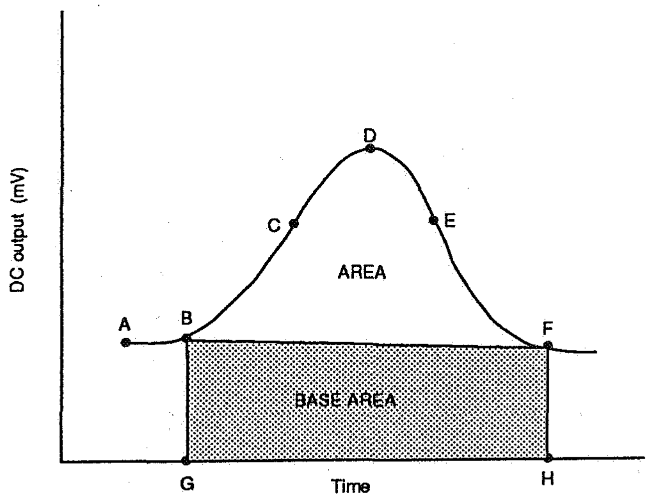

Figure 6: Example chromatograph peak

Point A. Start of data logging.

Point B. Slope> 5. 10^{-5} v/s. This was the minimum slope that ensured base line drift (A-B) did not prematurely trigger peak area analysis routine. This is the start of area integration.

Point C. Maximum slope. Start testing for the maximum Dat(n).

Point D. Maximum height. This defines the retention time. Start testing for minimum slope.

Point E. Minimum slope Start testing for off slope.

Point F. slope > -5. 10^{-5} v/s. End of peak area integration.

The line joining G-H is the zero. Integrated area is the total area under the curve B C D E F H G. Area B F H G is calculated and subtracted to give the effective peak area.

Where multiple gases were being detected, the gas type was determined from the time between sampling and arrival of the gas at the detector (the retention time).

4.2 Tracer Concentration Control

A number of tracer concentration control functions have been investigated but in most cases simple proportional control has proved adequate. It has been used to top-up tracer concentrations in both constant composition and decay modes. Because data analysis using a derivative method[2] with averaging over two hour time periods does not assume constant concentration, the main role of the control function has been to keep tracer concentrations within detectable range. The limiting factor in using more sophisticated control functions has been the speed at which concentration measurements could be made. With two zones being controlled, this transport delay was approximately six minutes and generally in excess of the tracer mixing time constant.

5 Results of Consistency and Reproducibility

Now, after a number of air infiltration and multizone airflow studies have been completed, a range of data can be brought together to review infiltration in New Zealand houses. The opportunity can also be taken to examine the consistency between different ways of measuring infiltration rates, and with infiltration rates calculated using numerical models having a physical basis.

5.1 Living Space Infiltration Rates

Infiltration rates have been measured in nine houses using the automated decay method. In all cases, wind speed and inside and outside temperatures were measured on site, together with the overall airtightness characteristics of each house. Infiltration rates averaged over the 1-3 day duration of the experiment were calculated using the LBL simplified method[4] and appear on Figure 7 compared with measured values.

The quality of agreement between measured and calculated infiltration rates has been found to be within 10% where wind speed measurements were made on site. This margin is equivalent to an uncertainty of about one site wind exposure class. Where wind data has been taken from a weather station some distance away, agreement has been found to be much less satisfactory.

