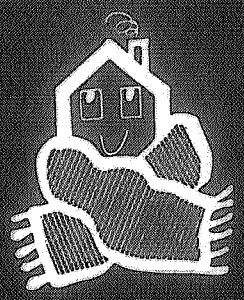

INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and community systems programme

6th AIC Conference

Ventilation strategies and measurement techniques

Supplement to Proceedings

AIC

Air Infiltration Centre
Old Bracknell Lane West, Bracknell,
Berkshire, Great Britain, RG12 4AH

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Annex V Air Infiltration Centre

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6th AIC Conference

Ventilation strategies and measurement techniques

(held at Het Meerdal Park
Southern Netherlands
16–19 September 1985)

Supplement to Proceedings

CONTENTS (i)

PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration Centre

The IEA Executive Committee (Building and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and to increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial groundwork the experts group recommended to their executive the formation of an Air Infiltration Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and a firm basis for future research in the Participating Countries.

The Participants in this task are Belgium, Canada, Denmark, Federal Republic of Germany, Finland, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

INTRODUCTION

This document is a supplement to the AIC's 6th Conference Proceedings AIC-PROC-6-85. It contains five additional papers presented at the Conference, together with a discussion record based on written questions and answers prepared by conference participants and authors.

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER S.1

THE PERFORMANCE OF VENTILATION IN AN UNTIGHT HOUSE

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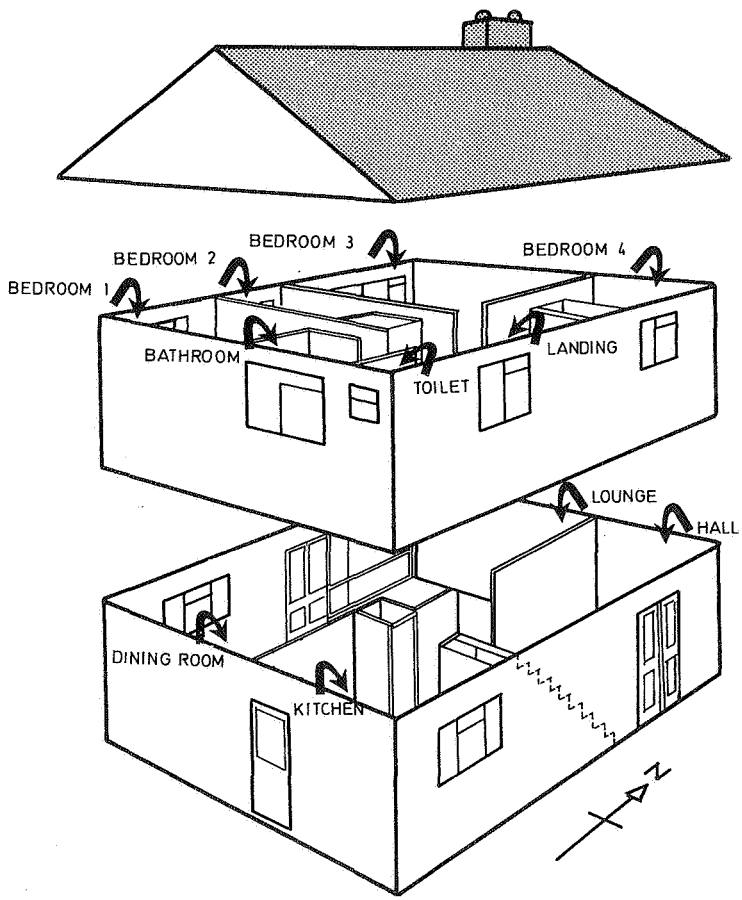
INTRODUCTION

This paper is a companion to the one presented by Sandberg et al later in this conference (1). In contrast to that paper, this one deals with the flow of fresh air into, and the spread of point source contaminants around an untight 2 storey, multi-roomed house. The layout of the house is shown in figure 1. The house, owned by Segas, was built about 15 years ago when energy costs were not a major design constraint . It was designed for natural ventilation and was later subjected to some sealing of the larger sources of air inlet. In addition to the natural ventilation system there is a mechanical ventilation system that can act as supply or extract only and as a balanced unit. Figure 1 gives details of the supply and extract points.

Despite the best endeavours, the house still has a specific flow rate of 8 house volumes/h through the building envelope when pressurised to 50 Pa. This is about 10 times the leakage of the house described in (1). This is the rationale for the title of the paper.



Supply:

Bedroom 1,2,3,4
Lounge
Dining room

Extract:

Bathroom
Toilet
Landing
Kitchen

Fig 1

1. Experimental

The experiment we undertook was designed as a two-way comparison of the effects of ventilation systems and the apperatures of the internal doors on the local ventilation rates and the spread of a contaminant released in an extract or a supply room. Thirteen separate experimental runs are analyzed in this paper. Details of these runs are given in Table 1.

Table 1. Detail of experiments undertaken. ΔT is the temperature difference between indoor and outdoor.

Ventilation system	Type of experiment	Apperture of doors	ΔT (°C)	Wind speed (ms^{-1})	Wind direction
Natural	Constant concentration followed by decay	Open	27	5.0	N
Extract			26	3.0	N
Balanced			19	2.4	W
Natural	Injection into bedroom 3		25	1.7	W
Extract			22	3.3	W
Balanced			23	2.5	SW
Extract		Closed	22	3.3	W
Balanced			19	2.3	SW
Natural	Injection into the kitchen	Open	22	1.9	W
Extract			23	2.1	W
Balanced			25	2.0	SW
Extract		Closed	21	2.8	S
Balanced			18	3.0	S
			22 ± 3	2.7 ± 0.9	

The experiments were made possible by the 'Autovent', computer controlled ventilation system (2). This equipment was designed around proprietory components and with programmable logic provided through a micro computer. It can inject gas or sample the atmosphere in 12 rooms. The 'Autovent' could easily be programmed to perform constant concentration measurements followed by decay or to follow the concentration history of a contaminant released in a room.

In these experiments nitrous oxide was used as the tracer gas. It was detected with a Leybold-Hereus infra-red analyser.

For decay and contaminant release experiments no mixing was used,

except in the initial dosing of the source room. For constant concentration experiments a small mixing fan was deployed in each room.

The experiments took place in the spring and high stack effects were achieved by the operation of a gas fired heating system with the thermostats set at 30°C. Table 1 gives the stack effect parameter for each run together with the wind speeds and directions. The means and standard deviations reveal a reasonably comparable set of conditions so that detailed comparisons between ventilation systems are justified. Time prevented a fuller experimental programme of more natural ventilation tests with the doors closed and repeat runs of all experiments.

Where conditions were repeated, the agreement between results was acceptable.

2. Theory

The framework for analysing these results is presented in detail in (1). The methods of reducing the experimental measurements to useful parameters have been described in (3). In examining the spread of a contaminant around a house the parameter which best characterises the effectiveness of the ventilation system is the ratio D_p/D_s. The time integrated exposure in a particular room, D_p, divided by the integrated exposure in the source room, D_s. This parameter is relevant when the major consideration is the ability of a ventilation system to deal with a contaminant. If, on the other hand, the major concern is to judge the way in which fresh outdoor air is provided by the ventilation system and stale air is removed from the house, then the parameters q_m/q_m^t and $\bar{\tau}_p/\langle\bar{\tau}\rangle$ are indicated. The flow of outdoor air to each room, q_m, expressed as a proportion of the total flow, q_m^t, is a simple way to reflect the distribution of air entry points to a house. The variation of the ratio with ventilation system provides some indication of the effect of the system on the incoming air distribution.

The mean age of the air in each room, $\bar{\tau}_p$, divided by the average mean age of the air in the whole house, $\langle\bar{\tau}\rangle$, gives a measure of the relative time taken to replace (exchange) the air in a room.

3. Results and Analysis

3.1 Relative flow rate

Figure 2 shows the results of the analysis of two ratios determining the relative values of fresh air intake and air replacement times for each of the three ventilation systems. Limitations of experimental time meant that only internal doors open cases were considered.

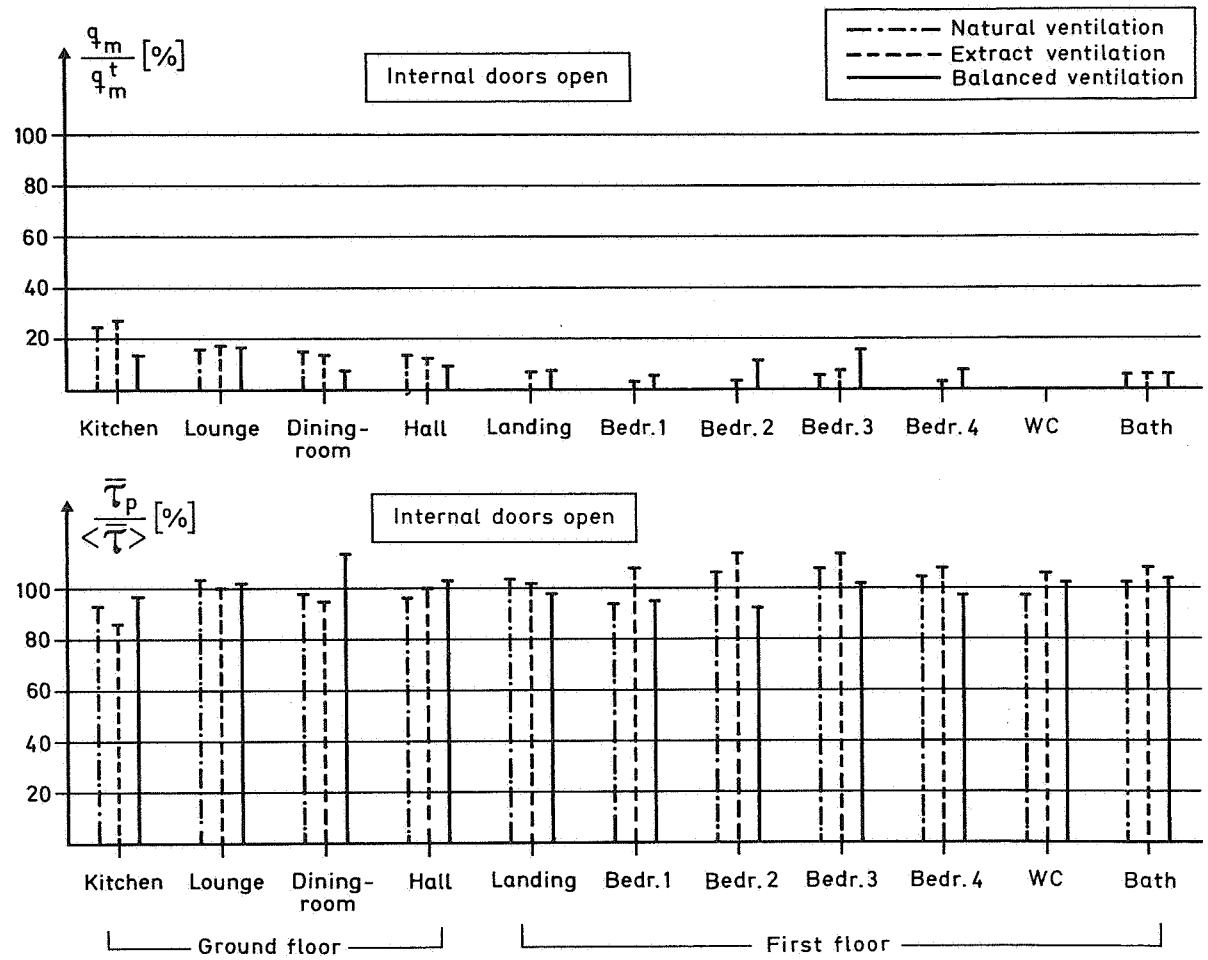


Fig 2

The ratio q_m/q_m^t shows that for natural ventilation most of the incoming fresh air enters on the ground floor and very little on the upper floors. This is the classical stack effect in operation. When the combined ventilation system is operated, however, fresh air enters all the supply rooms and there is some modification of the stack effect dominated ventilation pattern.

The relative air replacement rate for each room is almost constant for each room under each ventilation system. From this result one could conclude that the exposure to a passive homogeneous pollutant,

such as Radon, would be the same throughout the house. The house is behaving very much like a leaky box with sources of leakage well distributed over its surface. The paper by Sandberg el al (1) demonstrated the contrast with a tight house where the leakage is concentrated to a few places.

3.2 Pollutant spread from the kitchen

Figure 3 shows the ratio D_p/D_s, the room exposure to a pollutant divided by the source room exposure. For this case the source room was the kitchen on the ground floor of the building

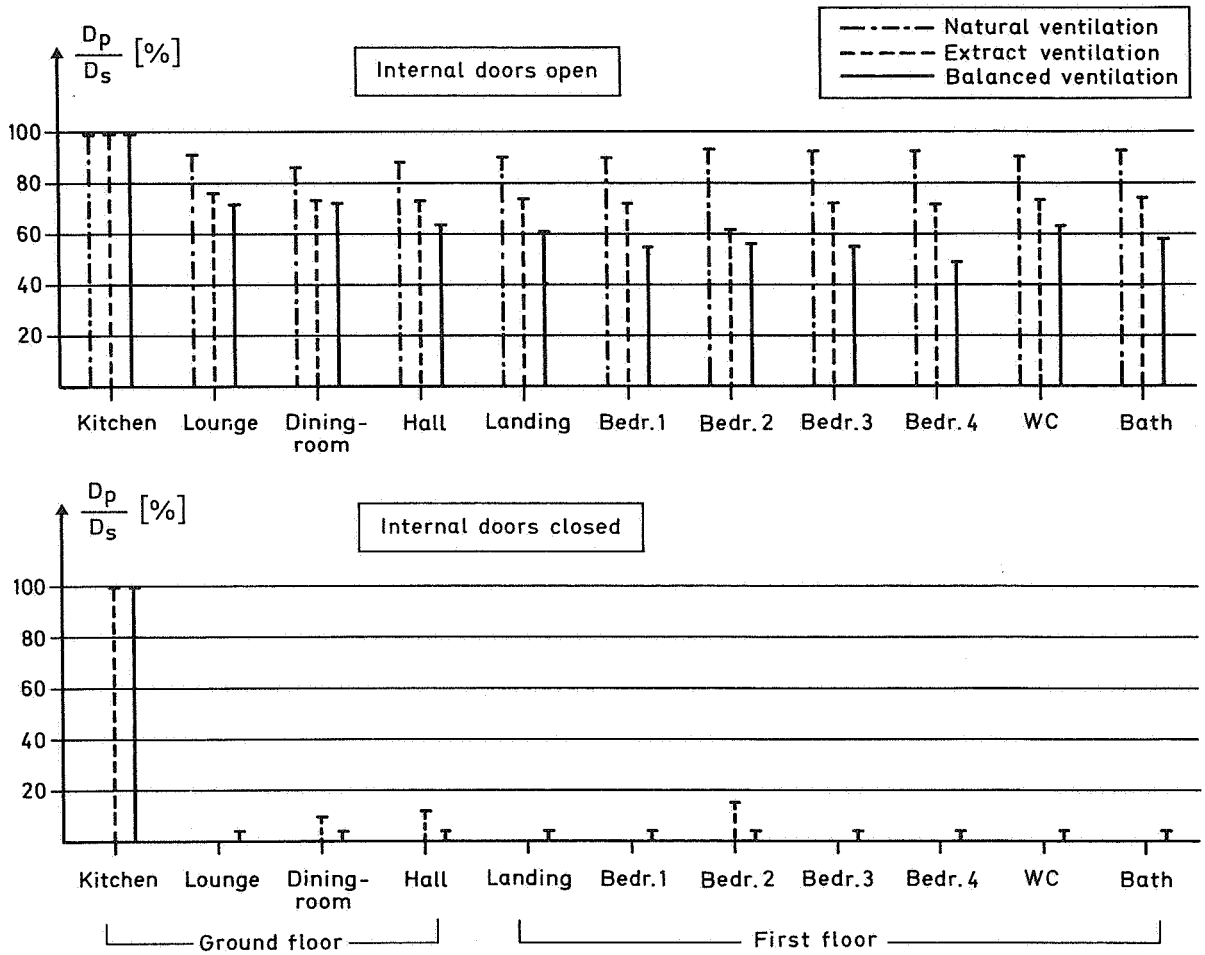


Fig 3

The first contrast to make is between doors open and doors closed cases. For the former the relative exposure is much more even than for the latter, where the source exposure is, at least, six times that for any other room.

For natural ventilation and open doors the most even pattern is observed. The explanation for this is in the driving force of the

stack effect, which carries air from the ground to the first floor and sets up recirculation patterns between the floors, particularly in the open stair well. When the extract system is used with doors closed the relative exposure in all rooms decreases. The kitchen is an extract room and so the pollutant is removed at source. Other extract points are in the bathroom, toilet and the landing. These three rooms have the highest relative exposures, presumably due to a small net increase in flow of air to these rooms as a result of the operation of the mechanical extract system. With the balanced system in operation, the combined effects of extract and supply mean that relative exposures are the lowest for this ventilation system. It is also noticeable that relative exposures on the first floor are slightly lower than those on the ground floor. This is also attributable to the effects on air being supplied to all the bedrooms and countering the stack effect to some extent.

3.3 Pollutant spread from bedroom 3

Figure 4 shows a similar set of relative exposure data for the case of the pollutant source room being on the first floor of the house. A comparison of the doors open and closed results reveals the same pattern as for the kitchen as source room, namely a fairly even exposure with open doors and a distribution biased to the source room for door closed.

In this case the effect of closing the door is less marked. This could be a function of the tightness of the internal doors and of the communication between bedroom 3 and the adjacent rooms as well as the location of the source room. Under natural ventilation and with open doors the relative exposures of the ground floor rooms are less than those of the first floor. This is as would be expected under stack effect dominated ventilation. With the extract system operating and doors open the same conclusion applies. Even in the kitchen, a major extract point, the relative exposure is not significantly different from other ground floor rooms. With the balanced system in operation, the ground floor relative exposures increase and approach those of the first floor. This result is somewhat unexpected and is attributed to the effect of air supply to the bedrooms opposing the stack effect and pushing pollutant air

out onto the landing and into the hall. When the doors are closed, the relative exposures are greater than when the pollutant was injected into an extract room. For the extract only system, bedroom 4 has a high exposure. Bedroom 4 is adjacent to bedroom 3 and could possibly have a large intercommunication. With the balanced system we again observe an increased relative exposure on the ground floor due to the effect of air supply to the source room and other bedrooms.

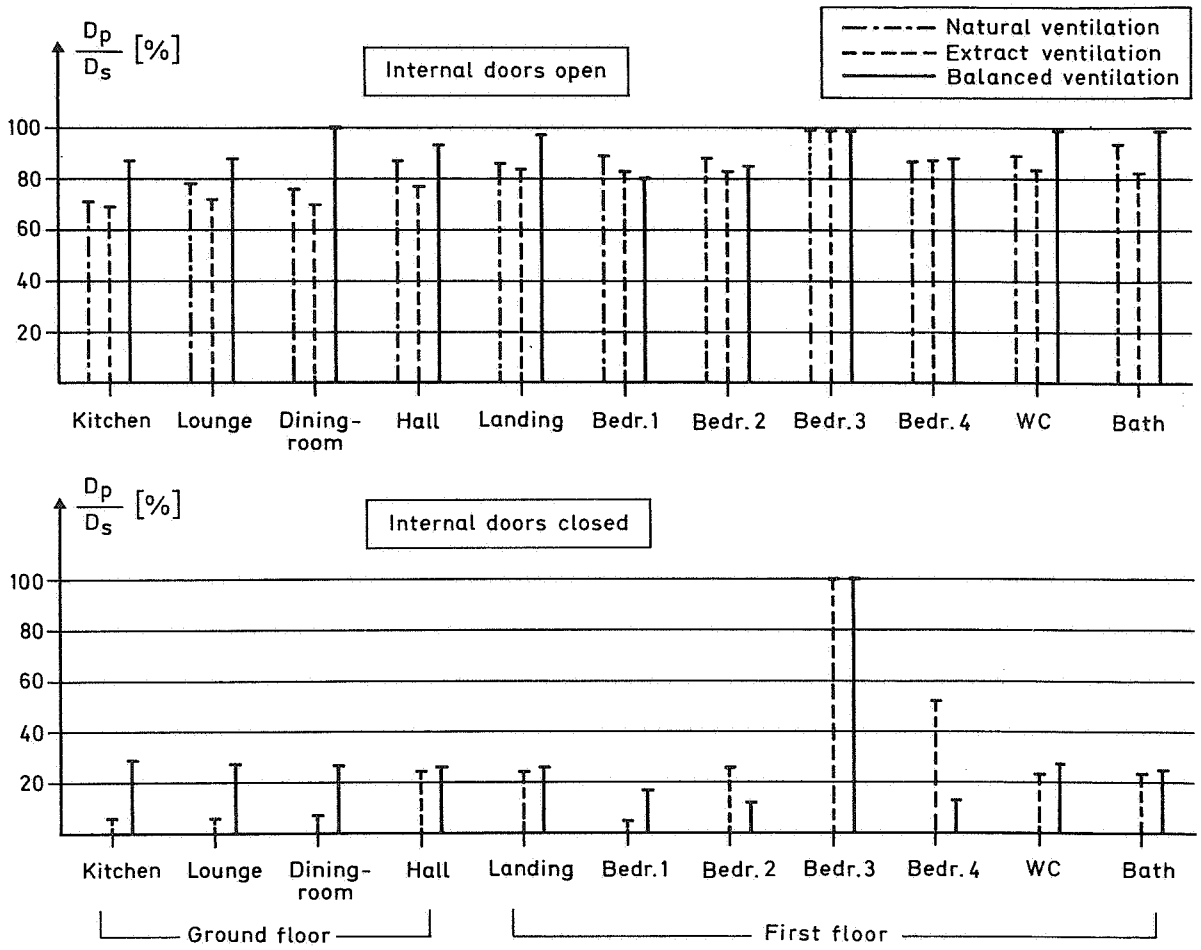


Fig 4

4. CONCLUSIONS

For an untight house a mechanical ventilation system has very little virtue. These results have demonstrated some small effects in the redistribution of pollutant from a source room but have also demonstrated that the natural, stack dominated ventilation pattern is not overcome by the mechanical system. The mechanical system does offer the assurance of a minimum flow rate to the supply rooms and a minimum exhaust rate from the extract rooms. It does not,

however, guarantee a predictable distribution of air supply to the rooms of an untight house.
The differences between relative exposures when the source is on extract or a supply room lend weight to the viewpoint that investment in extraction facilities in pollutant source rooms is much more cost beneficial than investment in complex balanced systems.

5. ACKNOWLEDGEMENTS

The work reported here was undertaken by Mats Sandberg, whilst on an exchange arrangement with Segas Central Laboratories. Their hospitality is warmly appreciated.
The computational skills of Jackie Freeman played a large part in the data reduction process.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER S.2

INFLUENCE OF OPEN WINDOWS ON THE INTERZONE AIR MOVEMENT WITHIN A SEMI-DETACHED DWELIING

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INFLUENCE OF OPEN WINDOWS ON THE INTERZONE AIR MOVEMENT WITHIN A SEMI-DETACHED DWELLING

by M D A E S Perera and P R Warren

1. INTRODUCTION

Although most buildings in a temperate climate such as the United Kingdom rely on natural ventilation, its prediction is one of the most difficult aspects of building design. When this is further clouded by occupant behaviour, eg. by opening windows, prediction becomes even more difficult.

Studies by Dick and Thomas[1] and Brundrett[2], amongst others, have shown that occupants of dwellings often open windows even in the winter. Brundrett showed that they do so in a systematic manner which is strongly correlated with the outside air temperature and modified by wind speed. It was also found that bedroom windows were those most frequently opened.

In this paper, a multicell airflow computer program called BREEZE is used to determine the influence of open windows on the ventilation rates of a semidetached house for a variety of weather conditions. For a limited number of cases, the predicted values are compared with field measurements to indicate the degree of confidence which can be placed in the computer simulation. The effect of closing internal doors on ventilation rates and interzonal airflows is also considered.

2. COMPUTER PROGRAM

For this work, the BREEZE program was used to determine the interzonal airflows as well as the ventilation rates. This program is a modified version of the SMOKE program[3]. BREEZE is written in FORTRAN-4 and, for the computer modelling reported here, was mounted on a DEC VAX mainframe computer. It requires about 84 kb of memory and takes about 20 seconds for a typical computer run.

In the program, the building is considered as a network with zones, in this instance rooms, represented by nodes and the air flow path by branches connecting the nodes. Pressure differentials are set up between nodes due to a combination of stack and wind effect. The relationship between applied pressure difference and the flow between nodes is defined for each flow path. The program allows for a number of different types of flow path, the most commonly used being of the general form

$$Q = K \ \Delta p^n$$

where Q is the volume flow rate, Δp the applied pressure difference and K and n characteristics of the opening.

Wind pressures are obtained from wind tunnel data, generally expressed in the form of pressure coefficients, C_p. Then the surface pressure at any external opening is given by,

$$p = (\rho/2) \ U^2 \ C_p + p_o$$

where U is wind speed, ρ air density and p_o the freestream static pressure in the wind.

The set of equations which derives from the network is solved by conventional network theory, analogous to that used for the solution of complex electrical circuits. The difficulty created by the nonlinear pressure-flow relationship is overcome by successive linear approximations. The linear approximations at each iteration are based upon the solution to the previous iteration.

In addition, the program contains a facility for taking into account 'single-sided' ventilation. This occurs when the openings connecting outside air to a space are much larger than the openings which connects it to other parts of the building. This form of air exchange may result from local stack effect or that due to the wind. The equations governing the magnitude of these interchanges are discussed in Reference 4. Having proceeded through the general solution to determine pressure driven flows, the program identifies spaces in which single-sided ventilation may be important and computes the flows due to wind and stack. These are compared with the result from the solution for pressure driven flows and the largest of these three taken as the solution.

3. VALIDATION OF COMPUTER MODEL

To investigate the validity of the computer simulation, a comparison has been carried out for a semidetached test house at Capenhurst, England belonging to the Electricity Council Research Centre (ECRC). Predicted whole house infiltration rates and room ventilation rates were compared with field measurements carried out by the Building Research Establishment (BRE).

3.1. Building

The test building is a two-storey, small, semidetached house with a brick gable wall and timber-framed front and back walls. This house lies (Figure 1) at the south-west end of row of three pairs of semidetached houses located in rural terrain. The predominant winds from the south-west blow over open ground onto the brick-built gable end-wall.

Figure 2 shows a plan of the test house. All windows are metal-framed, single-glazed windows horizontally pivoted at the midpoints of the vertical sides. All external doors are wooden framed with single glazing. The test house is 5.6 m wide and 7.2 m deep. Each floor is 2.3 m high and the roof pitch is about 22^{o}.

3.2. Leakage characteristics

Component pressurisation tests were carried out on all windows and doors to determine their leakage characteristics. The results were expressed in the form,

$$Q = Q_{50} \, (.p/50)^{n} \; m^{3}h^{-1}$$

where Q is the flow rate for an applied pressure differential .p (Pascals) between inside and outside, n is an exponent and Q_{50} is the flow rate at 50 Pascals. Measurements showed that the overall flow through closed windows and external doors could be represented by the above expression.

Whole house pressurisation tests were also carried out. Large differences between the whole house leakage and the summed component leakages showed that there was substantial background leakage. These can be summarised as follows:

	Q_{50}	n
Whole house leakage	2325	0.570
Total leakage through components	858	0.706
Resulting background leakage	1468	0.501

This large background leakage must be taken into account in any modelling procedure[5]. In this instance, this was carried out by apportioning part of the leakage to each purpose-built component and the other part to leakage through cracks into the attic and into the crawl-space.

The apportionment was carried out by area-weighting the permeable area appropriate to that leakage path as a proportion of the total permeable area of the building[6]. For this purpose, the latter is defined as the sum of the areas of the external walls of the house together with the area of the ground floor (which was permeable to air flow) and the area of the surface between the house and roof space. The leakage characteristics thus calculated for the ECRC house are tabulated in Table 1. The Table also gives the equivalent areas[7] corresponding to the main bedroom window when they could be opened to three 'notch' settings.

3.3. Wind pressure coefficients

Wind pressure coefficients (Table 1) for winds from the south-west and north-west striking the gable end-wall and the rear wall respectively were obtained from a series of wind-tunnel model studies[8]. The airflow for these tests was modelled to simulate the boundary layer flow over flat, open countryside with few obstacles. The pressure coefficients are defined with reference to an unobstructed wind speed measured at a height of 10 m in full scale.

3.4. Comparison between measured and predicted rates

In Figure 3 the predicted whole house infiltration rates are plotted against various wind speeds for three temperature differentials between inside and outside air. In the computer runs, all internal doors were kept open and the wind was taken to blow from the south west towards the gable end-wall. Superimposed are field measurements of whole building infiltration rates

measured using the conventional tracer decay technique.

These field measurements were also carried out with all windows and outside doors closed and with all internal doors open. During the measurements, the temperature differential between inside and outside was about 5°C. On average, the wind was also blowing onto the gable end-wall of the house in a manner similar to the computer simulations. Figure 3 shows the good comparison between measured and predicted whole house infiltration rates. The predicted curves also show the influence of temperature differential and the regions over which buoyancy effects dominate.

Figure 4 shows similar comparison between measured and predicted room ventilation rates in Bedroom 1 (Figure 2) with and without the window in that room kept open to Notch 3 (Table 1). During this set of field measurements, all internal doors were kept closed. The wind, as before, was blowing from the south west and the temperature differential was about 10°C.

The exact comparison between measured and predicted room airchange rates is not good. This was to be expected since the background leakage was distributed on an area-weighted basis. Etheridge and Alexander[9] have shown that this problem can be solved in an iterative manner by choosing several different distribution patterns which satisfy the whole-house leakage characteristic and then applying other conditions (such as comparing predicted rates with measured ventilation rates) to obtain the best possible distribution. Alexander et al[10], however, describe an experimental pressurisation technique whereby the distribution of background leakage areas may be determined for use with these prediction methods.

Figure 4 shows that the predictions overestimate the measured room rates when the room window is closed but underestimate when the window is opened. Both predictions and measurements, however, show the expected increase in the room ventilation rate with increasing wind speed and with the opening of the window.

The results were considered to be sufficiently good to proceed to a series of calculations of whole house and zone ventilation rates for a standardised house. The zones were large, i.e. either the whole upstairs or downstairs space, and were expected to be less sensitive to background leakage than individual rooms.

4. PREDICTIONS USING 'STANDARD' HOUSE CONFIGURATION

If the total permeable area of the building is A_p, then it has been shown[6] that Q_T/A_p is a good indicator of the overall permeability to airflow of the building envelope. For the ECRC house, this index works out as 11.8 m^3h^{-1}/m^2. This is much tighter than the average index of 22.1 m^3h^{-1}/m^2 found[6] in a small sample of UK housing.

