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6th AIC Conference

Ventilation strategies and measurement techniques

Proceedings

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6th AIC Conference

Ventilation strategies and measurement techniques

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Proceedings

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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, Finland, Federal Republic of Germany, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES
6th AIC Conference, September 16-19 1985, Netherlands

PAPER 1

VENTILATION, THE BALANCE BETWEEN ENERGY AND WELL-BEING

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Synopsis

A survey is given of the sitution in The Netherlands with regard to ventilation and infiltration.
Starting from a point of generally very leaky and hardly insulated buildings now the necessity is felt on the one side to make standards for the airtightness to prevent energy wastes by too high infiltration rates and on the other hand to define minimum ventilation rates to secure safe and hygienic conditions in well insulated and airtight buildings.
This minimum ventilation rate is based on contaminants, caused by the occupants themselves, the so-called unavoidable sources.
The emission of avoidable sources, like gases from building materials, should lead to concentrations at the given minimum ventilation rate, which are not harmful. This requires adequate regulations for these contaminants.
Minimum ventilation can be obtained either by mechanical ventilation (cost aspect, especially for dwellings) or natural ventilation (requiring insight from occupants in ventilation parameters).
The research activities are related to the mentioned developments:
- ventilation/infiltration versus energy consumption
- influence of contaminants from avoidable sources (building materials etc.)
- mechanical ventilation in dwellings
- ventilation instructions for occupants.

INTRODUCTION

Ventilation of dwellings is a hot item, also in The Netherlands. Two questions are essential; firstly which ventilation rate is required to provide safe and comfortable conditions for the occupants and secondly how can this ventilation rate be obtained and maintained.

Since building design is becoming more and more energy conscious, the airtightness of new buildings is improving in the same measure. From the point of view of energy conservation existing buildings are also insulated, so that in many cases the infiltration has decreased considerably.

Dutch buildings, which have always had a bad reputation as for the degree of insulation and airtightness, now are confronted with a new situation, carrying unforeseen problems.

Where in the past infiltration was only a nuisance, causing uncomfortable conditions like draughts and low indoor temperatures, in the present situation a shortage of ventilation could result in real problems. So in 1979 the Ministry of Health asked the Health Council to report on the indoor climate and on the minimum ventilation rate in dwellings in particular (1).

This very interesting report was published in 1984. Even more important than the recommended amount of fresh air (7 dm^3/s, i.e. 25 m^3/h per person) is the motivation of it.

According to the Council the indoor climate should be of such quality that no harm is experienced by the occupants, even not on the long term. The minimum ventilation rate should be based on unavoidable sources, i.e. originated by the occupants themselves, such as body odours, carbon dioxide and moisture.

In principle all other sources of pollution are regarded as avoidable. They should be avoided or restricted to such extent, that they are harmless. For building materials and household chemicals standards should be developed such that no health risks can occur at a ventilation rate of 1,4 dm^3/s (5 m^3/h) per person, being the lower limit of infiltration quantities measured in practice. Adaption of the fresh air amount to present - possible - concentrations of avoidable pollution sources would result in big and uneconomic air quantities, as will be illustrated by the following example. In Germany pressed wood board is classified in three categories, dependent on the formaldehyde emission, according

to the Uniform Technical Building Regulations (ETB-Richtlinien). The requirement of a maximum formaldehyde concentration of 0,1 ppm in the room air can be satisfied with an air change rate of 0,8 to 1 per hour, when board of the first, the least harmful, category is used. Application of material of the third category (the most unfavourable) requires an air change rate 20 times as high (2).

Even in the first case the occupant should take care that the minimum required ventilation will take place. So the two principal questions could also be formulated in this way:

- what are avoidable sources and what are their effects, based on a minimum ventilation rate.
- to what extent can the handling of the ventilation means be left to the occupant. What will be the result.

MINIMUM VENTILATION RATE

An important part of the energy spent in buildings is used for ventilation; therefore the cost aspect cannot be neglected, explaining the interest for a minimum ventilation rate. An interest, which is very lively in the present time, due to the high energy prices.

The question of minimum ventilation quantity has a long history. Already in 1861 the Barrack and Hospital Commission in the United Kingdom required 9,4 dm^3/s (34 m^3/h) per person for this type of buildings.

Although it is acknowledged that CO_2 is not the cause of a stuffy atmosphere, the CO_2-concentration is often used as measure for the aircontamination.

Over a century ago Pettenkofer introduced as limit 0,1% CO_2. For average indoor activities the production of CO_2, depending on the type of person and activity, varies between 0,0028 and 0,01 dm^3/s between (10 and 36 dm^3/h), resulting in an average of 9,2 dm^3/s (33 m^3/h) fresh air per person for not surpassing Pettenkofer's limit.

As Fitzgerald recently reported in the ASHRAE-Journal (3) the standard for ventilation, used in the USA and also in many other countries, is based on the work of Yaglou, being about 50 years old. Efforts for updating this work some 15 years ago in the U.K. were prevented by lack of funds.

Notwithstanding the high quality of the work of Yaglou new investiga-

tions certainly would have sense, since the problem is clearly influenced by time dependent factors like hygienic habits and use of building and furnishing materials. Yaglou e.g. recommends 6,7 dm^3/s (24 m^3/h) per person for well-off adults and 15,8 dm^3/s (57 m^3/h) for children of the lower social classes.

For this reason ISSO, the Dutch Institute for Study and Stimulation of Research in the field of Heating, Ventilation and Air Conditioning initiated an investigation in 1979 to determine the minimum fresh air supply per person,required in order to prevent the occurrence of inacceptable offensive odours due to stale-smelling air in offices and similar buildings.

Offensive odours, regarded in this investigation, originate from building materials, furniture and upholstery, office materials and people (cosmetics, body odours). In order to establish the degree of offensiveness and acceptibility of odours, test subjects were questioned, both occupants and visitors, according to a scale as given in fig. 1. (from (4))

ODOUR (OFFENSIVENESS) SCALE

5	repulsive, nauseating, etc.
4	objectionable, much too strong
3	no longer acceptable
2	still just acceptable
1	distinctly perceptible but not offensive
½	just perceptible
0	not perceptible

FIG.1 THE SCALE USED FOR ODOUR OFFENSIVENESS

The result of the investigation is, that the minimum fresh air supply would have to be adjusted to 9,7 dm^3/s (35 m^3/h) per person in order not to get more than 5% complaints from occupants of "odour not (no longer) acceptable". Since it is difficult to measure odours by use of instruments, this investigation worked with panels of 8 persons in a so-called "sniff-car", who where asked whether they still could distinguish odour carrying air from fresh air. The panel got samples

of room air, diluted with various amounts of fresh air. The odour concentration was defined by the dilutation factor, required for the sample for which just 50% of the individuals would still perceive the odour in the diluted odour-carrying air. As indication can be given, that in moderately ventilated rooms without smoking the odour concentration is of the order of 10; when there is considerable smoking the odour concentration is of the order of 100.

The report concludes that in view of the results and the remaining uncertainties there is no justification for reducing the minimum fresh air supply in offices and comparable buildings to a considerably lower value than 9,7 dm^3/s (35 m^3/h) per person.

Ventilation rates can be given either in dm^3/s per person or in times of air changes per hour. In our conception, that the contaminants are mainly caused by the occupants, the expression in dm^3/s per person is a logic approach. For offices the value of 9,7 dm^3/s (35 m^3/h) per person equals about 1-1½ air changes per hour.

For dwellings this depends to a great extent on the size of the room and the member of occupants; only as an indication can be said that it will be about ½ - 2 air changes per hour.

EFFECT OF AVOIDABLE CONTAMINANTS

The minimum ventilation rate as mentioned before, resulting from the most recent studies, is based on the odour load of the room air, which is caused mainly by the occupants themselves.

This fresh air quantity however should also be able to keep the concentration of noxious gases, vapours or particles well below safe limits.

The number and variety of air pollutants in dwellings is big. Generally maximum allowable concentrations have not yet been determined for dwellings; for many substances even no recommendations are given. In houses these concentrations should be kept as low as possible both since special risk groups are concerned (babies, old and sick people) and as the exposure time can be permanent.

It is important, that the characteristics of the relevant materials are known, as e.g. is the case for formaldehyde from building materials.

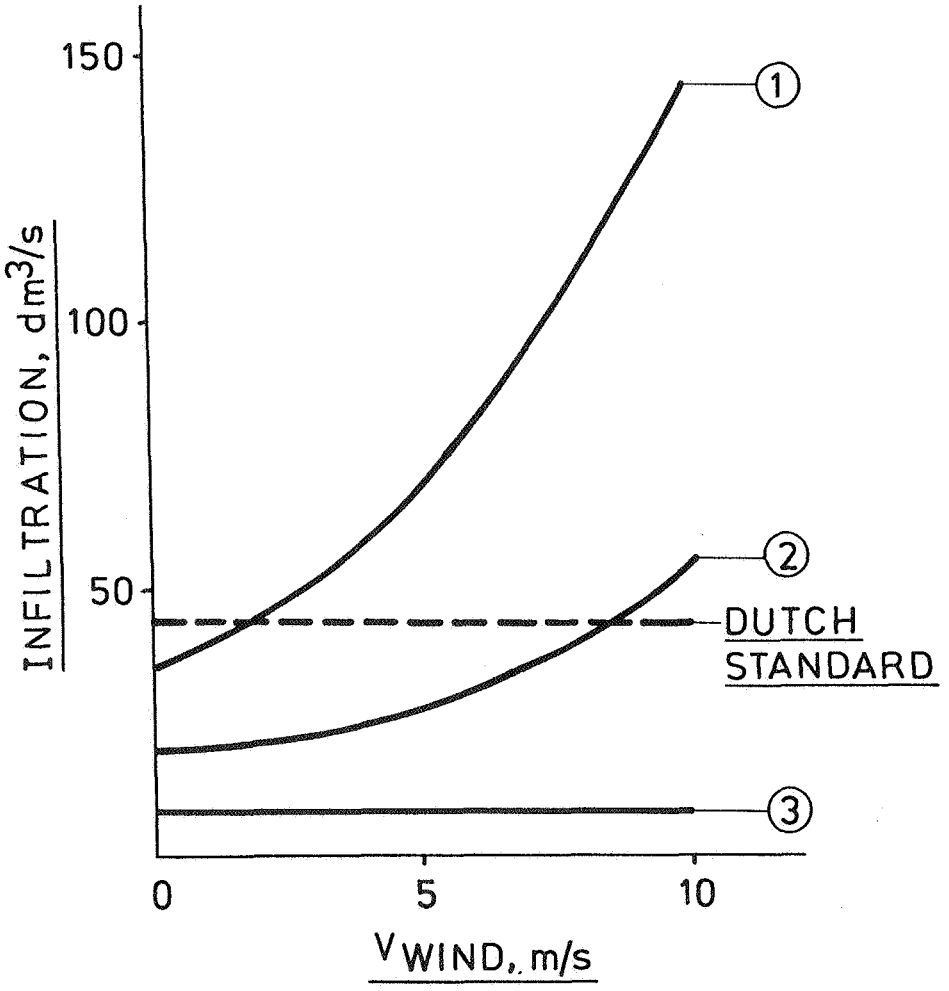
For formaldehyde an air change rate of 0,8 - 1 h^{-1} should be sufficient; this also applies to the CO, CO_2 and NO_2 concentration, resulting

from cooking with gas (2).
In - mechanically ventilated - offices the requirement of an air change rate of 1 certainly will be met during working hours. The Dutch Standard for ventilation in dwellings requires 0,001 m^3/s per m^2 floor area, which also means that an air change rate of 1 is met. However the total ventilation amount for a dwelling can be confined to 0,042 dm^3/s, which equals about an air change rate of 0,5. Here we see the contradictory interests of comfort and energy conservation.
It can be concluded, that a ventilation rate based on "freshness" generally will also be sufficient from the point of view of health. Nevertheless it is of big importance to have regulations for the maximum emission of building materials.

VENTILATION OR INFILTRATION

To satisfy the condition of freshness in a room is a matter of sufficient fresh air; it is not relevant whether the air is supplied by ventilation or infiltration.
In case of infiltration the air quantity is not constant but depends on the meteorological conditions (wind and temperature).
The flow through the rooms depends on the wind direction and the resistance in the dwelling. Opening of doors can make a considerable difference and the situation is even more complicated, when exhaust fans are used.
Exact calculation of infiltration and inter room air flows is only possible using a multiroom model computer programme.
It will be clear that generally the air flow will be too big, which means a waste of energy, or too small, which is undesirable for comfort reasons. In the latter case the air quantity can be increased by opening a window but here the same problem arises with regard to the adjusting of the correct quantity. Moreover for rooms at the leeside opening of a window is not a guarantee for more freshness in the room.
For the conventional type of Dutch houses the airtightness is such that the required fresh air quantity is obtained by infiltration in about 85% of the time, which means that most times the ventilation rate is (much) higher than necessary. From the energy point of view this is very uneconomical.
New houses, designed in a energy conscious way, appear to be very

well airtight with hardly any infiltration. This is clearly to be seen in fig. 2. (4). For those houses the best - and only - solution is a mechanical ventilation system; i.e. both supply and exhaust in a balanced system.



① average dutch one family house

② ditto; energy-consciously designed

③ dwelling in very well constructed apartment building

FIG. 2 INFILTRATION VS. WINDVELOCITY
(at 10m height over open country)

However mechanical ventilation, which is in all cases the best provision for a constant air renewal in all rooms, often is prohibited by the costs; this applies to houses in particular.
Therefore a study is running now in The Netherlands which conditions dwellings should meet to enable a cheap and yet effective combined air heating and ventilation system. To keep the investment costs low a simple duct system is required, ma inly restricted to a vertical duct in the core of the house with air outlets practically directly on the vertical duct.
The specification of the outlet grilles is important to obtain a uniform air and temperature distribution in the room, also at high supply air temperatures, which occur at low outside temperatures. Special problems are met during the starting period when the relatively small amounts of warm air, supplied just under the ceiling to the cold room, tend to build up a very big and uncomfortable temperature gradient.
To reduce the running costs heat recovery from the exhaust air is applied, since the Dutch standard does not allow recirculation of air from kitchen, bathroom and toilets.
For existing dwellings it is not possible to install mechanical ventilation systems; in most cases the costs will be prohibitive. For ventilation the windows or similar provisions have to be used; the correct operation is a matter of importance, to which more attention will be paid later.
For big buildings mechanical ventilation is common practice now in The Netherlands; it is felt a necessary condition to prevent cold draughts or offensive odours in wintertime. Most of these installations are provided with heat recovery systems.
Once again the choice of the type of air outlet is very important for a uniform distribution of the fresh air throughout the room. Modern air supply grilles have a high induction rate, which favours a good circulation in the room and thus a uniform air and temperature distribution.

CONTROL OF VENTILATION RATE

Natural ventilation

The most common system for air renewal is natural ventilation, the opening of windows, as is the case in most dwellings. The ventilation

rate is controlled manually by the occupant. Research in The Netherlands (5) showed that all kinds of operation of windows or similar openings occur, varying from always closed to permanently open. For a good operation the ventilating means have to be well designed and dimensioned; they should be easily adjustable. But this is only the first step. Next, and very important, the occupant should know when to ventilate and to which extent; he should know e.g. that airing for half an hour during the day is sufficient for bedrooms but that a bathroom requires permanent ventilation. More difficult to instruct is the influence of all factors, which play a role in the ventilating process like airtightness of the dwelling, wind and temperature, open staircases and open kitchens. Therefore this point has to be given much attention.

A good ventilation attitude is important from the energy point of view as shown by the distribution of energy losses owing to the ventilation of a rather leaky Dutch dwelling (5):

energy required for:	percentage
- 0,5 h^{-1} air change rate	35
- The rest of the infiltration	59
- Ventilation of bedrooms; open window for 1 hour during working days.	6

Mechanical ventilation

Compared to natural ventilation the control of the air quantities is much simpler for mechanically ventilated systems. Once more the airtightness of the building is an important factor. For an reasonably airtight building and a well designed and adjusted ventilation system, the air quantity to a room is practically independent of wind and outside temperature. It is determined by the design conditions, i.e. the number of occupants in the room. Generally the design condition is the situation of maximum occupancy, which means that often less fresh air could be supplied. This applies to congressrooms, canteens and similar rooms in particular.

Automatic control of the fresh air amount, either by changing the fan capacity or by adaption of the recirculation rate, would result in more economical operation of the system. The sensor of the control system should react on changes in air quality. Since the CO_2-concentra-

tion of the room air is one of the best indicators for air quality - especially when people are concerned - equipment has been developed, based on CO_2-absorption.
Unfortunately problems arise, when tobacco smoke is involved.
Another apparatus has been developed, which uses the conductivity of a semi-conductor; this conductivity is a function of the concentration of gases and vapours, which result from human activities. As such can be mentioned ammonia, methane, tobacco smoke etc.
For our purpose it is a favourable property of the sensor, that it works cumulative, when more gases are concerned. (6)
It is evident, that these systems only can be considered for installations of some importance, otherwise the return on the investment will take too long. Up till now they are hardly met in building systems.

TRENDS OF AIR INFILTRATION RESEARCH IN THE NETHERLANDS

The research trends in The Netherlands are determined by the development as outlined before.
Essential is the point of view of the Health Council, that the minimum ventilation rate should be based on "offensive odours" and that for avoidable pollution sources standards and regulations should be developed.
There are four main topics of research.

1. Ventilation/infiltration vs. energy consumption
   More fresh are than required results in energy waste. For this topic the research can be subdivided as follows.

1.1. Regarding the present situation
   - Field experiments on the air tightness of dwellings
   - Investigation of the energy consequences as part of a study of reference values for energy consumption of dwellings, offices and schools.

1.2. Reduction of energy consumption.
   The preparation of a standard on airtightness requirements for buildings.

2. Mechanical ventilation in dwellings.
   From the energy point of view mechanical ventilation is the most economical way to realise the required air renewal.

In big buildings this is common practice but for dwellings the costs are prohibitive.

It is studied how to develope a cheap combined air heating and ventilation system for dwellings, paying attention to the comfort as well.

3. Influence of contaminants from building materials etc.

   Since the minimum ventilation rate is based on unavoidable sources it is important to know the characteristics of avoidable contaminants, so that standards and regulations can be made to limit the emission to not harmful concentrations. This applies to dwellings in particular, in view of the special risk groups and the possibility of permanent exposure. Studies are running, also in connection with IEA Annexe IX.

4. Instructions to occupants

   Where air renewal must be obtained by natural ventilation it is important that the occupants know how to handle the ventilation means in a correct way. Before making instructions how to use them properly, it is necessary to have a good insight in the present ventilation habits of the occupants.

   Research projects on this topic are running, of which the IEA Annexe VIII can be mentioned (study of behaviour of the occupants towards ventilation).