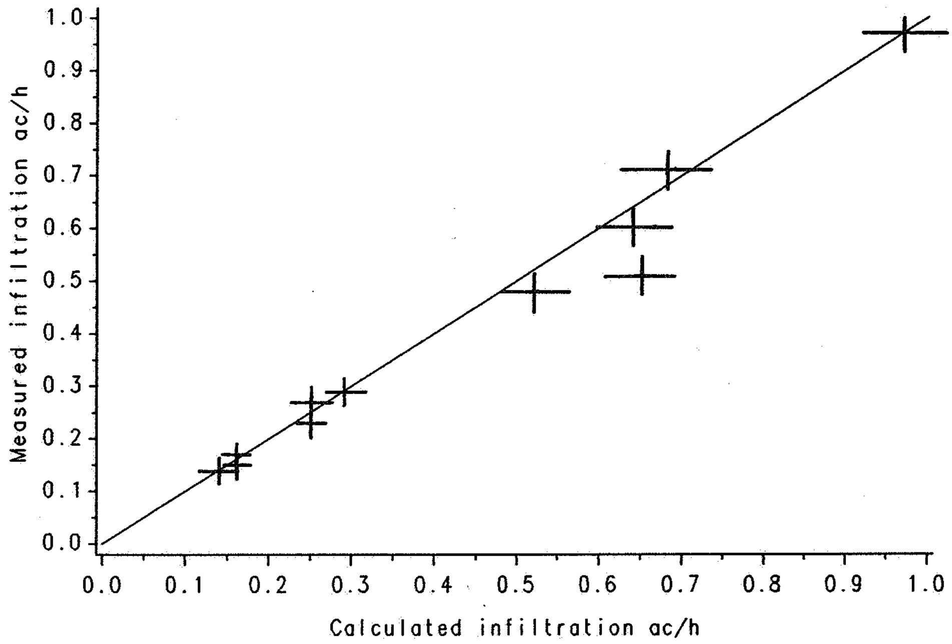

Figure 7: Comparison of measured and calculated infiltration rates with wind speeds measured on site

5.2 Comparison of Decay and Constant Composition Results

Consistency has been observed between results of applying the constant composition and decay methods. Figure 8 illustrates this by comparing one hour averaged infiltration rates measured in the living space of a house using both methods. Although the two methods were not run simultaneously, it has been possible to demonstrate consistency by plotting infiltration rates against the dominant influence of wind speed.

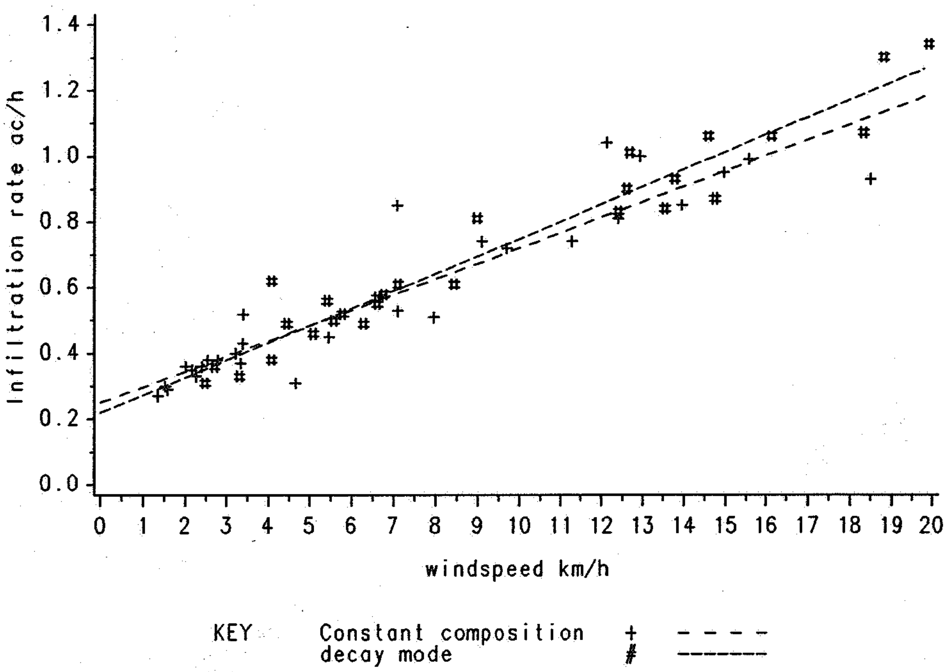

Figure 8: Infiltration rates measured with decay and constant composition methods

5.3 Multizone Results and Predictions

Multi-tracer studies of air flows between the living space, subfloor and roof cavities of houses have been completed and described[2]. Airflows between zones, and infiltration rates into the zones, were measured over periods of several days in five separate houses with the constant concentration method. The airflows measured in these houses have also been modelled using the Walton computer program[5], basic airtightness data for each zone, and wind speed and temperatures measured at each of the five houses. The study[6] allowed a comparison to be made of measured and calculated inter-zone airflows. Figures 9 and 10 are reproduced from[6] to show the extent of agreement between measured and calculated data.