It was decided that further computer predictions should be carried out in a 'standard' house with leakage characteristics more representative of existing UK dwellings. Using the same house and room configuration as the ECRC house, a 'standard' house model was set up using values[6] of 200 m^3 (compared to 197 m^3 for the ECRC house) for the house volume together with Q_T = 2740 m^3h^{-1} and n = 0.60. The component and crack leakages were determined as before using area-weighting and are tabulated in Table 1. Calculations show that this distribution results in 62% of the leakage at 50 Pa being background crackage. This compares with the average 60% as found by Warren and Webb[6].

Various computer simulations are now considered based on the standard house. Unless otherwise stated, all simulations were carried out with the following configuration:

- Wind blowing onto the rear of the house.
- Temperature differential of 5°C.
- Internal doors open.

4.1. Effect of wind direction

Simulations were carried out for winds blowing towards the front, rear and end walls of the test house. Figure 5 shows the whole house infiltration rates obtained. At low windspeeds, buoyancy effects dominate and wind direction has only a small influence on the airchange rates. At higher wind speeds, and as expected, the infiltration rates are much greater for winds blowing onto either the front or rear of the building than for winds blowing onto the end wall. The leakage distribution is such that there is no discernible difference in the rates for winds blowing either towards the front or the rear of the house.

4.2. Effect of opening an upstairs bedroom window

The influence of opening an upstairs window on the ventilation airflows was determined by a series of simulations carried out with the window in the leeward Bedroom 1 open to various notches on the window catch.

Figure 6.a. shows the increase in the whole house ventilation rate when the window is opened to Notch 3 (Table 1). Figure 6.b. shows that this is brought about by an increase in the fresh air inflow into both storeys of the house. It should be noted that more fresh air flows into the downstairs region than the upstairs and that there is a net flow upwards within the house. In all these and subsequent figures, the flow rates relating to each floor have been normalised by the floor volumes of 100 m^3 each.

The effect of gradually opening the window was also examined. At a windspeed of 4 ms^{-1}, representative for the locality in which the test house is situated, the resulting whole-house ventilation rates were as follows:

Window opening pattern	Ventilation rate (ach)
Window closed	0.69
Window open to first notch (#1)	0.75
Window open with catch resting on frame (#2)	0.84
Window open to main stop (#3)	1.21
Windows in Bedrooms 1 and 2 (windward) both open to Notch #3	2.09

4.3. Effect of opening banks of upstair windows

The effect that opening all windward or leeward upstairs windows (i.e. 'banks' of windows) has on the ventilation airflows within the building was examined. Simulations were carried out with various combinations of open leeward and windward banks of windows.

Figure 7.a. shows the increase in the whole house ventilation rate when the windows were opened. At a wind speed of 4 ms^{-1}, the ventilation rates from

these simulations were;

Windows		Ventilation rate
Windward	Leeward	(air changes per hour)
closed	closed	0.69
closed	open	1.57
open	closed	1.82
open	open	4.33

The total airchange rate in each floor for each of the window opening patterns is also shown in Figure 7.a. in a manner similar to that given by Dickson[7]. It shows that the most significant increases occur upstairs. For a 4 ms^{-1} wind speed, the airchange rate upstairs triples in value when either the windward or leeward windows are opened. This increase is eightfold when all upstair windows are opened. Qualitatively, these effects are similar to those observed by Dickson[7] from field measurements on a detached house.

The ventilation rate downstairs is seen to decrease when all upstairs windows are opened. This can be traced (Figure 7.b.) to a reduction, in this instance, of the inflow of fresh air into that region. It is also interesting to note that, in the simulations when the upstair windward windows were opened, there is a flow reversal with air flowing down the stairwell.

4.4. Influence of internal doors

A series of simulations were carried out to determine the effect, if any, of closing internal doors on the ventilation flows. Simulations were carried out with the window in either the upstair leeward Bedroom 1 open to Notch 3 or with the downstairs kitchen window open by the same amount. Since it has been shown previously that there is no discernible difference in the airchange rates for winds blowing either onto the front or rear of the house, the wind was taken to blow towards the front of the house when the kitchen window was opened.

Figures 8.a. and 8.b. show clearly that the whole house ventilation rate is reduced only when internal doors are shut in the floor in which the window is open. At 4 ms^{-1}, this reduction was 25% when the upstair window was open and 18% when the downstair window was open.

5. DISCUSSION

Predicted whole house infiltration rates have been shown to compare very well with field measurements. The comparison was, however, poor when individual room rates were determined. It was suggested that this was possibly due to an incorrect distribution of the background leakage amongst the rooms when input as data into the computer model.

For this study, it was shown that opening upstairs windows strongly influences the ventilation flow. Opening a leeward window was shown to double the whole house infiltration rate whilst opening a window in each of the two main bedrooms, one on the windward and the other on the leeward side of the house, trebled the rate. This increase was magnified when banks of windows were opened upstairs.

Finally, for the particular conditions considered, the simulations showed that closing internal doors reduces the whole building ventilation rate but only if the doors are shut in the floor in which a window is open.

6. CONCLUSIONS

The computer program BREEZE has been used to evaluate the importance of

- window opening patterns,
- open or closed internal doors,
- wind speed, wind direction and difference in internal and external temperatures,

on the ventilation airflows in a typical semidetached house.

It is shown that BREEZE can provide a useful design tool with which to assess the influence of changes of building fabric, of form or location on the ventilation of that building. It is equally applicable to larger buildings such as offices and to smaller buildings such as the dwellings discussed in this paper. To make this program more widely available, BREEZE has now being developed and implemented as an interactive user-friendly package on an IBM personal computer.

ACKNOWLEDGEMENTS

The stimulus to this work arose from work carried out by the Building Research Establishment (BRE) for the Electricity Council Research Centre (ECRC) under Contract No. CON/80/8030. The field measurements described in this paper were carried out by Brian Webb and Lynn Parkins. The work described has been carried out as part of the research programme of BRE of the Department of the Environment and this paper is published by permission of the Director.

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Leakage path	ECRC TEST HOUSE				STANDARD HOUSE*			Pressure coefficents, C_p for winds blowing towards	
	Leakage Coeff (metric units)	Cracks length (m)	Coefficient K	Exponent	Leakage Coeff. (metric units)	Cracks length (m)	Coefficient K	end-wall	rear-wall
Hall door	2.744			0.818	1.761			0.09	-0.19
Kitchen window	2.284			0.518	2.935			0.09	0.22
Diner window	2.134			0.600	2.348			-0.01	0.15
Porch door	1.599			0.775	0.587			0.15	-0.07
Living room window	3.094			0.518	3.522			-0.01	-0.15
Hall floor		13.36	3.01	0.501		13.36	4.12	0.04	0.01
Kitchen floor		11.90	3.38	0.501		11.90	4.63	0.04	0.01
Diner floor		12.00	3.35	0.501		12.00	4.59	0.04	0.01
Living room floor		14.64	4.32	0.501		14.64	5.91	0.04	0.01
Bathroom window	4.328			0.500	1.761			0.09	0.22
W/C window	5.218			0.475	0.587			0.09	0.19
Bed #2 window	2.389			0.579	2.935			-0.01	0.15
Bed #1 window	2.809			0.579	3.522			-0.01	-0.15
Bed #3 window	2.354			0.531	2.348			0.09	-0.19
Landing ceiling		11.32	3.04	0.501		11.32	4.17	0.00	-0.06
Bathroom ceiling		6.70	1.71	0.501		6.70	2.35	0.00	-0.06
W/C ceiling		4.90	1.17	0.501		4.90	1.61	0.00	-0.06
Bed #2 ceiling		13.40	3.43	0.501		13.40	4.70	0.00	-0.06
Bed #1 ceiling		13.88	3.72	0.501		13.88	5.10	0.00	-0.06
Bed #3 ceiling		9.16	2.51	0.501		9.16	3.43	0.00	-0.06
Internal doors					*Note: Exponent = 0.600 in all instances				
- open	84.24			0.500					
- closed	16.38			0.500					
Open window									
- Notch #1	13.00			0.500					
- Notch #2	26.00			0.500					
- Notch #3	110.00			0.500					

Table 1 Leakage characteristics and pressure coefficients for the ECRC and 'Standard' house models

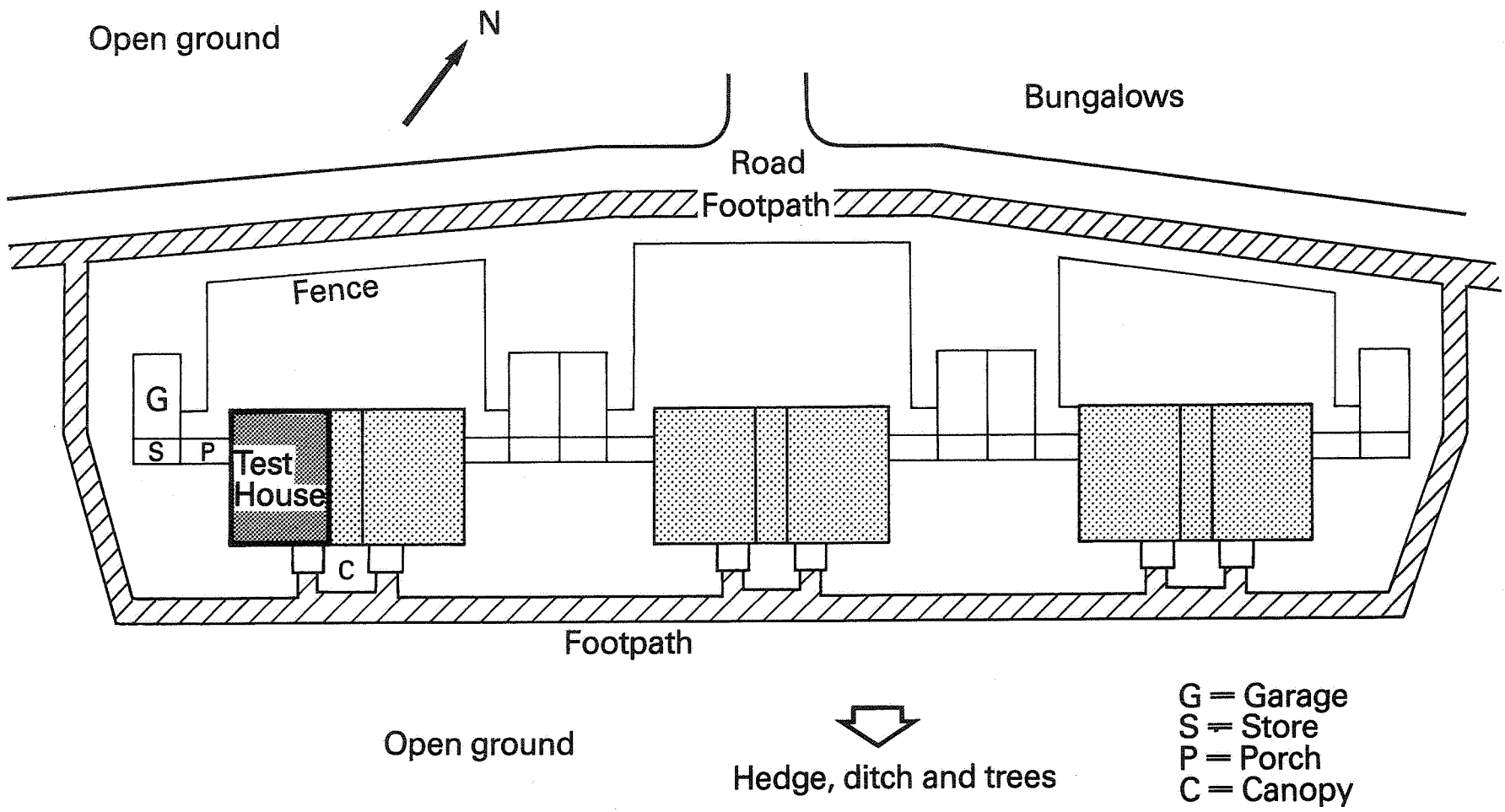

Figure 1 - Site plan of houses

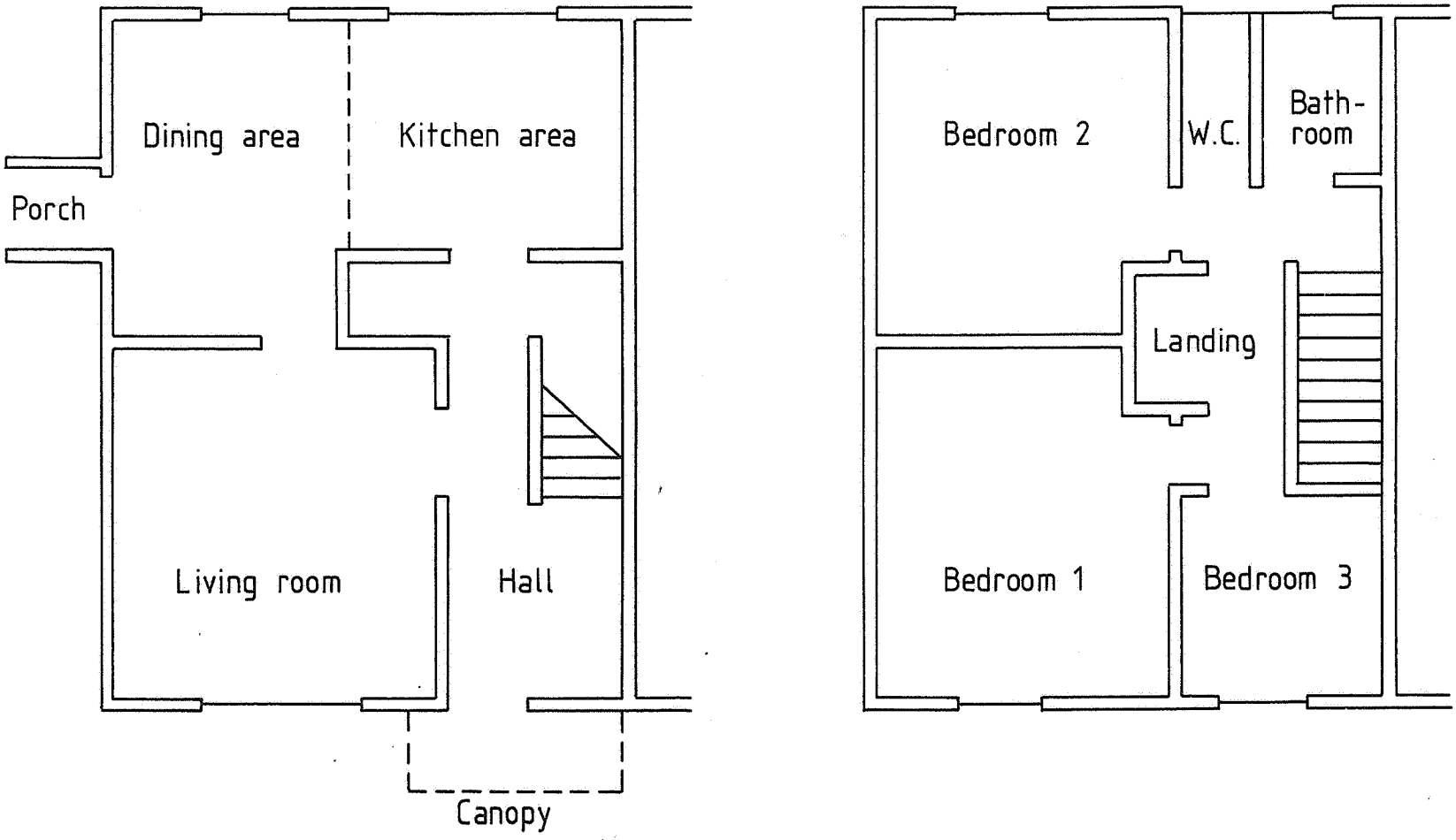

Figure 2 - Plan of test house

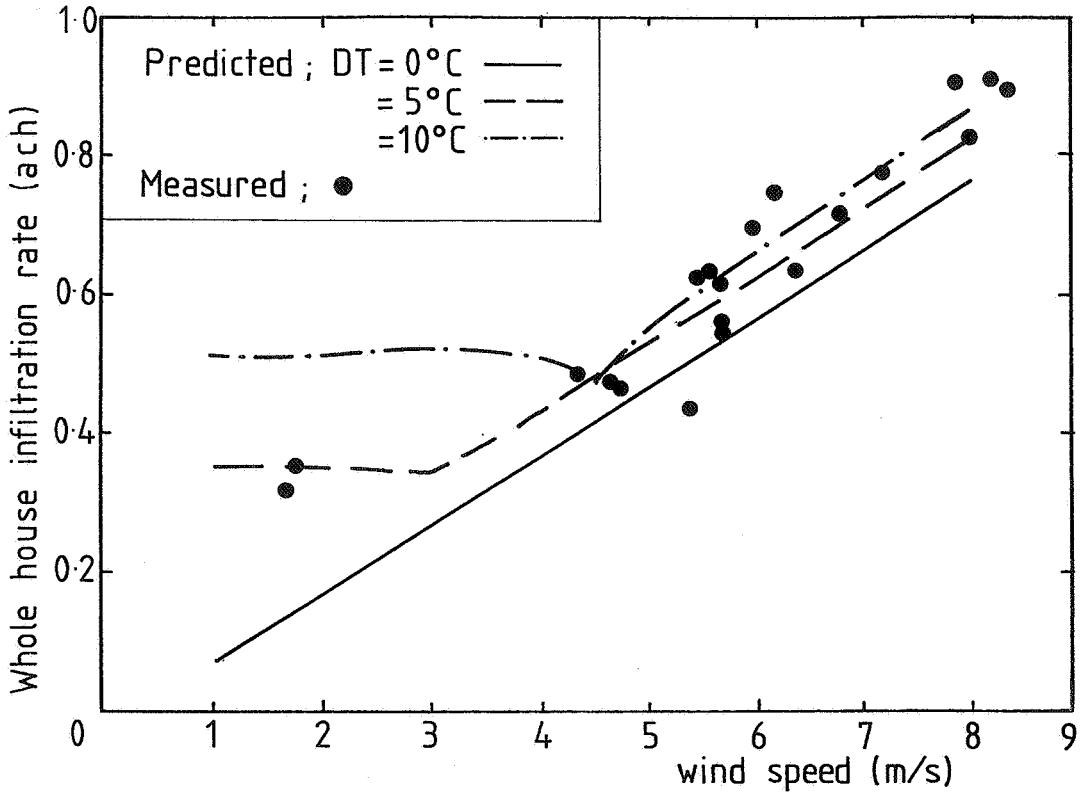

Figure 3 - Comparison of measured versus predicted infiltration rate for ECRC house

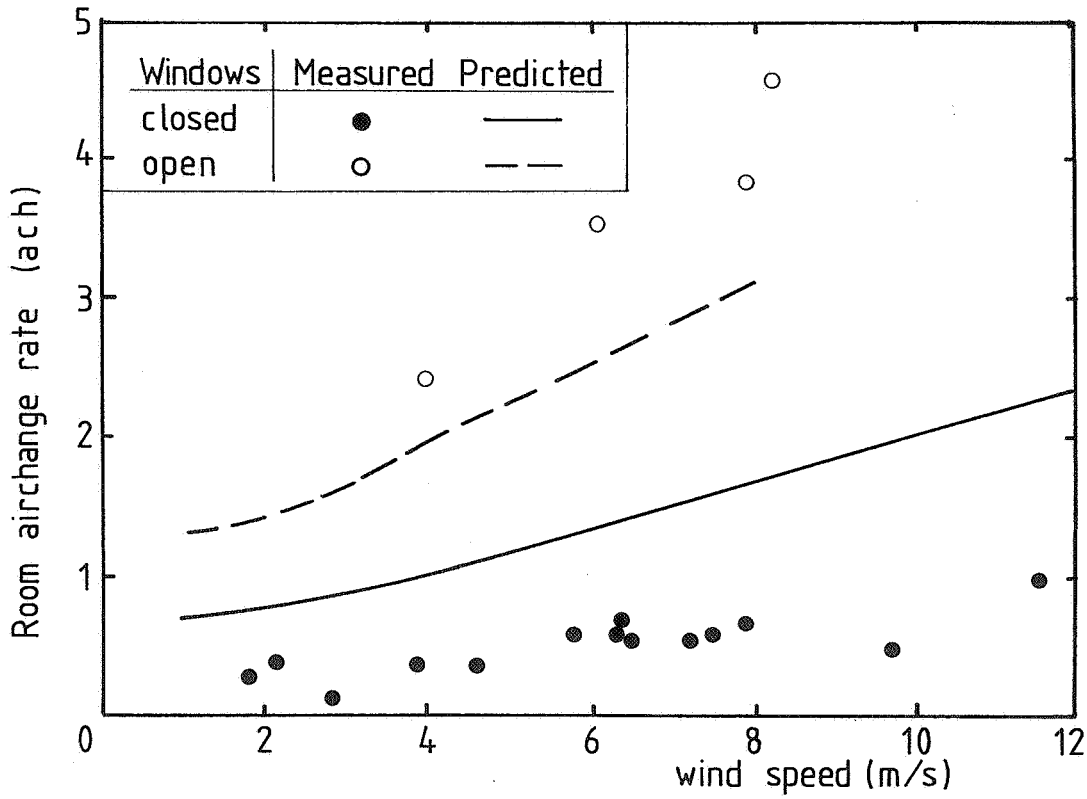

Figure 4 - Airchange rate in Bedroom # 1 for ECRC house

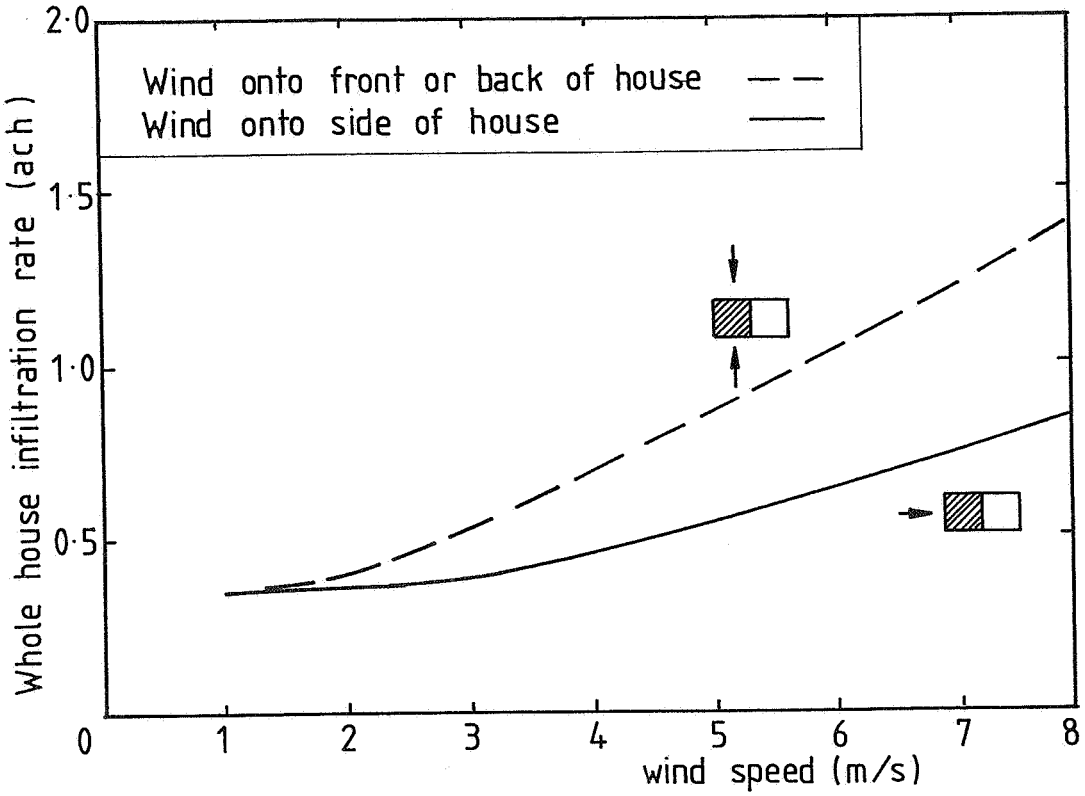

Figure 5 - Effect of wind direction for standard house

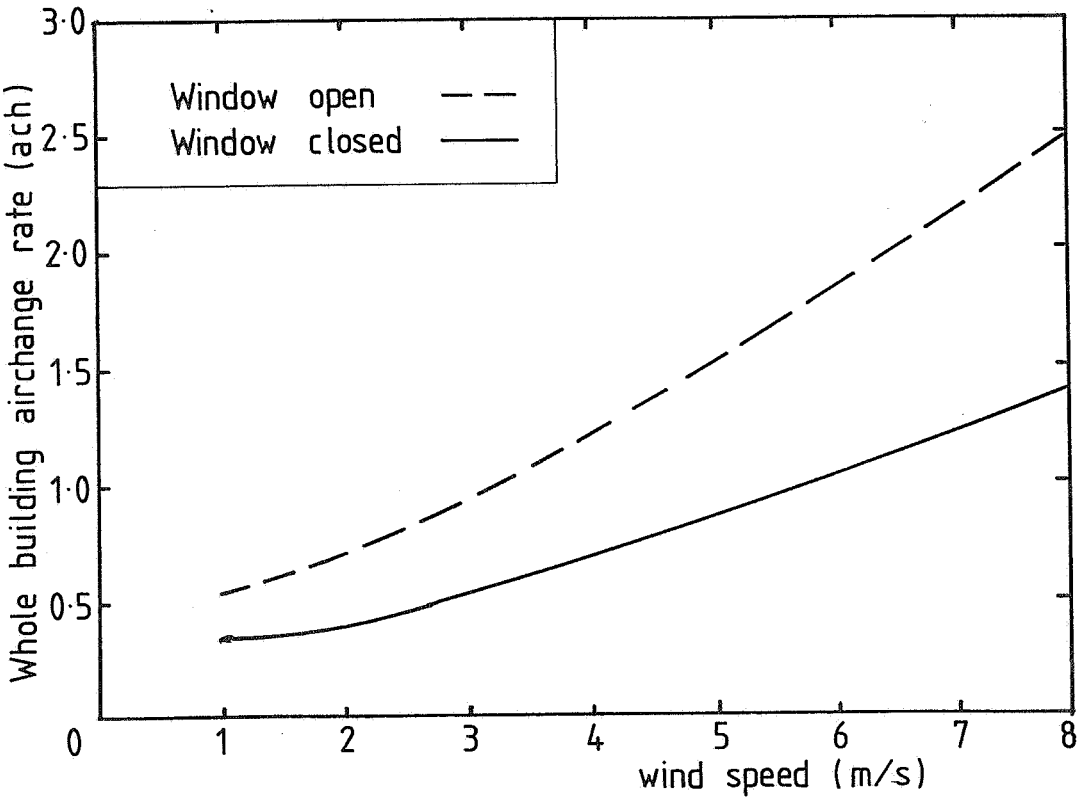

Figure 6.a - Effect of opening bedroom window

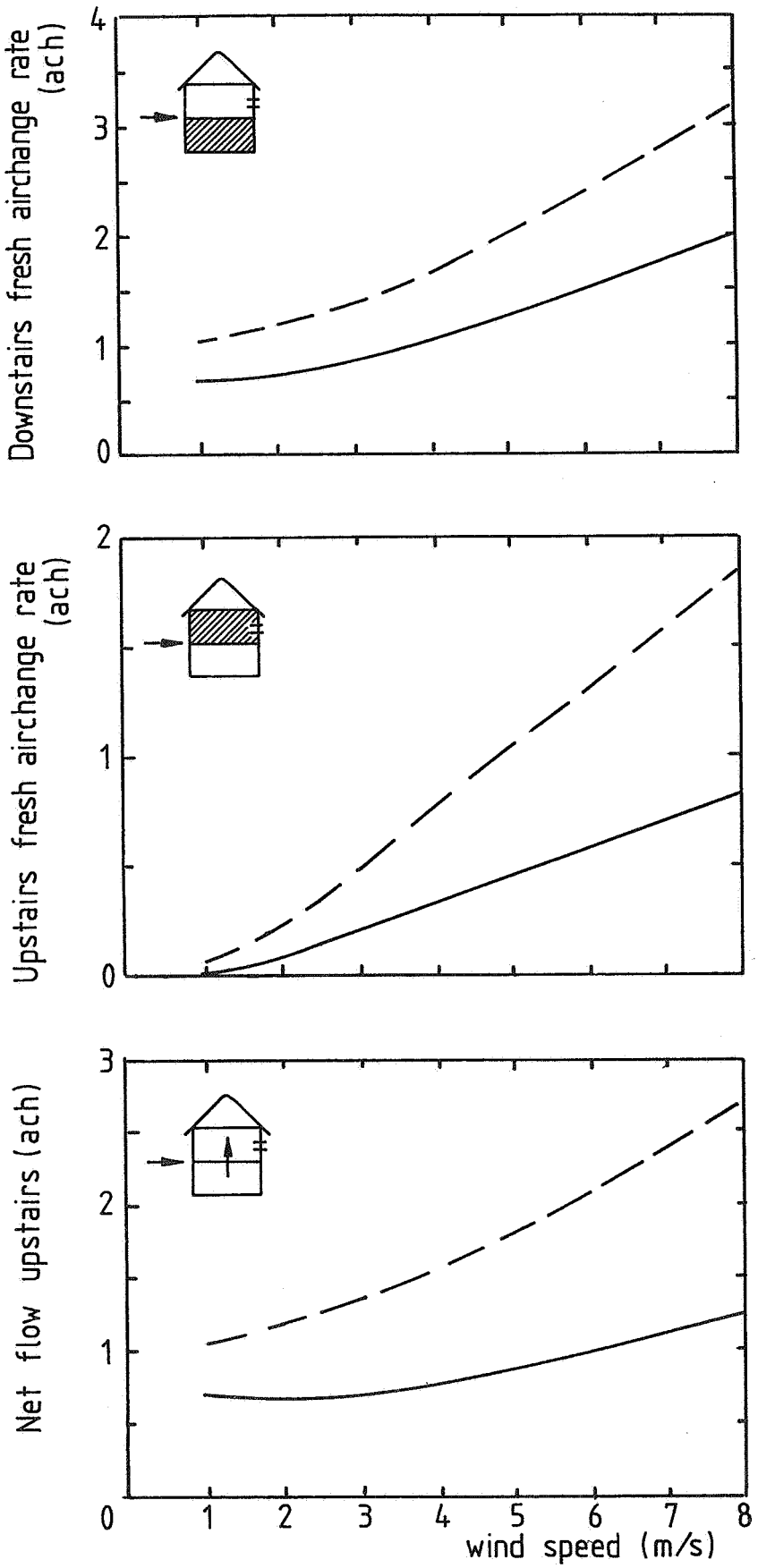

Figure 6.b - Effect of opening bedroom window (key as in Figure 6.a)