It cannot be said that the above-mentioned trends are typical Dutch; they are rather international, having a Dutch accent now and then. International collaboration is necessary to answer the questions and solve the problems in an efficient way. Therefore international exchange of knowledge and research results as is realised by this AIC-conference is of great importance.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 2

THE INFILTRATION COMPONENT OF VENTILATION IN NEW ZEALAND HOUSES

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ABSTRACT

The air infiltration component of house ventilation is calculated and discussed in relation to winter space heat losses and measures necessary to control moisture. The airtightness of 80 houses sampled from three major urban areas was inspected for association with location, external cladding materials, and design features such as the shape and complexity of the building envelope. A useful correlation of airtightness with envelope complexity emerged which gives a coarse but useful way of forecasting airtightness from building design information. Winter season infiltration rates were calculated using hourly weather records, airtightness and wind exposure data and the Lawrence Berkeley Laboratory infiltration model. These infiltration rates represent the minimum ventilation rate currently achieved in New Zealand houses and are used in a discussion of the value of further improving house airtightness. Finally, results of surveying moisture problems in houses of known tightness are used to help establish the respective roles of ventilation and space heating in the control of indoor moisture in a temperate climate.

1. CURRENT VIEWS ON DOMESTIC AIR INFILTRATION

New Zealand houses do not have to conform to a standard for airtightness but they must have insulated walls, roof and floor. Infiltration heat losses have been ignored in the bid for more energy-efficient houses mainly because there has been little indication of the size of infiltration rates in relation to ventilation needs. It has nevertheless been expected that air infiltration could dominate space heat losses from insulated houses and therefore represent the next target for improved thermal performance.

Another aspect of house performance depending on ventilation is moisture control. Dampness problems are common in New Zealand because the warm maritime climate limits the moisture pick up capacity of ventilation air. The ventilation rate needed to cope with condensation depends on a number of lifestyle and house management factors but it is expected that this requirement will establish a limit to the degree of airtightness worth achieving in the absence of more sophisticated and expensive hardware to remove moisture.

2. AIRTIGHTNESS OF HOUSES

2.1 A Survey of House Airtightness

Airtightness results from a pilot survey of 25 houses in the city of Wellington (Ref 1), Fig 1 were used to help design a more extensive survey of a greater range of house types and geographic locations (Ref 2). This added a further 55 house results, giving a more secure basis for commenting on the airtightness of current and recent additions to the housing stock. All airtightness tests were made using the method of fan depressurization and equipment described in Ref 3.

The initial results of these surveys are given in Fig 1 which shows the distribution of house airtightness for each of three urban regions: Auckland, Wellington, and Christchurch. Houses built in these regions form about 50% of the new houses built in New Zealand during the period 1979-1984. Most houses in this age group (93%) have 50Pa airchange rates between 5-16 ac/h while the remaining 7% fall in the range 16-30 ac/h. A combined histogram of data for all regions is also shown in Fig 1.

A large group of houses (40%) falls within the 0-8 ac/h range occupied by conventional houses in very much colder climates such as those in Canada and Scandanavia. This finding conflicts with a widely held view within New Zealand that houses are typically quite loose by international standards. There are no special reasons for expecting to see houses of even modest airtightness. Since vapour barriers have not been found necessary to control cavity moisture they make no contribution to airtightness. Neither are gaskets used in joints nor special control of tolerances of timber frame joints to be found. However, in recent years there has been wider use of sheet lining materials both internally and externally together with prelaid particle board or slab-on-ground floors.

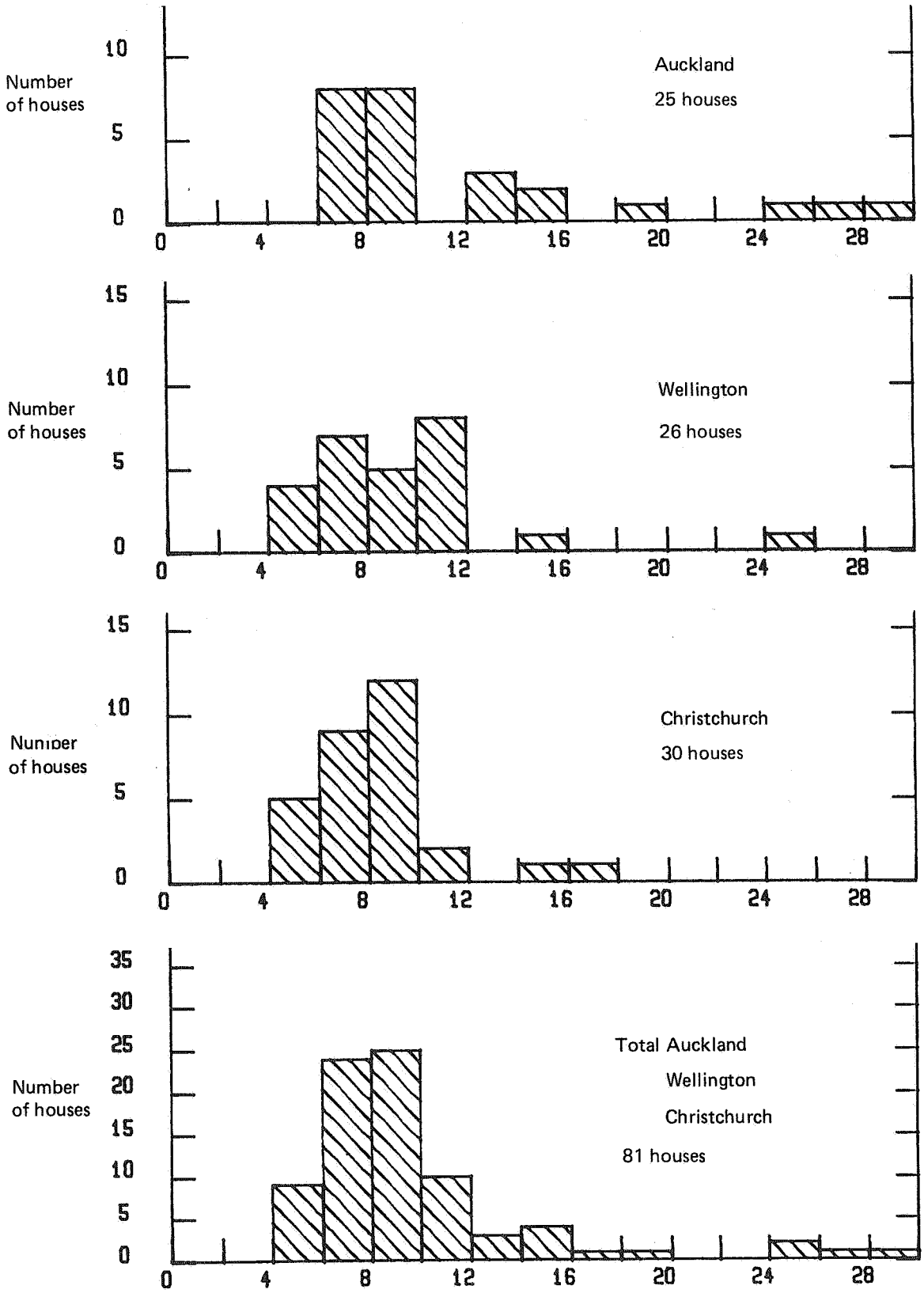


Fig 1: Histograms of house airtightness expressed as airchanges/hour at 50 Pa.

2.2 Dependence on Envelope Complexity

The possibility of a correlation between some of the broad characteristics of houses and the air leakage rate under test pressure has been investigated. While it is well known that the air leakage rate will depend more fundamentally on the microscopic detail of cracks, there is value in looking for correlation with some of the bulk characteristics such as the surface area of the building envelope, the complexity of the plan or the types of material used in construction. There may even be regional differences arising from construction detail or choice of material. If this approach can be shown to succeed then a valuable, simple tool will be available to predict house airtightness at the planning stage.

Two factors of building geometry considered likely to have an influence on airtightness are the surface area of external envelope and the complexity of construction. They are defined here as follows:

Envelope area: Area of external walls + ceiling + floor
(where a floor is slab-on-ground it is excluded)

Envelope complexity: Joint length / Envelope area
where joint length is the total length of the following joints in the envelope:
1. Wall-Floor perimeter
2. Wall-Ceiling perimeter
3. Wall-Wall vertical lengths of joint at changes of wall orientation
4. Boundaries of changes in ceiling pitch

An earlier analysis of the Wellington data (Ref 3) showed that complex houses tended to be more leaky than those of simple design. The same conclusion holds for houses tested in Auckland and Christchurch so the data for all three regions can be combined as shown in Fig 2. Here the tendency for complex building shapes to be less airtight than an equal shell area of simple shape is illustrated.

Fitting the following linear equation to the data:

$$Q = A + B\,Je + CSa \qquad (1)$$

where
Q = Leakage rate at 50Pa m^3/s
A, B, C are the regression constants
Je= Joint length m
Sa= Envelope surface area m^2

gives the following coefficients:

	Coefficient	Standard deviation
A	0.1	0.1
B	$4.7\ 10^{-3}$	$0.7\ 10^{-3}$
C	$-0.1\ 10^{-3}$	$0.4\ 10^{-3}$

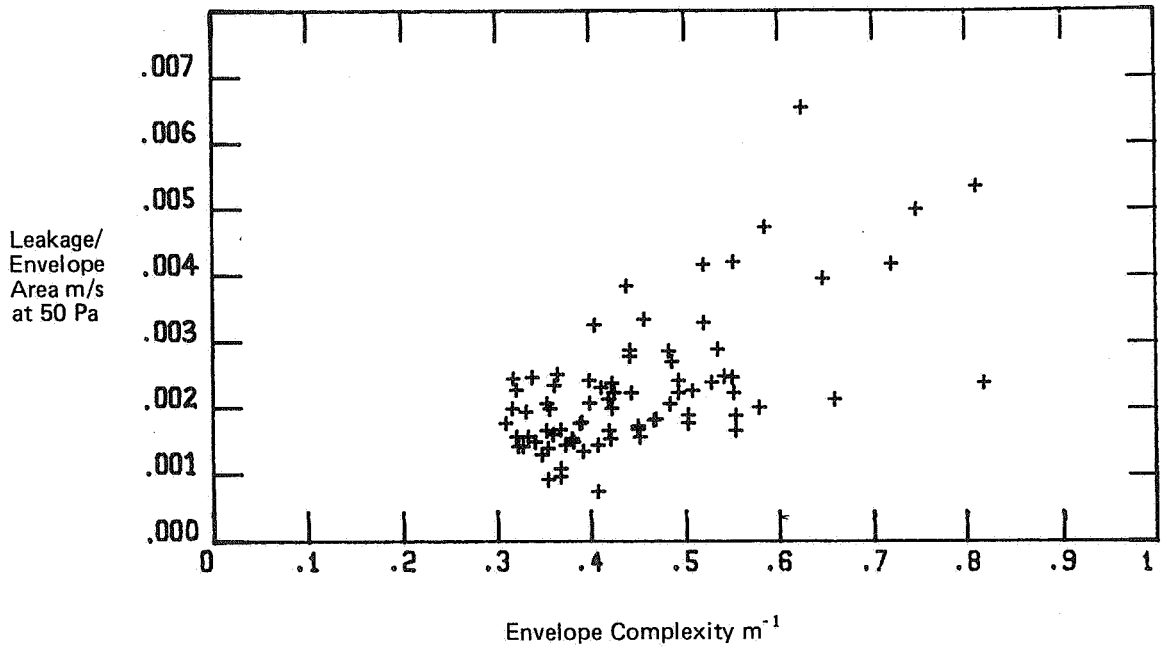


Fig 2: Measure of building envelope complexity against leakage/shell area at 50 Pa.

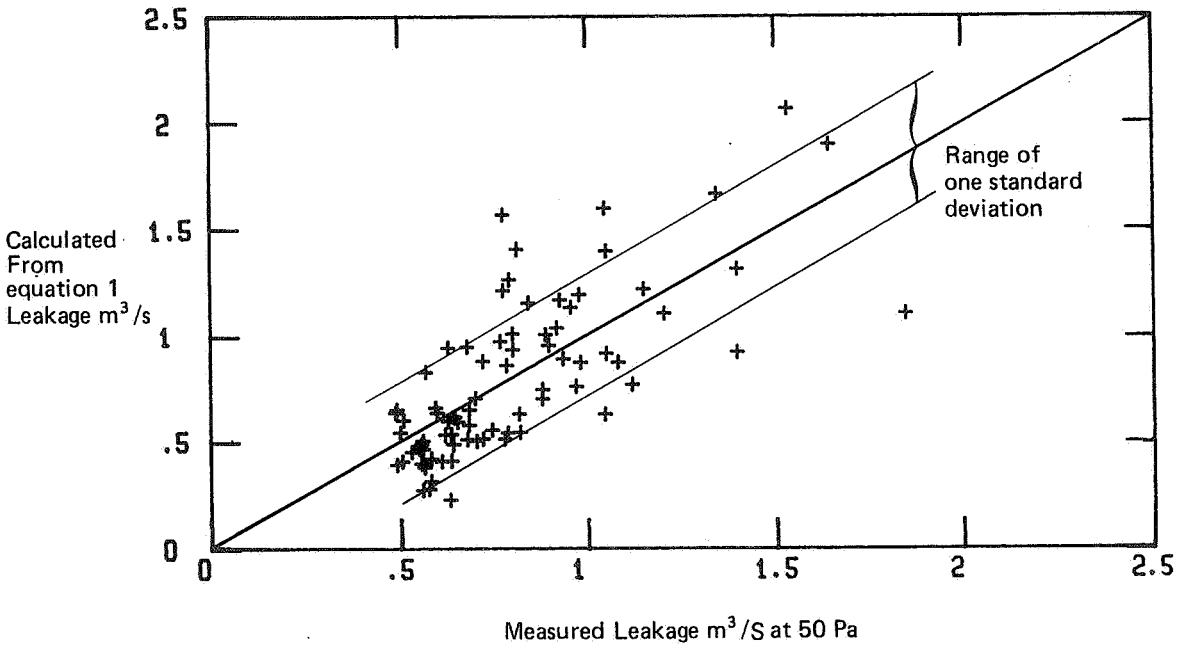


Fig 3: Measured leakage at 50 Pa against leakage correlated with a measure of building joint length. See equation 1.

Joint length is clearly more strongly related to airtightness than envelope area. Reversing the order of variables in the regression confirms that houses of large envelope area tend also to have longer joint lengths but that envelope area alone is a much less significant factor in the model. Over 50% of the variance in the leakage rate data is accounted for, yielding predictions within one standard deviation (0.3 m^3/s) of the measured value. Fig 3 shows the correlated component plotted against measurement, indicating that the resolution of the model does not extend much beyond giving an answer in terms of high, average, or low; but guidance of this sort may be useful in the future for distinguishing broad house types that could benefit from improved airtightness from those that need some form of ventilation control. Reinhold and Sonderegger (Ref 4) have calculated house airtightness values from tables of component leakage resistance. Their more detailed approach gave predictions falling within 20% (range of 1 standard deviation) of final measured values.

2.3 Regional and Cladding Material Effects

The 80 airtightness results are spread across three urban areas and two external cladding types. The cities Auckland, Wellington and Christchurch were chosen to cover a large range of the New Zealand climate with winter degree day values of 400 dd (base 18 ^oC) for Auckland in the north to 1100 dd for Christchurch in the south. The objective was to see whether local construction methods and materials have an influence on airtightness.

In some countries, masonry buildings are more airtight than those of timber construction. Kronvall Ref 5 has shown that concrete houses in Sweden are 46% tighter on average than those made of wood. The closest equivalent to concrete houses in New Zealand are those clad with a veneer of masonry. In Auckland and Christchurch the airtightness of houses with masonry and alternative cladding types were measured. With envelope area and crack length effects removed from the data, the adjusted mean leakage rates in Table 1 can be used to resolve regional and cladding type differences.

Location	Cladding Type	Adjusted Mean leakage rate in m^3/s at 50Pa	Standard Error of Mean
Auckland	masonry	.95	.10
	other	.89	.07
Christchurch	masonry	.76	.06
	other	.74	.10
Wellington	other	.76	.05

Table 1 Adjusted mean leakage rates in m^3/s at 50 Pa for three locations and two cladding categories.

Houses in Auckland are less airtight than those in Wellington and Christchurch but the difference is 20% and of limited practical importance. There is no evidence that masonry clad houses are more or less airtight than those clad with alternative materials.

3. INFILTRATION RATES

3.1 Method and Assumptions

An earlier comparison (Ref 6) of infiltration rates calculated using the LBL model (Ref 7) with measurements made using a tracer gas showed the calculation procedure to be as good as our ability to choose the appropriate wind exposure factor. Similar conclusions are drawn by Liddament and Allen (Ref 8) and Grimsrud Modera and Sherman (Ref 9).

A range of infiltration rates have been calculated using the LBL model, the building airtightness data presented in this paper and data on the way leakage openings are distributed around the envelope taken from (Ref 6). A reference building of median tightness was defined with a typical distribution of leakage openings. Hourly weather records, assumed indoor temperatures and wind exposure factors were then used to calculate infiltration rates averaged over a winter season.

3.1.1 Reference Building of Median Tightness

Beginning with the power law equation (2) for the leakage rate under test pressures, an effective leakage area can be defined by equation (3).

$$Q = C\Delta P^{n} \tag{2}$$

$$L = C\sqrt{\frac{\rho}{2}}\,(\Delta P)^{(n-\frac{1}{2})} \text{ for } \Delta P = 4\text{Pa} \tag{3}$$

where
- L = effective leakage area m^2
- Q = volume flow rate m^3/s
- n = exponent
- ρ = density of air kg/m^3
- ΔP = pressure difference across envelope Pa

Effective leakage areas were calculated for 80 houses using equation (3). The median effective leakage area is $0.71 m^2$ and the 10 and 90 percentile values are $0.41 m^2$ and $1.25 m^2$ respectively. Data from Ref 6 were used to assign 20% of the effective leakage area to windows and doors with the remainder area weighted to walls, roof and floor. This generalisation allows wind and stack parameters of the LBL model in equation (4) to be considered independent of building type with all the variation in airtightness characteristics lumped into the effective leakage area.

$$Q = L\,(fs\,\Delta T + fw\,V^2)^{\frac{1}{2}} \tag{4}$$

Q = infiltration rate	m^3/s
L = effective leakage area at 4 Pa	m^2
ΔT = indoor-outdoor temperature difference	K
fs = stack parameter	
V = wind speed at the house	m/s
fw = wind parameter	

Infiltration rates for the reference building can then be adjusted to suit another building in the same climate and exposure class by scaling in the proportion of the effective leakage areas. The reference building has national average values for the floor area and perimeter length of 135 m^2 and 56 m respectively.