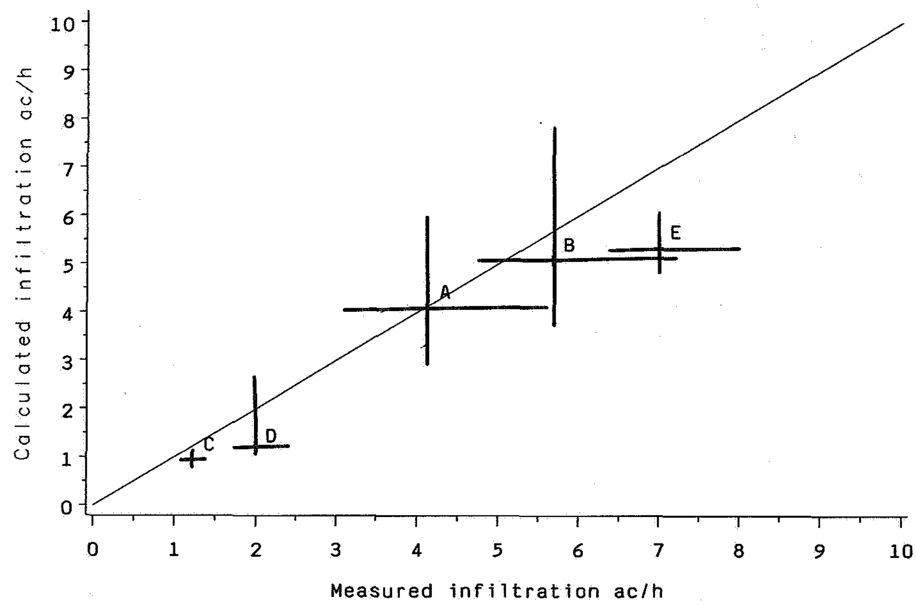

Figure 9: Measured and calculated infiltration rates in the crawl space of five houses A-E

The study has shown that there are no major systematic differences between the results of multi-tracer measurements and calculation but that there is scope for bringing the two closer together. This will involve work in the following areas:

1. Establishing a more comprehensive database of wind pressure coefficients.
2. A better understanding of the distribution of leakage openings in a building, in particular those linking the living space and major construction cavities.

The results of modelling infiltration into construction cavities have generally come within 75% of measured infiltration rates averaged over the same two hour period. On the same basis, 30% to 40% of data points agreed within 25%. In Figure 9 the infiltration rates averaged over the 2 to 3 day duration of the experiment are shown with error bars representing two standard errors of the mean, calculated on the basis of a log-normal distribution of infiltration rate.

The inter-zone air flows compared in Figure 10 were modelled on the fairly severe assumption of a uniform distribution of leakage openings over the building envelope. The data in Figure 10 shows that in some cases the air flows were well reproduced from these simple assumptions but in others, better definition of the linking air flow resistances was needed.