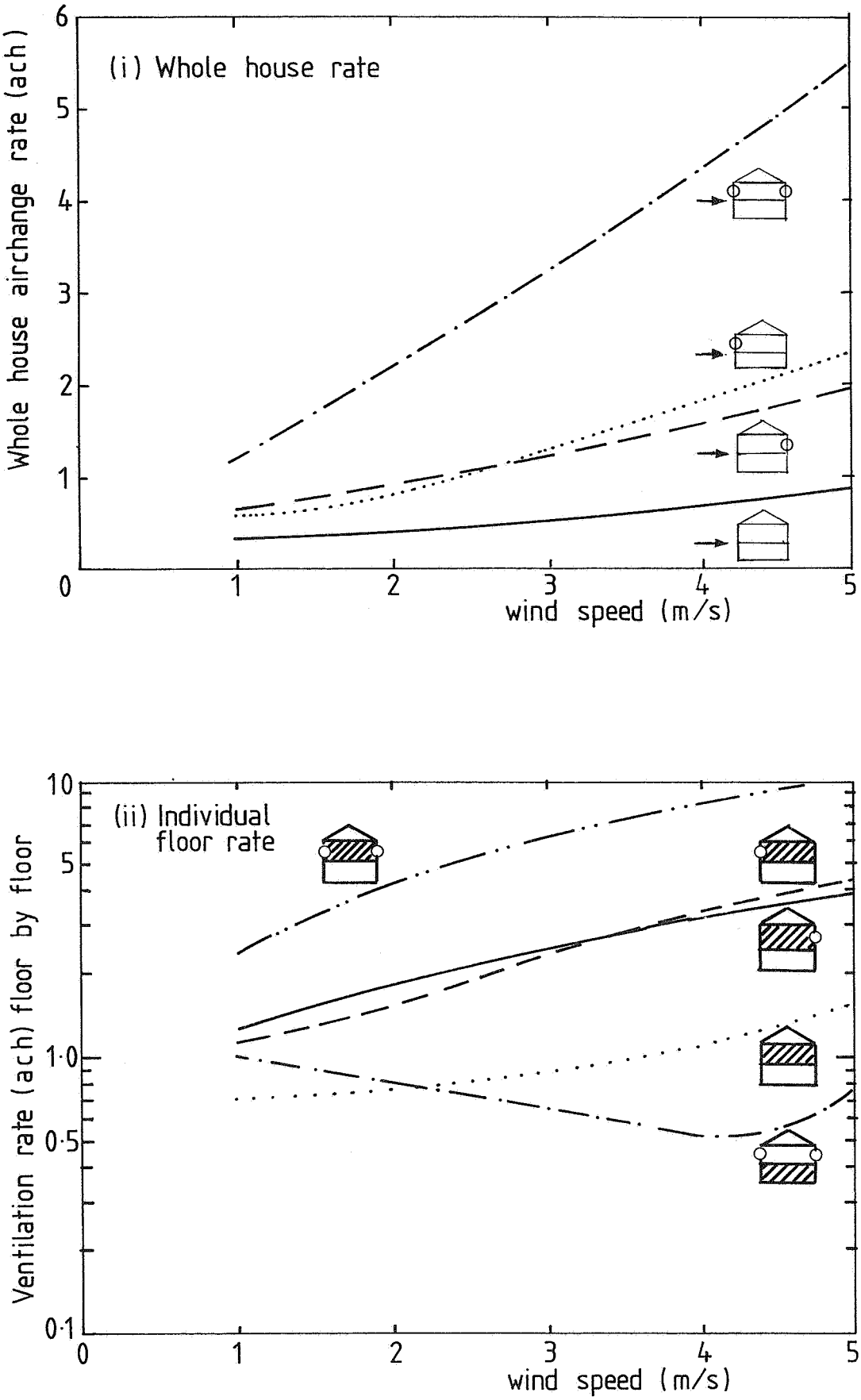

Figure 7.a - Effect of opening banks of upstairs windows

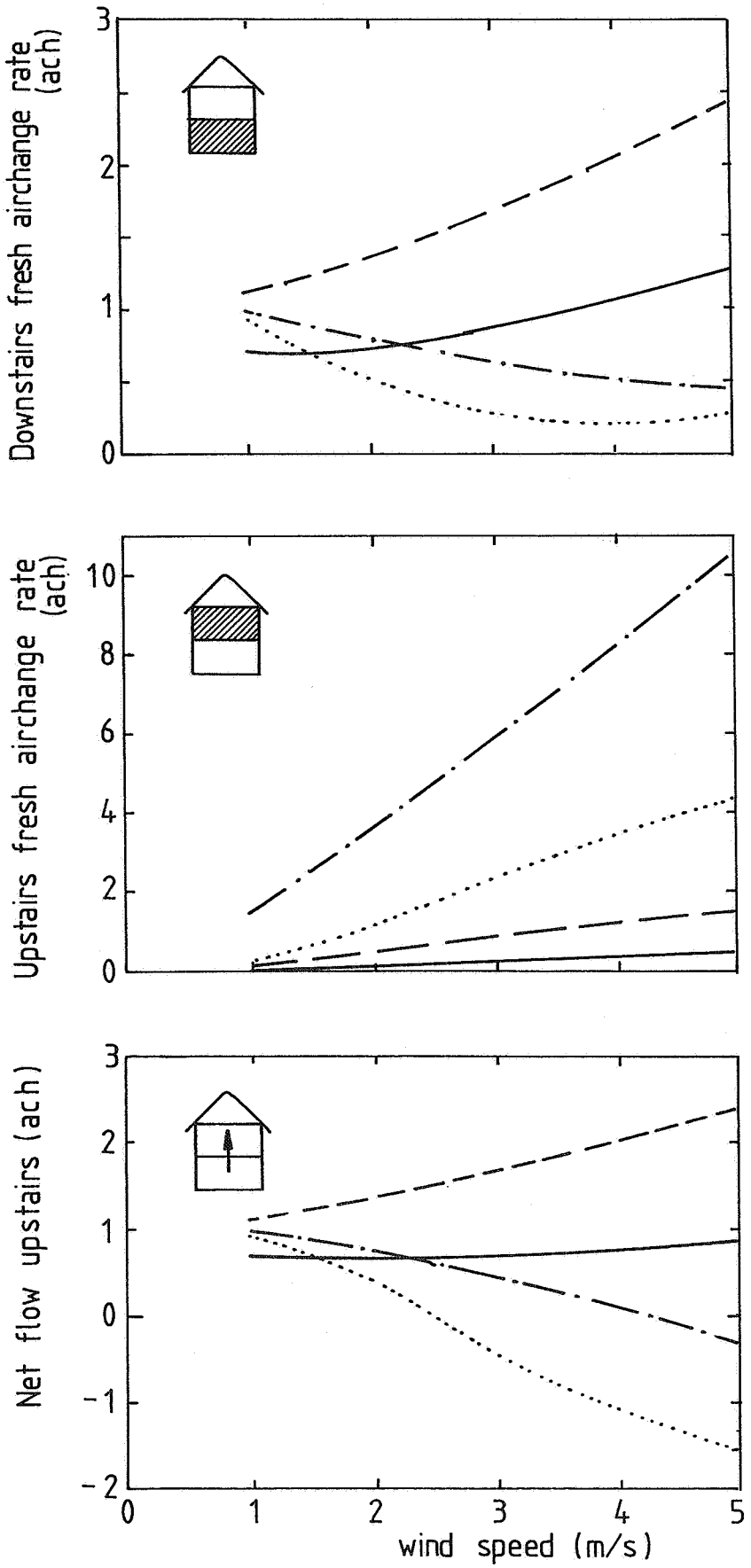

Figure 7.b - Effect of opening banks of upstairs windows (key as in 7a(i))

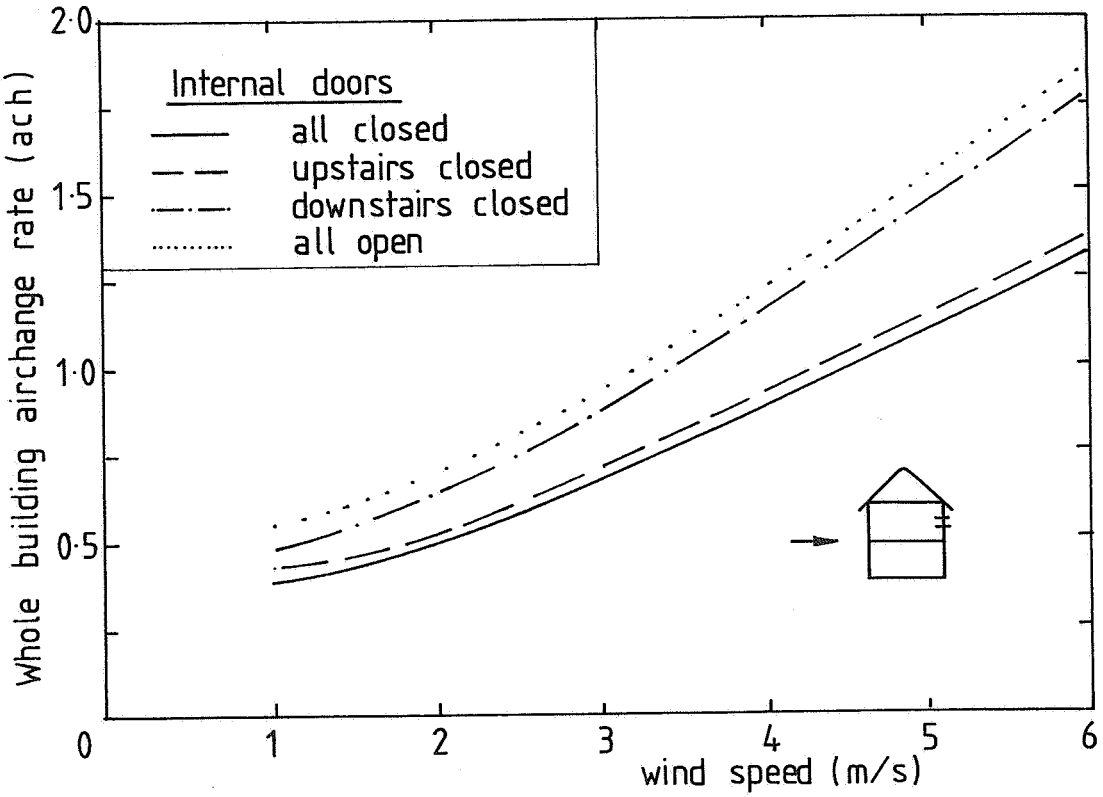

Figure 8.a-Effect of closing internal doors with bedroom window open

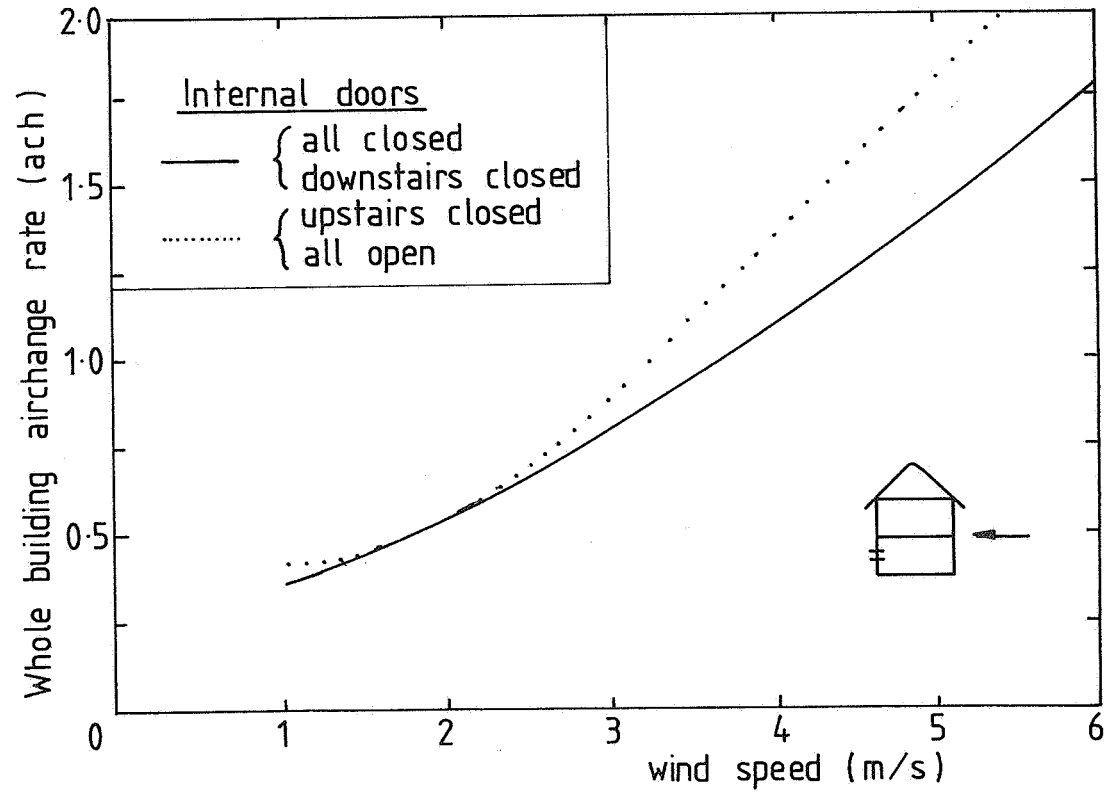

Figure 8.b-Effect of closing internal doors with kitchen window open

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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PAPER S.3

INTERPRETATION AND ERROR ANALYSIS OF MULTI-TRACER GAS MEASUREMENTS TO DETERMINE AIR MOVEMENT IN A HOUSE

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INTERPRETATION AND ERROR ANALYSIS OF MULTI-TRACER GAS MEASUREMENTS TO DETERMINE AIR MOVEMENT IN A HOUSE.

by R R Walker

1. INTRODUCTION

Although infiltration of outside air across the envelope of a building has been considered of prime interest in relation to energy conservation and indoor air quality, it also important to understand the way in which air moves between zones within a building. A knowledge of the air movement pattern enables the transfer of pollutants or heat to be determined. In order to achieve this, a number of experimental methods have recently been developed, using either single or multiple tracer gases. (See, for instance, references 1,2,6,7,9).

It is important in any method to assess the confidence which can be placed in the resulting flow rates. This paper discusses methods for analysing and evaluating errors arising from measurements made using three tracer gases. The test data presented are taken from a programme of measurements to determine the infiltration rates and air interchange between three zones of a mehanically ventilated experimental house. The full programme is designed to investigate the effect of operating the mechanical ventilation system and the use of internal doors, as well as meteorological factors.

2. THE TEST HOUSE

The house was built on site at Garston in 1978 as a 'low energy' test house, and incorporates a high standard of insulation and a mechanical ventilation system with an air to air heat exchanger for heat recovery. The elevations and floor plans are shown in Figures 1 and 2.

The mechanical ventilation system supplies fresh air via ducting to the three bedrooms and the living room. Stale air is similarly extracted from the bathroom, downstairs toilet, kitchen dining area and from the cooker hood.

The supply and extract flow rates have been measured to be approximately $81m^3/hr$ to the bedrooms and $41m^3/hr$ to the lounge. The individual extract rates have not been measured, and are esimated to be approximately in the ratio 1:3 from the bathroom upstairs and from both kitchen and toilet downstairs. The total supply and extract rates are in balance.

3. INJECTION STRATEGY

For the present purposes the house was notionally divided into three zones; the ground floor, first floor and loft space, called zones 1, 2 and 3 respectively. Zones 1 and 2 have a nominal volumes of $97.5m^3$. The loft space, which is common to all three houses and extends across the whole terrace, has a volume of $260m^3$.

Three tracer gases, CO_2, N_2O and SF_6 were used, one initially distributed throughout each zone. CO_2 was injected to a target of 2000-5000ppm in the ground floor, N_2O to 200ppm in the first floor, and SF_6 to either 50 or 200ppm in the loft. These choices were determined by the available analysers, described below.

Tracer gas was delivered to each zone via single 4mm ID nylon tubes. In zone 1 this then branched into each room and the hall. There were similar networks for zones 2 and 3.

The tracer gas delivered by each branch was dispersed through fans, and the delivery rate adjusted with needle valves. Fans were used during injection to aid mixing of tracer gas within each zone. These consisted of pairs blowing in opposite directions, located on the thresholds of each room and along the loft space. In addition, oscillating desk top fans were placed in the centre of each room.

Injection times for each tracer were established by trial and error. These were all less than one minute. The mixing fans were switched off fifteen minutes after injection.

4. SAMPLING OF TRACER GASES

The analysers used were two continous output, dual channel, non-dispersive infrared instruments by Leybold Heraeus. Channels were dedicated to analysis of either one of SF_6, N_2O or CO_2. Depending on the unit used, SF_6 analysis was on either a 200ppm or a 50ppm range, and injection times were altered accordingly.

Air samples were drawn from each zone via a network of tubing, which exactly mirrored the injection network. Thus samples from each location within a zone were blended before passing back to the analysers. In addition, a single line ran to outside to obtain a reference level for each trace analysis. Two further 'flying leads' were used to obtain individual ground and first floor room samples. In this way the evenness of initial concentration levels within each zone could be checked, and the tracer injection rate set accordingly.

The total of six sample lines were then brought back to individual solenoid valves, which were under the control of an ITT Director microprocessor unit. This unit was programmed to connect each sample line in turn to the two analysers. The concentrations of the three tracers present in each sample were recorded on cassettes by a data logger unit, using an arbitrary scale of 0 - 200 units. The data were later transcribed using an off-line computer. A shematic layout of this system is shown in Figure 3.

Tests began by switching off the mixing fans and by starting the sampling system. Each test continued for thirty minutes.

5. THEORY

The theoretical basis for deriving ventilation and interzone airflow rates from measurements of multiple tracers is detailed in Reference 1. It was shown how in the 'decay method' the conservation of tracer gas in a zone (k) can be written in the form:

$$[A].\{X\}_{(k)} = \{B\}_{(k)} \qquad .....(1)$$

where the corresponding elements are, respectively:

$$a_{ij} = C_{ij}$$

$$b_{i(k)} = V_{(k)} \cdot \dot{C}_{i(k)}$$

$$x_{i(k)} = -S_{(k)} \cdot \delta(ik) + Q_{i(k)} \cdot (1 - \delta(ik))$$

where $\delta(ik)$ is the Kronecker delta, and the order of the matrices is equal to the number of zones, n. The measurable quantities are:

$V_{(k)}$ = the volume of zone (k)

C_{ij} = the concentration of tracer (i) in zone (j)

$\dot{C}_{i(k)}$ = the time derivatives of the concentrations $C_{i(k)}$

which are used to solve for the unknowns:

$S_{(k)}$ = the total outflow of air from zone (k)

Q_{ij} = the flow from zone (i) to zone (j)

and subsequently also for the infiltration (Q_{0i}) and exfiltration (Q_{i0}) terms.

Equation (1) can be replaced by n(n+1) simultaneous equations describing the mass balance of n tracers and air, in terms of n(n+1) unknown exchanges between n zones and the outside. This is considered later in Section 11, and Appendix B.

It will be noted that in order to solve the equations in their present form, the input data require the 'slopes' of the $C_{ij}(t)$ curves to be established for each tracer in each zone. This will be referred to as the Gradient Method. An alternative approach is to integrate the mass balance equations throughout with respect to time, over some period τ. τ might be chosen to be the whole duration of the test for example. The flow matrix remains unaffected, but the elements of [A] and {B} become:

$$a_{ij} = \int_{\tau} C_{ij} \, dt$$

$$b_{i(k)} = V_{(K)} \cdot \Delta C_{i(k)}$$

where

$\int_{\tau} C_{ij}.dt$ = the area under the curve $C_{ij}(t)$ of the tracer(i) recorded in zone (j), over the period τ.

$\Delta C_{i(k)}$ = change in concentration of tracer (i) in zone (k) over the duration τ.

There will be a 'smoothing effect' on the data by using the equations in this integrated form. This will be referred to as the Integral Method.

6. DATA ANALYSIS

For the Gradient Method the concentrations and derivatives at a single time point were obtained from the concentration profiles plotted on a semilogarithmic scale. A straight line was drawn through data points local to the specified time. The derivative was then computed from the concentration at that time, on the line fit, and the slope of the line.

For the Integral Method the curves were integrated numerically over a specified period using a simple trapezoidal method. The overall changes in concentration over this period were also noted.

The data, in either time derivative or time integral form, were then used to solve for the flows by computer, using the Gauss elimination method. It is possible for small negative values to be computed; these have no physical interpretation in the present context. A least squares procedure[2] advocated by Penman and Rashid[3] was available to constrain the solutions to have positive values. For the purposes of error analysis, this was not used.

7. ERROR ANALYSIS

The aims of the data analyses in the following Sections are fivefold:

1. to discuss processsing by the Gradient Method and Integral Method

2. to evaluate three schemes of error analysis, based on vector norms, perturbation, and differentiation, respectively

3. to discuss the role of reconstructed concentration profiles in validating solutions

4. to compare the performance of the schemes of error analysis against other published data.

5. to establish confidence levels in the flow solutions

All error estimates are based on the fluctuations in the concentration profiles, which represent zonal averages in the sense that they are measurements of physically blended air samples. These fluctuations were taken to approximately average +/-1 logger units. In the time integration procedure, say over N points, the error was assumed to sum in proportion to $1/\sqrt{N}$, to take some account of the 'smoothing' effect. Over this period the net change in concentration of tracer was estimated to be accurate within +/-2 units in the zone of seeding, and +/-1 unit elsewhere. Errors in derivatives using the Gradient Method were estimated visually.

8. AIRFLOW RESULTS

Figure 4 shows the concentration profiles of CO_2 recorded in Test 1. The reconstructed curves are also shown and are discussed in Section 13. The data extracted for processing by the Integral Method are given in Table 1, and for processing by the Gradient Method in Table 2.

For Tests 1 and 2, solutions were obtained using the Integral Method over thirty minutes (I_{30} data) and fifteen minutes (I_{15} data), and the Gradient Method at eleven minutes elapsed time (G_{11} data) and at five minutes (G_5 data). These are listed in Table 3 for Test 1, and in Table 4 for Test 2. The mean and standard deviations were calculated for these solutions. For Test 1 these are listed in Table 5. The G_5 solutions were discounted for reasons discussed below.

Where a particular concentration profile departs significantly from a smooth curve, then it is very difficult to measure an appropriate derivative. In Test 1 a low estimate of the decay rate of N_2O in the loft, at five minutes, led to values being computed for Q_{03} and Q_{30} which were approximately 50% lower than the mean results. Similar discrepencies are apparent in the G_{11} results of Test 2.

The problem arises because a curve was fitted over a limited number of data points only. Other researchers (I'Anson, Irwin and Howarth[6], and Prior et al[7]) have used procedures which entail a theoretical curve being fitted to the whole of the data. However, it is not always possible to fit an appropriate curve, and these procedures are not without problems. It is suggested that repeated solution at several time points would be an improvement on the method presented here, perhaps using finite difference techniques to obtain the gradients.

Solutions obtained using integration are not subject to such large variations. In Tests 1 and 2, the solutions obtained by integration exhibited less variation about the mean.

9. THEORY OF ERROR ANALYSIS USING VECTOR AND MATRIX NORMS.

A procedure for the rigorous error analysis of matrix processes is given by Wilkinson[4,5]. The following is a brief summary of this procedure, which is presented more fully in Appendix A.

Use is made of vector and matrix norms. The norm gives an assessment of the size of a vector or matrix. The (infinity') norm, $\|X\|$, of a vector $\{X\}$ is interpreted as the modulus of the largest element. Corresponding to this vector norm, the matrix norm A is defined as the maximum row sum of the modulii of the elements.

With reference to equation 1, perturbations in the matrix [A] and the right-hand sides 'B' are considered. The following expression is derived:

$$\|\delta X\| \leqslant \frac{\|A^{-1}\|.\|\delta A\|.\|X\| + \|A^{-1}\|.\|\delta B\|}{1 - \|A^{-1}\|.\|\delta A\|} \quad ....(2)$$

This result provides an upper bound for the largest expected perturbation in the elements of $\{X\}_{(k)}$, due to perturbations $[\delta A]$ and $\{\delta B\}_{(k)}$ in the elements of $[A]$ and $\{B\}_{(k)}$, respectively.

It is instructive to consider equation 2 expressed in terms of relative errors:

$$\frac{\|\delta X\|}{\|X\|} \leq \frac{\|A\|.\|A^{-1}\|.\left[\frac{\|\delta A\|}{\|A\|} + \frac{\|\delta B\|}{\|B\|}\right]}{1 - \|A\|.\|A^{-1}\|.\frac{\|\delta A\|}{\|A\|}} \qquad \ldots.(3)$$

It can be seen that a decisive quantity is $\|A\|.\|A^{-1}\|$. This expresses the sensitivity of the solution to perturbations in the parameters, and is termed a 'condition number' for the problem. Ill-conditioning is indicated by $\|A\|.\|A^{-1}\|$ much greater than unity.

Expression 2 was evaluated for the results of four tests. As an example, results are listed for the Test 1, I_{30} data in Table 5. In any zone, $\{\delta X\}$ appears pessimistic compared to the standard deviations of the flow solutions, especially in zone three. Error norm limits computed from the data of the Gradient Method were generally larger.

For the Integral Method the greater proportion of the computed error bound was due to the uncertainty in the measurement of the net changes in concentration. For the Gradient Method, the dominant contribution came from the uncertainties in the derivatives.

The values computed cannot strictly be ascribed to, or distributed amongst, any particular airflows. At best they are an indication of the possible size of errors in the flows.

10. ERROR ESTIMATION USING PERTURBATION OF DATA.

The sensitivity of the solutions to changes (perturbations) in the data can be checked directly by making small changes in the data, and then computing new (perturbed) solutions. A particular set of perturbations could be chosen, say all errors occuring together with the same sign. This can be taken a step further, to take into account all possible combinations

of errors, with the proposed scheme as follows.

Consider any airflow solution Q_{ij} as a function of all measured quantities a_{ij}, $b_{i(k)}$

$$Q_{ij} = f(a_{ij}, b_{i(k)})$$

A small change (δQ_{ij}) in Q_{ij}, due to small changes (δa_{ij} and $\delta b_{i(k)}$) in a_{ij} and $b_{i(k)}$ can be expressed using partial differentials:

$$\delta Q_{ij} \approx \sum_{i,j} \left[\frac{\partial f}{\partial a_{ij}} . \delta a_{ij} + \frac{\partial f}{\partial b_{i(k)}} . \delta b_{i(k)} \right]$$

where f is assumed to be approximately linear over the small changes δa_{ij} and $\delta b_{i(k)}$. Approximating the differentials themselves by the small changes δf_{ij} and δa_{ij}, and $\delta f_{i(k)}$ and $\delta b_{i(k)}$, we obtain:

$$\delta Q_{ij} \approx \sum_{ij} (\delta f_{ij} + \delta f_{i(k)})$$

$$|\delta Q_{ij}| \leq \sum_{ij} (|\delta f_{ij}| + |\delta f_{i(k)}|) \qquad ....(4)$$

This says that the size of the error, $+/-\delta Q_{ij}$, in a solution Q_{ij} is less than the sum (without regard to sign) of all the small perturbations in Q_{ij}, found by making small changes in all a_{ij} and $b_{i(k)}$ in turn.

The results of this scheme for the I_{30} of Test 1 are presented in Table 5. For the largest airflow, 188m^3/hr, the computed error was 72m^3/hr. 92% of this error is due to errors in $\{\delta B\}$, i.e. in the estimation of the nett changes in concentration.

11. ERROR ANALYSIS BY DIFFERENTIATION - MATRIX FORM

It was stated above that the basic equations can be written in the form of n(n+1) simultaneous equations, so as to explicitly include exchanges between the zones and the outside air mass:

$$\{B\} = [A].\{X\}$$

It is difficult to derive a systematic notation which defines each of the matrix and vector elements. It was found necessary to set out the equations in full, as given in Appendix B.

Using a standard technique of error analysis and differentiating (as outlined by Perera[10]) we obtain, in matrix notation:

$$\{dB\} = [A].\{dX\} + [dA].\{X\}$$

$$\{dX\} = [A^{-1}].(\{dB\} - [dA].\{X\}) \quad \ldots\ldots\ldots\ldots(5)$$

The appropriate absolute errors are inserted in place of the infinitessimal quantities $\{dB\}$ and $[dA]$, and $[A^{-1}]$ is computed from $[A]$. Matrix computations are then made, without regard to signs, to compute error limits $\{dX\}$.

This procedure was performed for the I_{30} data of Test 1, and the results are listed in Table 5. These do not significantly differ from the results obtained using the perturbation scheme above.

12. PERFORMANCE OF SCHEMES OF ERROR ANALYSIS USING OTHER PUBLISHED DATA.

The author is unaware of any published results of measurements of interzonal air movement which include a full error analysis of results. However D'Ottavio working at Brookhaven, U.S.A., has performed an error analysis[8] (unpublished) on measurements made with Dietz and Goodrich[9]. Unfortunately details of the scheme were not available, however it is known that it involves partial differentials to express the sensitivity of the computed airflows to errors of measurement in the concentrations.

Two of the schemes of error analysis described above were applied to the data supplied by Dietz, and the results inter-compared.

Dietz's experiments differ from those reported above in that continuous emission of tracer gas was employed, and average, quasi steady-state concentrations were measured in each zone. Different types of tracer source were placed with one in each of three zones.

The release rates of the sources and the concentration measurements are listed in Table 6. No error estimates were provided for measurements of source rates. To solve for airflow rates, this data set can be processed in exactly the same way as for the data (eg. Table 1) of the tests above. Table 7 lists the solutions and results of the error analysis as provided.

The error norm scheme was applied by treating the standard deviations as simple errors. In applying the perturbation scheme, equation 4 was modified in the form of a sum of squared terms, and the square root of the total was taken to give the standard deviation. The matrix differentiation scheme could not be so simply converted to deal with standard deviation, and was not applied.

The results of the error analysis by perturbations are listed in Table 7. Good agreement is evident between the supplied results and those of the perturbation scheme. However, the computed error norm limits were more than an order of magnitude greater, and as such are useless.

13. VALIDATION BY RECONSTRUCTING CONCENTRATION PROFILES

Equation 1 describes a set of first order linear differential equations. Knowing the interzone airflows and the initial concentrations, it is possible to obtain the particular solutions for the concentrations in each zone as a function of time. To perform this, a computer program has previously been written[1] utilising the Runge-Kutta-Merson routine from the NAG library[11].

As an example, Figure 4 shows the reconstructed curves for both the I_{30} and G_5 solutions for Test 1, superimposed over the experimental data points obtained for the CO_2 data.