3.1.2 Indoor Temperature Profiles

Calculation of stack induced leakage requires a knowledge of both indoor and outdoor temperatures. Three indoor temperature profiles were modeled to represent heating regimes of continuous, intermittent and zero heating. The intermittent and zero heating regimes were based on temperature records made in occupied houses. Implementing these first involves calculating an indoor temperature for the unheated case which floats on average 6 ^{o}C above outdoor temperature. The indoor temperature swings are phase delayed 3 hours and damped by a factor found appropriate to light-weight houses. In the intermittent heating regime the minimum temperature between 5 and 10pm is 18^{o}C and in the continuously heated case the indoor temperature is 20^{o}C at all times.

3.2 Calculated Infiltration Rates

Average infiltration rates have been calculated for a 4 month (May-August) winter season using hourly weather records (Ref 12). Average air change rates are given in Table 3 for the reference house of median tightness located in 4 cities and exposed to the wind in varying degrees. The wind exposure classes are the same as those given in (Ref 9) except that the local shielding and terrain class numbers are taken to be the same. The exposure classes described in Table 2 encompass quite a wide range and it is likely that most houses will be either medium exposed or medium sheltered.

Name	Description
Exposed	Flat terrain with few obstacles and well separated from other buildings.
Medium exposed	Rural area with low buildings some obstruction within two house heights.
Medium sheltered	Urban or industrial area and obstruction around most sides of building.
Sheltered	Center of city with large obstruction surrounding perimeter within two house heights.

Table 2 Description of wind exposure classes

Table 3 shows that the inter-city effect on the infiltration rate is less than that of altering the wind exposure class. Similarly, changing the indoor temperature from a relatively high standard of continuous heat to the unheated case has only a small effect on the infiltration rate, although it will be more important as far as heat loss and condensation control are concerned, see Table 4).

City	Exposed	Medium exposed	Medium sheltered	Sheltered
Auckland	0.61	0.46	0.33	0.25
Wellington	0.72	0.54	0.39	0.28
Christchurch	0.56	0.46	0.37	0.32
Invercargill	0.63	0.50	0.40	0.33

Table 3 Winter average infiltration rates in air changes per hour for a house of median tightness and constant indoor temperature of 20 ^{o}C.

The distribution of daily infiltration rates is shown in Fig 4 and Fig 5 for the house of median tightness in Wellington and Christchurch. While the mean infiltration rates are comparable, the distributions (which are characteristic of local weather patterns), are quite different.

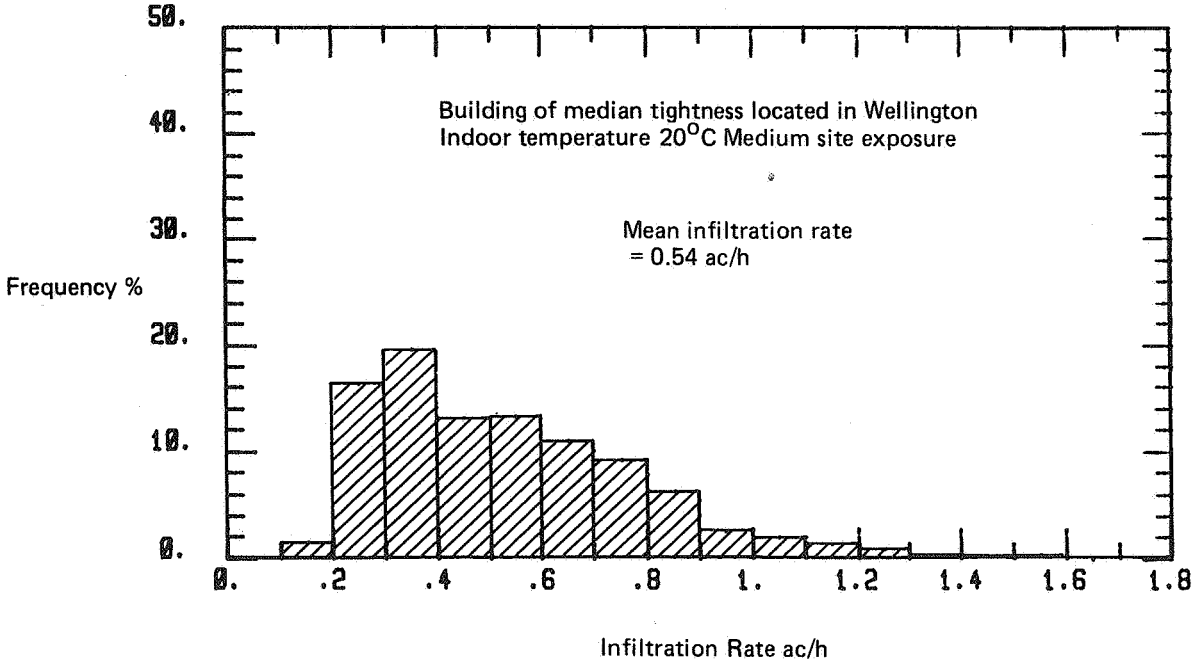


Fig 4: Frequency distribution of day average infiltration rates for a winter season

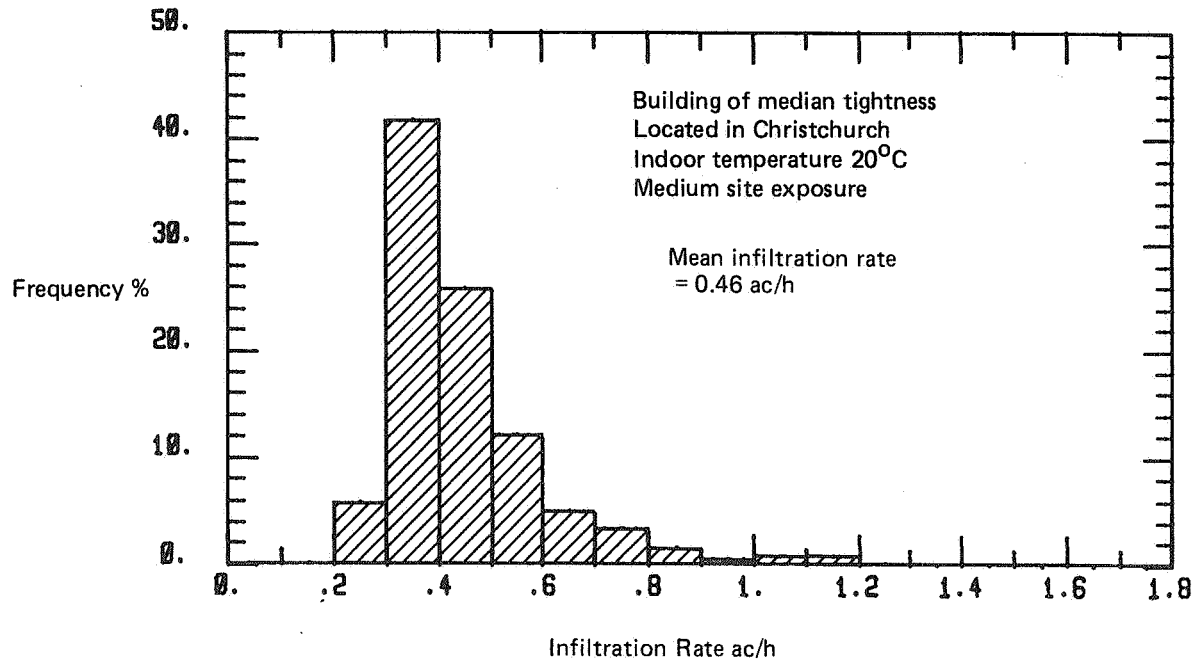


Fig 5: Frequency distribution of day average infiltration rates for a winter season

An indication of the range of infiltration rates in houses can be gained by scaling the distribution of airtightness by the ratio of effective leakage areas as outlined in section 3.1.1. Examples are given in Figs 6,7, and 8 of the distribution of winter infiltration rates for houses over the full range of airtightness but with fixed medium exposure. In fact the wind exposure will vary with house location and this will broaden the distribution slightly but not undermine its value in indicating the range of minimum infiltration rates. Since it is universal practice for home owners in New Zealand to add extra ventilation by opening windows, the infiltration rates in Figs 6,7 and 8 must be regarded as the lowest that can be achieved in existing houses and not representative of actual house ventilation rates. Another factor not accounted for is the action of combustion appliance flues which can drive additional infiltration. For the moment, air leakage through vents, flues and open windows is ignored because it is the uncontrolled infiltration or the 'lower infiltration limit' that is of interest.

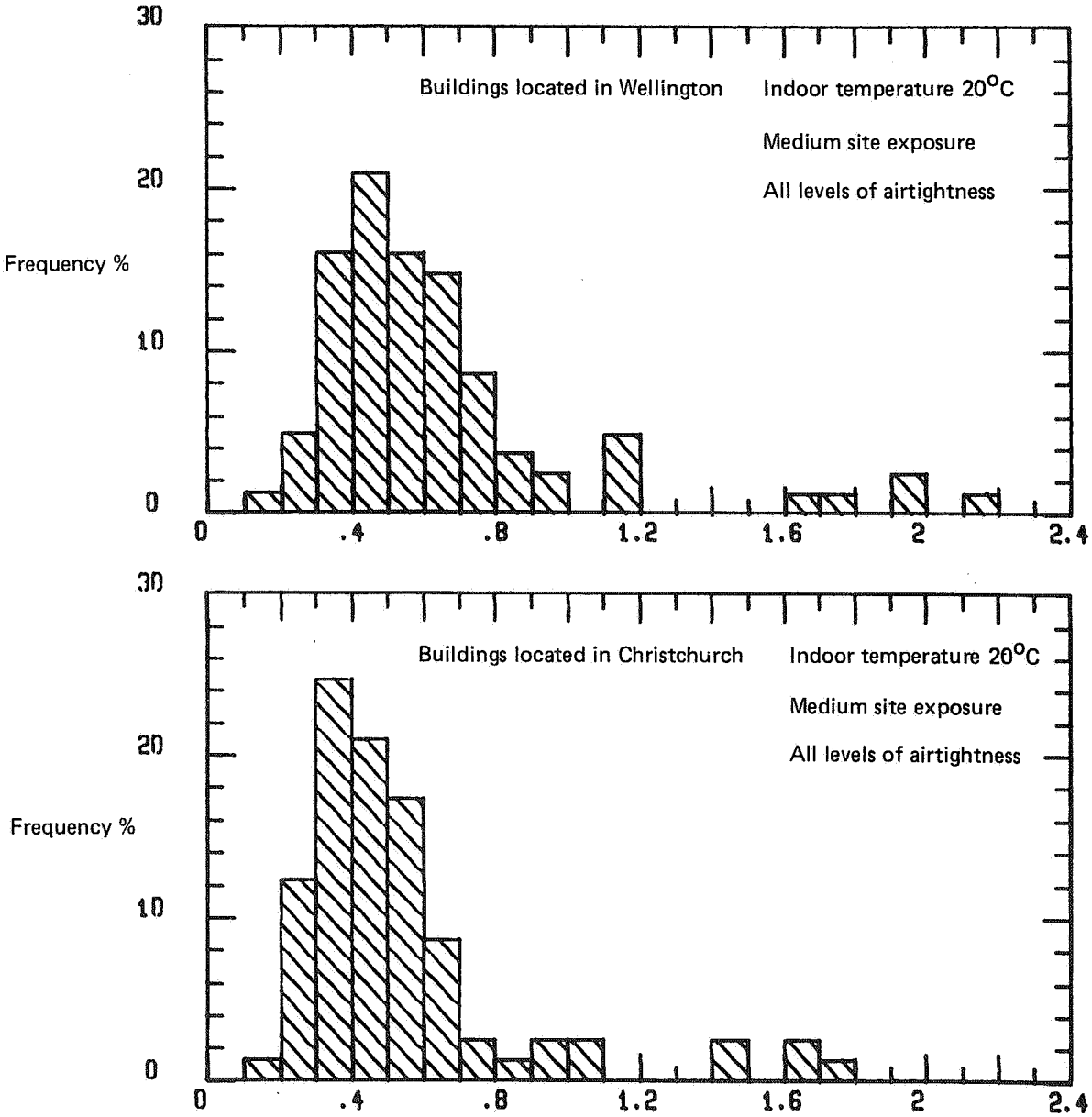


Fig 6 and 7 : Mean winter infiltration rates for buildings over the entire range of air tightness but with fixed wind exposure class.

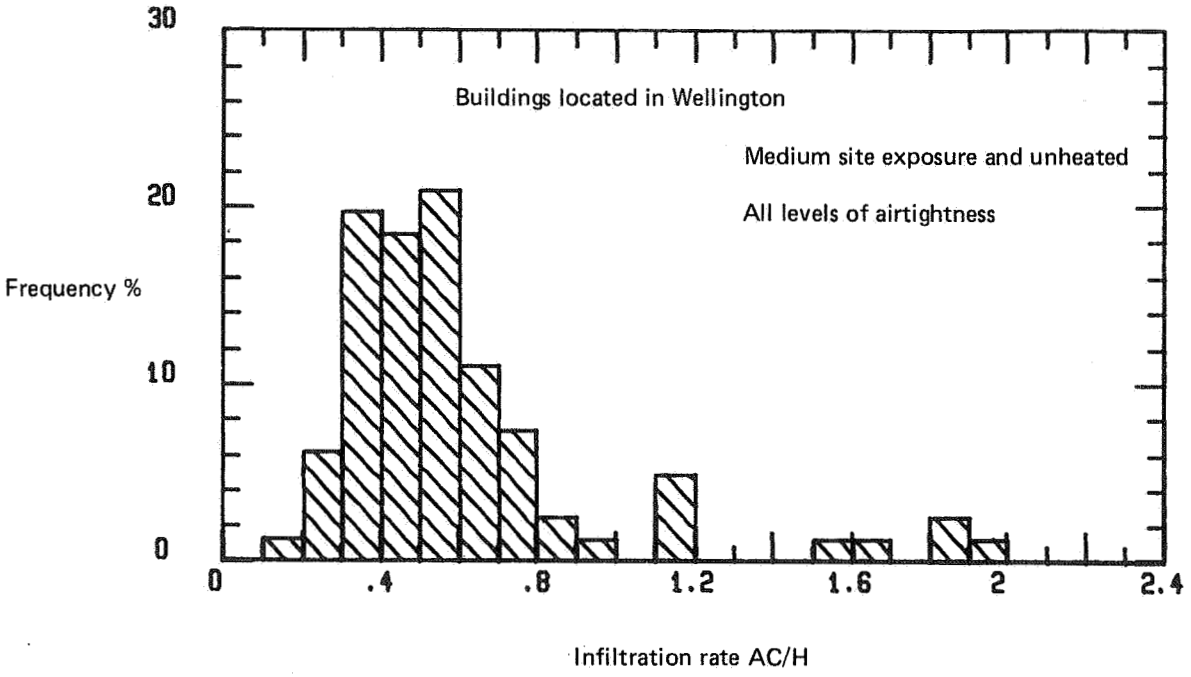


Fig 8 : Mean winter infiltration rate for buildings over the entire range of air tightness but with fixed wind exposure class.

3.3 Space Heat Loss through Infiltration

Average infiltration heat losses have been calculated and presented in Table 4. The data applies to the reference building of median tightness with two levels of site exposure and three alternative standards of heating.

Location	Standard of heating					
	Continuous		Intermittent		No Heating	
Auckland	0.40	0.30	0.32	0.23	0.32	0.23
Wellington	0.61	0.44	0.41	0.28	0.37	0.25
Christchurch	0.73	0.61	0.36	0.29	0.28	0.21
Invercargill	0.83	0.68	0.41	0.32	0.30	0.23
Wind Exposure	ME	MS	ME	MS	ME	MS

Wind Exposure classes ME=Medium exposed
MS=Medium sheltered

Table 4 Average infiltration heat loss in Kw for a house in winter

These heat losses can be placed in perspective with conduction heat losses through walls roof and floor. For the reference building heated continuously, medium exposed and insulated to the standard required in new houses (see heading of table 5), air infiltration makes up 15% of the total fabric heat loss in all four cities. For a house of loose construction at the 90 percentile of airtightness the fraction rises to 25% and for a house of tight construction at the 10 percentile it is 10%. In practice there will be an additional component of user-supplied ventilation but in these calculations it is not considered part of the building fabric loss. Mean winter day heat loss profiles due to infiltration are given in Figs 9 and 10 for the reference house located in four cities. The data show that heat loss is more sensitive than the infiltration rate to indoor/outdoor temperature differences.