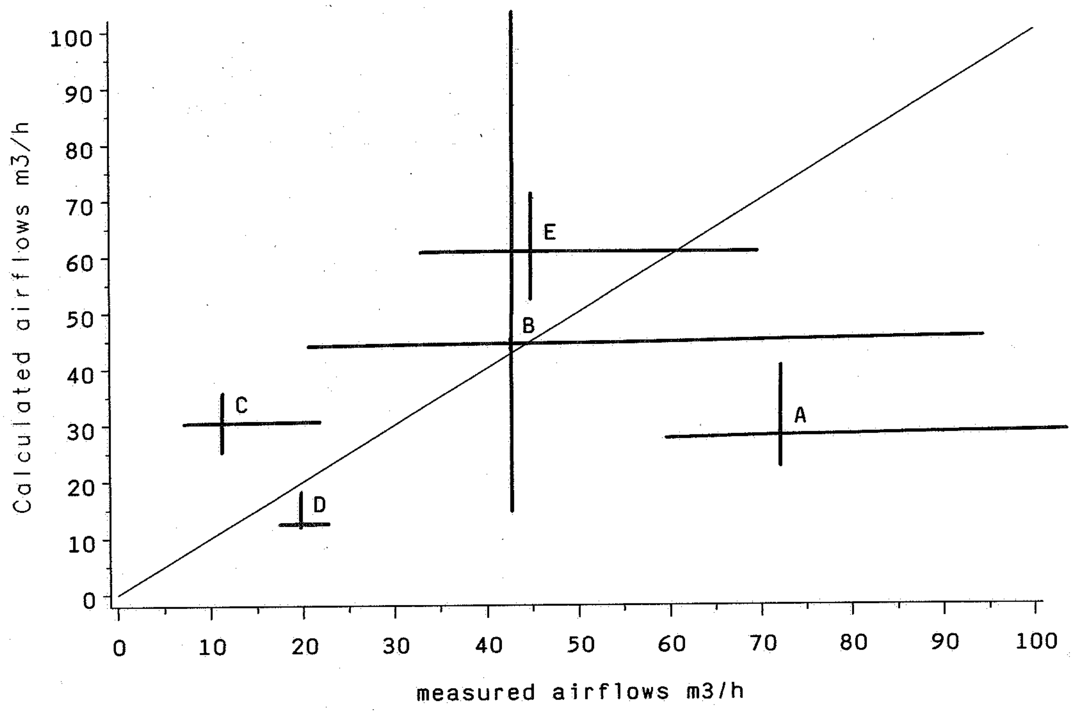

Figure 10: Mean values of calculated and measured air flow rates between living spaces and roof spaces in houses A-E

5.4 Comparisons with a Passive Method

The passive Brookhaven National Laboratory/Air Infiltration Measurements System (BNL/AIMS) developed by Deitz[7] promises to give easily measured average infiltration rates and inter-zone airflows. Recent comparisons between this and traditional tracer methods by Harrje et al[8] and Piersol et al[9] show reasonable agreement in some cases and important differences in others. Both authors highlight adequate mixing as being essential in arriving at agreement between two simultaneously applied tracer gas methods. Major tracer gas concentration gradients caused by open windows for instance, will give results that depend on the location of tracer sources and concentration measuring points. In buildings with ducted air distribution systems, such as the houses surveyed[9], there is generally no problem in achieving uniform tracer gas mixtures. This convenient mixing system is absent in most New Zealand houses and it has been customary to mix the air with portable fans during infiltration measurements. In the following comparison of infiltration measurements, those conducted with the PFT method were carried out without fan assisted mixing, relying instead on natural thermally driven air flows within the building.

Perfluorocarbon tracer (PFT) emitters and capillary adsorption tube samplers (CATS) were maintained for two weeks in two houses (A and B) located in Wellington, New Zealand. Basic airtightness and construction data for the two houses are given in Table 2, together with an infiltration function determined using airtightness data and the simplified LBL method[4]. Infiltration rates measured with the two tracer techniques are separately compared with the average of infiltration rates calculated using the infiltration function.

Details		House A	House B
House	Volume m^3	195	225
	Surface area m^2	252	290
	Floor area m^2	72	94
Airtightness Details			
	Air changes at 50 Pa	9.4	3.5
	Leakage function m^3/s	$0.0417\Delta P^{0.64}$	$0.0195\Delta P^{0.62}$
Measured and calculated infiltration rates in ac/h			
Calculated using infiltration function		0.25	0.16
Measured using tracer decay method		0.23	0.15
Calculated using infiltration function		0.18	0.08
Measured using PFT method		0.12	0.08
Infiltration functions			
House A	$Q = 0.049(0.133^2\Delta T + 0.0405^2V^2)^{0.5}$		
House B	$Q = 0.018(0.144^2\Delta T + 0.0765^2V^2)^{0.5}$		
Where V is the wind speed in m/s at roof height and ΔT is the indoor outdoor temperature difference in C			

Table 2: Details of infiltration study in houses A and B

Although infiltration rates measured with the tracer decay method and with PFTs were conducted at different times, respectable agreement is indicated with the infiltration function in both cases.

6 Conclusions

A gas chromatograph and electron capture detector has been automated to carry out long term surveys of air flows in buildings. Using halocarbon tracer gases in ppb concentrations, the system is shown to be versatile and to give results that are consistent between two modes of operation and with the results of accepted numerical modelling techniques. In more detail, the comparisons between tracer gas studies and modelling show:

1. No major systematic differences between the results of air flow studies using tracer gases and numerical modelling have become apparent.

2. Further improvements in the agreement between tracer measurements and modelling can be expected as more extensive databases of wind pressure coefficients and more detailed descriptions of the distribution of leakage openings in buildings become available.

3. The BNL/AIMS passive tracer method was used to measure infiltration rates in two unoccupied houses and the results were found to be consistent with conventional tracer measurements and numerical modelling.

7 References

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