The question arises as to how far such comparisons of reconstructed curves with the original data can be used to validate the airflow solutions. We should expect the reconstructed curves to reflect the errors in the original measured quantities. Clearly the G_5 solutions are not acceptable.

However, it should be clear that the errors in the airflows represent an accumulation of the errors in taking measurements from the original data, and cannot therefore be quantified through this exersize.

13.1 Implications for Predicting Contaminant Levels

The reconstructed curves also illustrate the sensitivity of predictions of concentration profiles to errors in the airflow solutions.

In this connection we might like to use the computed airflow rates to predict the concentration levels of a contaminant which result due to a known constant source rate. We are then interested to know how sensitive are such predicted levels to errors in the airflows. An example of such a relationship between airflows and concentration levels is illustrated by Dietz's results, Table 6.

For the purposes of comparison, the errors in the airflows might be expressed in terms of the largest error divided by the largest flow, i.e. vector norms $\|\delta X\| / \|X\|$, and similarly for the errors in the concentrations, $\|\delta A\| / \|A\|$. For the results in Table 6, these quantities are 45% compared with 10% respectively. This demonstrates how relatively insensitive are the predicted concentration to errors in the airflows.

14. DISCUSSION

Error analysis showed that for the Integral Method the influence of uncertainties in the measurement of net changes in concentration were dominant. Similarly for the Gradient Method errors in the estimates of derivatives were the most important, and occasionally these could be very large. It was suggested that this Method could be improved by solving at many time points.

Error norm analysis produced large error bounds for airflows associated with zone 3 in Test 1, and uselessly pessimistic values when applied to Dietz's data. There is evidently a fundamental failing.

The underlying problem is that the elements of the matrix $[A]$ in Test 1 are spread in value over a range of two orders of magnitude, as are those of $[A^{-1}]$ in consequence. The corresponding quantities of Dietz' data are spread over four orders of magnitute. In taking norms, i.e. maximum row sums, the influence of the smaller elements is not represented. As a result a greater accumulation of error is computed.

There is no evidence that the problem is ill-conditioned, for any of the data sets considered. Similar condition numbers (<10) were computed for both Dietz's and the test data reported here. In addition, inspection of the standard deviations and perturbations listed in Tables 5 and 7 does not suggest that the solutions were over-sensitive to changes in the input data.

The schemes of matrix differentiation and of repeated perturbation were shown to be in good agreement with each other when applied to the Test 1 data, and produced plausible results. Furthermore, the latter scheme gave similar results to an independantly proposed procedure, when applied to the same data.

The airflows and their associated errors computed using the perturbation scheme are shown for Test 1 (I_{30}) in Figure 5. The small downward airmovements from zone 3 may be due to leaks in junctions of the mechanical ventilation system situated in that zone.

It should be noted that no account has been taken of possible errors in the measurements of the effective zone volumes. The effect of any such errors can be seen by considering equation 1 for the zone flow solutions $\{X\}_{(k)}$. The differential form, analogous to equation 5, shows that an error in a zone volume (i.e. $\{dB\}_{(k)}$) produces a proportional error in all flow solutions for that zone.

15. FINAL CONCLUSIONS

Two methods of processing multitracer decay measurements to obtain interzone airflows were considered. In the Gradient Method, the derivatives of the concentration-time curves were measured. The Integral Method, in which the areas under the concentration curves are measured, was found to be the more reliable.

Although relatively simple to calculate, error norm limits were shown to be an unreliable indicator of errors in airflow solutions obtained from multitracer measurements.

The two schemes of error analysis involving differentiation in matrix form, and the sum of perturbations, produced similar and plausible results. They are ideally suited to a computer. The latter of the two was found to be the simplest to apply in practice. This scheme was shown to be in good agreement with an independantly developed procedure, in one case.

The procedure of reconstructing concentration profiles was shown to be a useful qualitative check on the airflow solutions.

Finally, an example set of results complete with error estimates, has been presented.

ACKNOWLEDGEMENTS.

Thanks are due to Dr M D A E S Perera and Dr P R Warren for their general help and advice in writing this paper. The author also acknowledges Dr Albasiny of The National Physical Laboratory for his assistance regarding the application of error analysis using vector norms.

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APPENDIX A

THEORY OF ERROR ANALYSIS USING VECTOR AND MATRIX NORMS.

The following is an example of a well established procedure for the rigorous error analysis of matrix processes, as given by Wilkinson[4,5]. This involves the use of vector and matrix norms, and these are now defined.

The norm gives an assessment of the size of a vector or matrix. There are three norms in common use, defined by

$$\|X\|_p = (|x_1|^p + |x_2|^p + \ldots\ldots + |x_n|^p)^{1/p} \quad \ldots(p = 1, 2, \infty)$$

where $\|X\|_\infty$ is interpreted as $\max_i |x_i|$. The norm $\|X\|_2$ is the length of the vector $\{X\}$. The 'infinity' norm is implied throughout this paper. Corresponding to this vector norm, the matrix norm $\|A\|_\infty$ is defined as

$$\|A\|_\infty = \max_i \sum_j |a_{ij}|$$

Wilkinson considers the factors which determine the sensitivity of a solution of the system of linear algebraic equations

$$[A].\{X\} = \{B\} \qquad \ldots\ldots\ldots(1)$$

with respect to changes in the matrix [A] and the right-hand sides {B}. These changes are represented by perturbations (which need not be small). In the discussion below, for clarity the square matrix [A] is represented by A and the column vectors {X} and {B} are represented by X and B respectively.

If A is changed to $(A+\delta A)$ and B is changed to $(B+\delta B)$ then

$$(A+\delta A).(X+\delta X) = (B+\delta B) \qquad \ldots.(2)$$

$$(A+\delta A).\delta X = \delta B - \delta A.X$$

$$A(I+A^{-1}.\delta A).\delta X = \delta B - \delta A.X$$

$$\delta X = (I+A^{-1}.\delta A)^{-1}.A^{-1}.(\delta B-\delta A.X) \qquad ....(3)$$

By making use of the property of norms

$$\|P.Q\| \leqslant \|P\|.\|Q\| \qquad ....(4)$$

for any two vectors or matrices P and Q, it can be shown that

$$\|\delta X\| \leqslant \frac{\|A^{-1}.\delta A\|.\|X\| + \|A^{-1}.\delta B\|}{1 - \|A^{-1}.\delta A\|} \qquad ....(5)$$

provided $\|A^{-1}.\delta A\| < 1$. The terms $\|A^{-1}.\delta A\|$ and $\|A^{-1}.\delta B\|$ (norms of matrix products) can further be replaced by $\|A^{-1}\|.\|\delta A\|$ and $\|A^{-1}\|.\|\delta B\|$ (products of norms). In doing this, the inequality becomes more pessimistic.

Referring to equation (1), this result (5) provides an upper bound for the largest expected perturbation in the elements of $\{X\}_{(k)}$, due to perturbations in the elements of $[A]$ and $\{B\}_{(k)}$. In the case where the equations of mass balance are set out as $n(n+1)$ simultaneous equations, then a single upper bound is computed for the largest expected error with regard to all of the flow solutions.

Application of the Error Norm Bound Expression

The error norm expression (5) involves the terms $\|A^{-1}.\delta A\|$ and $\|A^{-1}.\delta B\|$, which require actual sets of errors and their signs. These are not normally known; usually we have a set of possible errors, which may have either sign, and which may occur in any combination. It is therefore difficult to choose an appropriate set of perturbations $[\delta A]$ and $\{\delta B\}$.

One possibility is to assume all experimental errors occur, with the same sign. In this case the error norm bound computed can only be taken as a guide, possibly erring on either the optimistic or the pessimistic side.

A second option is to replace the above terms by the norm products $\|A^{-1}\|.\|\delta A\|$ and $\|A^{-1}\|.\|\delta B\|$, respectively. The definitions of the vector and matrix norms given above involves only the moduli of the elements, and so in this form the problem of choosing signs for the errors is avoided. The drawback is that there will be a tendency to compute an over-pessimistic limit for $\|\delta X\|$.

Condition Number

It is instructive to consider equation 5 expressed in terms of relative errors:

$$\frac{\|\delta X\|}{\|X\|} \leqslant \frac{\|A\|.\|A^{-1}\|.\left[\frac{\|\delta A\|}{\|A\|} + \frac{\|\delta B\|}{\|B\|}\right]}{1 - \|A\|.\|A^{-1}\|.\frac{\|\delta A\|}{\|A\|}} \qquad \ldots.(3)$$

where the norm products have been substituted throughout, and use has been made of the properties of norms (4) to replace $\|X\|$ by $\|b\|/\|A\|$ on the right hand side.

It can be seen that a decisive quantity is $\|A\|.\|A^{-1}\|$. This expresses the sensitivity of the solution to perturbations in the parameters, and is termed a 'condition number' for the problem. Ill-conditioning is indicated by $\|A\|.\|A^{-1}\|$ much greater than unity.

APPENDIX B

The equations governing the continuity of air and three tracer gases in three zones are set out as follows

$$[A].\{X\} = \{B\}$$

$$\begin{bmatrix}
CO1 & 0 & 0 & -C11 & -C11 & -C11 & 0 & C21 & 0 & 0 & C31 & 0 \\
CO3 & 0 & 0 & -C12 & -C12 & -C12 & 0 & C22 & 0 & 0 & C32 & 0 \\
CO3 & 0 & 0 & -C13 & -C13 & -C13 & 0 & C23 & 0 & 0 & C33 & 0 \\
1 & 0 & 0 & -1 & -1 & -1 & 0 & 1 & 0 & 0 & 1 & 0 \\
0 & CO1 & 0 & 0 & C11 & 0 & -C21 & -C21 & -C21 & 0 & 0 & C31 \\
0 & CO2 & 0 & 0 & C12 & 0 & -C22 & -C22 & -C22 & 0 & 0 & C32 \\
0 & CO3 & 0 & 0 & C13 & 0 & -C23 & -C23 & -C23 & 0 & 0 & C33 \\
0 & 1 & 0 & 0 & 1 & 0 & -1 & -1 & -1 & 0 & 0 & 1 \\
0 & 0 & CO1 & 0 & 0 & C11 & 0 & 0 & C21 & -C31 & -C31 & -C31 \\
0 & 0 & CO2 & 0 & 0 & C12 & 0 & 0 & C22 & -C32 & -C32 & -C32 \\
0 & 0 & CO3 & 0 & 0 & C13 & 0 & 0 & C23 & -C33 & -C33 & -C33 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & -1 & -1 & -1
\end{bmatrix}$$

$$\times \begin{Bmatrix} Q01 \\ Q02 \\ Q03 \\ Q10 \\ Q12 \\ Q13 \\ Q20 \\ Q21 \\ Q23 \\ Q30 \\ Q31 \\ Q32 \end{Bmatrix} = \begin{Bmatrix} V1.C'11 \\ V1.C'12 \\ V1.C'13 \\ 0 \\ V2.C'21 \\ V2.C'22 \\ V2.C'23 \\ 0 \\ V3.C'31 \\ V3.C'32 \\ V3.C'33 \\ 0 \end{Bmatrix}$$

Where

CIJ = Concentration in Ith zone, of Jth tracer
QIJ = Airflow from zone I to zone J; zone O refers to the outside air mass
VJ = Volume of zone J
C'IJ = Time derivative of CIJ

To obtain the equivalent expression for the equations in integral form, replace CIJ by $\int_{\tau} CIJ.dt$, and C'IJ by ΔCIJ (nett change in concentration over the period τ.

ZONE:	1	2	3	1	2	3
VOLUME:	93.5	81.5	260 m^3			
	$V_j \Delta C_{ij}$: m^3 xconc			$\int_\tau C_{ij}.dt$: conc.xmin		
CO_2 (1)	-3179 ± 187	-1060 ±81.5	-260 ±260	1098	696	120
N_2O (2)	-3833 ±93.5	-4971 ± 163	-2340 ± 260	1910	2708	854
SF_6 (3)	0 ±93.5	- 326 ± 163	-15080 ± 5020	377	585	4987
				estimated error ± 7 concxmins		
200 conc. units = 200 ppm SF_6/N_2O ; 5000ppm CO_2						

Table 1 : Integral Method, Test 1. Measured quantities evaluated over 30 minutes

ZONE:	1	2	3	1	2	3
VOLUME:	93.5	81.5	260 m^3			
	$V_j . \dot{C}_{ij}$: m^3 xconcxmin^{-1}			C_{ij} : conc.units		
CO_2 (1)	- 119 ± 10	- 33 ± 6	- 16 ± 5	41.5	26	4.5
N_2O (2)	- 105 ± 19	-161 ± 24	-101 ± 21	72.5	103.5	31.5
SF_6 (3)	0 -	0 -	-629 ±109	13.5	21.5	186
				estimated error ± 1 conc.unit		
200 conc . units = 200ppm SF_6/N_2O ; 5000ppm CO_2						

Table 2 : Gradient Method, Test 1. Measured quantities evaluated at 11 minutes elapsed time

	Integral Method		Gradient Method	
	I_{30}	I_{15}	G_{11}	$*G_5$
Q_{10}	188	162	223	272
Q_{20}	62	113	0	-10
Q_{30}	164	152	187	83
Q_{01}	142	149	128	178
Q_{21}	64	79	104	108
Q_{31}	9	8	5	7
Q_{02}	97	102	79	89
Q_{12}	23	28	21	33
Q_{32}	10	11	11	13
Q_{03}	175	176	202	78
Q_{13}	4	47	6	-12
Q_{23}	3	-51	7	38

m^3/hr

* suspected underestimation of zone 3 N_2O derivative

Table 3 : Test 1 airflow results by all methods

	Integral Method		Gradient Method	
	I_{30}	I_{15}	G_{11}	G_5
Q_{10}	223	242	164	271
Q_{20}	-2	-4	40	-2
Q_{30}	323	334	256	357
Q_{01}	148	159	131	174
Q_{21}	124	132	93	138
Q_{31}	6	9	1	12
Q_{02}	115	118	116	122
Q_{12}	71	71	87	66
Q_{32}	14	13	13	14
Q_{03}	281	295	213	330
Q_{13}	-16	-13	-26	-13
Q_{23}	78	74	83	66

m^3/hr

Table 4 : Test 2 airflow results by all methods

	Means; Test 1	Std.Devn. measured	Norm.limit	Pertbns	Differn.
Q_{10}	191	25		73	77
Q_{20}	58	46		67	71
Q_{30}	168	14		10	12
Q_{01}	140	9		9	10
Q_{21}	82	16	36	20	21
Q_{31}	7	2		2	2
Q_{02}	93	10		6	6
Q_{12}	24	3	28	14	15
Q_{32}	11	<1		3	1
Q_{03}	184	12		17	17
Q_{13}	19	20	67	36	36
Q_{23}	-14	26		34	34
			m^3/hr		

Table 5 : Mean and standard deviation of Test 1 results, and error estimates using I_{30} data Test 1

ZONE:	1	2	3		1	2	3
VOLUME:	255	250	123	m^3			
	SOURCE RATE nl/hr				AVERAGE CONC. nl/m^3		
GAS:							
PDCH (1)	1319	-	-		19.22 *(1.5)	9.12 (2.39)	0.17 (0.02)
PMCH (2)	-	3045	-		23.51 (0.29)	24.99 (0.39)	0.44 (0.06)
PDCB (3)	-	-	1153		9.08 (0.19)	9.63 (0.23)	25.3 (4.29)
(no error estimate supplied)					*( ) standard deviations		

Table 6 Measured data, continuous source method (Dietz et al)

	Dietz/D'Ottavio airflows Std. Devn.		Pertbns $\sqrt{\delta f^2}$	norms $\|\delta X\|$
Q_{10}	20	28	30	
Q_{20}	103	33	28	
Q_{30}	-1	7	2	
Q_{01}	7	3	3	
Q_{21}	117	32	35	388
Q_{31}	<1	2	2	
Q_{02}	70	11	8	
Q_{12}	104	53	64	690
Q_{32}	47	10	7	
Q_{03}	45	9	7	
Q_{13}	<1	<1	1	115
Q_{23}	1	<1	1	
		m^3/hr		

Table 7 : Results of error analysis using perturbations and error norm bounds, compared with independant scheme.

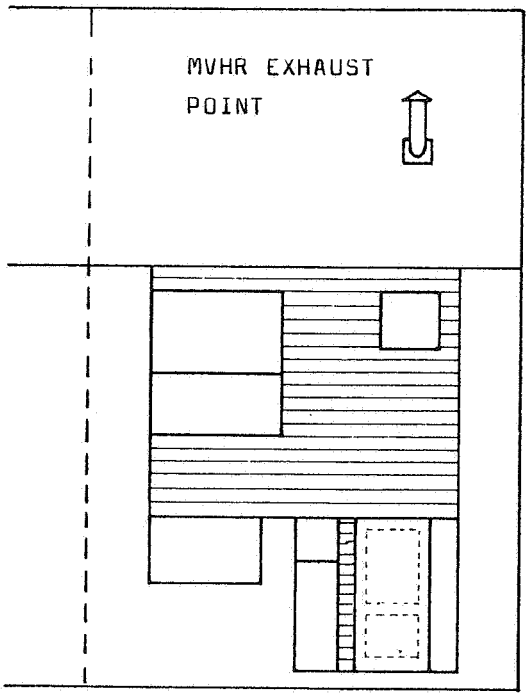

FIGURE 1. TEST HOUSE: NORTH ELEVATION

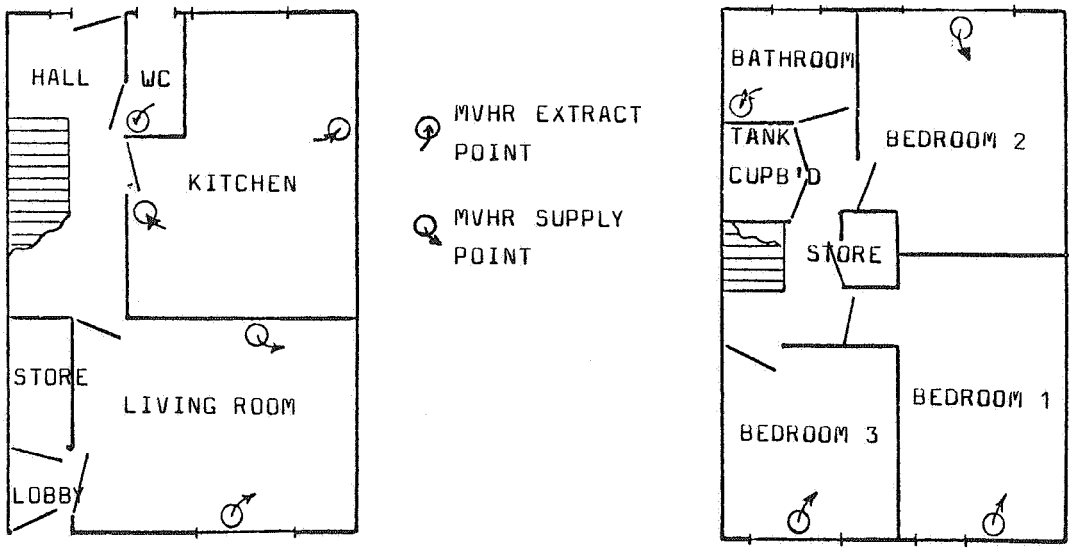

FIGURE 2. TEST HOUSE: FLOOR PLANS

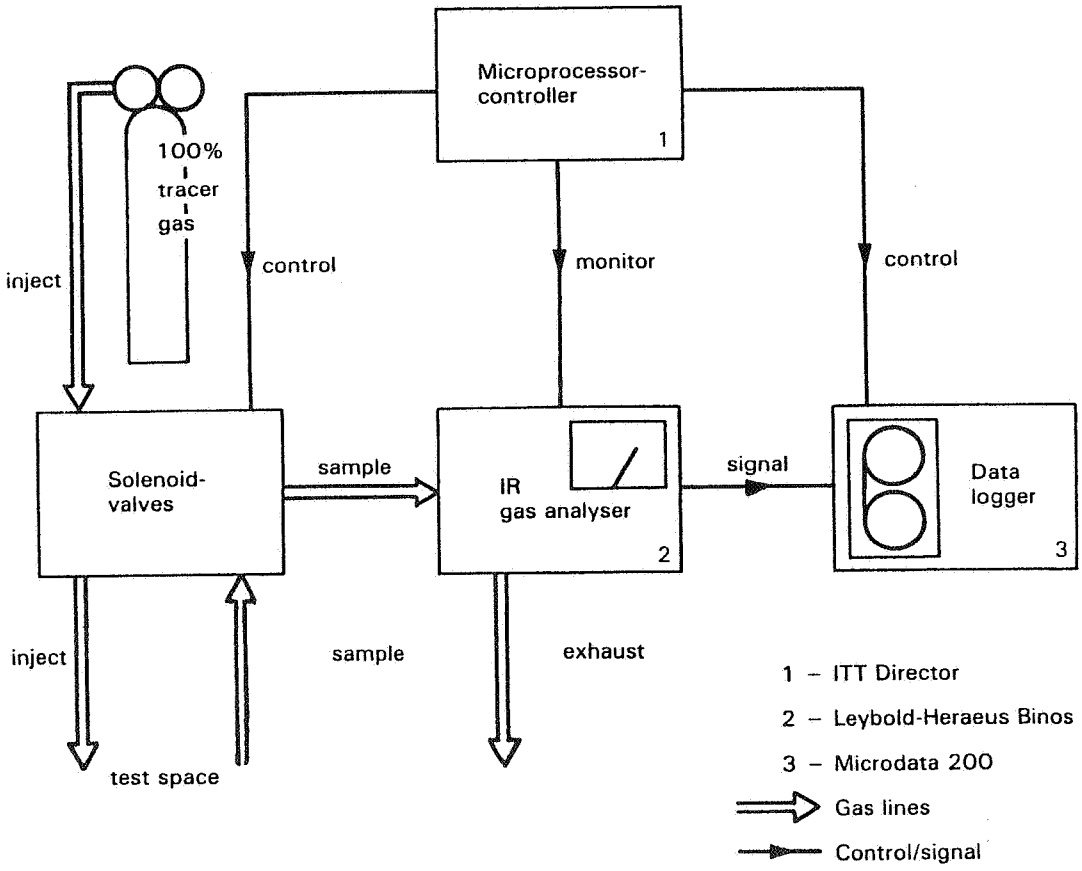

FIGURE 3. Microprocessor-controlled ventilation rate measuring system (Tracer gas decay)

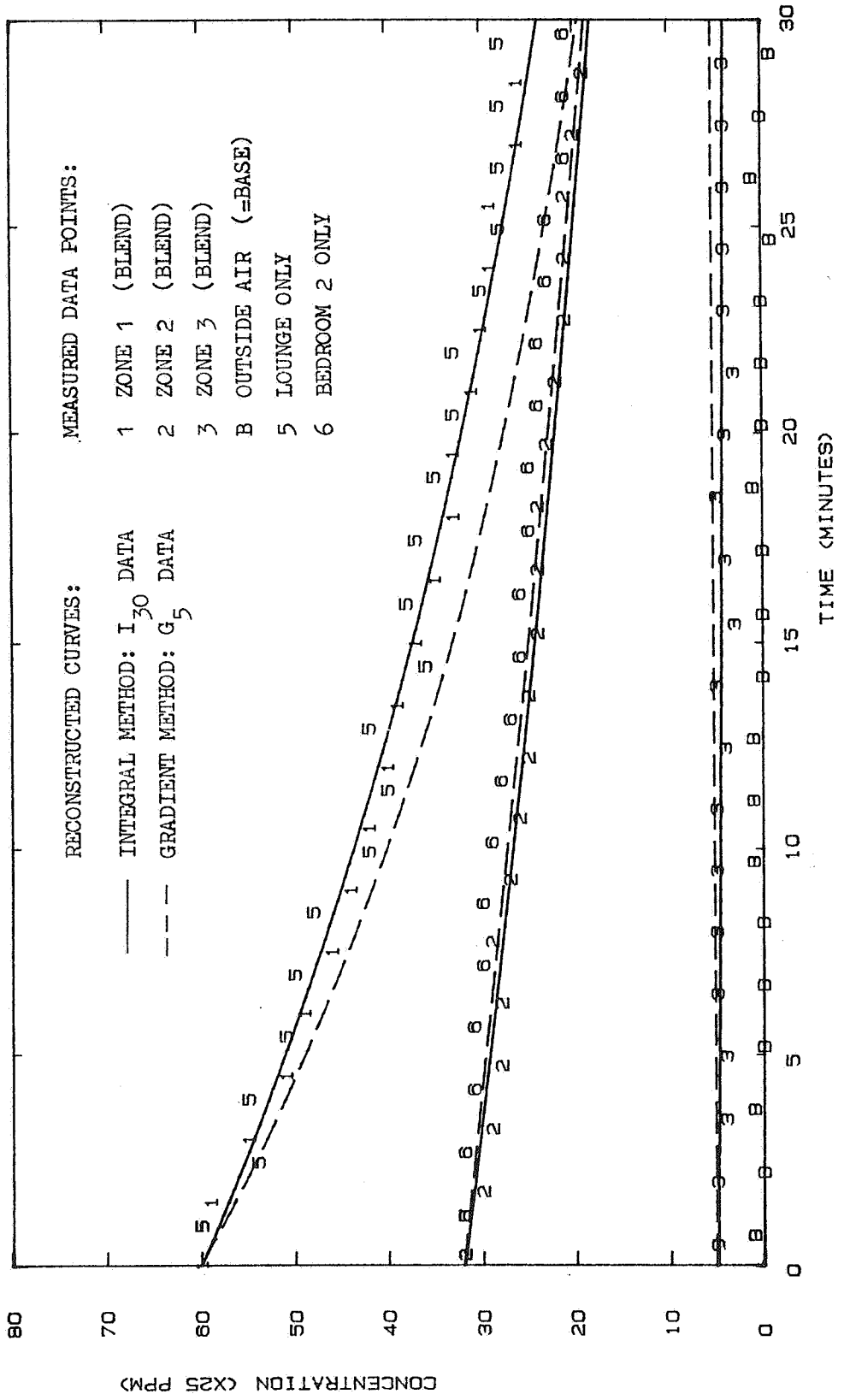

FIGURE 4. Test 1 CO_2 - measured data points and reconstructed curves

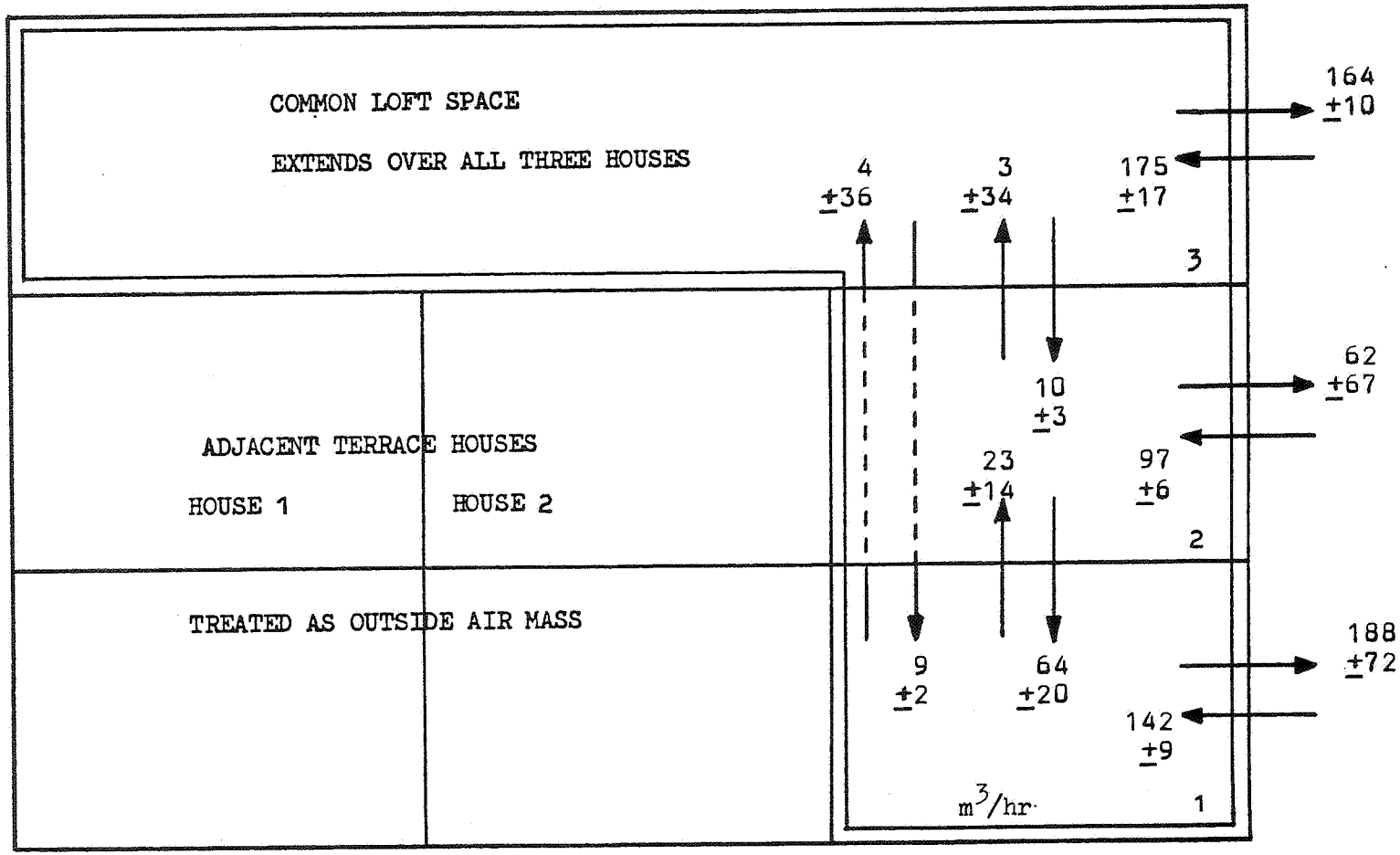

FIGURE 5. Airflows and error estimates Test 1: Integral method (I_{30} Data)

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER S.4

INHABITANTS' BEHAVIOUR WITH REGARD TO VENTILATION. A REPORT OF THE WORK OF THE ANNEX VIII

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SYNOPSIS

If the energy losses due to ventilation have obviously become an important problem since the energy crisis, there is still a lot to be done with respect to the behaviours. Previous research has given results about the share of ventilation losses in the energy balance, and the rational reasons to introduce fresh air into the house.
Annex VIII is specialized in the attitudes of the inhabitants, in their habits with regard to ventilation and even in their apparent irrationality. That should lead to know whether the ventilation behaviour of the inhabitants can be modified and to estimate the amount of energy savings which might result therefrom. To reach these final goals, the Annex VIII foresees three levels. The first one will tempt to describe how people behave with regard to ventilation, the second level will try to find the reasons of such a behaviour, and the third level will estimate the amount of energy loss due to this behaviour.