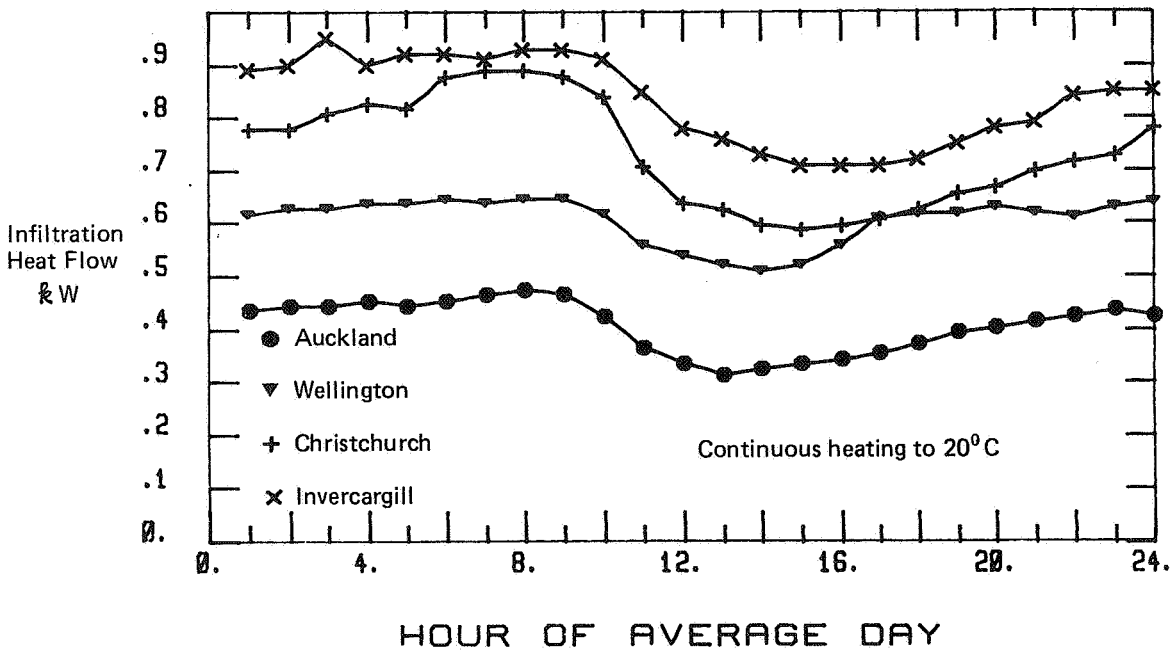


Fig 9: Winter average infiltration heat loss for a reference building sited with medium wind exposure and heated continuously to 20° C

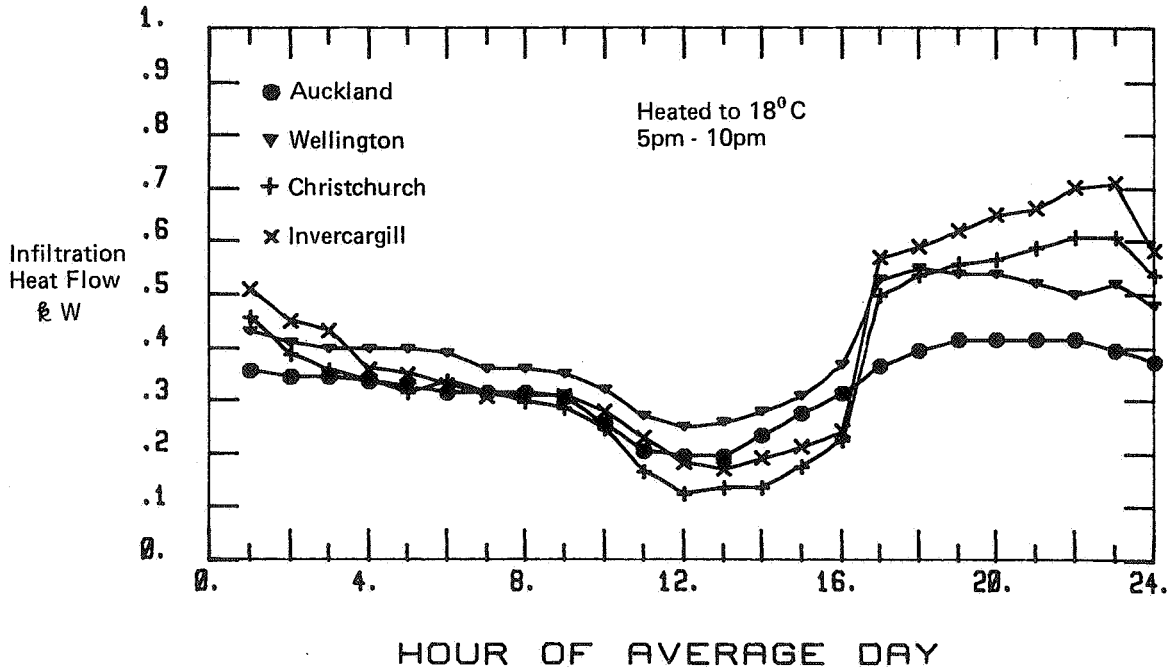


Fig 10: Winter average infiltration heat loss for a reference building sited with medium wind exposure and heated intermittently

4. VENTILATION TO CONTROL MOISTURE

In this section an attempt is made to relate levels of mould/condensation observed in houses with the measured airtightness.

4.1 Indoor Moisture Control

The contaminant most likely to place a lower limit on desirable ventilation rates is moisture. Trethowen (Ref 10) has calculated moisture release rates in houses and balanced these against removal rates in ventilation air and by diffusion. Ventilation is the more important process but the optimum air change rate depends very much on the moisture release rate and the standard of heating. Outdoor relative humidity is generally quite high in the main residential areas in New Zealand, for over half the time it is over 80%. Consequently the moisture pick up capacity of ventilation air is sensitive to the indoor/outdoor temperature difference. Ventilation rates sufficient to avoid mildew on walls have been calculated for a wide range of conditions but for the purposes of this paper a limited range of data is given in Table 5 based on the following assumptions.

Moisture emission rate g/s	high	low
bedrooms	0.03	0.008
kitchens	0.3	0.07

Relative humidities - Outdoor relative humidity is 90%, a value exceeded for 20-50% of the time at urban meteorological stations. The relative humidity at which mildew will grow is taken to be 90% at the wall surface temperature.

Thermal insulation	Roof R=1.9, Walls R=1.5, Floor R=1.3 m^2K/W
Standard of heating	As described in Section 3.1.2
Room size	The room volume is $36m^3$

	Low Moisture Load			High		
Outside temperature ^oC	5	10	15	5	10	15
	Required Ventilation rates in air changes/hour					
Bedroom						
unheated	0.3	0.2	0.2	1.1	0.8	0.6
continuously heated	0.1	0.1	0.1	0.4	0.5	0.5
Kitchen						
unheated	2.6	1.9	1.4	11.0	8.2	6.0
continuously heated	0.8	1.0	1.0	3.5	4.5	4.5

Table 5: Ventilation rates (ac/h) needed to avoid mildew on walls for given conditions.

Ventilation air sufficient to prevent surface mildew can not always be supplied by infiltration. In bedrooms with a low rate of moisture release or a high standard of heating, natural infiltration will be normally sufficient but in wet areas such as a kitchen or bathroom, additional ventilation will usually be necessary.

4.2 Survey of Moisture Problems

Moisture problems in houses were surveyed in 1972 by Trethowen (Ref 11). House age and external cladding types were recorded and found to have little influence on the incidence of moisture problems. During the survey of house airtightness in Christchurch and Wellington, moisture problems were again surveyed to look for association with airtightness. The questionnaire in Table 6 was completed by the home occupier and a moisture score worked out as the total of the highest bedroom score and the lounge score in two categories 'mould on wallpaper' and 'condensation on windows'. For a house free from condensation problems the condensation score is 4 and for severe dampness problems it is 16.

MOULD ON WALLPAPER						
Severity	Lounge	Score	Bedroom 1	Bedroom 2	Bedroom 3	Score
None		1	*	*		1
slight	*	(2)			*	(2)
common		3				3
severe		4				4
CONDENSATION ON WINDOWS						
Severity	Lounge	Score	Bedroom 1	Bedroom 2	Bedroom 3	Score
none		1	*			1
condensate forms but doesn't run		2		*		2
condensate forms and runs	*	(3)			*	(3)
pools of water on sills and floors		4				4
				Total moisture score 10		

Table 6 Example of a filled-in moisture questionnaire

The average moisture scores for Auckland and Christchurch were 6.6 and 5.8. respectively, supporting the earlier conclusion of Trethowen (Ref 11) that moisture problems were more prevalent in warmer regions of New Zealand. For both locations there is no useful correlation between the fan-induced leakage rate and the moisture score. Data for both cities have been pooled in Fig 11 to show that occupants of comparatively tight houses are no more likely to report surface condensation problems than occupants of houses of loose construction.

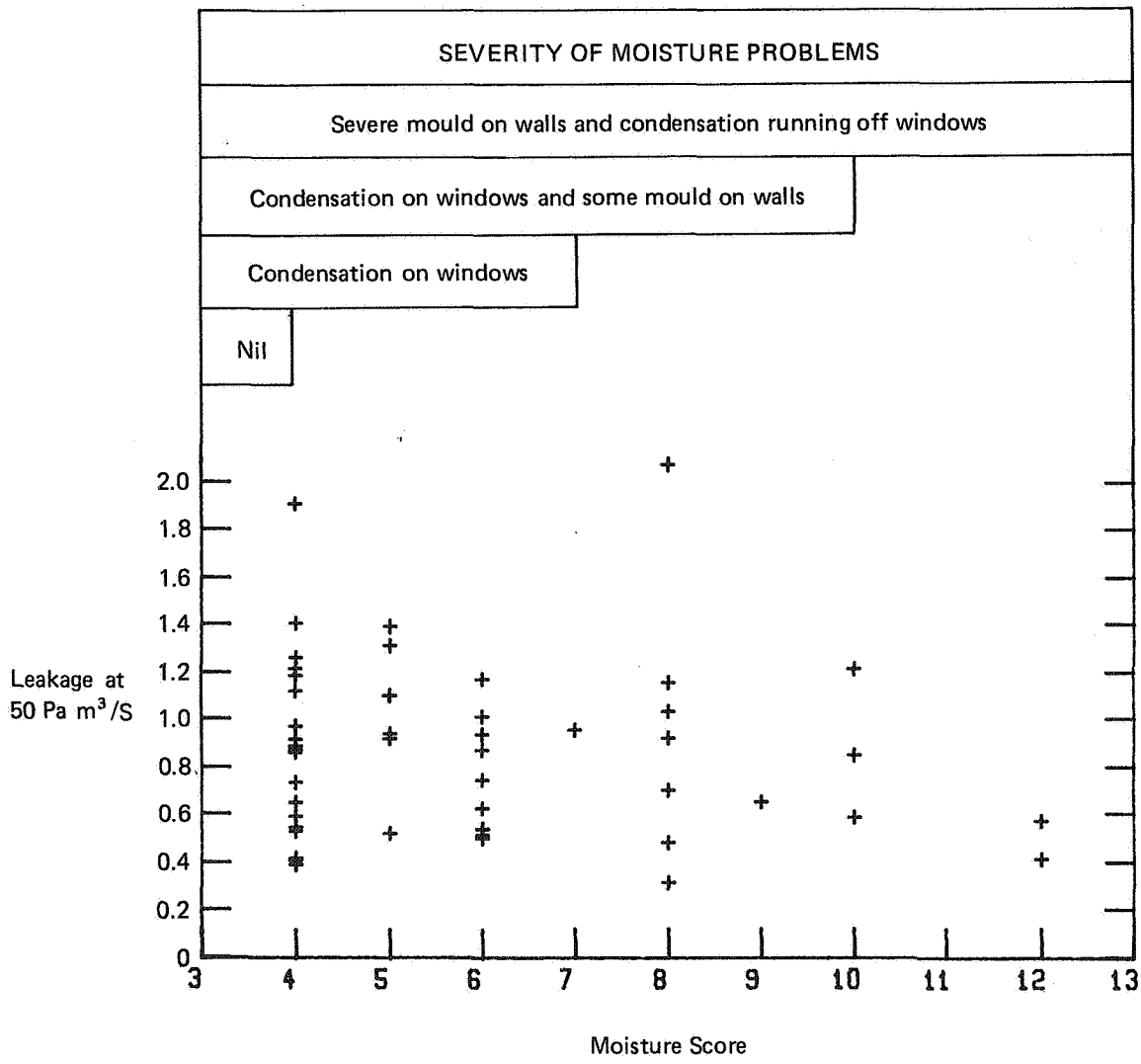


Fig 11: Leakage rates at 50 Pa for houses in Christchurch and Auckland against moisture scores

This survey result is consistent with the observation that even in houses of comparatively loose construction there will be times when the infiltration rates given in Table 3 will not provide sufficient ventilation (see Table 5). This will occur when moisture release rates, low indoor heating and a lack of supplementary ventilation coincide to an unfavourable extent. Because these aspects of house management are so important and so individual it is not possible to say that infiltration rates are generally excessive or insufficient for moisture control, except for wet areas such as kitchens and bathrooms for which it can be said that infiltration alone is unlikely to provide sufficient ventilation.

4.3 Options for Improved Moisture Control

A number of strategies exist for removing moisture from room air. Some require additional hardware to dehumidify or regulate the supply of air through a heat exchanger, together with some degree of improved airtightness. These options have not yet been investigated in detail. For the moment it is assumed that houses will continue to be constructed in the same airtightness range and operated with extra ventilation from open windows. In this case there are a number of strategies which help reduce the likelihood of mildew and other surface dampness problems.

1. A uniform standard of insulation in wall, ceilings and floor will help raise the indoor dew point and interior surface temperatures to discourage condensation.

2. Ventilators close to the point of moisture release in kitchens and bathrooms reduce the need for very high room ventilation rates. Popular examples are fan extraction hoods and window-mounted extraction fans.

3. Single glass windows with a catch and drain channel can allow condensation to escape outside. The amount of moisture removed this way is small compared to ventilation but condensation on windows can then be more easily tolerated.

5. CONCLUSIONS

On the basis of airtightness and air infiltration rate measurements, infiltration rates have been calculated for houses with windows doors and vents closed. This defines a lower limit for ventilation and allows the following comments to be made.

Airtightness

1. The airtightness of houses tested in the 0-5 year age group falls largely (93%) in the range 5-16 ac/h at 50 Pa. A significant proportion (40%) are tighter than 8 ac/h at 50 Pa.

2. A large part (50% of the variance) of building airtightness correlates with a measure of joint length. This is a simple summation of boundary edge lengths between floor, wall and ceiling and it can be used as a guide to whether a building is likely to have high, medium or low airtightness.

Infiltration rates

3. Calculated infiltration rates are sensitive to the building airtightness and the degree of exposure to wind. They are less sensitive to the indoor temperature and to the city in which the building is located.

4. Calculated mean season infiltration rates generally fall in the range 0.2-1.0 ac/h. Unusual combinations of airtightness and wind exposure are required to give winter infiltration rates outside this range.

5. The infiltration load on space heating has been calculated for an insulated house ranging between the 10 and 90 percentile levels of airtightness. It represented from 10 to 25% of the fabric heat loss.

6. There will be times in most houses when infiltration alone gives insufficient ventilation to control condensation. In general, the standard of heating and the extent of supplementary ventilation determined by the building occupier, will have more control over condensation than will air infiltration.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 3

VENTILATION RESEARCH AND CHARACTERIZATION IN THREE TYPES OF RESIDENCES

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VENTILATION RESEARCH AND CHARACTERIZATION IN THREE TYPES OF RESIDENCES

SYNOPSIS

Pacific Power and Light Company and Battelle PNW Laboratories have completed a project which investigated residential ventilation rates. The results presented in the report discuss evaluation of methods used to measure ventilation rates, the behavior of ventilation rates in residences and the comparison of ventilation rates among home construction types.

The perfluorocarbon tracer gas decay technique for measuring ventilation rates was concluded to be the best method used during the testing. This technique was easy to perform and resulted in highly accurate data when compared to a recognized standard. It was also found that fan depressurization results overpredicted air exchange rates in all three homes. The ventilation rate results of the three homes indicated the energy-saver home had the lowest rate, followed by the unoccupied home with the next higher, and the pre-weatherized home with the highest rate.

1.0 INTRODUCTION

Air exchange between a home and the surroundings has come under increasing scrutiny. This is a direct result of the interest in reducing space heating consumption by weatherization and infiltration reduction efforts. Up until recently, little attention was given to quantifying the existing ventilation rate in the home or, what the resultant ventilation rate was after energy conservation measures were applied. There is a greater concern now about the ventilation rates of homes and the impact of conservation measures and efficient building design on those ventilation rates. However, the task of determining the ventilation rate of the home exists. And, even if a ventilation rate for the home was measureable given codes or standards are not in place which specify a target ventilation rate. Understanding ventilation rates remains a problem of measurement technique, evaluating what ventilation rate (minimum) is needed and, obtaining the correlation that relates the two variables.

This paper describes a research project undertaken in 1982 by the Pacific Power & Light Company and its Contractor, Battelle Northwest Laboratories to investigate residential ventilation rates. The primary objective of the study is to evaluate the impact upon ventilation rates resulting from:

(a) infiltration weatherization measures,

(b) operation of an air-to-air heat exchanger, and

(c) occupancy

A second objective of the study is to evaluate present techniques for determining or monitoring ventilation rates in homes.

2.0 PROJECT PLAN

The test plan developed for this project investigates ventilation rates of three different homes for a period of two years. Selected homes were chosen which would satisfy the primary study objective. One home is a standard construction home which would receive weatherization. A second home is an energy efficient home and would have an air-to-air heat exchanger installed. The third home is a vacant home which would be occupied in the second year of monitoring. The results available from the first year's data would provide an evaluation of methods used for determining ventilation rates, an analysis of the dynamic behavior of ventilation rates in residences and comparison of ventilation rates among residential construction types.

The first year of monitoring gathered data in the "before" condition, i.e., pre-weatherization, pre-air-to-air heat exchanger and, unoccupied. The second year of monitoring recorded data after the modifications to the homes had been made. The focus of the monitoring period falls during the time of year when residents are indoors the most often and when the house is sealed off from the outdoors.

Data collected at all three homes is identical in format and can be categorized into three areas: electrical end-use, meteorological and environmental and, ventilation data. The ventilation data consists of tracer gas monitoring using SF_6 and perfluorocarbon in parallel. Fan pressurization tests were run for comparison to the tracer data and to evaluate modifications made to the weatherized home. Hourly meteorological and environmental data consisting of outdoor temperature, windspeed, wind direction, horizontal radiation, indoor air temperature and indoor relative humidity were monitored in all homes. Electrical end-use data was recorded for various circuits and major appliances in the home as well as the total electrical.

3.0 DESCRIPTION OF TEST HOUSES

The test houses were chosen to represent the specific construction conditions affected by infiltration

reducing weatherization measures, energy efficient construction techniques, and occupancy. The three homes in this project are an existing pre-weatherized home ("weatherized home"), an energy efficient new home ("energy saver home"), and an unoccupied home ("control home"). A description of each home and its characteristics is given in the following sections.

3.1. WEATHERIZED HOME

The weatherized home is a wood frame type residence built in 1974. The home is approximately 920 square feet (85.47 meters^2) of heated floor area constructed on a crawlspace with a pitched roof enclosing an attic space. The home design is three bedrooms, two baths, kitchen, and adjoining living room/eating area. There is an attached garage as well. This home is typical of the construction quality during the time it was being built. There are minimum insulation levels in the ceiling and walls and the windows are single-pane, aluminum casing.

A distributed electric baseboard heating system and living room fireplace provides space heating in the home. The home is equipped with exhaust fans in the bathrooms and above the kitchen electric range. There is no air conditioning system in the home.

A young family of three occupies the home which is located in Portland, Oregon, USA in a large residential area.

3.2 ENERGY SAVER HOME

This passive solar home was built in 1982 and incorporates energy efficient design features to reduce its space heating needs. The home is a ranch style design with wood frame construction including additional amounts of thermal storage mass. The wall construction is 2 X 8 framing with an R-30 insulation batting, one inch styrofoam insulating board, one inch sprayed foam and a 6-mil infiltration barrier. The heated floor area of the home is about 1,370 square feet(127.27 meters^2), excluding an attached garage and solarium air lock entry. The ceiling is a vaulted design with an R-38 insulation level. The floor is built on a crawlspace with R-30 insulation under the floor.

This home is two bedrooms and two baths and has electric forced-air heating. The home is equipped with exhaust fans in the two bathrooms. A young couple occupies the home which is located in Bend, Oregon in a high desert, open residential area.