At the present time, some countries have already carried out one or several steps of the Annex, but it is still too early to go deeply into the conclusions. A behaviour as plain as open a window, but so important with regard to energy still stays partly an unknown.

I. INTRODUCTION

The Annex VIII started officially one year ago, the 24th July 1984, but Switzerland had already proposed to create it in 1978. Unfortunately, although Switzerland made a pilot study, it could not act as operating agent. Nevertheless, the subject had interested other countries and in 1982, Holland, Germany and Belgium presented a project for the Annex VIII to the Executive Comittee with Belgium as operating agent. Since the official starting meeting, the United Kingdom and Switzerland have followed the progress of the Annex as observers, and there is hope that they will join as officially participating countries.

This short history of the Annex shows that the problem of the inhabitants' behaviour with regard to ventilation is not a new one, but has aroused an increasing interest since the energy crisis. Although some researches have already been done on this topic, none has gone as far as to assess whether and how the ventilation behaviour can be modified in order to save energy. The final aim of Annex VIII is to try to answer these questions.

II. BACKGROUND

Why does inhabitants ' behaviour with regard to ventilation become so important for energy policy ?
In order to answer this question, let us briefly examine the energy balance of an occupied residential building as in figure 01.
The energy balance of a residential building gets, on the one hand, as energy inputs, obviously the heat plant and the solar radiation, but also extra inputs from the electric and cooking appliances, the hot water generation and even from the occupants themselves.
On the other hand, the energy losses consist of the transmission losses, the discharge water losses and the infiltration, ventilation and airing losses.

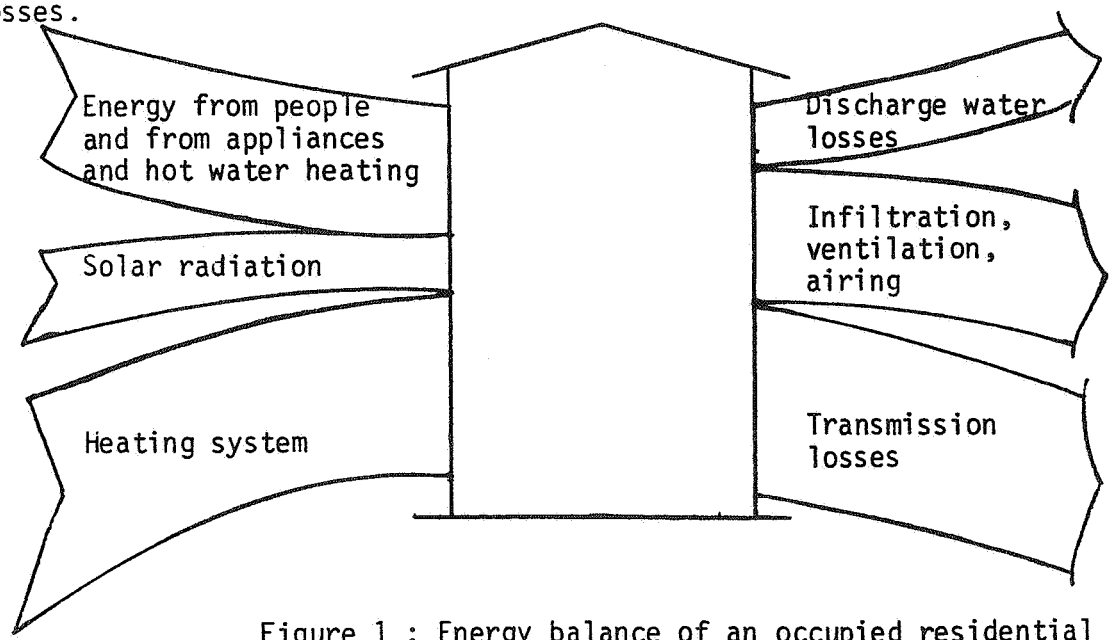

Figure 1 : Energy balance of an occupied residential building.

Homeowners have done a lot since the energy crisis to restrict the transmission losses, by attic insulation for instance, or by side-wall and crawl space insulation. However, they do not appear to get a fair appraisal of the heating and cooling energy load which can be attributed to air infiltration and to ventilation. Yet, it takes a part in the energy consumption that may not be neglected.
For example, one study showed about 35 percent energy loss in a well insulated house under both heating and cooling modes due to air infiltration (1). Another study explained that the recent improvements in fabric insulation make this ventilation factor proportionately more important and can represent 50 % of the total loss (2). Moreover, the major unknown in all the energy consumption patterns is the energy loss due to the ventilation behaviour of the occupants. Indeed, this cannot readily be calculated directly and has to be estimated.

This short review of the energy losses shows that the consumption of the heating energy in residential buildings is not only a question of the heat-insulation of the exterior walls and the efficiency of the heating system, but is also decisively influenced by the ventilation habits of the residents. This leads us to the conclusion that the variety and the causes of inhabitants ' behaviour with regard to ventilation have to be looked into carefully.

There are a lot of good reasons to introduce fresh air into a room. As the figure 2 shows it, one of them is the moisture control (3). The values of 70 % and 40 % relative humidity are the upper and lower limits of relative humidity usually recommended With values higher than 70 %, the risk grows of creating a mould problem inside the house. Values below 40 % are likely to introduce electrostatic shocks when walking on the carpet. These limits depend on the temperature of the room.

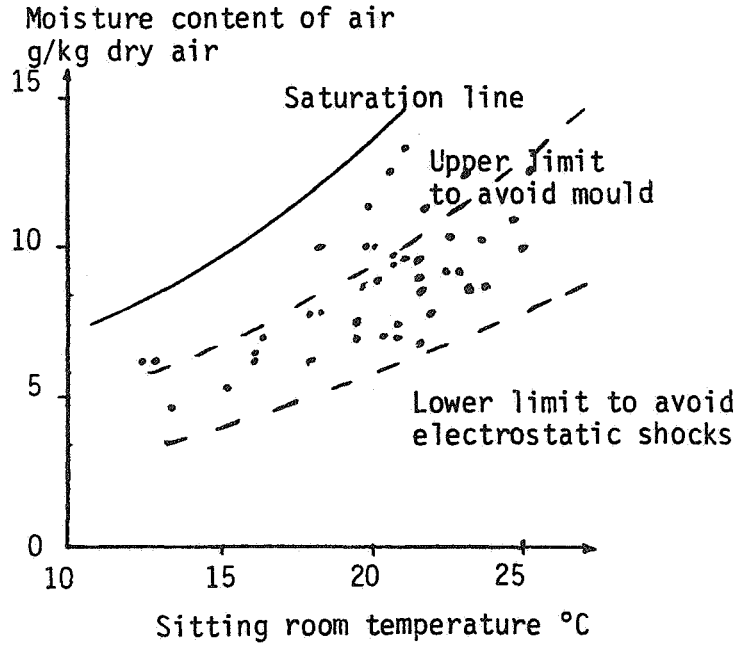

Figure 2 : Moisture level in sitting room according to spot measurements (N = 42). Source : (3)

Another aim of ventilation as illustrated in figure 3 is to provide the necessary oxygen for survival and to dilute the level of contamination to one that is acceptable and safe (3). The contamination can simply be odours coming from the occupants themselves or from the cigarette smokers.

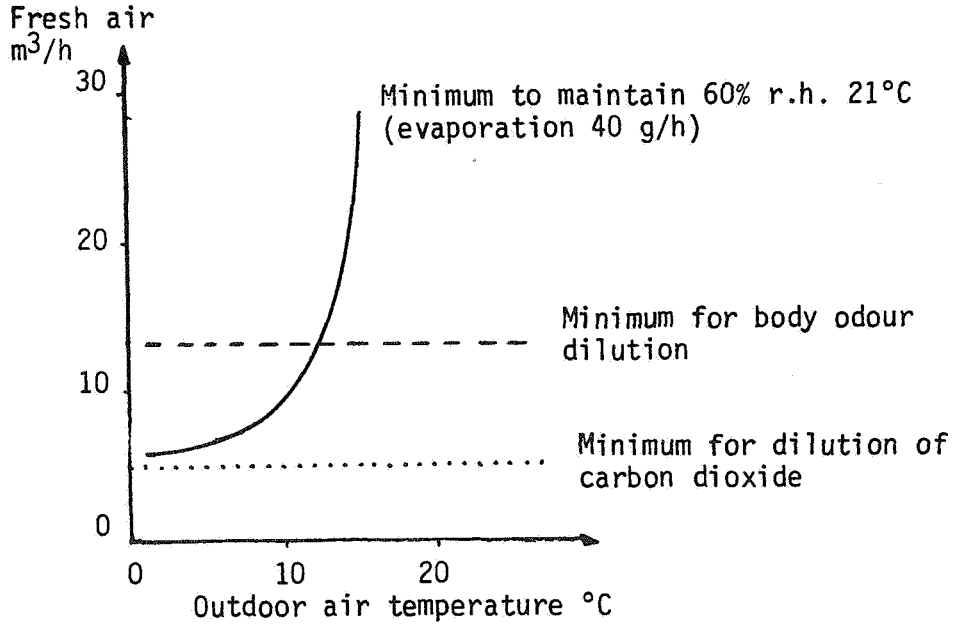

Figure 3 : Ventilation needs for an adult in Britain.
Source : (4).

Last, it may not be forgotten that one of the main objectives of introducing fresh air is the cooling of the house. Indeed, in some well insulated houses with some twenty square meters of south facing windows, the solar gains can easily lead to overheating. Even in winter, ventilation is the easiest way to refresh an overheated room.

So, it is obvious that some ventilation is necessary. In theory it is possible to calculate the needed ventilation rate for each house under any weather conditions. But in practice, the occupants often choose a "wrong behaviour", that is to ventilate less than necessary, or as showed in figure 4, to do it more than useful. The shaded area indicates excess energy consumption due to excess ventilation compared to theoritical consumption with closed windows.

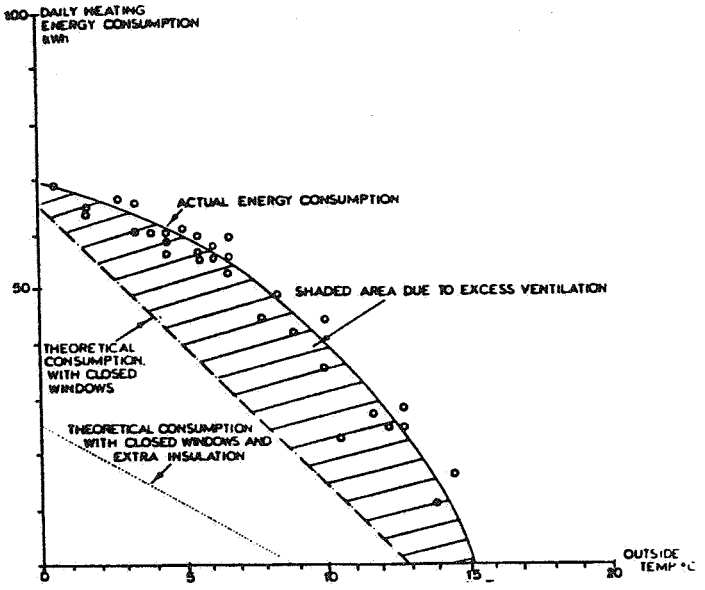

Figure 4 : Actual daily energy consumption for a 4.5 kW terraced house according to ventilation and outside temperature.
Source : (4).

Hypotheses have been expressed concerning the differencies between the expected behaviour and the real behaviour. The "wrong behaviour" that leads to under ventilation should be explained by the motivations of the inhabitants with regard to the energy savings or by a lack of full and accurate informations (5). The overventilation should be due to the attitudes of the occupants with regard to hygiene, health and comfort.
It should also result from the habits of using the windows and from the irrationality of the people who, for instance, forget to shut the casements when they leave their house. These factors are those which are the less well-known whilst they are the only ones that could be modified in the short run by an energy policy, taking the form of a social marketing strategy (6-9).

III. OBJECTIVES

The trick of such a research is, precisely, to distinguish the desirable behaviour from the "wrong behaviour". Previous research has shown, that ventilation patterns change with the climate (sunshine duration, humidity, wind ...), with the different physical features of the house, with the size of the households, and with the house occupancy. But these findings do not give informations about the frequency of the "wrong behaviour", its determinants and the way to change it. These are, in fact, the main questions for the Annex VIII, schematized by figure 5.

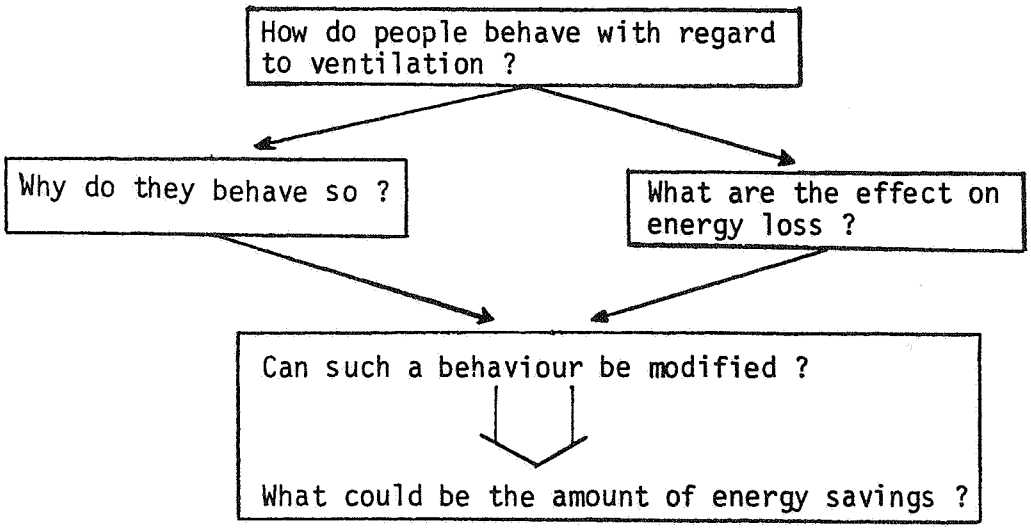

Figure 5 : Objectives of the Annex VIII.

The first objective of the Annex is to determine the actual behaviour of the inhabitants and to correlate it to the outdoor and indoor climate. Indeed, almost every author agrees to assert that the number of open windows is a direct function of outdoor temperature and of the wind speed. For instance, in a study of DICK and THOMAS, it was found that the external temperature alone accounted for over 70 percent of the observed variance in the number of vents and casements open, and a further 10 percent of variance could be attributed to wind speed (10).

The second aim is to estimate the amount of energy loss due to this behaviour. Available analysis suggests that a third of the losses are attributed to ventilation, the remainder through the building fabric (11). This ventilation loss seems equally divided between infiltration and window opening. It is in the range of Annex VIII to calculate

these proportions for different kinds of houses and for different insulation levels.

The third objective is to study the inhabitants ' relevant behaviour motivation. It is now accepted that there are three types of ventilation needs : a physiological one, a dilution of contaminants need and a summer cooling. It is important to know to what extent each type has a great influence on the behaviour, and what has to be devoted to culture, habit or irrationality.

Finally, the last objective is to study whether such a behaviour can be modified, and to estimate the amount of energy savings which might result therefrom.

IV. METHODOLOGY

To reach these objectives, Annex VIII foresees three levels of studies. The first one is an enquiry on at least 500 dwellings to describe the actual behaviour of the householders with regard to ventilation, and to give a first look at their motivations. The sample size and design must ensure statistically valid results. The aim of the second step is to study more precisely the way and the reasons of such behaviours on a sample of 40 dwellers; and finally, each participant will execute elaborate measurements on ventilation patterns in at least 4 dwellings to assess the energy lost due to the ventilation behaviour. The results provided by these steps will allow to define some kinds of actions that can modify the behaviour in order to respect two points of view : the energy consumption and the comfort of the inhabitants. The figure 6 illustrates the methodology followed by the Annex VIII, and the way to execute it.

Questions	Answer by at least	How ?
How do people behave ?	500 dwellings	Questionnaires
Why do people behave ?	40 dwellings	Questionnaires Observations Measurements
What are the possible effects on energy ?	4 dwellings	Elaborate measurements

Figure 6 : The methodology followed by Annex VIII.

To achieve the first level, each country will interview householders with the help of a questionnaire. Its main topics will be the composition of the family, the periods of occupation, the heating system, and, of course, the ventilation pattern. Questions will be aimed at the physical possibilities of ventilation, the frequency, the duration and the reasons for opening and closing the frames. The attitudes of the occupants with regard to energy, comfort, health and hygiene will also be considered. The method of interviews is necessary to provide a lot of informations but there is a problem of reliability. Indeed,people are tempted to explain what they have done only related to the two or three weeks before the interview, and they tend also to adapt their answers to how they think they ought to behave. One solution to control the reliability of the results concerning the ventilation pattern is to observe the fronts of the houses; but this is only possible for a small sample.

This control can be done at the level of the 40 dwellings. There are different methods to observe the casements. The best one is the use of the switches and microswitches fixed on the frames. In theory, there is no feedback on the behaviour and it is a very accurate method. But it is very expensive and it is not always accepted by the inhabitants. Another way is to use observers who will photograph the windows open at different moments during the day. This method has the advantages to be cheap as well as easy to carry out and to have no influence on the behaviour. But it has as drawbacks that the duration of the openings is not known, that all kinds of houses cannot be observed because some windows are invisible and that no observations during the night are possible. At the same time that these observations are made to determine how people behave, a very detailed questionnaire will be administrated to the 40 occupants to know how they say they behave and the reasons they give. From the comparison between the actual observed behaviour and the admitted behaviour, the reliability of selfadministrated questionnaires and the attitudes of the inhabitants with regard to ventilation can be inferred. In addition, measurements will be undertaken to analyze the technical features of the houses. This measurements will be inside and outside temperature measures, humidity level, air leakage or pressurization tests; moreover the climate data that could partly explain the ventilation pattern will be collected.

In the last step, elaborate technical measurements will be undertaken in four dwellings to assess the effect of ventilation behaviour on the energy consumption. The needed data to compute it are supplied by air leakage tests of the building envelope and of the distribution over the envelope, by analysis of the pressure distribution and by indoor and outdoor air temperature. The previous step (40 dwellers) will provide with a ventilation behaviour pattern so that we will be able to introduce this pattern and the measurements data in a model that will compute their effect on energy consumption.

V. STATE OF PROGRESS

Some of the participating countries and of the observers have already carried out one or several steps of the Annex. The results will be compiled and published under a same reporting format.

From the preliminary reports, some results seem interresting to present. The Dutch team found that the frequency and the length of time the windows and the ventilation grilles are used in occupied dwellings are influenced by the following factors. Especially in bedrooms, the airing is correlated with the wind speed, the wind direction, the snow, the rainfall, the sunshine, and the outside temperature. The ventilation behaviour is also higher, in the whole house, when the basic ventilation is lower, when the room is very well insulated, when there is condensation on the glasses, and when the inside temperature is not easy to regulate. The habits of the inhabitants are very important in the way they air their house. Indeed, the dwellers who smoke a lot open more their casements, and the opening of the window in the living room varies with the clothing habits, with the presence of little children, and is often due to the cooking smells. The dwellers who think ventilation is important and who prefer freshness usually use more the ventilation grilles, too.

At this stage, it is still too early to draw general conclusions, but it seems that the results obtained by the research made in each countries will corroborate to some extend the hypotheses coming from the literature. But it is not yet possible to answer to the final questions : "Can the ventilation behaviour be modified ? And what is the amount of energy savings which might result therefrom ?" A first summary report of the surveys which are already finished will be presented by the end of the year. The final publication will synthetize all the investigations and will be available by the end of 1986.

VI. CONCLUSIONS

If the energy losses due to ventilation have obviously become an important problem since the energy crisis, there is still a lot to be done with respect to the behaviours. Previous research has given results about the share of ventilation losses in the energy balance, and the rational reasons to introduce fresh air into the house; in other words, moisture control, oxygen for survival and cooling of the house. Annex VIII is specialized in the attitudes of the inhabitants, in their habits with regard to ventilation and even in their apparent irrationality. That should lead to know whether the ventilation behaviour of the inhabitants can be modified and to estimate the amount of energy savings which might result therefrom. To reach these final goals, the Annex VIII foresees three levels. The first one will tempt to describe how people behave with regard to ventilation on a sample of 500 dwellings at least, the second level will try to find the reasons of such a behaviour on 40 dwellings at least, and the third level will estimate the amount of energy loss due to this behaviour on 4 dwellings.

At the present time, some countries have already carried out one or several steps of the Annex, but it is still too early to go deeply into the conclusions. A behaviour as plain as open a window, but so important with regard to energy still stays partly an unknown.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER S.5

A Multi-Tracer System For Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically-Ventilated Buildings

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SYNOPSIS

Measurement of air exchange rates, ages of air, and nominal and local ventilation efficiencies in large buildings is often complicated by the building size and compartmentalization, and by the presence of multiple ventilation systems. To allow characterization of the ventilation process in such buildings, a unique experimental system, that employs multiple tracer gases, is being developed at Lawrence Berkeley Laboratory. The tracer gases are sulfur hexafluoride and five halocarbons. The system is designed to be non-obtrusive, highly automated, and relatively easy to install in buildings. Included in the system is a programmable tracer-gas injector that automatically initiates and terminates the process of tracer injection. One injector will be used for each tracer gas. Another component of the system is a programmable sampler that collects up to 15 small samples of air; these samples can be stored and analyzed at a later time in the laboratory. One sampler will be placed at each sampling location. Because each tracer gas injector and sampler is a stand-alone device, long runs of tubing are not required to inject tracer or take samples. The concentrations of tracer gas in the samples are determined using a gas chromatograph with an electron capture detector.

This paper first provides background information on the ventilation of large buildings and a discussion of age of air and ventilation efficiency. Various tracer gas techniques are briefly reviewed and equations to analyze the tracer gas data from the step-up and decay techniques are presented. The experimental system is described in detail and the results of two tests of system performance are presented. In these tests, four of the six tracer gases yielded the same result (i.e., air exchange rate, age of air, or ventilation efficiency) within approximately 15 percent. In an experiment conducted in a well-mixed test space, these four tracer gases also yielded an air exchange rate, or age of air, that differed by no more than 12 percent from a reference measurement made with an orifice plate flow meter. Further work is required to increase the accuracy of our measurements with the other two tracer gases.

1. INTRODUCTION

1.1 Ventilation Systems

Large buildings almost always contain a mechanical ventilation system and some also have provisions for natural ventilation (e.g., openable windows). Uncontrolled infiltration (air leakage) can also be significant in these buildings. Several independent or semi-independent mechanical ventilation systems may be present in a single building. A number of ventilation system designs are in common use; only features that are common in many of these designs and that are especially relevant to this paper are described here.

The airflow configuration of a typical large-building ventilation system is shown in Figure 1. The air supplied to the building is generally a mixture of outside air and a larger amount of recirculated air. When heating or cooling loads are high because of high or low outdoor temperatures, the entry rate of outside air may be adjusted to a minimum value in order to save energy. Conversely, when outdoor air is at a temperature that makes it useful for cooling, the supply air may be entirely outdoor air. The position of the three major dampers in the system, which determines the flow rates of outside air and exhaust air, is regulated automatically in response to thermal loads and outdoor temperature. Some ventilation systems also contain variable air volume (VAV) control units, which regulate the flow of supply air out of a group of supply diffusers in response to thermal loads in the region served by the diffusers.

It is important to recognize that actual ventilation systems are much more complex than indicated by the simple diagram in Figure 1. Actual systems generally contain a complex system of ductwork and dampers, large numbers of supply diffusers and exhaust registers, heating and cooling coils, filters, and a complex control system that regulates supply air temperature and humidity and air flow rates.

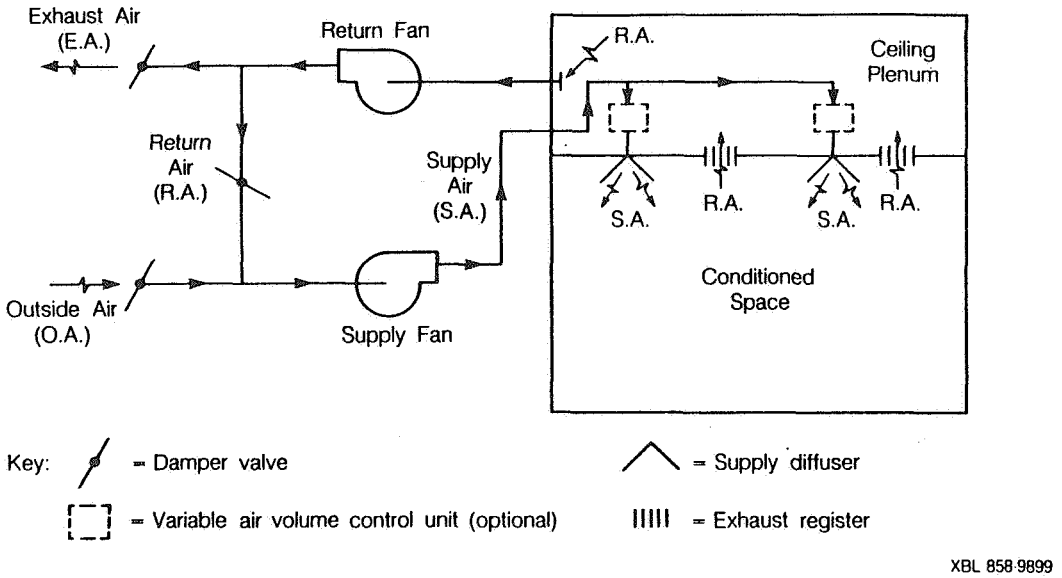


Figure 1. Simplified schematic diagram of air flow pathways in typical large-building ventilation systems.

1.2 Air Exchange Rate, Age of Air, and Ventilation Efficiencies

The objectives of the ventilation process in a large building are to remove or supply heat and moisture and to remove indoor-generated pollutants from the building. These objectives are accomplished by conditioning (e.g., heating or cooling) of the recirculated air and by exchange of indoor air with outside air. Numerous factors affect the performance and efficiency of the ventilation process. In this paper we are concerned primarily with the following factors: 1) the nominal air exchange rate; 2) the overall pattern of air flow between supply diffusers and exhaust registers; and 3) the spatial pattern (e.g., evenness) of outside air distribution throughout the building.

The nominal air exchange rate is simply the rate at which outside air enters the building divided by the indoor volume. A nominal time constant or turnover time can be computed by taking the inverse of the nominal air exchange rate.

The second parameter, the overall airflow pattern, is more difficult to describe. The pattern of airflow can, in theory, vary from one extreme, in which much of the air exiting the supply diffusers rapidly short-circuits to the exhaust registers, to the other extreme where the flow between supply and exhaust approaches a piston-type or displacement flow. Between these extremes is perfect mixing of the indoor air. The benefit of displacement flow and disadvantage of short-circuiting is perhaps best understood if one considers a hypothetical room throughout which pollutants or heat are generated uniformly. In the case of displacement flow, the air exiting the room will contain pollutants (or heat if the room is being cooled) at a concentration that is higher than the average within the room. Conversely, with a less-efficient short-circuiting flow pattern, the exiting air will have a lower pollutant concentration or temperature than the average within the room.

The performance index that characterizes the overall airflow pattern is the nominal ventilation efficiency. The most unambiguous, but unfamiliar, interpretation of this parameter is provided by Sandberg and Sjoberg in their paper that applies age distribution theory to ventilated buildings.[1] In this theory, the age of an infinitesimal parcel of air is the elapsed time since that parcel entered the building and the nominal ventilation efficiency equals the turnover time (described above) divided by the mean age of all air parcels within the building. Because the turnover time equals the age of air within the building for the reference case of perfect mixing, the nominal ventilation efficiency also equals this reference case age of air divided by the actual mean (spatial average) age of air within the building. The theoretical maximum value of nominal ventilation efficiency is two for a perfect displacement flow, the theoretical minimum is zero for complete short-circuiting, and this nominal efficiency equals

unity with perfect mixing.

Sandberg et al.[2] and others[3-5] have shown in laboratory and field experiments that the nominal ventilation efficiency can vary widely, from substantially below unity to substantially above unity, and that efficiency depends on such factors as the relative positioning of supply diffusers and exhaust registers, the type of supply diffuser, the relationship between supply and exhaust temperature, the nominal air exchange rate and the geometric configuration (e.g., number of rooms) of the ventilated space. However, the applicability of available data on ventilation efficiency for the majority of large buildings is uncertain. Previous studies of ventilation efficiency were conducted with ventilation systems that did not recirculate indoor air, which contrasts with the typical system in a large building. In addition, the majority of available data are based on laboratory experiments with supply air that was warmer than the indoor air (i.e., when the building was being heated). In many large buildings, the supply air is often cooler than the indoor air (i.e., supply air is used for cooling). Virtually no measurements of nominal ventilation efficiencies have been made large, mechanically-ventilated buildings.

The third factor of interest is the spatial pattern of outside air distribution throughout the building. The pattern of outside air distribution is influenced by several characteristics of the ventilation system including the balancing of air flow through various sections of supply ductwork and supply diffusers, the degree of mixing between the outside air and recirculated air, and the modulation of air flow by the VAV control units. In buildings with multiple ventilation systems, the various systems may also supply different amounts of outside air to the zones they serve. The degree of short-circuiting in various regions of the building, as noted above, is one final parameter that will influence the distribution of outside air.

The appropriate performance index for outside air distribution patterns is the local ventilation efficiency. Again, age distribution theory provides the most unambiguous interpretation of the performance index[1]. The local ventilation efficiency is the turnover time, which equals the age of all air within the building if the air is perfectly mixed, divided by the age of air at a specific point within the building. By comparing local ventilation efficiencies measured at different locations, the evenness of ventilation can be assessed[4].

Each of the parameters described above, nominal air exchange rate and mean and local ages of air and ventilation efficiencies, can be measured using tracer gases. Various tracer gas techniques are reviewed in the next section and expressions for computing the age of air and ventilation efficiency are given. Finally, in the remainder of the paper,

a multi-tracer experimental system being developed at Lawrence Berkeley Laboratory (LBL) is described in detail.

2. TRACER GAS TECHNIQUES

A variety of tracer gas techniques can be employed to assess ventilation system performance in a large building. In this paper, these techniques are divided into two categories: transient techniques and the constant injection rate technique.

2.1 Transient Tracer Gas Techniques

Tracer decay: The most common transient technique is the tracer gas decay[6-8]. With outside air dampers closed, a volume of tracer gas is released, usually at a number of locations, within the building. After mixing between the tracer and the indoor air has occurred for a period of time, outside air dampers are opened and fresh tracer-free air is brought into the building. The dilution of indoor air with outside air causes indoor tracer concentrations to decrease or decay. Tracer concentrations are monitored as a function of time at various locations within the building and in the exhaust ductwork. Two methods of data analysis can be employed. In the first, the natural log of tracer gas concentration is plotted versus time, and the slope of the straight line that is the best fit to the data is computed and used as a measure of ventilation rate. If the slope is computed from the latter linear portion of the decay curve, it is an appropriate indicator of the overall ventilation rate (i.e., nominal air exchange rate multiplied by nominal ventilation efficiency). However, it has been shown clearly that the slopes of decay curves are poor indicators of local ventilation rates[9] if there is a substantial amount of air exchange between the different points or zones of measurement. In fact, under such circumstances the slopes measured at different locations will, in theory, eventually become equal[2,9].

The second method of analyzing tracer gas decay data is to apply age distribution theory[1]. The mean age of air ($\bar{A}$) within the room or zone and the local age of air (A_p) at point p can can be computed using the equations:

$$\bar{A} = (Q/V) \int_0^\infty \tau \, C_e(\tau) / C_e(o) \, d\tau, \text{ and} \qquad (1)$$

$$A_p = \int_0^\infty C_p(\tau) / C_p(o) \, d\tau \qquad (2)$$

where $C(\tau)$ is a tracer gas concentration at time τ, subscript e refers to the exhaust duct, V is the indoor volume, and Q is the entry rate of outdoor air. The nominal air exchange rate

(Q/V) and its inverse the turnover time (V/Q) are computed with the equation

$$Q/V = C(o) \; / \int_o^\infty C_e(\tau)\, d\tau \qquad (3)$$

which is easily derived from mass balance considerations. The turnover time (V/Q) also equals the age of air in the exhaust duct (A_e); therefore, it can also be computed directly from Equation 2. The nominal and local ventilation efficiencies, ϵ_n and ϵ_p, are then calculated using the expressions

$$\epsilon_n = (V/Q) \; / \; \bar{A}, \text{ and} \qquad (4)$$

$$\epsilon_p = (V/Q) \; / \; A_p \quad . \qquad (5)$$

A major constraint associated with usage of equations 1-3 above is that the tracer must be uniformly mixed throughout the building at the start of the decay. The tracer decay technique has been employed in 38 commercial buildings by our colleagues at LBL[8] and in the majority of these buildings, especially those with multiple ventilation systems, satisfactory mixing could not be achieved. Therefore, the requirement of initial mixing limits the usefulness of the decay technique in large buildings.

Tracer step-up: A second transient technique, referred to as the step-up method, involves continuous injection of tracer into the stream of outside air that enters the building. The injection is continued until steady state concentrations are achieved. Tracer concentrations are measured as a function of time in the building and at points within the HVAC system. The step-up technique is analogous to a tracer gas decay. In the decay technique the indoor air is uniformly labeled with tracer gas and in the step-up technique the incoming outside air is uniformly labeled with tracer gas. The mean and local ages of air from a step-up are computed with the expressions[1]:

$$\bar{A} = (Q/V) \int_o^\infty \tau \; (1 - C_e(\tau) \; / \; C_e(\infty))\, d\tau, \text{ and} \qquad (6)$$

$$A_p = \int_o^\infty (1 - C_p(\tau) \; / \; C(\infty))\, d\tau \qquad (7)$$

and the entry rate of outside air (Q) is computed with

$$Q = \dot{m} \; / \; C_e(\infty) \qquad (8)$$

where $\dot{m}$ is the injection rate of tracer gas into the incoming outside air. The indoor volume (V) is determined from physical measurements and ventilation efficiencies are computed from Equations 4 and 5. Alternately, the turnover time (V/Q), which equals A_e, can be computed directly from Equation 7 and then the ventilation efficiencies from Equations 4 and 5. A disadvantage of the step-up technique is that only the air entering the building through the HVAC system can be labeled with tracer gas, i.e., infiltrating air can not be labeled. However, the infiltration rate can be determined by comparing the steady state concentration of tracer in the incoming outside air to the steady state concentration in the exhaust. An important advantage of the step-up method is that initial mixing of tracer throughout the building is not required, however, the tracer must mix well with the outside airstream and good mixing may be difficult to achieve in some ventilation systems. In a building with multiple ventilation systems, and air flow between the zones served by separate systems, it is necessary to have the same concentration of tracer in each stream of outside air, which is impractical, or to use a unique tracer in each system.

Tracer pulse: A third transient technique, which is only mentioned here, is to suddenly release a fixed volume or pulse of tracer in the incoming outside air. Expressions for the entry rate of outside air and mean and local ages of air and ventilation efficiencies are provided by Sandberg and Sjoberg[1].

2.2 Constant Injection Rate Technique

An alternative to transient techniques, which require tracer concentrations to be measured as a function of time, is to employ a constant injection rate technique[10] which relies on measurements of time-averaged tracer concentration. Typically, tracer is injected continuously at a controlled and known rate for an extended period of time (e.g., several days) into the supply airstream(s) or at a number of locations within the building and some technique is used to measure the time-averaged tracer concentration at several points within the building. If the building has multiple ventilation systems a unique tracer should be used with each system. The data are generally analyzed using a single-zone or multi-zone steady-state mass balance model to compute the entry rate of outside air and, if multiple tracers are employed, to compute rates of air flow between zones. An assumption implicit in the steady-state models is that the air within each zone is perfectly mixed. In addition, the measurement period should be much greater than the amount of time required to achieve steady state tracer concentrations, which is roughly three to four turnover times. The constant injection rate technique is best suited for buildings that have a nearly constant or slowly-changing ventilation rate. An assessment should be made of the errors that result from using this technique over an extended period of time in buildings with large deviations from steady state, such as nightly shutdowns of the HVAC

system.

The primary advantages of the constant injection rate technique are that only a simple experimental system need be deployed in the building, such as the convenient passive tracer gas sources and samplers developed at Brookhaven National Laboratory[11], and that the average ventilation rate for an extended period of time can be measured in a single experiment. The nominal ventilation efficiency and local age of air or ventilation efficiency cannot be measured using the constant injection rate technique because the data analysis is based on the assumption of perfect mixing within each zone and ventilation efficiencies result from imperfect mixing.

3. MULTI-TRACER EXPERIMENTAL SYSTEM

The remainder of this paper describes a multi-tracer experimental system under development at LBL and summarizes the results of experiments conducted to verify system performance. The design objectives were as follows: 1) a flexible system that can be utilized for a variety of tracer gas techniques without major modifications; 2) a system that can measure ventilation efficiencies and local ages of air within a zone; 3) a system that can be deployed rapidly in a building; 4) a system suitable for use during periods of building occupancy; and 5) a system suitable for use in buildings with multiple ventilation systems. We plan to use this multi-tracer system to study ventilation system performance in a substantial number of large mechanically-ventilated buildings and to assess the impacts of changes to ventilation systems. Some of these future studies will be conducted as part of more comprehensive investigations of ventilation and indoor air quality in large buildings.

The experimental system consists of six tracer gases and instrumentation for measuring tracer gas concentrations, stand-alone tracer gas injection systems, and stand-alone samplers. In buildings with six or fewer ventilation systems, the step up or constant injection rate techniques can be employed by injecting a different tracer gas into each ventilation system. The injection of each tracer gas will be controlled by a distinct stand-alone injection system placed in the building near the point of injection. The stand-alone samplers will also be placed at various locations within the building near to points where the time-history of tracer gas concentration is required. These samplers collect and store small air samples taken at different times during an experiment (e.g., every 15 minutes during a step up experiment). The concentration of each tracer gas in the samples can then be determined in the laboratory after completion of the experiment.

3.1 Tracer Gases and Tracer Gas Measurement System

Selection of tracer gases: Selection of tracer gases was a

major early consideration. Suitable tracers must be non-toxic, chemically unreactive in buildings, naturally present in buildings only at concentrations that are low compared to those encountered during experiments, readily available at an acceptable cost considering the amount of tracer required, and not prone to substantial physical adsorption on indoor surfaces. Another consideration is whether the tracer is a gas or liquid at normal indoor temperature and pressure; liquids are more conveniently stored, but gases are more easily injected into the building at a controlled rate and may be less prone to physical adsorption. The measurement process also imposes important constraints on tracer selection. Measurement of tracer concentration over approximately two orders of magnitude, is highly desirable. The time required to separate and analyze a mixture of tracers must be reasonable (e.g., less than about ten minutes). Finally the cost of the measurement system is a major consideration.

The two groups of tracers that were considered are: 1) a set of four perfluorocarbon tracers (PFTs) used routinely at Brookhaven National Laboratory[10,11], and 2) sulfur hexafluoride plus selected halocarbons. The PFTs can be utilized at very low concentrations[11] (parts per trillion) due to their extremely low background concentrations. Generally to collect sufficient PFT for analysis, the PFT from a volume of air is adsorbed and thus concentrated onto a solid sorbent[11]. The PFTs are then thermally desorbed from the sorbent just prior to analysis in the laboratory. An expensive analytical system (approximately $30,000) is required to desorb the PFTs from the solid sorbent and determine the amount of each PFT desorbed. If PFTs were used in the parts per billion concentration range, a less expensive analytical system might be suitable, however, this alternative is impractical because of the high cost of PFTs, 100 to 500 $/kg[12] (45 to 225 $/lb). The fact that PFTs are liquids at room temperature makes storage convenient, however, an automated system for evaporation and injection of PFTs at a controlled rate posed a difficult design challenge considering the extremely small quantities of liquid required.

Because of the considerations regarding the use of PFTs noted above, and the expectation that a system of more than four tracers could be developed, we selected sulfur hexafluoride (SF_6) and several halocarbons as a preferred group of tracers for our application. Each of the tracers selected is a gas at typical indoor temperature and pressure. SF_6 has been used routinely as a tracer in large buildings[6-8] and three halocarbons have also been previously used as tracers in buildings[13]. After preliminary experimentation with a large number of halocarbons, a group of five (R-13B1, R-115, R-12, R-12B1, and R-114) plus SF_6 were selected. The chemical formula, approximate cost, and other relevant data on these tracers are given in Table 1. We intend to conduct our experiments so that the peak concentration of R-13B1, R-115, R-12, and R-114 is 1000 parts per billion (ppb) and the peak

concentration of SF_6 and R-12B1 is 100 ppb. In buildings with substantial leakage of refrigerants from refrigeration equipment, one may encounter substantial background concentrations of R-12 and R-115. We have taken air samples from several buildings, and in one building, specifically chosen because its mechanical system had a large refrigerant leak, the concentration of R-12 was approximately 225 ppb, which is sufficiently high to prohibit our use of R-12 as a tracer in this building.

Table 1. Selected Properties of Gaseous Tracers

Refrigerant Number*	Chemical Name	Chemical Formula	Molecular weight	Boiling Point (°C)	TLV (PPM)+	U.L. Safety Group**	Approx. Cost ($/Kg)++
---	Sulfur Hexafluoride	SF_6	146.1	-64	1000	-	12
13B1	Bromotrifluoromethane	$CBrF_3$	148.9	-58	1000	6	21
115	Chloropentafluoroethane	$CClF_2CF_3$	154.5	-39	1000	-	19
12	Dichlorodifluoromethane	CCl_2F_2	120.9	-30	1000	6	5
12B1	Bromochlorodifluoromethane	$CBrClF_2$	165.4	-4	--	-	12
114	1,2-dichlorotetrafluoroethane	$CClF_2CClF_2$	170.9	+4	1000	6	11

* Refrigerant number designation of the American National Standards Institute.

\+ Threshold Limit Value published by the American Conference of Governmental Industrial Hygienists.

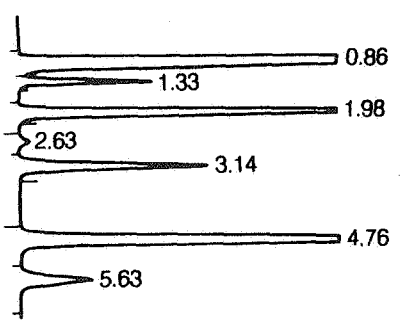
** Underwriters Laboratories safety Group 6 is for "gases or vapors which in concentrations up to at least about 20 percent by volume for durations of exposure of about 2 hours do not appear to produce injury".

++ Costs vary widely depending on purity and quantity purchased.

Tracer gas analysis: A microprocessor-controlled instrumentation system is used to determine the amount of each tracer present in small air samples. This system consists of a Hewlett Packard (HP) 5890A Gas Chromotagraph (GC) with an electron capture detector and a ten-port sampling valve with a 0.25 cc sample loop, a HP 3392A Integrator, and a HP 19405A Sample Event Control Module which controls operation of the sampling valve. This instrumentation system costs approximately $14,000. The carrier gas is a mixture of 7% methane and 93% argon. A standard backflushing procedure, with a 0.15 m (0.5 ft) pre-column and 2.4 m (8 ft) main column, is employed to prevent extraneous high-retention-time gases within the sample from entering the main column. Backflushing is initiated 0.75 min after injecting the contents of the sample loop into the pre-column. Both columns

contain Chromosil 310, 60/80 mesh packing in a stainless steel tube with an outer diameter of 0.32 cm (0.125 in). The flow rate of carrier gas is maintained at 20 cc/min. The initial oven temperature of 35°C is maintained for 2.75 min after which the oven temperature is increased at a rate of 30°C/min to a maximum of 60°C. The entire cycle is completed in approximately eight minutes.

Figure 2 shows a typical chromatogram, a tabulation of retention times and areas under each peak based on the printout of the HP 3392A Integrator, and additional information for characterizing each peak. The sensitivity of the electron capture detector to each tracer can be computed from the information given. The printed output of the integrator is also recorded on magnetic tape and subsequently read into a mainframe computer system. Calibration is accomplished by injecting and analyzing six to eight mixtures of calibration gas with known concentrations of each tracer. Because the calibration curves are not entirely linear, a third degree polynomial is fit to the calibration data using a curve fitting routine available on the mainframe computer system.



Retention Time (min)	Area	Component	Conc. (ppb)
0.86	1.9700E+07	Air	—
1.33	529140	SF_6	5
1.98	3098700	R-13B1	50
2.63	74651	R-115	50
3.14	1426800	R-12	50
4.76	7478000	R-12B1	50
5.63	657790	R-114	50

XBL 858-9897

Figure 2. Example chromatogram and table of information that characterizes each peak.

Tracer gas safety considerations: It was stated above that a suitable tracer must be non-toxic. However, any tracer can be hazardous to health if sufficiently high concentrations are encountered. A more precisely-stated requirement is the following: the investigators must be sure that normal usage of the tracer gas, and feasible accidents, will not harm any of the building occupants. In the following paragraphs we discuss briefly the safety of our selected tracer gases and tracer gas technique. However, until this issue is reviewed by qualified experts, no definitive conclusions should be made by the reader regarding the safety of these tracers or our procedures.

Included in Table 1 are two safety-related parameters. The first of these is the Threshold Limit Value-Time Weighted Average (TLV) published by the American Conference Governmental Industrial Hygienists (ACGIH). The TLV is defined by the ACGIH as follows: "time-weighted average concentration for a normal 8-hour work day and a 40-hour work week to which nearly all workers may be repeatedly exposed, day after day, without adverse affect". The maximum TLV established by the ACGIH is 1000 parts per million (ppm) even when no harm is expected from exposures to concentrations much higher than 1000 ppm. For all of the tracers except R-12B1, the TLV is 1000 ppm which is 1000 to 10,000 times greater than the maximum concentrations that will be encountered in our experiments. No TLV has been published for R-12B1. In his review of fluorocarbon toxicity, Clayton[14] indicates that R-12B1 should be less toxic than R-12B2, for which the TLV equals 100 ppm or 1000 times greater than the maximum concentration of R-12B1 expected in our experiments. However, Clayton indicates that R-12B1 should be more toxic than R-13B1 for which the TLV is 1000 ppm. Other information on the toxicity of R-12B1 is provided by Beck et al.[15] who exposed various animals to R-12B1. Most of the experiments involved concentrations in the range of 1 to 30 percent and significant adverse effects were noted, however, no adverse effects were noted when rats were exposed to 3300 ppm of R-12B1 (i.e., 33,000 times our maximum) 6 hr/day, 5 days/week, for three weeks.

The second safety-related parameter in Table 1 is the Underwriters Laboratories (U.L.) safety group. Three of the tracers have been assigned to Group 6 which is for "gases or vapors which in concentrations up to about 20 percent by volume for durations of exposure of about 2 hours do not appear to produce injury". A concentration of 20 percent is 200,000 times greater than the one ppm maximum of our experiments. U.L. has not assigned a safety group number for SF_6, R-115, or R-12B1.

Based on these two safety-related parameters, exposure of building occupants to maximum concentrations of tracer gas of 1000 ppb or 100 ppb, depending on the tracer, does not appear to be of concern. However, an accidental rapid release of a large amount of tracer gas from a pressurized cylinder into a small room could result in tracer concentrations much higher than 1000 ppb. To preclude this possibility, we have designed a tracer injection system (described later) that eliminates the need for pressurized cylinders in the building and that limits the maximum quantity of each tracer within the building to approximately 100 liters.

A third safety-related issue is the thermal decomposition of the halocarbon tracers. It is known that halocarbons can decompose to toxic products (phosgene, halogens, and halogen acids) if heated to high temperatures such as those

encountered in gas flames or at the surface of electric heating elements[16]. Neither open flame gas heaters nor a substantial quantity high-temperature electric heating are generally present in the buildings we plan to study; when present we will avoid usage of the tracer system. Another concern is the possibility of decomposition of the tracers when they pass through burning tobacco. Hanst et al.[17] determined that R-11 and R-22 did not decompose when 2000 ppm of these gases passed through a lighted cigarette within their detection limit of 0.1%. However, we have identified no analogous experimental data for the five selected halocarbons tracers. Based on some preliminary calculations we believe that decomposition of these tracers in burning tobacco is unlikely to be a problem. Further analysis is warranted before these tracers are used routinely.

One should place our safety concerns into proper perspective. We are trying to be extremely careful. It is our impression (as yet unconfirmed) that many industrial workers and others including smokers, are routinely exposed to these halocarbon gases in concentrations and for a duration that greatly exceed those in our experiments without any apparent adverse affects.

3.2 Programmable Stand-Alone Sampler

Real time analysis of tracer gas concentrations during an experiment, by placing the GC in the building and drawing samples to the GC through sample tubing run to various locations within the building, is generally not a practical alternative when multiple tracer gases are employed. For example, the time required to analyze a single sample with our system is eight minutes. If measurements are required at ten locations, and often monitoring at more than ten locations is desirable, data could be obtained from each location only once every 80 minutes, which is too infrequent for any transient tracer gas technique. Even without this constraint, we would have decided against real-time analysis and multi-point sampling using sample tubing because of the large amount of time and labor required to set up the GC in the building and string the sampling tubes out of the way of building occupants.

To meet our sampling requirements we designed the programmable stand-alone sampler depicted in Figure 3. The sampler utilizes a 34-port, 16-position valve (Valco Instruments Multiposition Valve with ST type flowpath) mounted on a Valco electric actuator. The valve has an inlet port, an outlet port and a pair of ports at each of the 16 positions. A six position version of the valve is shown schematically in Figure 4. In each valve position, a different sample collection loop can be purged and filled with a sample. In our experiments a 2.1 m (7 ft) length of copper tubing, with outer and inner diameters of 0.32 cm (0.125 in) and 0.165 cm (0.065 in.), respectively, is used as the sample collection

loop; a shorter piece of tubing with a larger inner diameter may be used in the future. Since one pair of valve ports must always be open to the inlet and outlet of the valve, a sixteen position valve can store only fifteen samples. A small pump is used to draw air through the valve.

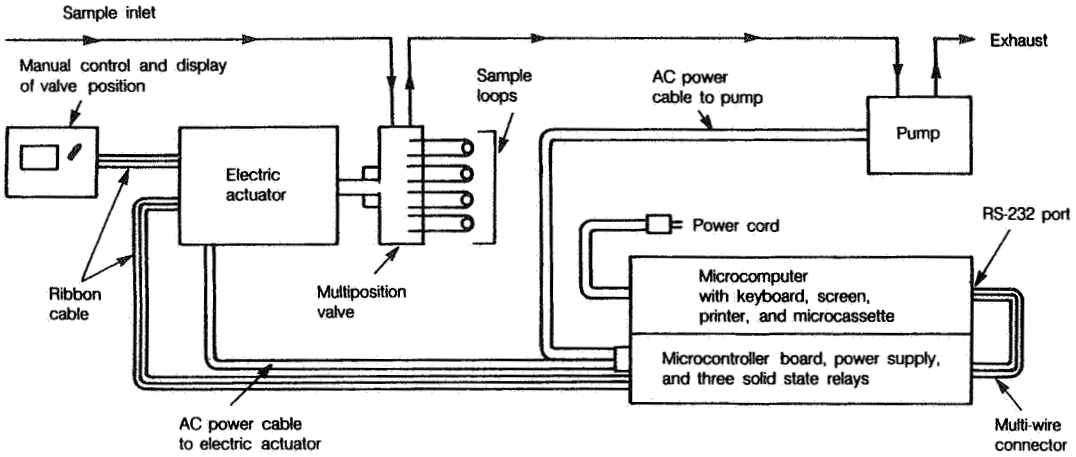


Figure 3. Schematic diagram of automated stand-alone sampler. The actual sampler contains 15 sample collection loops.

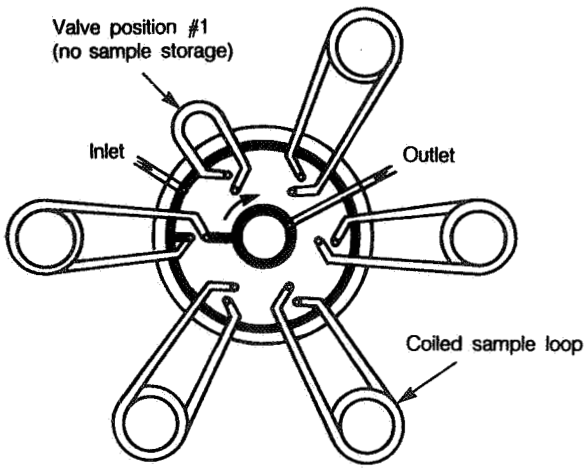


Figure 4. Schematic diagram of flow path in six position valve. A-16 position valve is used in sampler.

The multiposition valve is positioned by the electric actuator. During normal operation a sampler control system (described later) uses binary coded decimal (BCD) logic to position the electric actuator, and thus the valve, in the desired position. The valve can also be stepped to the next position or moved to position #1 manually, using a toggle switch.

The sampler control system consists of an Epson HX20 microcomputer, communicating via its serial RS 232 port with a small microcontroller board (Basicon MC-1N). The microcontroller board, along with a power supply and three miniature solid-state relays are installed in a small metal housing attached to the underside of the HX20. The microcontroller board has three eight bit binary ports which sends control signals to the electric actuator, senses actuator position and controls the solid state relays. One of the relays controls the pump, one turns the electric actuator on and off, and the remaining relay is a spare. A BASIC program burned into read-only memory of the microcontroller allows communication with the Epson HX20. The Epson microcomputer is also programmable in BASIC, keeps track of date and time with a real time clock, and contains a built-in keyboard, liquid-crystal display screen, printer, and micro-cassette tape system.

To minimize programming or operator errors when numerous samplers are deployed, a single micro-cassette tape can be used to load programs or control data files into each sampler. An appropriate operating procedure is the following. Prior to the experiment a control data file is loaded into the Epson and also printed on the Epson's printer. The valve is automatically rotated to position #1, which does not contain a sample loop, and all solid state relays are switched to the off position. A few minutes before the first sample is required, the electric actuator is turned on, the valve is rotated to position #2 and the pump and actuator are turned on. During the following few minutes the sample loop and the short length of tubing leading from the sampler to the desired sampling location is purged of the previous sample. At the desired sample collection time, the valve is rotated to position #3 and the pump is turned off. This basic procedure is repeated until all samples are taken. A record of all valve operations and changes in state of the relays can be printed on the Epson's printer or recorded on magnetic tape. The system is highly flexible; the sample loops can be filled in any desired sequence and at any desired time in the future. By repositioning the pump, the sampler can also automatically inject samplers into the GC for analysis.

The multiposition valve with sample collection loops connected is easily removed from and reinstalled on the electric actuator. Thus, by purchasing more than one multiposition valve for each sampler, the sampler can be reused before or during analysis of the previous samples. However,

the $375 price of the multiposition valve makes the purchase of more than a few valves for each sampler prohibitively expensive. The total cost of all major components of a sampler with a single multiposition valve, excluding a case to house the components (which has not yet been selected), is approximately $2000.

Mixtures of calibration gases containing all six tracer gases have been stored in the sample loops connected to a multiposition valve for as long as three weeks. Within the precision of our measurement system (approximately five percent) the concentration of each tracer within these sample loops has remained constant except in a few instances that we attribute to procedural errors. Longer-term tests of tracer storage are planned.

3.3 Tracer Gas Injection System

To complete our experimental system a subsystem for injection of tracer gases is required. We have designed a simple stand-alone automated injection system that is well suited for the step-up tracer gas technique. A separate injection system will be utilized for each tracer gas. The major components are depicted in Figure 5. As shown, a peristaltic pump (Cole Parmer Masterflex) draws tracer gas from a 100 liter gas storage bag (Calibrated Instruments) and pumps this tracer through a length of injection tubing. The rotational speed of the peristaltic pump is regulated within ±1% of the digital set point (according to manufacturers specifications) with a variable speed drive (Cole Parmer Ismatec No. T-7610-30). Because several different size peristaltic pumps can be mounted on the variable speed drive, and two pumps can be mounted simultaneously, the rate of tracer gas injection can be varied over a wide range (approximately 1 to 1200 cc/min). Starting and stopping of the drive is under control of a programmable timer. The optional integrating flowmeter placed downstream of the pump (Singer Model DTM-115-3), with a manufacturers rated accuracy of ±2% and a resolution of 10 cc, can be read before and after each experiment to determine the total amount of tracer injected during the experiment. The system should be calibrated by measuring flow rate versus the digital set point on the variable speed drive with a highly accurate flow meter (for example, the Mast Development Co. Model 832 electronic bubble flowmeter). The cost of all major system components, excluding a housing, is approximately $1900.

The 100 liter volume of tracer in the gas storage bag should be sufficient for the majority of experiments and two or more bags can be connected together if desired. The bag holds sufficient tracer to maintain 100 ppb of tracer in the supply air of a large ventilation system (47 m^3/s or 100,000 cfm) for a period of six hours with 100% outside air. In more typical situations, with smaller ventilation systems and/or less than 100% outside air, a 100 liter bag will hold enough

tracer for more than a single experiment. The seven-layer bag is fairly rugged but should be protected by some type of enclosure. The bag with enclosure will occupy a comparable volume to a large pressurized cylinder of tracer gas, but is lighter and thus easier to carry. The bag is also less hazardous than a pressurized cylinder of tracer gas.

This tracer injection system, without an integrating flow meter or a programmable timer, has been used to inject tracer gas in five experiments. During each experiment, the tracer injection rate was measured periodically with an electronic bubble flow meter. Except for two unexplained high readings of flow rate during one experiment, the measurements indicate that this system injects tracer at a highly stable rate (i.e., 2% maximum variation in injection rate).

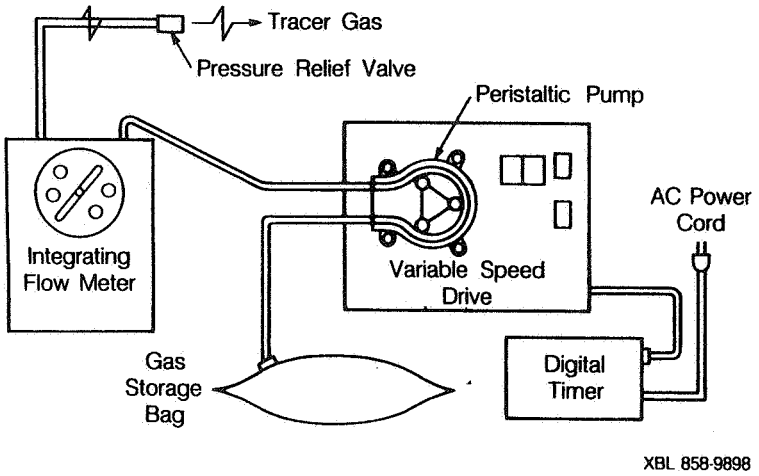


Figure 5. Schematic diagram of tracer gas injection system.

4. VALIDATION OF PERFORMANCE

A tracer gas intercomparison is an important test of any multi-tracer system. When a mixture of the tracer gases is utilized in the same experiment, the data from each tracer gas should yield the same nominal air exchange rate, ages of air, and ventilation efficiencies. Discrepancies could result from such factors as substantial adsorption of one or more of the tracers on indoor surfaces, inaccuracies in sampling, loss of tracer during storage of samples, and inaccurate analysis of tracer concentrations. Highly consistent results from a tracer gas intercomparison do not, however, ensure that the results are accurate because the same error(s) could occur with each tracer. Therefore, the performance of a tracer gas system should also be tested in a building with good mixing

and a known air exchange rate. Each type of test has been performed with our multi-tracer system and the results are described in the remainder of this section.

To conduct the tests we utilized the following procedure in two different buildings. The 100 liter gas storage bag was filled with a mixture of the tracers. (Note that in normal operation each storage bag would be filled with a single tracer.) A step-up experiment was then performed using a single injection system to inject the mixture of tracers into the building at a controlled rate. The injection rate was monitored using a bubble flow meter. After steady-state tracer concentrations were achieved, tracer injection was stopped and a tracer decay ensued. The stand-alone sampler was not used in these experiments; instead the GC was located within the building and samples of air were drawn to the GC from a single location through a small-diameter copper tube. A data point was taken every ten minutes. The GC was calibrated prior to each experiment, and prior to the first experiment we determined that there were negligible tracer losses in the copper sample tubing. Data from the HP Integrator was recorded on magnetic tape and processed on a mainframe computer after completion of the experiments.

The experimental procedure was first employed in a two-room test space of a research house (experiment #1) with a total internal volume of 69.1 m^3 (2400 ft^3). The two rooms were connected by an open door. Indoor surfaces consisted of plasterboard and plywood on walls and ceilings, a carpeted floor in one room and a vinyl tile floor in the other. A variety of furnishings were also placed within the rooms. To ensure good mixing, the air within the test space was vigorously mixed with five oscillating fans, eight wall-mounted fans, and a large ceiling fan. Tracer gas was injected at the back side of two oscillating fans and air samples were withdrawn from a location in the open doorway. Air was exhausted mechanically through a duct that penetrated the ceiling of one room and the flow rate of this exhaust airstream was monitored with an orifice plate flowmeter[18]. By combining the flow rate measurement with a physical measurement of test-space volume the actual air exchange rate of the test space can be determined with an estimated uncertainty of ±5%.