3.3 CONTROL HOME

This is a three bedroom, two bath home with 2 X 4 wood frame construction over a full crawlspace. This ranch style design was built in 1974 and has about 1,470 square feet (136.56 meters^2) of heated floor area and an attached garage. It is located in a residential area northeast of Vancouver, Washington, USA. Minimum levels of insulation were installed during original construction. Floor insulation and storm windows were added several years before the testing at this home.

The heating system in the home is principally an overhead electric radiant system. A woodstove is used in the family room as a space heating device and a fireplace is located in the living room but does not receive any use. Exhaust fans are located in both bathrooms and above the kitchen stove. The home has not been occupied at any time during the first phase of monitoring.

4.0 METEOROLOGICAL, ENVIRONMENTAL AND ELECTRICAL DATA

All of the test homes were instrumented to gather data on outdoor and indoor conditions as well as energy use. This was desirable because infiltration is directly related to space heating load in the home. Outdoor measurements of air temperature, wind speed, wind direction and horizontal insolation were taken using a 10-meter weather station. These data were summarized and stored as hourly data.

Indoor air temperature and relative humidity data were recorded on an hourly basis. Electrical energy use in each home was recorded using sub-metering and summarized into hourly data. All of the above measurements were recorded using a programmable data logger. This data logger gathered data for the entire year.

5.0 AIR EXCHANGE RATE MEASUREMENTS

The air exchange rate in each of the three residences was measured during the heating season months of 1983-1984 using tracer gas. Both sulfur hexafluoride (SF_6) and perfluorocarbon (PFT) tracer gas were used and the air exchange rate was determined by measuring the decay of the tracer gas released in the residence. The decay of sulfur hexafluoride was measured using a Systems Science and Software portable gas chromatograph with an electron capture detector which is sensitive to sulfur hexafluoride at concentrations as low as 1 part per billion. Periodic samples of the inside air produced a plot of SF_6 concentration versus time over several hours. The slope of the line

for this plot is the air exchange rate in the residence during the time of the measurement.

The principle and techniques of measuring air exchange rate using perfluorocarbon tracer are described elsewhere 1,2. The perfluorocarbon is released from source capsules at a constant rate at a given temperature and the air-borne perfluorocarbon is captured using small capture tubes (capillary-type tubes) filled with a solid sorbent.

Perfluorocarbon was also captured using a Gillian[1] Programmable Atmospheric Tracer sampler (PATS) deployed in each residence. The PATS can be programmed to measure infiltration in a residence from 1-hour to several hundred hour periods for each of its 23 tubes.

Several time periods were chosen for measuring air infiltration that were designed to take advantage of potential large inside outside temperature difference or high windspeed or both. This is why periods during the middle of winter (where high inside-outside temperature differences would be expected) and during the beginning of the spring season (where high winds would be expected) were chosen.

6.0 FAN DEPRESSURIZATION TESTS

Fan depressurization tests were performed on each of the three homes. The tests collect data on the induced ventilation of the residence. The fan depressurization is performed by forcing a flow of air out of the home through an orifice. The exiting air volume results in a pressure gradient which causes air to enter the home through leakage paths in the home's envelope. A series of pressure gradient data points are generated by varying the fan speed across the orifice. An air density normalizing technique is employed during the analysis of this fan depressurization data to allow a better comparison of the results. A summary of the fan pressurization tests are presented in Table 1.

It is important to note that using this methodology to induce a ventilation is extremely useful for identifying leakage paths within homes. It does not, however, represent real conditions imposed upon a home. A wind induced ventilation rate in a home causes a pressure gradient between the windward side(s) of a home and the leeward sides of the home.[2] Wind-induced infiltration is a dynamic variable and involves complex analysis.

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[1] Gillian Instrument Corp, Wayne, New Jersey.

[2] It is noted here that a thermal stack component for natural ventilation exists in the overall ventilation rate.

TABLE 1. Summary of Fan Depressurization Testing

	Test Homes		
	Weatherized	Control	Energy Saver
Floor Area m^2(sq ft)	85(917)	129(1387)	142(1528)
Volume m^3(cu ft)	200(7059)	295(10415)	406(14340)
Pressurization ELA* cm^2(sq in)			
Trial #1	265.0(41.08)	415.0(64.33)	350.0(54.25)
Trial #2	265.0(41.08)	415.0(64.33)	350.0(54.25)
Trial #3	285.0(44.18)	390.0(60.45)	350.0(54.25)
Trial #4	285.0(44.18)	390.0(60.45)	350.0(54.25)
Depressurization ELA cm^2(sq in)			
Trial #1	385.0(59.68)	405.0(62.78)	455.0(70.53)
Trial #2	385.0(59.68)	405.0(62.78)	455.0(70.53)
Trial #3	410.0(63.55)	425.0(65.88)	455.0(70.53)
Trial #4	410.0(63.55)	425.0(65.88)	455.0(70.53)
Average Depressurization Air Change per Hour (ACH)**	0.50	0.42	0.31

*ELA is Equivalent Leakage Area.

** Depressurization ACH is defined here as the air flow (cubic feet per minute) divided by the interior house volume.

6.1 FAN DEPRESSURIZATION ANALYSIS

Results from the fan depressurization data provide a "snap-shot" picture of the leakage potential of each home. The fan depressurization analysis looks at the artificially induced leakage conditions at 0.016 inches of water (4 Pa) pressure drop between the inside and outside of the house. The selection of 0.016 inches of water (4 Pa) corresponds to conditions that represent average outdoor wind effects.

The equivalent leakage area (ELA) results of each home would seem to suggest that the energy saver home has the greatest amount of leakage associated with it. However, this result is misleading since the volume of the energy saver home is also the greatest and, therefore, it has more wall surface area involved and a lower house air change per hour (ACH) value. This later result is borne out by the value under depressurization ACH. The depressurization ACH represents a uniform leakage across all walls at the induced pressure gradient. Therefore, by evaluating ACH with only depressurization data, you may be masking any opposite or neutral effects encountered under actual conditions where the windward walls contribute to infiltration and leeward walls contribute to exfiltration. The variation of ELA results between pressurization and depressurization in Table 1 suggests that the leakage paths behave differently under the two induced conditions. Therefore, the results obtained from pressurization and the results obtained from depressurization should not be combined in a simple fashion.

The repeatability of the measurements is examined by looking at the individual trials (one set of four measurements either pressurization or depressurization). In each of the homes, measurements #1 and #2 didn't vary from #3 and #4 by more than 7.5 percent. Measurements #1 and #2 were performed in the morning hours, while #3 and #4 were collected in the afternoon. Considering the percent error attributable to the various instrumentations, this data would suggest a good degree of repeatability in measurements of pressurization or depressurization for a specific home.

The fan depressurization does permit location of gross leakage paths of the home. This procedure, using smoke sticks, was used to identify leakage sources to be sealed in the weatherized home at the end of the first year's testing. The same procedure was used in all the homes.

7.0 RESULTS

The data presented in Table 2 was taken when the houses were in the "before" condition as discussed earlier. This data is referred to in the ANALYSIS AND DISCUSSION OF

RESULTS which focuses on the correlation of measured air exchange rates with the meteorological factors of temperature and windspeed at each residence.

The air exchange rates measured in the three residences using the various measurement techniques are summarized in Table 2. Average values are given for the air exchange rates. In addition, the average values of wind speed and inside and outside temperature difference for the time periods indicated are given in the table as taken by the meteorological sensors at each residence.

8.0 AIR EXCHANGE RATE CORRELATIONS WITH WIND SPEED AND TEMPERATURE

The nonlinear dependence of air exchange on temperature difference and wind is usually modeled as a linear relation in the equation:

$$I(\text{air exchange}) = A(\text{constant}) + B(\text{constant})\,\Delta T + C(\text{constant})V^2$$

where ΔT = inside-outside temperature, V = wind speed

Other equations have been used to fit or predict air exchange rate data, all of which are derivatives of this basic equation. Because the relation of infiltration rate and the wind and temperature is nonlinear, the constants A, B, and C will vary among houses due to the weather conditions during the infiltration measurements as well as because of variations in the structures themselves (including shielding). In order to obtain estimates of A, B, and C for any given house under any given tightness, many infiltration measurements over a large range of wind and temperature difference need to be taken. This was done for the three homes in this study. A linear regression analysis to find a fit to the equation and to determine the variable A, B, and C was performed for each house for the measurements of air exchange and windspeed and inside-outside temperature difference during the air exchange measurements. A "goodness of fit" or r^2 value was computed for each regression to see how well the equation could determine the variables and thus be able to yield air exchange values for the homes based upon these variables for each home.

This regression analysis was performed for the short term PATS measurements in each home as well as for the longer term CATS measurements combined with the average air exchange, average wind speed and average temperature difference values over the time period of the PATS analysis.

TABLE 2. Air Exchange Rates and Ventilation Rates in the Three Residences

Residence	Time Period	Measurement Method	Wind Speed, V M/S	Inside-Outside Temperature (C)	Air Exchange Rate (ACH)
Vancouver					
	1/30-2/6	PFT-PATS	0.85 ± 1.5	18.5 ± 2.3	0.27 ± 0.1
	1/29-2/7	PFT-CATS	0.43 ± 1.3	18.4 ± 2.2	0.29 ± 0.03
	1/29-2/13	PFT-CATS	1.05 ± 0.8	17.5 ± 2.2	0.27 ± 0.03
	2/26-3/5	PFT-CATS	0.93 ± 1.1	16.3 ± 1.9	0.20 ± 0.02
	2/7	SF6	0.0 ± 0.0	16.7 ± 1.5	0.29 ± 0.04
	3/5	SF6	0.25 ± 0.5	19.75 ± 2.36	0.35 ± 0.05
Portland					
	1/31-2/7	PFT-PATS	1.1 ± 1.4	13.5 ± 3.6	0.45 ± 0.17
	2/27-3/3	PFT-PATS	0.9 ± 1.0	12.9 ± 1.4	0.29 ± 0.03
	1/30-3/18	PFT-CATS	1.3 ± 1.1	13.0 ± 3.3	0.34 ± 0.01
	1/30-3/5	PFT-CATS	1.2 ± 1.1	12.0 ± 3.1	0.28 ± 0.01
	1/30-2/8	PFT-CATS	1.8 ± 1.6	13.4 ± 3.6	0.38 ± 0.04
Bend					
	11/22		2.8 ± 0.4	21.5 ± 1.9	0.31
	12/5-12/10	PFT-PATS	2.3 ± 1.1	18.8 ± 2.5	0.18 ± 0.14
	3/18-3/23	PFT-PATS	2.2 ± 0.6	17.7 ± 3.9	0.22 ± 0.1

The regression coefficients are all different for each set of regression analyses. The fit of the curve (r^2) for all three homes using the PATS data is very poor ranging from 0.01 in the Vancouver home to 0.36 in the Portland home. Taking the PATS exchange data for the Portland and Bend homes for only the quiescent periods of the day (2400hrs-0800hrs) and performing a linear regression analysis did not yield any better fit to the curve. The r^2 values were 0.01 and 0.00 for the Portland and Bend homes respectively. The fit of the curve using the average of the PATS data combined with the CATS data, which are both longer term measurement data (greater than 5 days average) yields a much better curve fit in the Vancouver and Portland homes. The r^2 value for these data are 0.84 in the Vancouver home and 0.69 in the Portland home. No long term CATS measurements were taken in the Bend home and not enough CATS data was taken to average for the long-term regression analyses.

The empirical equation for infiltration that gives the best fit for the regression analysis (largest r^2 value) can be used to predict infiltration given the temperature and windspeed parameters. This was done for the Vancouver home for the days in which SF_6 decay analyses was performed to measure the infiltration. The observed infiltration on 2/7 from SF_6 decay analysis was 0.31 ACH; the predicted infiltration using the empirical equation is 0.29 ACH. The average relative error is 6%. The observed infiltration on 3/5 from SF_6 decay analyses was 0.23; the predicted infiltration using the empirical equation is 0.35 ACH. The average relative error is 52%.

Air infiltration was also predicted for the Bend home for the period when the blower door measurements were made by using the best-fit empirical equation. The Bend home is chosen for this analysis because it is the only home for which temperature and windspeed data are available on the same day that the blower door test was performed. For the Bend home, the measured air exchange from the blower door measurements on 11/22 was 0.31 ACH; the predicted air exchange for that day is .23 ACH. The average relative error is 26%.

9.0 OBSERVATIONS AND CONCLUSIONS

The experiences in measuring air exchange rates in these three residences led to the following observations and conclusions about the use of the different tracer gases and measurement techniques.

The use of SF_6 as a tracer gas combined with onsite analysis is a sensible approach to measuring air exchange rates in unoccupied structures or in occupied structures

where there is freedom to move about and disperse and collect the tracer sample. Access to the residence must be gained several hours prior to the measurement of SF_6 decay so that the gas can be released and to allow time for complete mixing in the structure. Although not done in this study, fans or the HVAC system of the residence can be used to mix the gas. The equipment used in this study to perform the SF_6 tracer analysis onsite is somewhat large and would need to be set up in an unused space in the residence. In the case of the Vancouver house, the kitchen was used for the analysis equipment since the house was unoccupied.

The use of SF_6 decay for air exchange rate determination is a time-tested and highly accurate method. It will yield results that are accurate within $\pm$10% of the true air exchange in the structure over short (hours) or long (several hours) time periods. However, a trained technician must be present to perform the analysis and interpret the results. The air exchange rate determination is available almost instantaneously using SF_6 tracer and this method can provide a valuable and valid check on the results of other techniques used to determine air exchange rate. This was the case for the Vancouver residence where the SF_6 decay data was used as a check on the accuracy of the PFT decay analysis data.

The use of PFT tracer gas and PATS seems particularly well-suited for measuring short term (<24 hours) air exchange in all of these residences. The PFT gas was easily deployed and analysis was fairly inexpensive. The deployment of the tracer gas is unobtrusive and was not noticed by any of the residents. The only difficulties experienced during the measurements in the three residences were malfunction of the printing of the time and pump stroke information on the paper tape of the PATS units. If this information is missing or not readable, the air exchange rates are difficult to analyze. Because only two places in the country presently have the equipment to perform low-level PFT analyses, it can take several months to receive results.

Using the CATS in combination with PFT was most helpful in determining long-term (>24 hours) average air exchange rates in the residences. (The CATS can also be used to determine short-term (<24 hours) air exchange rates.) The CATS require no attention or moving parts and can be left in a residence for weeks or months with little notice from the residents. These can be recovered by the resident and mailed to the investigator if necessary. As with the PATS, the temperature of the PFT sources must be known to determine the airborne concentration of the PFT during the measurements. Analyses of CATS measurements also take several weeks to months.

The regression analysis of the air exchange rate data and for each residence and a discussion of the results is present in the following sections.

9.1 OBSERVATIONS IN THE VANCOUVER HOME

Short term infiltration measurements (8-hour) from 1/30 - 2/6 using the PATS yield infiltration data gave a poor linear regression correlation (curve fit). This may be due to the poor mixing in this residence which was unoccupied during these tests. This is especially evident when examining Figure 1. Figure 1 is a plot of the air exchange rate, ΔT and V^2 for the time period 1/30 - 2/6. Figure 1 shows the large increase in air exchange between 2/5 and 2/6 lagging by several hours a significant increase in wind between the same days. The wind may be incident on one side of the house (which may be on the other side of the house from the PATS measuring instrument) and dramatically affect the infiltration in that portion of the house nearly instantaneously; but the actual air exchange rate measured in another part of the house where the measurement equipment is placed, may not change as dramatically or as suddenly. Eventually this change in air exchange will be measured, but will be lagging the actual event that caused the change (increase in windspeed in this case) by several hours or more.

The long term (greater than several days) air exchange measurements tend to reduce the effects of this lagging phenomenon. This is borne out by the fact that the regression analysis of the long term (CATS and average PATS) data yielded a better curve fit. The number of data points are fewer for the long-term analysis which will also contribute to a better curve fit.

9.2 OBSERVATIONS IN THE PORTLAND HOME

The regression analysis of the short term PATS data yielded a very poor curve fit. This poor curve fit is most likely due to a the fact that the house is not only occupied, but the fireplace was used during the air exchange measurements. Use of fireplace and to a lesser degree occupancy, will dramatically affect the air exchange rate in relatively short time periods (the fireplace uses combustion air drawn from the outside through cracks and openings in the house). The effect of fireplace use will overshadow the effects of windspeed and ΔT making it difficult to establish any correlation for the variables of windspeed and ΔT.

Figure 3 is a plot of air exchange, ΔT and V^2 for the time period 1/31 - 2/7. As noted in Figure 3, the air exchange seems to be more dependent upon the ΔT than upon the

windspeed. As the ΔT increases (decreasing outdoor temperature), the likelihood of wood consumption increases with a corresponding increase in the air exchange. This air exchange rate increase however, is not just due to the temperature difference because of the poor correlation seen in Figure 2, indicating that the fireplace use was a major contributor to the infiltration. The one day of high windspeed on 2/4 was not reflected in a corresponding increase in the air exchange rate. This increase corresponded with a decrease in the ΔT and probably a decrease in fireplace use. This again points out that the fireplace use may have the most pronounced effect on air exchange.

An attempt was made to factor out the occupancy and perhaps the fireplace use by using only the infiltration data during the quiescent periods of the day (2400hrs-0800hrs) from 1/31 - 2/7 and performing a linear regression analysis. The analysis indicated a very poor correlation. This was perhaps due to either poor mixing (as in the Vancouver home) or due to the fireplace damper being open as the fire died down which would create air leakage into the house which may overshadow the infiltration due to either the windspeed or the ΔT. As in the Vancouver home, the best correlation of the linear regression analysis occurred by taking the longer terms infiltration data (CATS and average PATS) which would tend to reduce the occupancy and fireplace use effects.

9.3 OBSERVATIONS IN THE BEND HOME

Like the other two homes, the regression analysis of the short term PATS data yielded a poor curve fit. This is the only home of the three with forced air heat which may have a greater influence on the air exchange than does the windspeed and ΔT. In addition, this house is very "tight" with the lowest overall air exchange rate compared to the other two houses.

As in the Vancouver home, there appears to be a lag in the response of infiltration to the changes in ΔT and windspeed (see Figures 4, and 5). This may be due to the fact that for long periods of time during the day, the house is unoccupied and therefore, there is poor mixing. This especially may be the case in this home because it is a very energy efficient structure, and it may be less responsive to changes in wind and temperature. Unlike the Vancouver and Portland homes, no long-term CATS data was taken to examine the regression of long term air exchange measurements to see if better correlations can be found for this house. It is expected that a better correlation would be found using long term data.

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2. Dietz, R. N. 1983. Brookhaven Air Infiltration Measurement System (BNL/AIMS) Description and Application. Prepared for the Office of Building and Community Systems and the Office of Health and Environmental Research of the United States Department of Energy.