The second experiment was performed at Building 50E at Lawrence Berkeley Laboratory, which is a single-story structure with a floor area of 931 m^2 (10,000 ft^2) and an estimated volume of 2620 m^3 (92,600 ft^3). The building is furnished in a typical manner for office buildings. Much of the building is subdivided into office cubicles with fabric-covered dividers. In addition, a number of more formal offices, with walls that extend to the ceiling and closable doors, are present around the perimeter of the building. A single constant-volume HVAC system serves the building with both supply diffusers and exhaust registers located at ceiling

level. An open entry way connects Building 50E to the remainder of the Building 50 complex which is served by other HVAC systems. The mixture of tracer gases was injected into the outside air duct and samples were drawn into the GC from the exhaust air duct. The outside air, return-air, and exhaust-air dampers were disconnected from their actuators during the experiment so that no automatic modulation of damper positions was possible.

Table 2 gives the local age of air measured in Experiment #1 at the Research House. Because the concentration of R-12B1 exceeded the maximum calibration gas concentration of 100 ppb, a local age from the R-12B1 data can only be computed using the latter portion of the R-12B1 decay curve. Ideally, the data from each tracer gas should yield the same local age of air; the step-up and decay procedure should yield the same local age; and, assuming we were successful in obtaining good mixing during this experiment, all the ages of air calculated from tracer gas data should equal the reference measurement of age of air (i.e., the inverse of the nominal air exchange rate) made with the orifice plate flow meter. If one excludes the results obtained with R-12B1, the different tracer gases yield the same local age of air within ten percent. If the R-12B1 result is included, the maximum deviation between tracer

Table 2. Local Age of Air from Experiment #1 Performed in Well-Mixed Test Space of a Research House.

Tracer Gas	Tracer Gas Step-up A_p^* (min)	Tracer Gas Decay A_p (min)
SF_6	55	64+
R-13B1	53	63+
R-115	52	58+
R-12	52	60+
R-12B1	--	69**
R-114	52	64+

* A_p is the age of air at the measurement point calculated from equation 2 or 7 as appropriate.

\+ Data analysis performed assuming time zero (see Equation 2) corresponds to time of first data point after tracer injection ceased.

** Data analysis performed assuming time zero (see Equation 2) corresponds to time of first data point after R-12B1 concentration fell below maximum of calibration range.

Note: Meaurement of air flow rate and volume of test space yield an age of air of 59 minutes with an estimated uncertainty of ±5%.

gases is 14 percent. Compared to the decay data, the step-up data yields 11 to 21 percent lower ages of air, perhaps because of physical adsorption of tracer gases on indoor surfaces or systematic errors in our determination of tracer gas concentrations. An encouraging result is that the reference measurement of age of air, made with the orifice plate flow meter, falls between the step-up results and the decay results. The maximum deviation from the reference measurement is 17 percent (12 percent if the R-12B1 data are excluded).

Table 3 presents the local and mean (spatial-average) ages of air and the corresponding ventilation efficiencies based on the tracer gas data of Experiment #2 performed in Building 50E. The correspondence of the results from four of the tracer gases (R-13B1, R-115, R-12, and R-114) is quite good, however, the SF_6 and R-12B1 data yield substantially different results. We believe that the discrepancies with these two tracer gases may be due, in large part, to inaccuracy in our analysis of tracer gas concentrations. The calibration curves for these two tracers were not as smooth as the calibration curves for the other four tracers. Improved calibration gas mixtures and

Table 3. Ages of Air and Ventilation Efficiencies from Experiment #2 Performed in Building 50E.

Tracer Gas	Tracer Gas Step-up				Tracer Gas Decay			
	A_p* (min)	ϵ_p+ (-)	$\bar{A}$** (min)	ϵ_n++ (-)	A_p* (min)	ϵ_p+ (-)	$\bar{A}$** (min)	ϵ_n++ (-)
SF_6	31	1.44	21	2.05	39	1.00	45	0.87
R-13B1	36	1.03	33	1.13	39	1.00	42	0.92
R-115	35	1.01	31	1.14	37	1.00	38	0.98
R-12	39	0.98	38	0.99	40	1.00	50	0.80
R-12B1	47	0.85	50	0.81	47	1.00	82	0.58
R-114	37	0.97	36	1.00	39	1.00	41	0.95

* A_p is the age of air at the measurement point, which was the exhaust duct, calculated from Equations 2 or 7 as appropriate.

\+ ϵ_p is the local ventilation efficiency at the measurement point, calculated from Equation 5.

** $\bar{A}$ is the mean (i.e., room-average) age of air calculated from Equation 1 or 6 as appropriate.

++ ϵ_n is the nominal ventilation efficiency calculated from Equation 4.

increasing the maximum concentration of these two tracers by a factor of two or three may reduce these discrepancies in the future. The mean ages of air and nominal (i.e., spatial-average) ventilation efficiencies vary more widely between tracer gases than their local counterparts because the mean parameters are more highly affected by the shape of the step-up or decay curves and are, therefore, more difficult to measure accurately. The local ages of air and local ventilation efficiencies from the step up correspond very well with those from the decay for all tracer gases except SF_6. However, the step up yields 13 to 27 percent lower mean ages of air and 5 to 22 percent higher nominal ventilation efficiencies than the decay, excluding the SF_6 and R-12B1 data. One cannot draw firm conclusions from correspondence between results of the step up and the decay because the overall airflow pattern and even the nominal air exchange rate may have actually changed during the experiment. The step up was performed during the day when the building was occupied and the decay was performed during the evening and night-time hours. In addition, we have no data to confirm that the tracers were fully mixed with the air at the start of the decay. A final interesting observation based on Table 3, is that the four closely corresponding tracer gases indicate that the nominal ventilation efficiency during the experiment was within 15 percent of unity.

The fourth table lists the flow rates of outside air and nominal air exchange rates determined from the tracer gas data of Experiment #2, and our estimate of the indoor volume. If one excludes the SF_6 and R-12B1 data, the correspondence between different tracer gases and between step-up and decay is good (i.e., the maximum difference between any two numbers is 14 percent). Even the SF_6 and R-12B1 results are in reasonable agreement with the results of the other tracer gases.

Table 4. Flow Rate of Outside Air (Q) and Nominal Air Exchange Rates (Q/V) from Experiment #2 Performed in Building 50E.

	Tracer Gas Step-up		Tracer Gas Decay	
Tracer Gas	Q^* (m^3/h)	Q/V^+ (h^{-1})	Q^{**} (m^3/h)	Q/V^{++} (h^{-1})
SF_6	3580	1.36	4030	1.54
R-13B1	4250	1.61	4050	1.54
R-115	4510	1.72	4240	1.62
R-12	4160	1.58	3920	1.49
R-12B1	3930	1.50	3320	1.27
R-114	4380	1.67	4050	1.54

* From Equation 5.

\+ From Equation 5 and estimate of indoor volume of 2624 m^3.

** From Equation 3 and estimate of indoor volume of 2624 m^3.

++ From Equation 3.

5. SUMMARY

A unique multi-tracer experimental system that utilizes up to six tracer gases, sulfur hexafluoride and five halocarbons, is being developed. This system is intended primarily for measurements of air exchange rate, ages of air, and ventilation efficiencies in large mechanically-ventilated buildings. Tracer gas concentrations are determined using a gas chromatograph with an electron capture detector. So that tracer-gas concentrations can be monitored at numerous locations and with sufficient frequency for transient tracer gas techniques, a programmable stand-alone sampler has been designed that collects up to 15 small air samples. The samples can be stored and analyzed in the laboratory after the experiment has been completed. A simple programmable stand-alone tracer gas injection system that injects tracer gas at a highly stable rate has also been designed and tested. One injection system will be used for each tracer gas and one sampler will be employed near each sampling location.

Two tests of the system, excluding the sampler, have been completed. Each test included both a tracer gas step-up and a tracer decay. Four of the six tracer gases yielded the same result (e.g., age of air) within approximately 15 percent. These four tracers also yielded an air exchange rate, or age of air, that differed by no more than 12 percent from a reference measurement made in a well-mixed test space with an orifice plate flow meter. Further work is required to increase the accuracy of our measurements with the remaining two tracers and to verify system performance in general.

6. ACKNOWLEDGEMENTS

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DISCUSSION

Paper 1: 'Ventilation, the balance between energy and well-being', presented by W.H. Knoll (Netherlands)

D. Fitzgerald (U.K.) Please tell us more about what is known of the medical effects of the 'unavoidable sources' of air contamination and about work in this area.

W.H. Knoll (Netherlands) *'Unavoidable sources' are the occupants themselves, producing CO_2, odours and moisture. The most important other sources, such as building materials and household chemicals, are avoidable which means that, by means of regulation, the effects in the room can and should be restricted to a harmless concentration at the minimum ventilation rate. Odours, as produced by human activities, are considered to have no influence on health although, so far as is known, there have been no experiments to support this statement. For CO_2, MAC-values are given; for permanent stay the value is about 0.15%, for an 8-hour stay it is 0.5%. For underground shelters the value is much higher, but still acceptable. At the usual minimum ventilation rate a value of 0.15% is not surpassed (it is reached at about 18 m^3/h per person fresh air supply).*

Paper 2: 'The infiltration component of ventilation in New Zealand houses' presented by Mark Bassett (New Zealand)

M. Sherman (USA) You stated that infiltration losses were not a significant heat loss source, yet the houses you showed were all very leaky. Is this because (a) conduction losses are quite high because of low insulation levels, (b) ΔT is so low that almost no heating is required, or (c) energy prices are so low that cost is not important ? Could you give typical insulation levels, indoor/outdoor temperatures and energy prices for dwellings in New Zealand ?

M. Bassett (New Zealand) *Infiltration heat losses are unlikely to fall outside 10-25% of the conduction heat loss but the total ventilation heat loss will be higher than this. Conduction losses are determined by the level of insulation (about RS12) and ΔT which varies from an average 18°C in the north down to about 4°C in the occupied southern coastal regions. Because the mean outdoor temperatures are quite high, heating is almost always intermittent so that space heat requirements vary from one house to the next. Furthermore, it is difficult to separate contributions to space heat from other energy demand. If there is a need to either save energy or improve standards of heating, then reducing infiltration is unlikely to be the first action taken.*

J. Railio (Finland) 1. Were there any intentional ventilation arrangements (vents, ducts, local fans, etc.) in your test houses, or is ventilation due to infiltration plus window opening only ?

2. What are the ventilation arrangements in New Zealand houses generally (existing and new houses) ?

3. What are the future trends concerning airtightness and ventilation ?

M. Bassett (New Zealand)

The infiltration rates given in the paper do not include ventilation through vents or chimneys. There is a growing trend towards using fan extract ventilators in kitchens and bathrooms which are turned on during periods of high moisture release.

The ventilation rates in houses are considered to be more dependent on the occupier opening windows than on the background infiltration. There are generally no ducted ventilation systems (fan-assisted or passive) installed in New Zealand houses.

Houses have become more airtight as a result of changes in construction materials and not as a result of a desire to reduce space heat loss.

I.R. Bealby (U.K.)

1. What heating systems are used in dwellings ?

2. What are the internal temperatures ?

3. Is there any correlation between internal temperature and the incidence of dampness problems ?

4. Is there are correlation between the ages and numbers of occupants and the incidence of condensation ?

M. Bassett (New Zealand)

Space heating is generally intermittent - heaters on during cold times when the building is occupied and off at other times. As a consequence, interior temperatures are quite variable. The inside/outside temperature difference will, on average, not fall below 6°C and it will be higher in the colder southern regions.

There is no survey data giving inside temperatures and the incidence of moisture problems. Calculations can show, however, that the standard of heating is of prime importance.

Survey results show little relationship between condensation problems and ages/numbers of occupants.

D. Fitzgerald (U.K.)

Please define in further detail 'envelope complexity'.

M. Bassett (New Zealand)

Information in Figure 2 shows complexity expressed as the summation of major joint lengths (top and bottom plate, vertical corner lengths) divided by the shell area - hence units of m^{-1}. In fact, the joint length is more influential than the shell area and this is supported by a linear regression equation (1).

A.I. Gaze (U.K.)

Please clarify:

1. Insulation standards for the house walls.

2. The use, or otherwise, of plywood as structural sheathing.

3. A typical wall construction.

M. Bassett (New Zealand)

1. *Current thermal insulation standards require about 2 m^2K/W over the envelope.*

2. *Plywood is not used as a sheathing underneath exterior cladding.*

3. *Typical cavity wall construction begins with an exterior rain screen, breather paper, stud cavity (including insulation) and finally a fibre board or jib board interior lining. Polythene vapour barriers are not generally part of New Zealand cavity wall construction.*

K.A. Johnson (U.K.)

You showed mould on a timber-framed wall and stated that no vapour barrier had been used. What insulation level was used. If high, why no interstitial condensation and why no surface condensation; if low, why ?

M. Bassett (New Zealand)

Interstitial condensation: Vapour barriers in the form of a polythene layer are not included in cavity wall construction. Dew point profile calculations do indicate condensation at times but, because the procedure does not consider storage of moisture in framing and changing temperatures, predictions are not considered reliable. More detailed work on this subject is in progress at BRANZ. Internal dampness problems are reduced by adding insulation but with limited indoor/outdoor temperatures, high relative humidities at the surface of external walls can and do support mould growth.

M. Liddament (U.K.)

You stated that the leakiness of a dwelling correlated with the length of joints (envelope complexity) rather than the surface area of the building. On the other hand, in your modelling exercises, you based leakage distribution on the surface area, i.e. 20% to walls, remaining 80% to walls, roof and floor. Is an area distribution valid ?

M. Bassett (New Zealand)

There is no doubt that the bulk of air leaks are associated with cracks and the reason why the envelope complexity concept is so successful is that it is a summation of major cracks in house construction. When infiltration rates are calculated, the location of openings must be known in order to calculate the size and polarity of indoor/outdoor pressure differences. That is why the total equivalent leakage area of houses has been assigned to roof, wall and floor locations.

Paper 4: 'A passive ventilation system under trial in U.K. homes' presented by Ken Johnson (U.K.)

I.R. Bealby (U.K.) The Inner London Building Regulations required an air brick in all habitable rooms without flues. However, some public sector occupants have systematically blocked up these apertures. Why should this system produce any better response from this important minority of occupants ? I suspect that the flue will require ½-hour fire resistance within the same dwelling and 2-hour fire resistance if it passes through different dwellings, e.g. flats.

K. Johnson (U.K.) *We would expect people to block up air bricks. They are found in properties which are often of poor thermal performance and thus will exacerbate unacceptable heating costs as well as creating draughts and possibly spreading moisture due to poor overall design.*

In the proposed system, draughts would only come from the trickle ventilators. If these are then closed in windy and/or cold weather, the system continues to work as it works 'in sympathy' with the expected occupant reaction.

As fas as we know, there are no requirements regarding the ducts and fire resistance in 2-storey dwellings. However, we think that it is advisable to take some precaution such as intumescent collars or fusable link closure devices. Ducts through flats, etc. would need some fire resistance.

P. Hartmann (Switzerland)

1. Is the tightness of these houses ($7 h^{-1}$ at 50 Pa) purposely designed to prevent too low ventilation at low wind speed ?

2. Did you test your concept also for new and tighter houses (following other standards, $n_{50} \approx 3.5\ h^{-1}$) ?

K. Johnson (U.K.) *The house would have been under-ventilated at low wind speed without the ventilation system and is very tight by U.K. standards. Houses at ∿ 3.5 ach at 50 Pa are very rare in the U.K.*

The concept did work successfully in the TRADA test house which is less tight than the Laing house, but still tight by U.K. standards, although opening the trickle ventilators increased the natural ventilation rate rather too much.

W.F. de Gids (Netherlands) You showed us an outlet tile on the roof. When you have snow falling, this tile will be covered. For that reason, in the Netherlands outlets must be at least 0.5m above roof level. Roof level outlets can also be exposed to positive pressures causing flow reversal, hence the spread of moisture from kitchen and bathroom throughout the whole house.

K. Johnson (U.K.)

We appreciate that snow accumulation could block the vent and therefore this is a point for further investigation. However, the plastic tile vent will be warmed by the extract air and should therefore melt any snow and reduce this risk. It is intended that the vents should be at the ridge and therefore the risk of flow reversal due to continuous positive pressure should be minimised.

D. Fitzgerald (U.K.)

In your moderately ventilated houses with your new system, did you make any measurements of concentration of phenols, vapours, etc. given off by modern materials around us ?

K. Johnson (U.K.)

No measurement of such contaminants was undertaken. The ventilation rates achieved should be adequate to avoid any harmful build-up.

J. Railio (Finland)

Did you measure, or otherwise make any observation, concerning the air change rates in various rooms, e.g. bedrooms, with windows or vents open/closed ?

K. Johnson (U.K.)

No. The house effectively had one downstairs room and two upstairs rooms and air change rates for individual rooms were calculated from the whole house air infiltration tests. Smoke tests confirmed airflow directions to be towards the rooms with the ducts.

D. Zerba (USA)

Would you consider the location of the exterior junction of the vent stack and the tile roof important when considering the influence of wind retarding the natural flow ? In other words, would not the wind tend to push the air down the duct if it were placed on the windward slope of the roof ? How might this consideration be resolved ?

K. Johnson (U.K.)

The duct termination position is important and it would be normal for it to be at the ridge, i.e. where negative pressure usually occurs on one side or the other. If, as in the tests described, the ducts terminate on the slope, the results show that there was considerable flow oscillation in the ducts under windy conditions and some flow reversal may have occurred. However, overall extraction continued because of the stack effect and lack of consistent wind back-pressure due to gusting or turbulence.

J.T. Reardon (Canada)

1. Would not the exit of ducts below the roof lead to severe condensation problems on inside surfaces of the roof in a cool (or cold) climate such as that in Canada.

2. Does not such a system leave the house open to overly large ventilation rates and hence an overly large heating bill, again in a cooler climate ?

3. I wholeheartedly support the system approach to house design. However, the type of occupant, for house design, should not be included because houses are sold again and types of occupants change.

K. Johnson (U.K.)

1. *Yes, the colder the external climate, the greater the risk. In the tests described, however, we saw no evidence of condensation throughout the winter. We are considering redesign of the outer roof connection.*

2. *Look at the two extremes of houses existing in the UK with condensation problems - new low energy houses built too tightly (by UK standards) and those older properties with poor thermal performance which are very 'leaky'. The former need a higher ventilation rate (and therefore increased energy usage), the latter are totally uneconomic to heat and therefore would benefit greatly from extensive draught stripping (and insulation and other measures of the 'combined approach') and then the passive system can be applied.*

3. *If a house is not designed for a particular type of person, then yes, a compromise 'combined approach' is necessary to try to cater for an 'average' person.*

Paper 5: 'Indoor air quality and air exchange in bedrooms' presented by Gunnar Lundqvist (Denmark)

O. Nielsen (Denmark) Don't any of the inhabitants use open windows during the night ?

G. Lundqvist (Denmark) *The measurements of ventilation rates were undertaken in closed rooms without occupants. Field measurements of carbon dioxide concentrations, temperatures and humidity in occupied bedrooms have been carried out under conditions where occupants could use their normal habits regarding window and door opening during the night. Those results will be reported separately.*

Paper 6: 'Effect of unvented combustion appliances on air exchange among indoor spaces' presented by N. Nagda (USA)

J. Dewsbury (U.K.) Are people often killed by unvented gas space heaters ? In the United Kingdom people are occasionally killed by flued gas appliances when the flue becomes accidentally blocked.

N. Nagda (USA) *No. However, as you have pointed out, any combustion appliance can be dangerous if used improperly.*

R. Gale (U.K.) Could you please tell us more about the method you used to measure the room concentrations of combustion products ? In particular, I am interested to know if you recorded vertical or horizontal profiles and if you think these have any impact on your measurements and theories.

N. Nagda (USA) *Analysers capable of providing real-time pollutant concentration data were used: non-dispersive infrared (NDIR) Beckman 866 for CO and gas-phase chemiluminescence CSI 1600 for NO_2. The measurements were carried out at three*

locations: upstairs (living/dining room and master bedroom) and at one downstairs location. Probe height at these indoor locations was 107 cm (measured from the floor).

We also measured NO_2 concentrations at different heights from the floor and at different locations upstairs. These measurements were conducted using diffusion samplers (Palmes tubes) to provide time-integrated average NO_2 concentrations. The following table shows average concentrations at the different heights for one set of experiments at the test houses:

Height above floor cm	*Average NO_2 concentrations ppb*
213	*35.0 ± 4.7**
160	*30.3 ± 5.6*
107	*28.2 ± 3.7*
61	*24.8 ± 6.9*
15	*24.0 ± 5.8*

* *mean ± standard deviation*

The concentrations tend to increase as distance from the floor increases. These measurements confirm the effect of buoyancy of combustion gases. Our model calculates only a spatial average or, in this case, it is similar to the average of concentrations at different heights at same location.

I.R. Bealby (U.K.)

The build-up of a pollutant from a single source is proportional to

$$EXP(kt)$$

where k = constant of the producing source
t = time

If two sources are used in the same enclosure, the build-up is proportional to

$$EXP[(k_1+k_2)t]$$

$$EXP[(k_1+k_2)t] > EXP(k_1t) + EXP(k_2t)$$

as confirmed by the experimental data. Other factors are not exponential.

N. Nagda (USA)

The comment is not valid. The build-up of a pollutant due to an indoor source can be given by the following mass balance equation:

$$\frac{dC_{in}}{dt} = \frac{S}{V} - \nu(C_{in} - C_{out}) \qquad (1)$$

where $C_{in,t}$ = *indoor concentration at time, t (units: mass/volume)*

$C_{in,0}$ = *indoor concentration at time, 0*

ν = *air exchange rate (1/time)*

C_{out} = *outdoor concentration (mass/volume)*

S = *indoor generation rate (mass/time); source operating from time 0 to t*

V = *indoor volume (volume)*

For a chemically stable pollutant, assuming a constant outdoor concentration, the solution to this differential equation is:

$$C_{in,t} = C_{out} + \frac{S}{\nu V} + \left(C_{in,0} - C_{out} - \frac{S}{\nu V}\right) e^{-\nu t} \qquad (2)$$

Thus, the source term is not an exponential term by itself but the exponential term consists of the air infiltration rate. Consequently, when all other conditions are the same, the effect of two sources on concentration is essentially additive. (If the outdoor concentration and initial indoor concentrations are zero, then the effect of two sources will be exactly additive).

Paper 7: 'Air exchange rates based upon individual room and single cell measurements' presented by David Harrje (USA)

Note: Figure 5 from this paper is reproduced here because in the original figure, AI should have been expressed in terms of wind speed, V, in miles-per-hour. The lower scale was also re-labelled to agree with the metric scale.

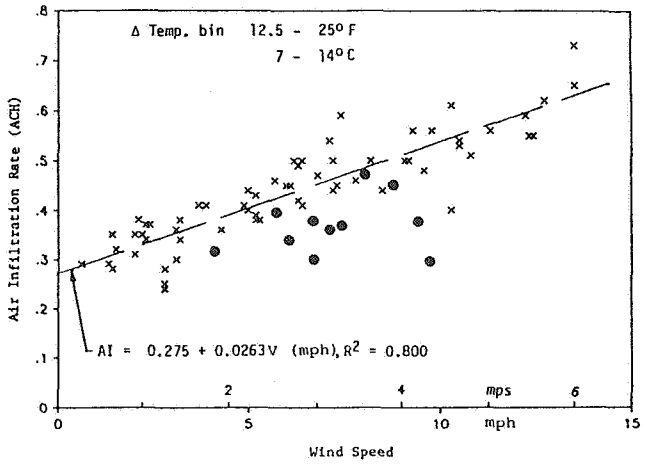

Figure 5. Binned temperature data showing the relationship of wind speed and air infiltration rate for wind direction. • Wind from "protected" direction; x All other wind directions.

W.F. de Gids (Netherlands) You have indicated the individual quantities of outside air reaching each room but have you investigated the actual locations of the air entry and individual room air tightness ?

D. Harrje (USA) *As part of the total investigation, infrared scanning of the building envelope revealed the locations of where air was entering the living space and where it was leaving. This information was used in the envelope retrofit part of the study where one house was tightened 40% (10 ach down to 6 ach at 50 Pa). Isolation of zones or components with plastic sheeting was not part of the program so there was always an opportunity for interzone exchange.*

R. Gale (U.K.) The constant concentration approach indicates the amount of outside air entering each zone, but what about those zones that are over-ventilated and therefore have a reserve of ventilating capacity ?

D. Harrje (USA) *The point you bring out is an important one. In the house example shown, one over-ventilated zone is in the basement because of the fact that this is the air entry point due to the stack effect. The additional capacity remaining in the basement air for supplying the needs to dilute the first floor pollutants depends on the detailed path of basement air flow through the living space and the circulation times in the first floor space. Multiple tracers are necessary to sort out these important details.*

Paper 9: 'Continuous air renewal measurements in different inhabited buildings' presented by A. Faist (Switzerland)

J. Railio (Finland)

1. Is there any information available concerning the airtightness or pressure conditions in the Apples home ?

2. You also mentioned (p. 9.10) the kitchen fan. How often/long was it operated and were any measurements of air flow rates made when the fan was on ? Any observation of backdraught (= air flow in via exhaust ducts from toilets) ?

A. Faist (Switzerland)

1. *Not yet. Pressurization tests are planned for the next months.*

2. *Kitchen fan switched on for about 1/4 hour once a day, when cooking hot meals. No measurements of air flow rate were made. The nominal air flow rate of the fan is 40 m^3/h. No backdraught was visible but, under certain wind conditions, it happens that a wood stove, located in the kitchen, does not function properly when the fan is on.*

M. Bassett (New Zealand) Can you give some description of the control function used to top up tracer gas concentration ?

A. Faist (Switzerland)

Proportional - Integral - Differential. Algorithms valid for discrete time interval for the data acquisition.

J.T. Reardon (Canada)

1. Can your gas analyser really analyse each sample in only 6-10 seconds ? I am only familiar with IR analysers which require in the order of 2 minutes per sample analysis.

2. Does your system instead contain multiple analysers to make possible the rapid sampling rates that you report ?

A. Faist (Switzerland)

1. *The analysing period per sample is now 50 seconds. This is governed by the time taken for signal 'saturation'. Reasonable interval could be decreased to 30 or 20 seconds with a small loss of accuracy (∿ 5%) on the measured concentration.*

2. *The equipment contains two IR analysers (N_2O and HO_2). HO_2 disturbance is corrected by software. Delay between analyses is decreased by means of pre- and post-pumping of measured point.*

Paper 10: 'The reduction of air infiltration in an industrial laboratory' presented by John Lilly (U.K.)

A.A. Nielsen (Denmark)

The fact that your tracer gas concentrations in 5 different sample points show similar decay rates (± 10%), in spite of the fact that the actual absolute levels of tracer gas concentration differ by a factor of 10 (?), leads one to believe that the decay rate reflects the infiltration rate of the entire building. I find that very hard to understand. Could you give indications of your considerations on that matter ?

J. Lilly (U.K.)

When the mixing path between zones in a building greatly exceeds the distance to the building envelope, the larger concentration gradient at the building envelope and relatively small distance over which it acts serves to dominate the concentration in that area. (In our building were N_2O concentrations of 160 ppm at one end and 30 ppm at the other both decaying at the same rate. At the point where 30 ppm is measured a concentration gradient of 30 to 0 ppm at 10m distance was a much greater influence than a concentration gradient of 160 to 30 ppm, 80m away). The large reservoir of tracer gas which normally takes at least 45 minutes to develop the concentration profile serves to change the local variations as any changes have a relatively much higher time constant than air exchange at the envelope of the building.

There are undoubtedly errors associated with these assumptions which will mean the decay rates measured are lower that the true ventilation rates. At present, no mathematical or practical assessment of these errors are available.

J.T. Reardon (Canada)

A general comment: Due to the unrealiable nature of measurements of low pressures ∿ 0-10 Pa, I believe that the practice of including data points for $Q = 0$ at $\Delta P \neq 0$ simply adds needlessly to the uncertainty of the $Q,\Delta P$ curve fit.

J. Lilly (U.K.)

The deviations from zero of ΔP at $Q = 0$ are due to naturally occurring pressure differences across the building envelope due in turn to wind effects. If this produces any uncertainty in any curve fitting exercise, it is unfortunate but I do not believe we should exclude these observations simply because it does not fit our equations. I do not believe accurate curve fitting is of vital importance when trying to link pressurization leakage with ventilation rates. I have seen no validated link between the two and, even if there were, the errors in ventilation rates used for validation are still likely to exceed the errors of primitive curve-fitting exercises.

R.R. Walker (U.K.)

1. I note that your graphs of decay rates do indeed show a significant distribution of concentration. Have you considered how well (or otherwise) the decay rates approximate to the ventilation rate ? I would suggest the observation that they are the same everywhere is not sufficient.

2. If you are able to measure at several locations, do you not therefore consider that a 'mean age' or 'residence time' type experiment, as advocated by Mats Sandberg (National Swedish Institute for Building Research), may be appropriate ?

J. Lilly (U.K.)

1. *The estimation of how well the uniform decay rates at greatly differing concentrations in the building approximate to the mean ventilation rate can only be estimated, as no suitable error analysis or mathematical model is yet available. The local ventilation rates are most certainly not the same everywhere, I agree, but can be estimated from the areas under the decay curves if a uniform concentration existed at the start of the day and in each sample zone considered. Table 1 shows the lack of correlation between local decay rate and relative area under the decay curves for a decay test from an initial uniform concentration.*

2. *The relative area under the decay curves mentioned above is proportional to the 'mean age' or 'residence time' of tracer gas in the building and may be used for determining mean ventilation rates if sufficient sample points are present. Again, the errors involved in doing this at present cannot be assessed accurately. The practical difficulties of obtaining a uniform initial concentration in the building type considered are also large, so an accurate reflection of tracer 'residence times' at many points is very hard to achieve.*

Paper 11: 'Ventilation of factories' presented by Phil Jones (U.K.)

D. Harrje (USA): What are the target values for ventilation/air infiltration levels in lightly-populated factory buildings ?

P. Jones (U.K.): *For small factories (about 200 sq.m. floor area) the target values for air infiltration rate used for heating system design lie between 0.75 - 1.0 ach for a well-sealed factory. Corresponding ventilation requirements for occupants are about 0.5 ach for a highly populated factory (say 20 people per 200 sq.m. floor area). For a lightly populated factory (say less than 5 people per 200 sq.m. floor area) ventilation requirements should be much less. However, in predominantly naturally ventilated factories it is probably not advisable to attempt to reduce infiltration rates to lower values without a better understanding of internal air flow paths.*

Paper 12: 'Advanced energy-efficient ventilation' presented by Jorma Railio (Finland)

D. Fitzgerald (U.K.): An excellent survey. Regarding item 7 on page 12.6, reference to this mean radiant temperature in relation to comfort is omitted. CIBSE considers that

$$\frac{TMR + TA1}{2}$$

is a 'comfort' temperature, and for the fabric heat loss calculation we use the 'environmental' temperature

$$\frac{2TMR + TA1}{3}$$

based on the fact that the heat transfer coefficient for radiation is about twice that for convective heat transfer when temperature differences are small.

J. Railio (Finland): *Your comment is really useful in our further development of indoor air characterisation. Mean radiant temperature is a key parameter concerning comfort.*

Paper 13: 'Design for ventilation' presented by Mike Holmes (U.K.)

O. Nielsen (Denmark): How did you manage the draught problem in the office building in winter, when you have an air exchange rate of of 3 ?

M. Holmes (U.K.): *The design air change rates presented in the paper were for the relief of high temperatures in summer. They were to be achieved by opening windows. In winter it was assumed that the windows would be mostly, if not all, closed. In addition, the heating control system (TRVs and weather compensation) will result in an inability to achieve design*

conditions if there are 3 air changes. Any draught through the window would be heated by passing over a radiator. This is the most frequently found system in the UK and is reasonably efficient when the daytime mean winter temperature is about 10°C.

Paper 14: 'Air quality and energy conservation by different ventilation strategies' presented by Lutz Trepte (Federal Republic of Germany)

B. Saxhof (Denmark): You mentioned that it was often necessary to increase the ventilation rate due to large internal gains (up to approximately 1.5 - 1.7 ach) and that it caused a decrease in energy savings so that heat recovery systems should be used. Why ? Actually, you have no heat demand if the internal gains are very large and you certainly would not want to recover heat when it was 'necessary' to increase the ventilation rate to get rid of excess heat.

L. Trepte (Germany): *The main strategy, for energy reasons, should be to minimise ventilation rates. If, in special circumstances, higher ventilation rates are needed or desired by the inhabitants, heat recovery will contribute to energy conservation. Then the heat losses by ventilation can be compensated to a great extent. The amount of recovered heat is dependent, among other things, on the inner heat loads, etc. The reverse conclusion, to increase ventilation for increased heat supply, should not necessarily be drawn. Ventilation is a measure for indoor air quality and energy conservation, not heat supply.*

J. Kronvall (Sweden): Could you explain why, for German conditions, you need 0.8 ach to ventilate a building to avoid damage to the building fabric when, as you say, the demand is nearly independent of the number of persons in the house ?

L. Trepte (Germany): *The value of 0.8 h^{-1} is based on the calculations of Gertis and Erhorn from the Fraunhofer-Institut of Building Physics in Stuttgart. In their calculations, Gertis and Erhorn (among others), investigating minimum thermal insulation under the existing building code DIN 4108, assumed outdoor temperatures, atmospheric humidity, indoor temperatures and moisture emittants typical for central Europe. The results are still under discussion, especially the variation width with changes in the influencing parameters. Also of importance, for example, is the building construction.*

With the table in my paper, I intended first of all to point out that humidity and related problems can play a major part and in Germany may exceed some other pollutants. The moisture content depends on several factors so there is no direct correlation between the number of persons and humidity concentration level. Therefore the situation is quite different from other pollutants, e.g. carbon dioxide.

J. Railio (Finland)

Concerning problems with mechanical ventilation related to inhabitants' behaviour, is it a problem caused by (a) complexity (should systems be made simpler to use), (b) lack of information and instruction for inhabitants or (c) the system breaking traditional behaviour, e.g. window opening habits ?

L. Trepte (Germany)

In Germany the typical ventilation method is still window opening, so indeed mechanical systems do not meet the traditional behaviour very well. However, there are also other reasons which contribute to the problems in accepting such advanced technical systems. For example, maintenance and operation should be simpler for the users, it should be stated which advantages or disadvantages the different mechanical systems have and the consequences of, for example, disturbing the operation of the ventilation systems. One important step to an efficient ventilation behaviour of the inhabitants will be information and motivation by illustrating the connection between ventilation, indoor air quality and energy conservation.

P. Hartmann (Switzerland)

Regarding the value of 0.8 h^{-1} for residential buildings, on behalf of humidity (a) do you not think that this value is an overcompensation to the existing situation where we frequently find values of 0.2 h^{-1} and (b) would it be advisable to distinguish between new houses ($\rightarrow n_L$ = 0.5 - 0 h^{-1}) and existing houses with poorer construction ($\rightarrow n_L$ = 0.8 h^{-1}) ?

L. Trepte (Germany)

The value of 0.8 h^{-1} is at present under discussion in Germany. It is based on calculations assuming thermal insulation under the German building code DIN 4108 and assumes typical climatic conditions in central Europe. But there are further influencing factors, such as building insulation, construction, moisture production and emission in the dwelling. There are, of course, different situations and conditions which result in different ventilation rates. Usually it is more appropriate to define the necessary outdoor air rate for these variants which results in a variation width in the ventilation rate. However, 0.2 h^{-1} will be too low for German cases. Probably different types will be distinguished, e.g. as you have proposed, a limited number of different types of building construction.

Paper 15:

'Exploration of ventilation strategies in domestic housing. Theory and experimental results' presented by Mats Sandberg (Sweden)

M. Sherman (USA)

Ventilation efficiency is such a difficult concept to define because it depends not only on the air flow patterns but on the location of the sources and the point of interest for the pollutant concentrations. A single number such as 'ventilation efficiency' is, by itself, meaningless unless the exact situation is defined. To be complete, ventilation efficiency is defined as a function of location and source location. The values usually quoted are particular integrals of this quantity.

M. Sandberg (Sweden) — *To specify the efficiency of ventilation systems, we suggest the use of two quantities, the air exchange efficiency and the ventilation efficiency. The first quantity is source-independent while the second depends on the type of contaminant source and its location. The reality is always very complex and one therefore has to specify for which situation the actual numbers are valid. However, I cannot see that this is any argument against their use.*

M. Holmes (U.K.) — Contaminant production is probably associated with occupant activity, i.e. movement of occupants between rooms, opening and closing doors. Can you comment on any effect this might have on the spread of contaminant ?

M. Sandberg (Sweden) — *I agree that the effect of occupant activity is important. However, I cannot quantify the effect on the dispersion of contaminants.*

Paper 16: — 'Mechanical ventilation system requirements and measured results for homes constructed under the R-2000 super energy-efficient home program' presented by Mark Riley (Canada)

D. Fitzgerald (U.K.) — The building heat loss seems incredibly small. Can you comment ? Also, what is the cost of/access to CATS ?

M. Riley (Canada) — *Many of these homes do not need conventional heating systems. Access to CATS is very difficult since Brookhaven is not set up to handle orders on a commercial scale. We waited almost a year for results. This should change by next spring. The cost for the four samplers and sources is about US$200. This cost can be for one zone or multi-zone measurements (up to four tracer gases).*

P. Wouters (Belgium) — Two important criteria for R2000 houses are

1. To maintain neutral pressure
2. $N_{50} \leq 1.5\ h^{-1}$

Table 1 indicates that 32% of the R2000 houses have fireplaces or wood stoves. Is it possible to describe the types used and is not the use of these appliances in contradiction of the mentioned criteria ?

M. Riley (Canada) — *Fireplaces and wood stoves must have sealed glass or metal doors and separate outside air supplied directly to the firebox for combustion. This direct air supply must provide all the combustion air. In addition, standards are being prepared to test fireplaces and wood stoves under negative pressure to determine leakage requirements.*

Note: Fireplaces are normally factory-built of sheet steel and are not site-built masonry fireplaces.

N. Nagda (USA)

You mentioned that SF_6 measurements for comparison with PFT (CATS) measurements were conducted as 'spot' checks. Were these over a period of several hours or were they really over a few minutes ? Also, will your planned effort in the same area for autumn 1985 include a time period of SF_6 measurement that is the same of that of the PFT ?

M. Riley (Canada)

Spot measurements were taken over a period of 2-3 hours. The autumn 1985 verification program will involve continuous tracer gas measurements in 3 to 4 homes. These homes have different degrees of airtightness.

J. Dewsbury (U.K.)

Who was responsible for (a) the design of the R2000 houses and (b) ensuring that they were built and commissioned according to the design ?

M. Riley (Canada)

The builders themselves are responsible for the design of each house but they must first attend training and education programs. In addition, mechanical contractors must be qualified before installing ventilation equipment.

An extensive inspection and verification program has been implemented. These include inspection of the houses at two stages of construction:

1. *When the house has been insulated and the air/vapour barrier installed.*

2. *When the house is almost complete.*

In addition, an airtightness test is performed and the ventilation system is inspected and airflows measured. Finally, the plans are examined prior to monitoring to determine any major changes to the design.

Paper 17:

'Indoor formaldehyde levels in houses with different ventilation strategies' presented by J. Reardon (Canada)

M. Sandberg (Sweden)

In Table 4, house group A, we see that the flow rates drop in occupied houses compared with unoccupied houses. We would expect the opposite effect. There are two possible explanations:

1. Infiltration (although the houses are very tight)

2. Accuracy of the tracer gas methods
   (assume ±20% → 0.2 x 0.4 = 0.8 ach)

Can you explain the differences in flow rates ?

D. Figley (Canada)

The total air exchange is calculated as

$$V_T = V_M + V_I \qquad \textit{(equation 3)}$$

Since the values of the infiltration (V_I) are very small, the primary source of ventilation is the mechanical system. It is controlled (ON/OFF) by a humidistat, hence the

ventilation is related to the occupant selected humidity setpoint and the interior moisture source generation rate. In general, the occupied house owners had selected operating conditions which reduced the operating time of their mechanical systems.

R. Grot (USA)

Our research and that carried out at Oakridge have shown the emission of HCOH from particle board is a function of temperature, humidity and the level of HCOH in the space

$$ER = \alpha(T,RH) - \beta(T,RH)C_{HCOH}$$

If you use this equation in a house model then the equilibrium house level of HCOH will be given by

$$C_{HCOH} = \frac{\Sigma A\alpha/_V}{\Sigma AB/_V + AI}$$

where A = area of each HCOH source

AI = air exchange

V = house volume

Thus an equation of the form

$$C_{HCOH} = \frac{a}{b + AI}$$

would better explain your data. Also, your $C_o = 26$ is high by US data for outside ambient concentrations. Was this measured ?

D. Figley (Canada)

Because of the difficulty in quantifying the emission sources directly, I chose to infer the net HCOH source strength from the simple mass balance model. Using all of the house data as if it were taken from one 'typical' house requires correction for individual house variations in indoor temperature, humidity and HCOH concentration. In this simplified analysis, the temperature and humidity effects were discussed (reference 1), but no correction was made for varying indoor HCOH levels.

The outdoor levels were not measured. The Dupont C-60 passive dosimeters that were used for the monitoring were not suitable for use in freezing weather. The outdoor values were calculated based on the best fit curve of the form of equation 1.

Paper 19:

'Multi-zone modelling and air leakage analysis' presented by Max Sherman (USA)

D. Zerba (USA)

Have you encountered the difference in leakage area data between pressurization and depressurization mode ? Can the model employed with your leakage area results account for this effect ?

M. Sherman (USA)

Blower door measurements often yield different results for pressurization vs depressurization. There are two reasons for this - valve action and measurements/noise error. Occasionally there are real valves, i.e. leaks which change their behaviour at some critical pressure. An example might be a French window which seals tight upon pressurization and opens on depressurization. Most cases of measured differences, however, are traceable to measurement difficulties. The most common problem is interference due to the wind. The wind can cause large errors (40%) manifested as differences between pressurization and depressurization ELAs. These errors can be minimised by averaging the two results, since valve action itself is usually only apparent at the large pressure of fan pressurization and are not important for infiltration.

Paper 20:

'Inhabitants behaviour with regard to ventilation: the use of windows. First heating season' presented by Hans Phaff (Netherlands)

I Bealby (U.K.)

How is the heating charged to the occupants ? Is there any risk of occupants controlling internal comfort during winter by opening the windows ?

D. Harrje (USA)

What about variations in habits between countries ? When airing, are heating systems turned off ? What is the energy penalty ? In the more severe weather regions of North America, windows in single family houses are rarely opened in winter. This is not true in poorly regulated apartment buildings where window opening is very common to regulate temperature.

M. Holmes (U.K.)

Was the heating system compensated ? In addition, do you think this is relevant to the use of windows ? It is usually assumed to be good design practice (UK) to use weather compensators to restrict heating capacity and so minimise the effect of opening windows on energy consumption in commercial or group heating schemes.

J.C. Phaff (Netherlands)

The central heating system has one main hot water supply. In the apartments is a 'one pipe' system with radiators and manual shutters or thermostatic valves. Every radiator has a heat cost counter of a simple evaporation type. A large quantity of heat comes directly from the uninsulated pipes and is not counted. The main supply temperature is weather controlled and has a daily and a weekly program. The concrete internal walls and pipes cause the bedrooms to be overheated. Also, with radiators shut off, there is a need to open a window to lower the temperature, though this aspect cannot be found in the inquiry. At low outside temperatures (-15°C) only 4% of the windows are not closed.

Most radiators are turned off during airing with large windows, but the heat flow through an open window comes mainly from the hot building mass (concrete inner walls) and only 10 - 30% comes from the radiator when it is not turned off. We will compare the percentage of open windows

with the annual results of the heat cost counters per apartment. This building was constructed in 1967. I agree that a better design of the heat distribution and pipe and wall insulation will minimise the number of open windows. I heard a rumour that some people keep their radiators shut off and complain to the caretaker that it is too cold in order to get a higher supply temperature. Thereby they get more heat from the pipes, lower their own bill and 'steal' from the overhead heat costs. But this only works when you steal a lot more than the mean inhabitant as the total costs are distributed with the aid of the heat cost counters. I hope that this behaviour is not common practice in other countries. This whole research has to be seen as a first trial to really measure the use of windows. There is a need for measurements to be studied in different types of buildings, countries and climates.

J. Kronvall (Sweden)

For this kind of investigation, do you not miss a lot of valuable information if you cannot make simultaneous checks on whether the inhabitants in the flats are at home or not ? Can you, for example, see in your results any differences in the window opening behaviour between weekdays and weekends ?

J.C. Phaff (Netherlands)

Yes, we will miss a lot of information. However, the occasions when a window position is changed can always be evaluated as it indicates that someone is at home. From our enquiries there is additional information on which rooms are occupied and when, although whether inhabitants are at home or not, the actual use of windows is one of the questions we have to answer. It was immediately apparent that window use at weekends differed from that on weekdays. We feel that although, as we have said, our information is not complete, we have gained a reasonable amount of valuable information about the use of windows.

Paper 22: 'Monitoring of ventilation and humidity in crawl-spaces of dwellings' presented by J. Oldengarm (Netherlands)

A.I. Gaze (U.K.)

1. What size and number of ventilators are provided in the house ?

2. Are any damp-proofing measures (membranes or damp-proof courses) incorporated in the basement construction in typical Dutch housing ? If not, this is surprising in a country where water levels are reported to be high.

J. Oldengarm (Netherlands)

1. The crawl space is provided with four periscope-type ventilation channels (see figure 4 in the paper), two for each facade, size 10cm x 4cm. The situation described is common practice in the Netherlands.

2. No, damp-proofing measures are not common practice. This is indeed surprising. The reason is that reliance is placed on the damp-proofing of the building materials. Cost factors, of course, are also a disincentive.

B. Saxhof (Denmark)

1. What did you expect to learn from pressurization of the crawl space ? Air can leak to/from the ground, the exterior and the house.

2. When suggesting the combined insulation and vapour barrier, are you then blocking the ventilation openings ? Are you trying to prevent ventilation of the crawl space ?

J. Oldengarm (Netherlands)

1. *Firstly, pressurization helps us to find the location of air leakages in the ground floor. Secondly, we can try to find the air leakage coefficient but this is, of course, more difficult because the leakage to neighbouring spaces has to be eliminated.*

2. *The ventilation is kept at the normal level.*

A. Faist (Switzerland)

Would it not be better to put the insulation under the slab and the vapour barrier on the ground ?

J. Oldengarm (Netherlands)

This is also a good, or maybe better, solution and it is often applied. However, the costs will be higher because it involves much more labour.

J. Brunsell (Norway)

Why do you insulate the 'floor' in the crawl space when you showed us that there is a net heat flow up from the 'floor' during the winter ? This should decrease the temperature in the crawl space. In Norway we use only a vapour barrier on the ground to stop the emission of moisture.

J. Oldengarm (Netherlands)

There is a net heat flow up from the soil bottom indeed, but remember that this heat is partly released by the radiative heat from the ground floor (see figure 6 in the paper). Hence this heat flow is closely related to heat loss through the ground floor. Insulation applied on the soil bottom increases the crawl space temperature. This is also confirmed by experimental measurements.

P. Wouters (Belgium)

Figure 13 seems to indicate that the moisture content in the crawl space determines very strongly the moisture content in the living space. Were there obvious indications of leakage between crawl space and living space ? Do you think that this house was a representative Dutch house or an exception ?

J. Oldengarm (Netherlands)

It is not correct to conclude from figure 13 that the crawl space humidity determines the humidity in the living space because both are strongly correlated to the outdoor humidity in an independent way. Severe air leakages between crawl space and living space are quite common in the Netherlands. All monitoring projects were selected as being representative of Dutch single family houses.

A. Faist (Switzerland)

What are the consequences on the summer temperature conditions of the insulation of the crawl space ?

J. Oldengarm (Netherlands) — *The result might be a somewhat higher indoor temperature in summer, but we do not believe this will lead to comfort problems. Because the heat loss through the ground floor is relatively small compared to the total heat loss, we should not expect a dominant effect.*

Paper 23: 'Ventilation strategies for crawl spaces, attics, etc.' presented by Johnny Kronvall (Sweden)

A. Faist (Switzerland) — What air change rate do you have for zero wind velocity ?

J. Kronvall (Sweden) — *From the calculations, by definition of the flow balance procedure, there are zero air changes per hour. If stack effect and dynamic infiltration effects had been taken into account, the result would be a low, but probably noticeable air change rate at zero wind velocity.*

Paper 24: 'Use of a single tracer gas for measurement of ventilation rates in a large enclosure' presented by Jonathan Dewsbury (U.K.)

I.R. Bealby (U.K.) — I have recently been trying to measure ventilation rates in poorly ventilated school halls (volumes above 1000 m^3). These have fairly high ceilings and a regular shape. My equipment for mixing was two 24" axial fans and I was sampling and recording N_2O concentrations at two positions.

Using an initial high concentration around 500 ppm, I was unable to obtain mixing to a point where my two concentrations were better than about 40%. However, the two decay curves gave similar results, i.e. ≈ 0.3 ach (fans off for the decay plot). I do not think it was possible to obtain an experimental mix, although my estimate was that the ventilation rate was about 0.5 ach (as you say, a guess) ± 0.5 ach which was sufficient for my purposes. Any comments ?

J. Dewsbury (U.K.) — *It would be possible to solve the problem for the ventilation rate by treating it as a 2-zone problem. The result would be no more accurate than the estimate of the zone sizes and could be less accurate depending on the unknown tracer concentrations in the rest of the room.*

Unfortunately, at present I do not think it is possible to calculate the accuracy achieved when measuring ventilation rates in poorly mixed spaces.

J.R. Waters (U.K.) — Why are the errors reported in Tables 2, 3 and 4 so large ? could these be due to:

1. Cumulative errors due to the time-discretisation method used to calculate the decay curves (1000 steps over 10 houses is rather coarse compared to the frequency of some of the oscillations), or

2. The integration represented by equation 1 over the time periods described leading to a badly conditioned set of equations and hence large rounding errors in the solution, or

3. Are the reported errors merely a peculiarity of the particular model and set of conditions chosen ?

Also, why did you not perform a complete matrix inversion to obtain all the integral flows and hence obtain a full check on the results ?

J. Dewsbury (U.K.)

The errors are mainly due to the ill-conditioning of the equations to be solved. This meant that it was not possible to perform a complete matrix inversion and obtain the integral flows. More accurate solutions could of course have been obtained by using a small simulation time step in the initial period and forming the concentration equations to be solved out of data with a stronger weighting to the initial period. However, I do not think much importance should be attached to the early part of a concentration decay measurement in a single, poorly-mixed space. This is because the measured concentrations in this period will tell us very little about concentrations between the measurement points, due to the turbulence of the air flows and consequent random fluctuations in tracer gas concentrations.

P.F. Collet (Denmark)

Why did you not mix the air and why did you use a method which makes a 3-decade instrument necessary ?

J. Dewsbury (U.K.)

If the problem of poor mixing can be analysed successfully, experimental work will be made easier by not having to arrange artificial mixing. A 3-decade measurement is not necessary nor can it be achieved by the instruments in common use today. A 3-decade simulation was presented in order to show most of the tracer gas concentration curves for the examples chosen. An important step forward will be to continue this work using realistic values of instrument range and incorporating instrument errors.

M. Sandberg (Sweden)

I quote from Section 4 of your paper:

"It is not difficult to produce good mixing in practice in small rooms by the use of oscillating fans."

Our experience from our indoor test house (see paper 15) is that it is not easy to create complete mixing in a whole house. The house was ventilated by a mechanical ventilation system. We tried 2, 5 and 10 mixing fans respectively and achieved the same decay rate at each point in the same room, i.e. uniform mixing within rooms. However, we did not obtain the same decay rate in each of the different rooms. This is due to the fact that the doorways act as hydraulic controls. In some cases the relative difference in mean-age of air between the rooms amounted to $\sim$ 25%.

J. Dewsbury (U.K.) — *I expect that it would be difficult to achieve good mixing between rather than within the rooms of a house unless the ventilation flow rates were very much smaller than the inter-room mixing flow rates. This would require the former to be very small (unlikely) or the latter to be very large (impractical). I have not attempted this in a mechanically ventilated house.*

Paper 25: 'Improving the accuracy of a constant concentration tracer gas system' presented by David Harrje (USA)

M. Bassett (New Zealand) — Have you any experience with teflon absorbing and modifying the concentration of SF_6/air mixtures and have you tried using heated molecular sieve columns that send SF_6 to the detector prior to the O_2 ?

D. Harrje (USA) — *Teflon was suggested to us as a material which would not absorb SF_6. However, certain compounds were given off by the teflon material itself that interfered with the column operation. We found that a very short time after using teflon in the system, the standing current dropped significantly. We have been satisfied with the operation of the alumina column and therefore have not experimented with any other columns. Using software to determine the SF_6 peak presents no particular advantage in reversing the O_2 and SF_6 peak occurence other than possibly reducing the cycle time between samples.*

Paper 26: 'Ventilation system performance evaluation using tracer gas techniques' presented by Richard Grot (USA)

W. Fisk (USA) — Based on my understanding of the application of age distribution theory to ventilated buildings, the presence of re-circulation in the HVAC system should not make it invalid to use the standard equations from age distribution theory for determining ages or air or ventilation efficiencies. Could you comment on this issue ?

R. Grot (USA) — *It is true that age distribution theory can be applied to buildings with re-circulation of return air. However, when there is re-circulation, the measured ages do not necessarily serve to evaluate the air distribution efficiency within the ventilated space as well as those measurements made with no re-circulation. The non-zero re-circulation measurements reflect both local mixing within the space and 'whole building' mixing which takes place due to re-circulation of the return air. Given the same air movement patterns within the space, the ages measured with no re-circulation will be less than those measured with non-zero re-circulation. While both quantities are of interest, only the first serves to evaluate only the air distribution effectiveness within the ventilated space.*

I.R. Bealby (U.K.)

Is the difference in the residence time results (table 3) related to the time taken for the complete mixing of gases, e.g. the experimental difficulties you have mentioned ? If so, should not far greater reliance be placed upon the decay measurements ? Do you think it is ever possible to obtain adequate mixing of gases and thus is not any measurement only a better method of giving a rough estimate of ventilation rate ?

R. Grot (USA)

The difference in residence time results between the build-up and decay measurements is due to the inability to tag all of the incoming air with tracer gas during build-up. Only the outside air that enters through the air handling system is tagged with tracer gas. The significant amount of air that leaks in through the building envelope is not tagged at all. Therefore, greater reliance should indeed be placed on the decay measurements.

It is possible to obtain 'adequate' mixing of tracer gas given sufficient time. The time that is required depends on one's meaning of 'adequate' and on the air movement patterns in any particular case.

Paper 27:

'Ventilation efficiency measurements in occupied mechanically ventilated buildings' presented by Don Dickson (U.K.)

D. Harrje (USA)

In the past, incidences of the pressure of halogen compounds have resulted in problems with sulphur hexafluoride tracer gas measurements. Have there been problems with chlorine in the swimming hall studies ?

D. Dickson (U.K.)

No problems were encountered in this respect.

Paper S.1

'The performance of ventilation in an untight house' presented by Rodney Gale (U.K.)

R. Grot (USA)

The flow through open doorway due to the temperature difference between rooms has been studied by several researchers (see Walton, NBSIR 83-2635 'A computer algorithm for estimating infiltration and inter-room air flow' for a list of references). These researches can be summarised (± 20%) by equation

$$Q_V = 125.7\ A\sqrt{H}\ (\Delta T)^{\frac{1}{2}} \qquad m^3/hr$$

where H = doorway height (m)
A = area (m^2)

For a 2m high doorway with a $2m^2$ area

$$Q_V \simeq 350\ (\Delta T)^{\frac{1}{2}} \qquad m^3/hr$$

which implies an air exchange of about 5∿6 ach for a $1^{\circ}C$ ΔT for a 5 x 5 x 2.5 m^3 room.

R. Gale (U.K.) — *Thank you for the information. In our case it is unlikely that temperature differences between rooms on a given floor exceed 1°C. There was a temperature differences of between 1 and 2% between the ground and first floors and presumably the equation would be applicable to these flows using the area of the floor occupied by the stairs.*

D. Dickson (U.K.) — In considering air interchange from room-to-room, is not the room-to-room temperature difference a more important variable than the type of ventilation system ?

R. Gale (U.K.) — *It may be, since an open door offers very little resistance to flow. In most of our experiments, however, the ambient conditions, wind speed and direction were similar. Any small differences in the indoor temperature were induced by the weather and not by the heating system. We think that it is possible, under these circumstances, to attribute some of the observed differences in pollutant dosage to the influence of the ventilation system.*

D. Harrje (USA) — What does not appear to be evident in the discussion of release of tracer gas in one room is the observation that mixing on one floor tends to occur relatively rapidly. Please comment.

R. Gale (U.K.) — *Our observation was that mixing on the same floor as the pollutant release was indeed fairly rapid. The spread to the other floor was slower. Our figures show the dosage or integrated exposure in each room and it is interesting to note that the exposure is not strongly dependent on the particular floor. Thus, the pollutant may reach the floor more slowly but this does significantly reduce exposure in the cases where the pollutant is not extracted.*

Paper S.2 — 'Influence of open windows on the inter-zone air movement within a semi-detached dwelling' presented by Richard Walker (U.K.)

P. Hartmann (Switzerland) — What were the door positions in figures 6a and 6b ?

R. Walker (U.K.) — *The conditions with regard to the standard house are given on page 7 of the paper. All internal doors were open, unless stated otherwise. In figures 6a and 6b they were all open.*

D. Harrje (USA) — The point that stack effect can aid or detract from wind effects in the determination of air infiltration associated with envelope openings does not appear to be emphasised. These points should be vital to the analysis. They are covered in theory by Sinden (Energy and Buildings) and experiments by Blomsterberg and Harrje (ASHRAE Trans.1979).

R. Walker (U.K.) — *Stack effect is included in the model. The predictions of the model in this respect can be seen at low wind speeds (see, for example, figure 3).*

W.F. de Gids (Netherlands)

Open or closed doors can have much more influence than you have shown because of the ratio between leakage of the facade/leakage of internal doors. Is flow reversal over one opening included in the model ?

R. Walker (U.K.)

It is possible that in certain circumstances the influence of closed internal doors on ventilation rates could be more than is shown in this paper. We have, however, only shown what was predicted for our 'standard' house.

With regard to flow reversals at internal doors, we have not modelled this within BREEZE.

Paper S.3

'Interpretation and error analysis of multi-tracer gas measurements to determine air movement in a house' presented by Richard Walker (U.K.)

R. Gale (U.K.)

One further source of error in the multi tracer gas experiments that you described is the cross-sensitivity of the Binos analyser to the different tracer gases. Could you please tell us what steps you took to minimise the effects of cross-sensitivity ? My own experience of a rather old Binos analyser with a range of 0-200 ppm N_2O was that it was quite sensitive to water vapour and to carbon dioxide.

R. Walker (U.K.)

To minimise the effect of water vapour, a dryer (magnesium perchlorate) was used in line and also a correction was applied using measurements of outside air.

Yes, there is the possibility of small cross-sensitivities which depend on the tracer analysis combination of the dedicated units. Where this is a significant effect, a correction must be made.

C. Irwin (U.K.)

1. Have you tried to quantify errors under controlled environmental conditions ? This would enable comparison of different analysis methods under repeatable conditions for the 2 & 3 cell case.

2. Have you encountered any difficulties in calibration of your infrared analysers for CO_2 ?

I have recently completed a study of error anslysis/ estimations using perturbation of data for 2 & 3 connected cells. I would be more than happy to supply a copy of this study.

R. Walker (U.K.)

1. *No, we have no facility for this at present.*

2. *The CO_2 analysers are generally very stable. I cannot recall any problems.*

Paper S.5 — 'A multi-tracer system for measuring ventilation rates and ventilation efficiencies in large, mechanically ventilated buildings' presented by William Fisk (USA)

P.F. Collet (Denmark) — Why did you have problems with the accuracy of measuring SF_6 ?

W. Fisk (USA) — *We added SF_6 and R-12B1 late in our development of the experimental system and did not have smooth calibration curves for these two tracers compared to the calibration curves for the other four tracers. In addition we are using lower maximum concentrations of SF_6 and R-12B1 than for the other tracers. I believe our measurement accuracy with SF_6 and R12B1 can be improved by preparing more calibration gases and more accurate calibration gases and also by using large maximum concentrations of SF_6 and R-12B1.*

M. Bassett (New Zealand) — Can you explain the procedure for obtaining detector calibration curves for each of the gases and the fitted function relating detector output to gas concentrations ?

W. Fisk (USA) — *Except for the method used to prepare calibration gases, our calibration procedures are explained in the paper. For these tests we prepared calibration gas mixtures by diluting pure tracer gases with air; generally two successive dilutions are required. The first dilutions are performed by metering about five litres of air into a gas sampling bag and injecting a small volume, such as 1cc, of tracer gas into the bag. In the future we will purchase calibration gases from a speciality gas supply company that uses gravimetric methods to verify calibration gas concentrations.*

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