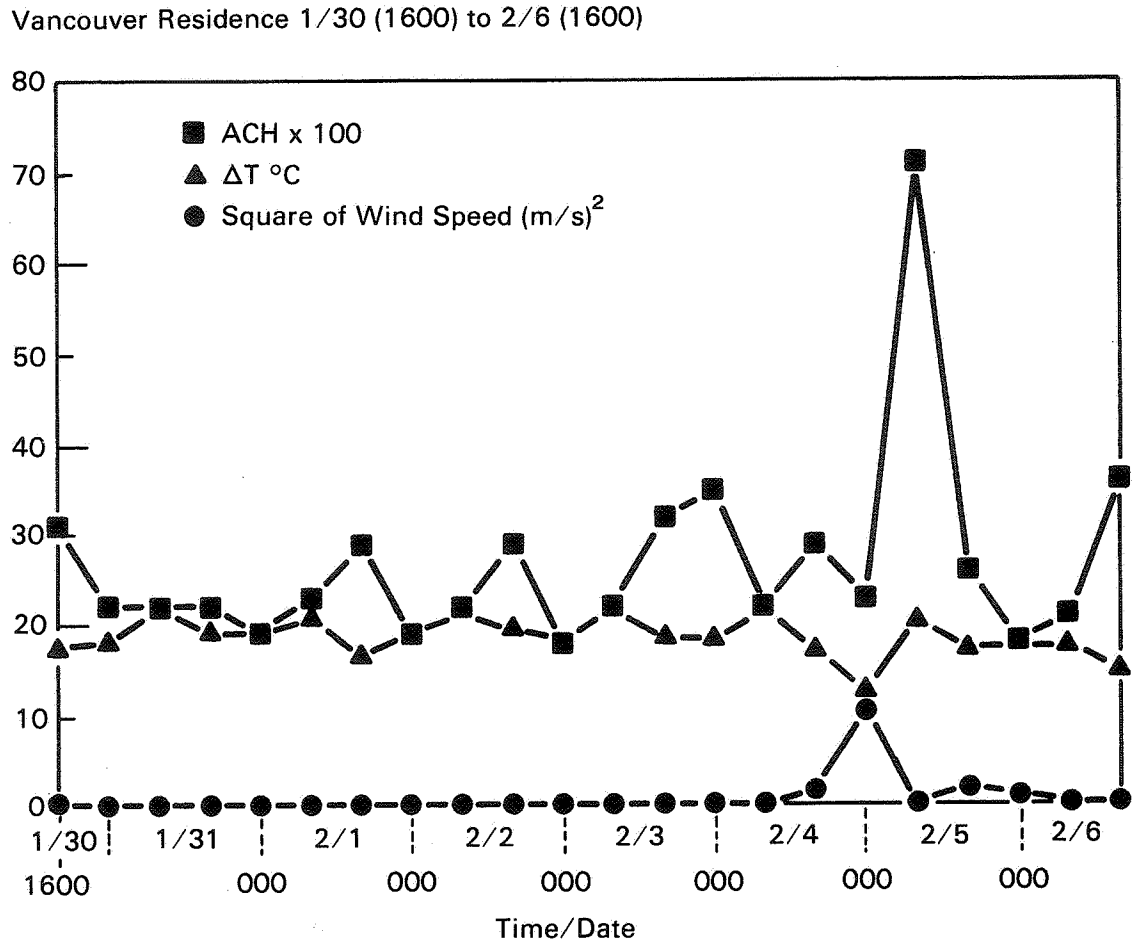


Figure 1. Measured Air Exchange Rate, Windspeed and Inside–Outside Temperature in the Vancouver Residence 1/30–2/6.

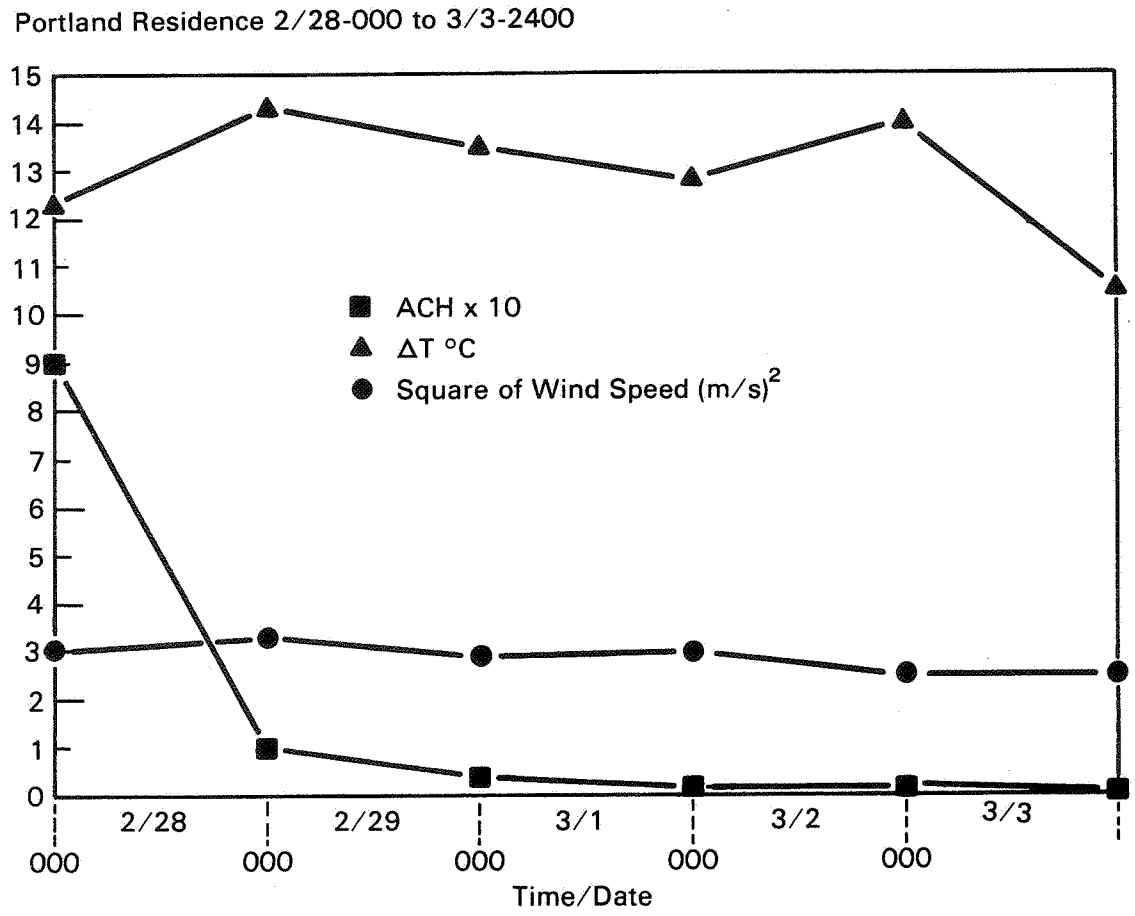


Figure 2. Measured Air Exchange Rate, Windspeed and Inside–Outside Temperature in the Portland Residence 2/28–3/3.

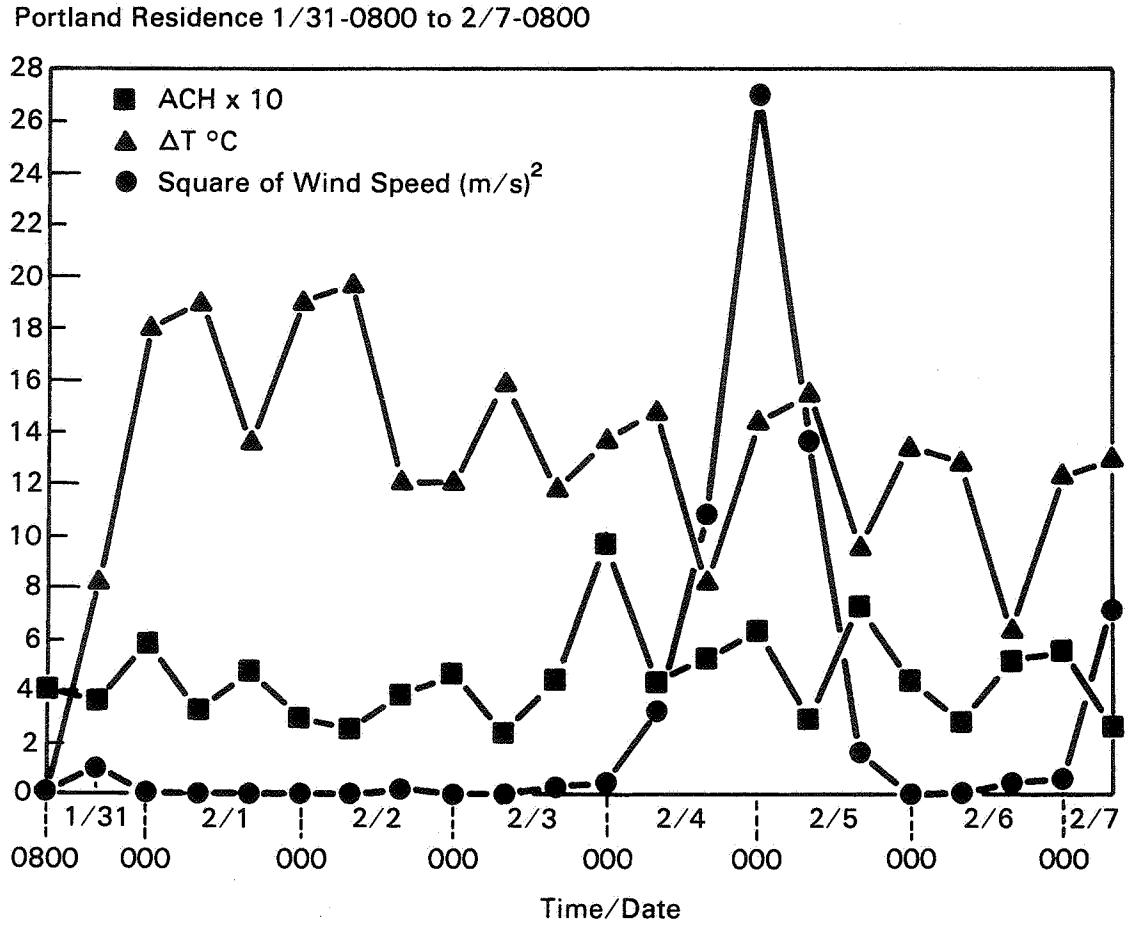


Figure 3. Measured Air Exchange Rate, Windspeed and Inside–Outside Temperature in the Portland Residence 1/31–2/7.

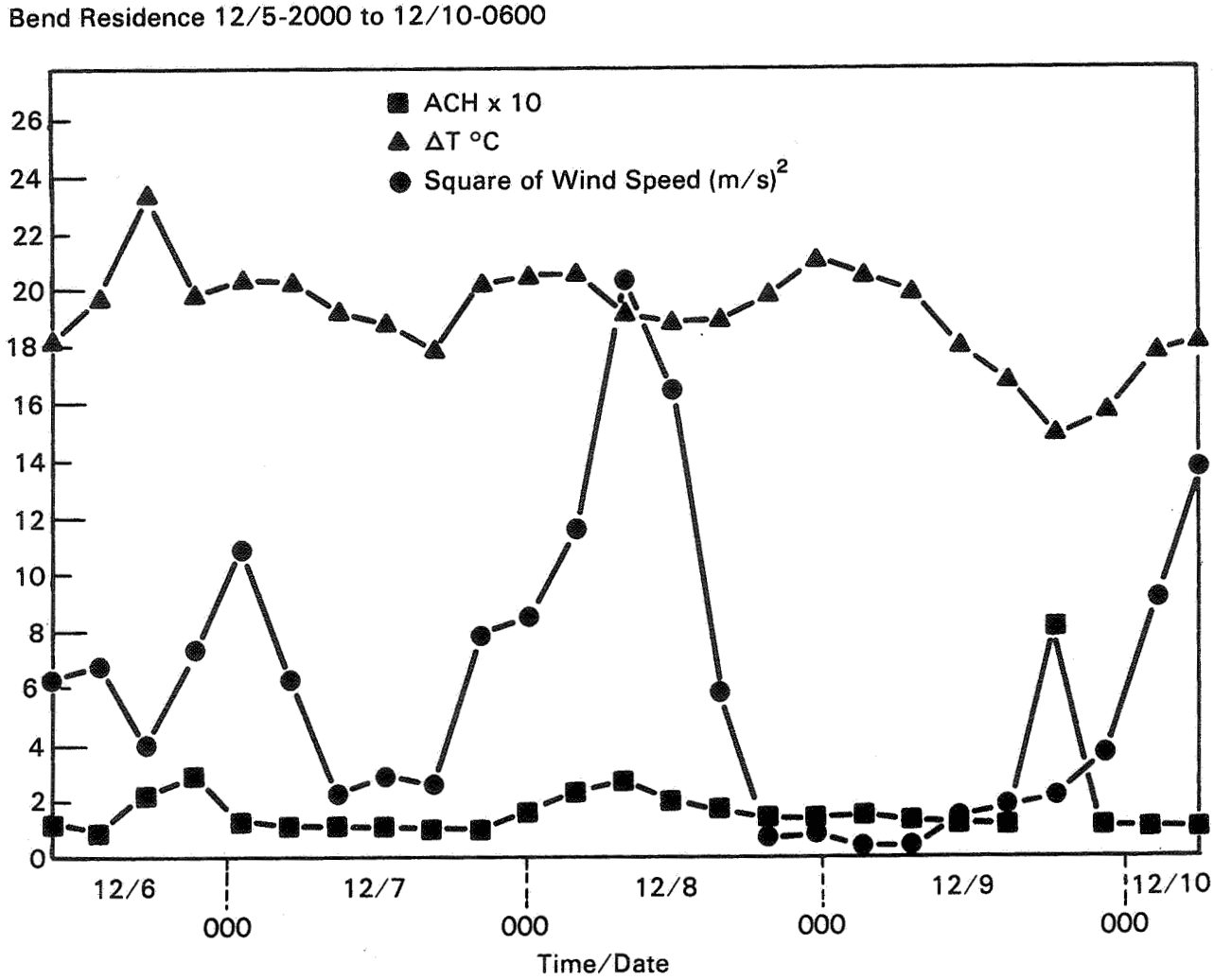


Figure 4. Measured Air Exchenge Rate, Windspeed and Inside–Outside Temperature in the Bend Residence 12/5–12/10.

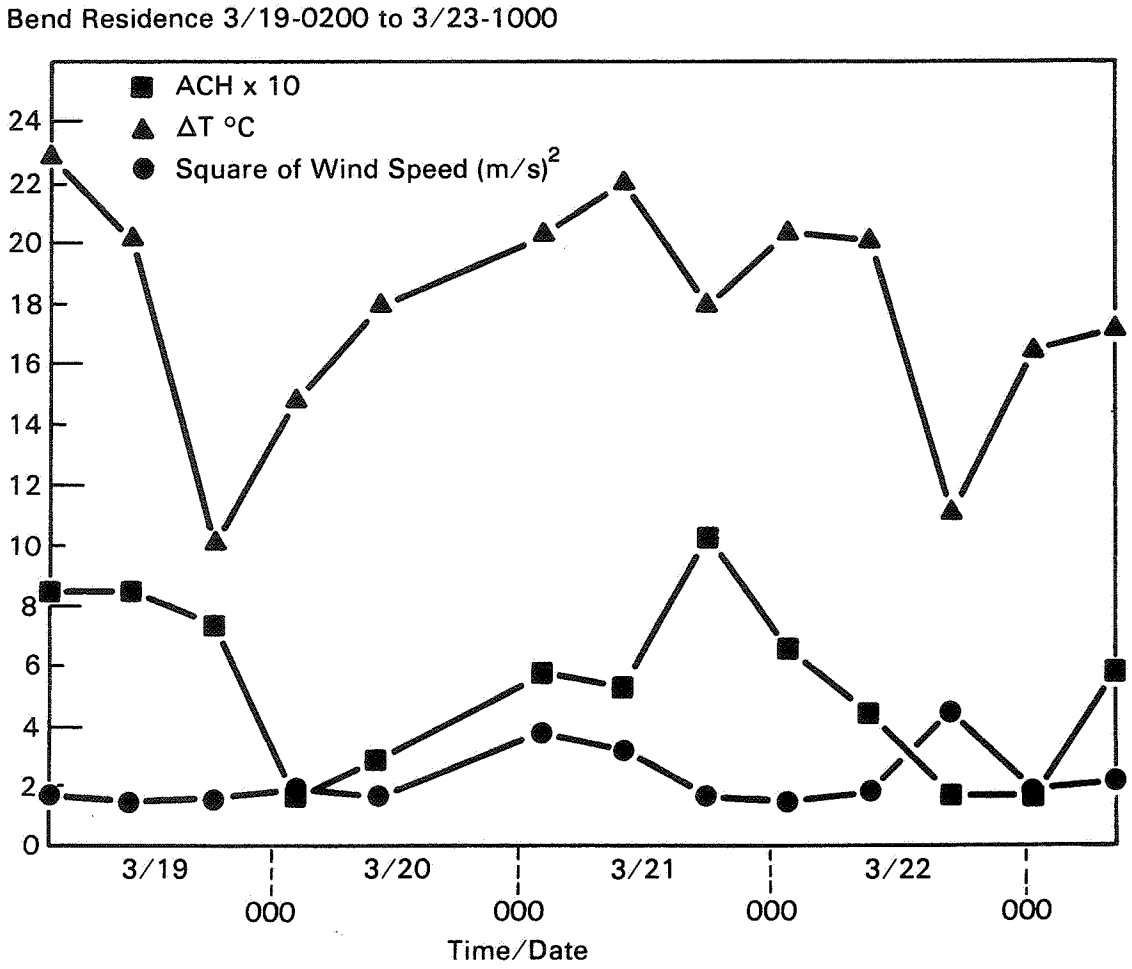


Figure 5. Measured Air Exchange Rate, Windspeed and Inside–Outside Temperature in the Bend Residence 3/19–3/23.

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 4

A PASSIVE VENTILATION SYSTEM UNDER TRIAL IN U.K. HOMES

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SYNOPSIS

A passive ventilation system has been installed in four new houses: it comprises simple ducts which lead up from the kitchen and bathroom to outside near the house ridge and utilise the wind and the temperature difference between inside and outside (the stack effect) as driving forces.

During occupation the system provided a consistent background ventilation rate: the flows dropped only when it was warm and calm outside (when other ventilation measures might be taken by the occupier); when it was very cold and windy outside the system did not over extract but appeared to self-throttle. Window vents gave the occupiers the option of an increase in ventilation.

The occupiers made many favourable comments about the system. Cooking smells and steam had cleared quickly, there were no musty smells in the bathroom, nor stale tobacco smells in the living room after being closed up over night, and there were no significant annoying side effects: they had been able to 'forget' about the system.

The fitting of the passive system and associated window vents is recommended in new tightly built houses as a means of providing a continuous controlled level of ventilation, and thus reducing condensation risk. For older less tight houses draughtproofing would be necessary in addition to the system, to prevent over-ventilation.

1. INTRODUCTION

Condensation continues to be a major problem in U.K. houses with a total of 3.5 million dwellings affected to some degree[1] even though the mechanism of formation is readily understood. It occurs on surfaces or within structures when they cool to a temperature corresponding to the dewpoint of the adjacent air or, conversely, when the dewpoint of that air increases to the temperature of the structure, due to moisture gain. Clearly, the effect can be avoided completely by the correct balance of thermal and moisture properties of the structure, the heating regime, the moisture generation pattern and the ventilation rate.

In older properties the balance is difficult to achieve economically, due to the high natural ventilation rates and the poor thermal performance of the envelope; this means that the absolute moisture level of the air is low but the structure is cold and therefore any warmed air cools quickly. In new property the thermal performance will be much improved (although certain detailing may cause cold spots), but in a number of cases ventilation rates are now too low, and so condensation problems are again encountered - although the structure is warm, the absolute moisture levels in the air are now high.

In theory the problems can be reduced by insulating and draught stripping the older houses (making heating costs reasonable), and increasing the ventilation rate in new houses; however, in practice it is near impossible to predict the natural ventilation rate following any such remedial measures, so the end result may not be as desired. One solution therefore is to seal the house as completely as possible, and then introduce a ventilation system which will induce a particular air change rate.

In 1981-82 Pilkington Bros. and the Timber Research and Development Association (TRADA) installed an experimental passive ventilation system in a test house built at TRADA's headquarters at High Wycombe; this comprised ducts which utilised the stack effect and the wind to induce air flow through the ducts from the moisture-producing areas to outside at the house ridge. There were clear benefits for condensation control, although extraction of air through the system was less than expected; it was concluded that the basic house would need to be tightly constructed for the system to have a significant effect, and it was known that the test house was largely sheltered from the effects of wind which would certainly have affected the results.[2] The work was fully reported at the 3rd AIC Conference in London.

During 1982-83 the system was redesigned to be more efficient and detailed experiments carried out on the effect of internal/external temperature differences and of various air inlet configurations. Only a brief summary of the results has been reported[3] and so details are given in Section 2: conclusions were very encouraging, but were still without the effects of wind.

In 1984 Pilkington Bros. and TRADA joined with Laing Homes to install the system in four new houses near Southampton: these were sold in the normal way and the purchasers' views sought on the effectiveness or otherwise of the system following the winter period 1984-85. In addition, one of the houses was monitored for system extraction rates, and air tightness measurements and various experiments concerning air inlets, etc., were carried out. The results are fully reported in Section 3.

2. FURTHER EXPERIMENTS IN THE TRADA TEST HOUSE

2.1 The System

The redesigned system comprised two completely separate ducts: one duct (153mm internal diameter), lead up from the kitchen and the other (103mm internal diameter), lead up from the bathroom, both terminating at the roof ridge with a simple rain cover. The ends of the ducts in the rooms were flush with the ceilings, with no inlet cowls fitted. Sharp bends were avoided and the ducts were well insulated in the loft space.

Air inlets into the house were provided by Titon Trimvents in the main room windows and by ventilation grilles in the front and back doors.

2.2 Measurements

Air flows in the ducts were continuously monitored using a thermistor bead air velocity meter with a sensor situated at the centre of each duct, making correction for turbulent flow. Checks on the values obtained were made by introducing carbon dioxide and timing its passage through the ducts, and also by introducing a known bleed of carbon dioxide into the duct and measuring its concentration at the outlet, hence computing the volume air flow. All gave good agreement, giving confidence in the method.

Whole house ventilation rates were determined using the carbon dioxide decay method.

The main objective was to monitor the flows of air out of the house via the extraction system and to see how these varied with changing internal/external temperature differences: these were measured with downstairs window vents and door vents open, and with all air inlets closed.

Information on whole house ventilation rates was needed to determine what proportion of the ventilation was provided by the duct system.

2.3 Results

Results are presented graphically in figs 1 and 2. Air movements are quoted as velocity in the appropriate duct and also as volume flows: from the latter, the appropriate air change rate per hour for the whole house, kitchen and bathroom attributable to the ducts can be calculated using the respective volumes of 240, 20, and 20m^3.

Whether the inlet vents were open or closed, the extraction rates increased with the increase in temperature difference, as expected.

In the kitchen duct, flows at 20^{o}C difference were 55m^3/h with all inlets closed and 75m^3/h with downstairs window and door vents open. These flows correspond to as much as 3.8 ac/h (air changes per hour) for the 20m^3 room. In the bathroom duct a flow rate of 20m^3/h at 20^{o}C difference would be expected irrespective of the inlet conditions, corresponding to 2.0 ac/h for this 10m^3 room. Thus, the flow out of the house via the complete system at 20^{o} C temperature difference varied from 75 to 95m^3/h depending on whether inlets were open or closed. This represents 0.3 to 0.4 ac/h for the whole house. It seems likely that these rates were influenced by the wind, at least at the small temperature differences, even though the house was protected from the direct effects of wind by adjacent structures.

These figures become particularly interesting when compared to the corresponding whole house ventilation rates measured at the same time at temperature differences in the range 12-15^{o}C, which is typical for an average winter day and heating level:

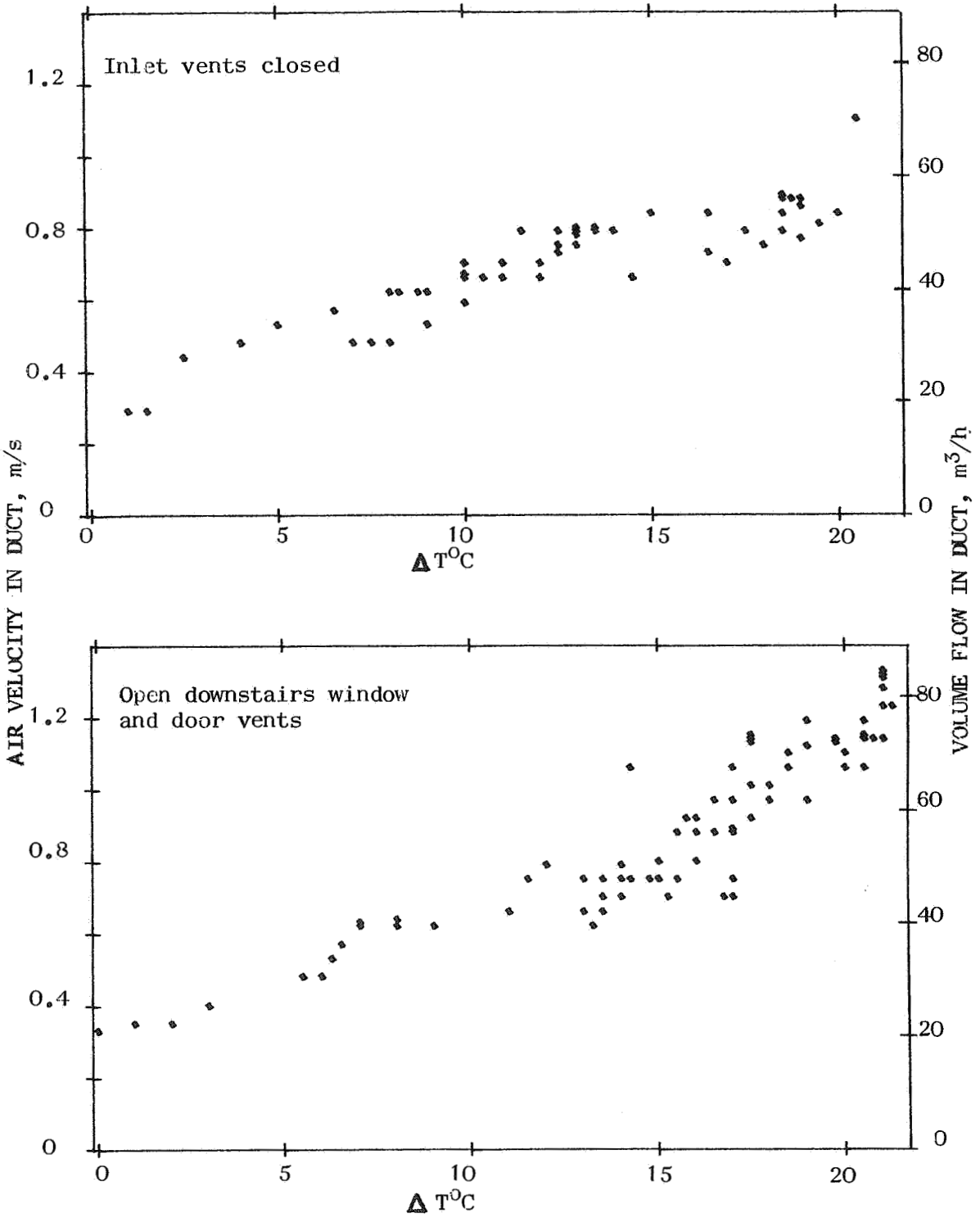


Fig 1. Flows in TRADA house kitchen duct.
(House - 240m^3; kitchen - 20m^3)
ΔT is the difference in internal/external temperatures.

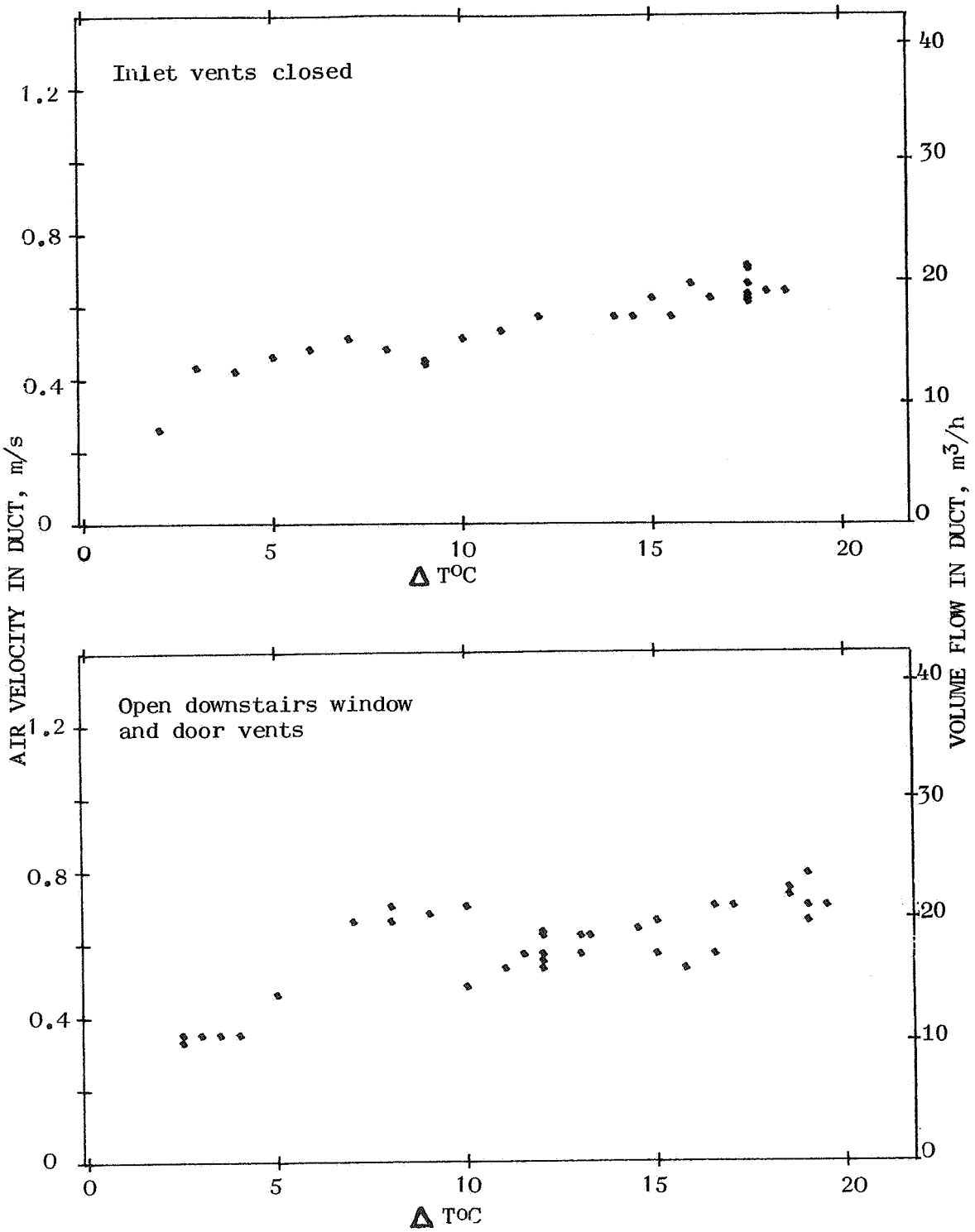


Fig 2. Flows in TRADA house bathroom duct.
(House - 240m^3; bathroom - 10m^3)

ΔT is the difference in internal/external temperatures.

TABLE 1. Ventilation rates in the test house

	Kitchen ac/h due to duct	Bathroom ac/h due to duct	House ac/h due to ducts	Total House ac/h
Downstairs window vents and door vents open	2.8	1.8	0.3	1.3
All inlet vents closed	2.7	1.8	0.3	0.6

2.4 Discussion

Under the conditions used, with the window and door vents closed, a total air change rate for the house would be 0.6; this compares to 0.4 ac/h found for the house without the ventilation system and inlet vents. Half the air left the building via the ducts, resulting in more air movement generally towards the moisture producing areas: this was confirmed by smoke tests. An increase in the ventilation level was achieved by opening the inlet vents giving a total air change rate of 1.3, whilst maintaining the 0.3 ac/h extracted by the ducts from the moisture producing areas.

The house with its natural ventilation rate of 0.4 ac/h (without the system) is considered to be fairly "tight" but when the air inlets were closed the flows in the ducts did not reduce at the typical winter day conditions. It is suggested that the explanation for this is that even at 0.4 ac/h a house has a considerable number of gaps in the structure, which would allow sufficient air inlet to "feed" the system.

As outside temperatures fell, the extraction rate through the system increased at the very time that an occupier would be likely to close the inlet vents (and windows).

2.5 Conclusions

The passive system provided 24-hour background ventilation to the house, with relatively high air change rates in the moisture producing rooms. It provided a better air flow pattern when windows and vents were closed, with the facility of increasing the ventilation rate by means of opening the vents in the windows - the use of the door vents is considered undesirable because of the likelihood of low level draughts. The major unknown was the effect of wind and of occupation of the house.

3. UNDER TRIAL IN LAING HOMES

3.1 The houses

The four houses fitted with a passive ventilation system were built near Southampton by Laing Homes, fig 3, and were all "Richmond" one-bedroom, two-storey, back-to-back, end-terrace houses. A site plan, block plan, and floor plan of the houses are given in figs 4, 5 and 6. The houses are timber framed and are well insulated with 97mm of mineral fibre in the wall cavities and 120mm in the loft; windows are single glazed and draught stripped and the entrance door is a foam-filled steel panel type, with a magnetic draught seal and "double" letterbox.

The houses have a floor area of $39m^2$ and a total volume of $92m^3$; the kitchen and bathroom have volumes of 11 and $8m^3$ respectively. Separate ventilation ducts were fitted to these two rooms and both were 103mm internal diameter, fig 7. These finished flush with the respective ceilings and were terminated with Bahco exhaust registers, which will automatically shut in the event of fire; the registers were adjusted to maximum opening. In the monitored house these exhaust registers were later removed.

Sharp bends and low angle ducts were avoided in the monitored house and the adjacent one, but in the other two the duct route through the loft was less than satisfactory due mainly to the roof pitch orientation. The ducts were well insulated in the loft spaces and were terminated just below a Glidevale tile vent situated near the top of the roof. It was suggested that the gap between the ducts and the terminal would "decouple" the system somewhat from the effects of strong wind and thus prevent excessive over-extraction.

Air inlets were provided by Titon Trimvents, fitted to each of the four windows of the houses. The total inlet area of these vents was approximately one and a third times the total cross-sectional area of the ducts.

3.2 Experimental Procedure

In the three non-monitored houses the principles of the system were explained to the occupiers, with a recommendation that the air inlets were in general left open. They were then left to use the system as they wished and their reactions sought at the end of the winter period.

For the monitored house, again in general, the occupiers were left to use the system as they wished, except during specific periods when they were asked, for example, to have the window vents permanently shut, or have the ventilation ducts sealed off.

During the full winter period the flows of air out through both the ducts were continuously monitored as before, using thermistor bead air velocity meters. Air flows were found to vary considerably: sometimes the flow would be very steady when

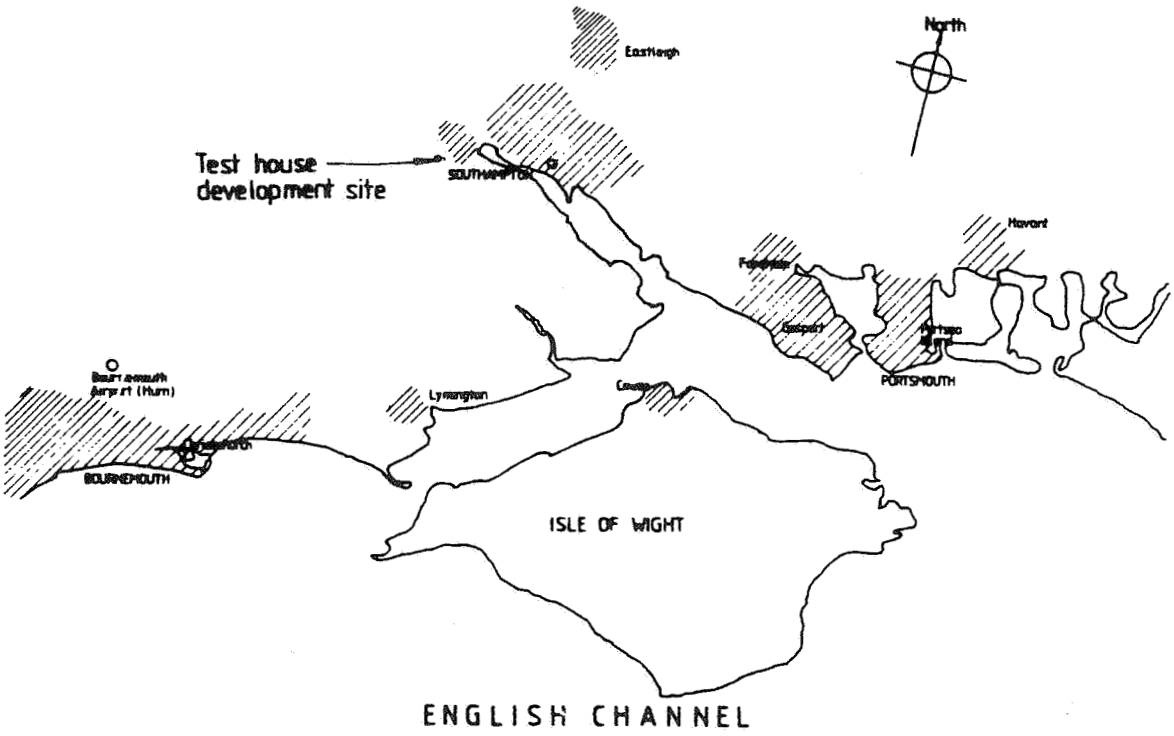


Fig 3. Location of the Laing development site



Fig 4. Site plan showing positions of houses fitted with the passive ventilation system.

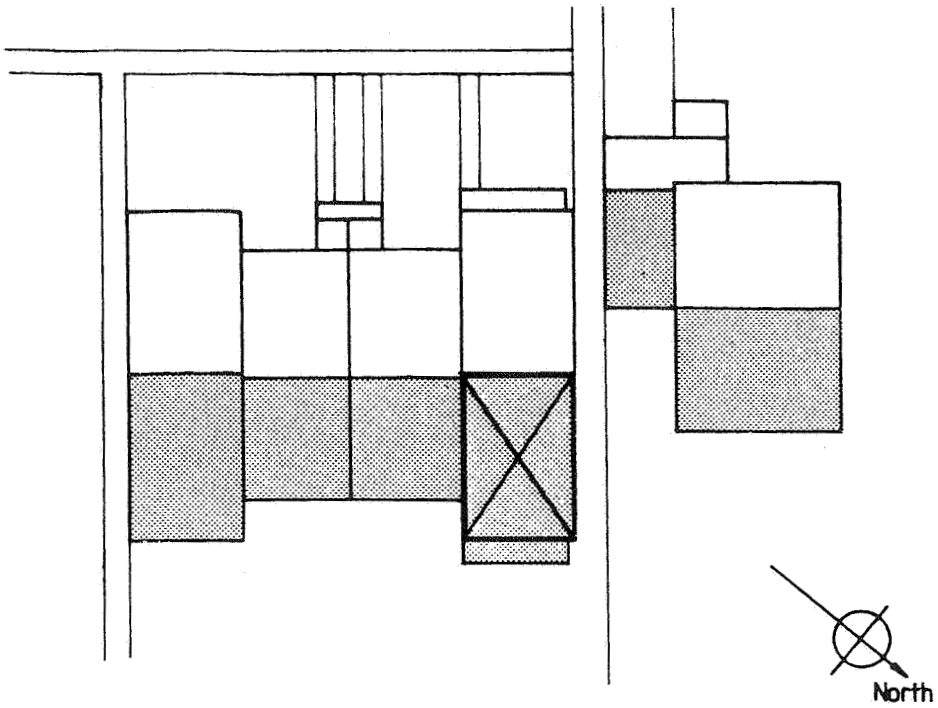


Fig 5. Block plan of the monitored house.

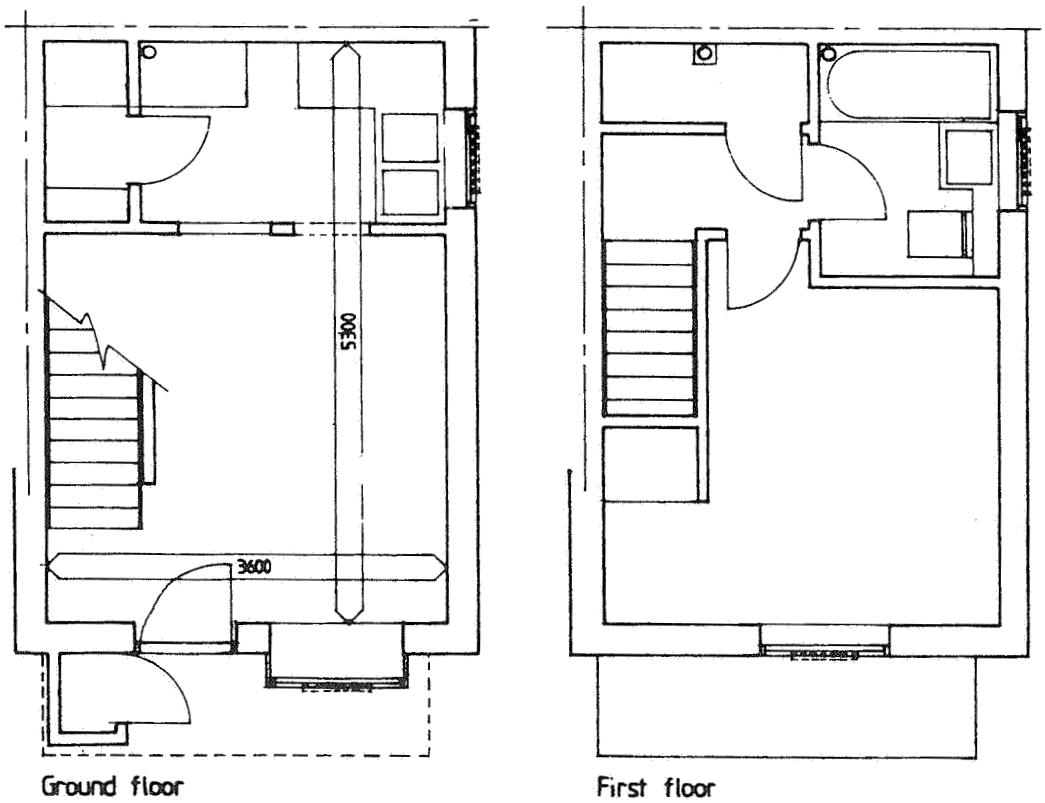


Fig 6. Floor plan of the 'Richmond' house.

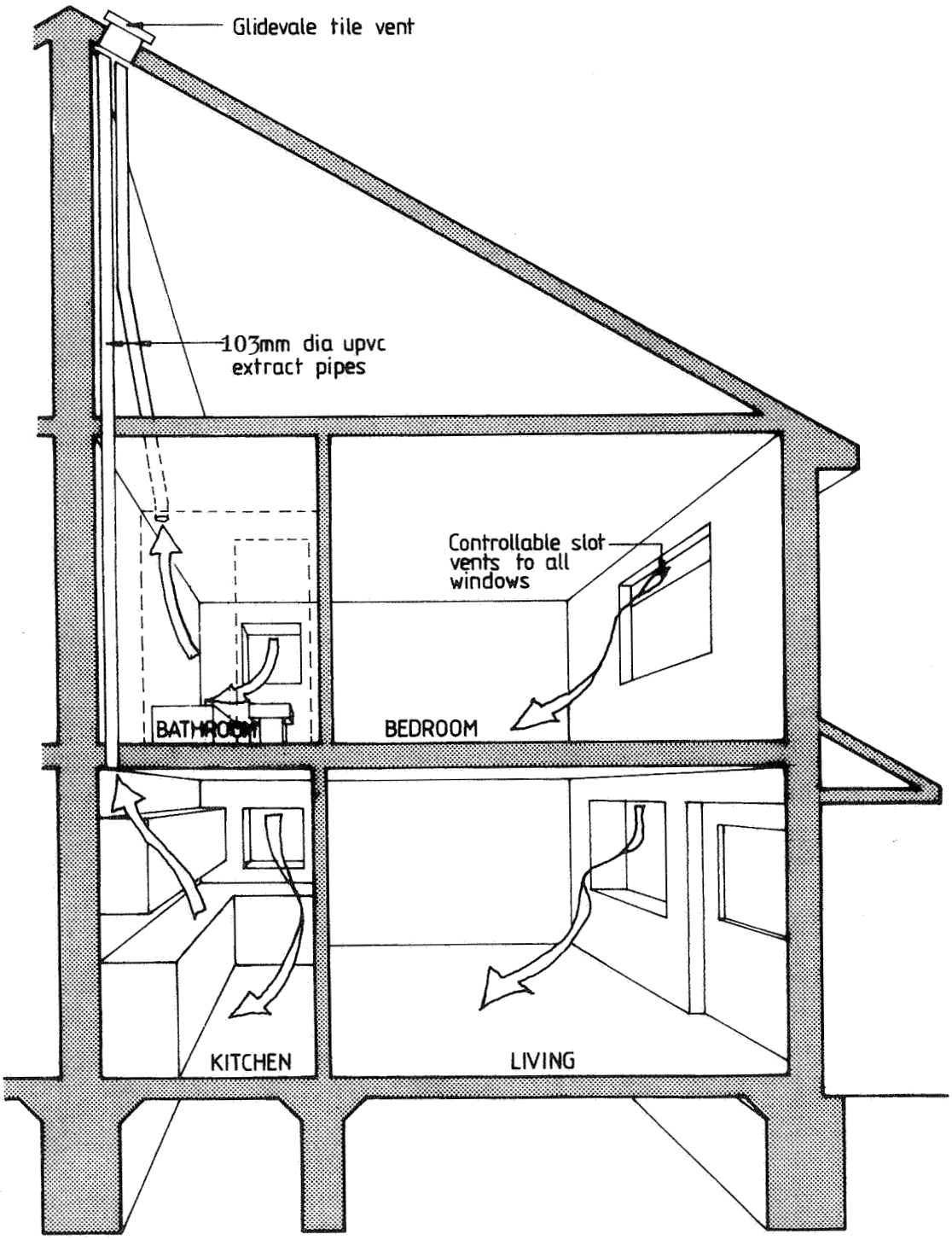


Fig 7. The ventilation system fitted in the 'Richmond' house.

indicated by direct connection to the recorder, e.g. fig 8a, and sometimes the flow would have fluctuations of the type and extent as in fig 8b (the reason is discussed in Section 3.6.1). For the long term recording, with its necessarily compressed time scale, the oscillations were damped by using a resistance/capacitance filter network (with a time constant of 100 seconds) fig 8c: this avoided wear of the paper by the pen, and made averaging easier. It is necessary to remember throughout interpretation of the results that the traces are damped.

Internal temperatures in the vicinity of the duct intakes were also monitored; external temperatures for nearby Southampton, and wind data for Hurn, were obtained from the Meteorological Office. Unfortunately Hurn is 17 miles away and so the data will not exactly match the area of the houses. However, it is a reasonable guide and spot checks confirmed this.

House tightness was determined by air pressurisation tests and air infiltration rates by carbon dioxide decay tests: these were carried out before occupation, September '84, and during the occupation period, February '85.

3.3 Air Pressurisation Tests

The September '84 tests were substantially confirmed by the February '85 tests (except that the house appeared to be a little tighter at the later date) and so the later tests are described here.

The house was pressurised and depressurised in the range 15-60 Pascals and the air leakage characteristics taken as the mean of the pressurisation and depressurisation tests. That rate at 50 Pascals can be used to compare the various conditions and other dwellings.

The results for the various air inlet and duct configurations are given in table 2.

TABLE 2. Air pressurisation tests

House Condition		Mean ac/h rate at 50Pa
Vent. ducts	Window vents	
Closed	Closed	7.4
Open	Closed	9.0
Open	Open	12.1
Bahco registers removed	Open	13.4

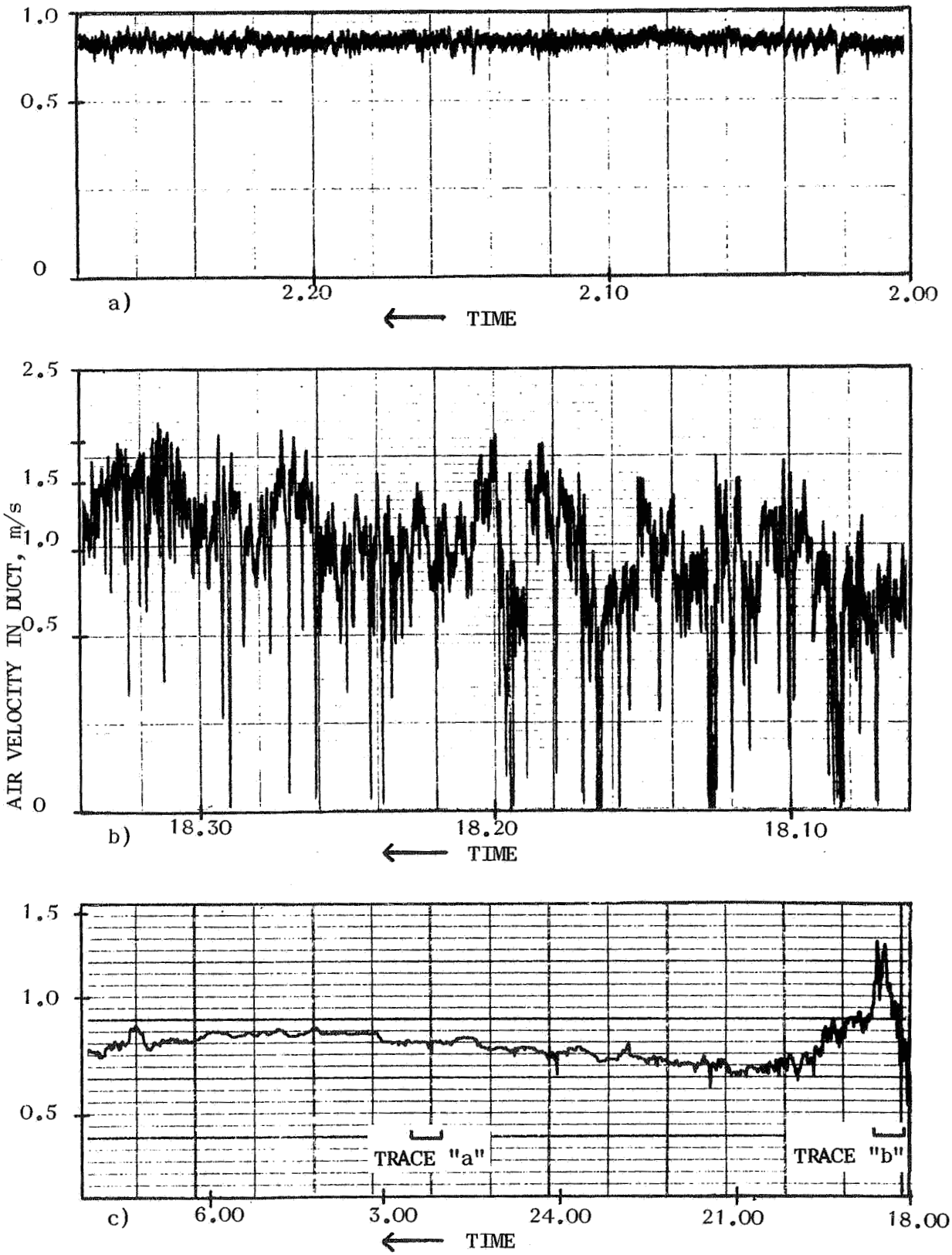


Fig 8. Typical air velocity traces (kitchen duct)
a) undamped trace - steady flow
b) undamped trace - irregular flow
c) damped trace - including periods of traces 'a' and 'b'.

3.3.1 Discussion

Without the ventilation ducts and window vents the dwelling would be under-ventilated[4], especially at times of high moisture production. The installation of the passive system would increase the ventilation rate by a useful amount and would be particularly beneficial in inducing air change to take place for the moisture producing areas. The window vents would give the occupier the opportunity to control the rate over a useful working range - for example, by opening the vents to increase air exchange rates during moisture production. Finally, it was seen that the inlet registers were throttling the flows somewhat.

3.4 Carbon Dioxide Decay Tests Before Occupation

The tests carried out before occupation were with the house unheated and consequently with small or zero internal/external temperature differences. Results are given in table 3.

TABLE 3. Decay tests

House condition		$\Delta T^{o}C$	Wind m/s	Ac/h
Vent. ducts	Window vents			
Closed	Closed	0	3	0.1
Closed	Closed	0	10	0.3
Closed	Open	1	10	0.6
Open	Closed	3	9 dropping to 4	0.3
Open	Open	5	4	0.4

ΔT is the difference in internal/external temperatures.
Wind speeds are for Hurn.

3.4.1 Discussion

Without the ventilation ducts or window vents, the house appears to be very tightly constructed (more so than indicated by the pressurisation tests) and it would be seriously under-ventilated: the minimum rate usually accepted is about 0.5 ac/h. The low figure might be explained to some extent because of the small internal/external temperature difference, but this does not appear to be the case in view of later tests in the occupied house.

Still without ducts or vents, and with a wind blowing stronger than the average 5 m/s, the ventilation rate increased, but still not to a satisfactory level. The use of window vents during

the strong wind resulted in a satisfactory level, but it can be argued that occupiers would close at least some of the window vents during such conditions.

The introduction of the ventilation ducts did not have a significant effect on exchange rates, which is not surprising at the low temperature difference; it is likely that opening the window vents would also be more significant with bigger temperature differences.

In the two tests with the ventilation ducts open, air flows measured in the ducts represented about 0.2 ac/h for the house, that is, with window vents shut, about two-thirds of the air leaving the building did so via the ventilation ducts, and with window vents open about half of the air leaving was via the ducts.

During the tests the wind was blowing from the side to the front of the house (west to east); smoke tests showed that with the ventilation ducts closed and the window vents open, air entered the house via the side windows and left via the front - with the ventilation ducts open as well as the window vents, air entered the house through all window vents. Although the wind was less during the latter condition and there was only a small temperature difference, the introduction of the ventilation ducts had altered the air flow through the house, which would be beneficial in controlling moisture removal and spread, and hence condensation problems.

3.5 Carbon Dioxide Decay Tests During Occupation

The carbon dioxide tests were repeated some months after occupation, to check on the very low basic infiltration rate found and to compare the effects of opening the ventilation ducts and window vents. At the same time, air flows leaving the house via the ventilation ducts were monitored to see how relatively significant these were. The house was, of course, now heated with temperature differences of 14-16^{o}C throughout the tests. Results are given in table 4.

TABLE 4. Decay Tests During Occupation

House Conditions		Wind m/s	Ac/h	Ac/h through vent ducts
Vent.ducts	Window vents			
Closed	Closed	4	0.15	-
Closed	Open	4	0.3	-
Open	Open	6	0.6	0.4
Bahco registers removed	Open	5	0.6	0.6
Bahco registers removed*	Open	3	0.6	0.6
Bahco registers removed	Closed	4	0.4	0.5

*Short check test.

Wind speeds are for Hurn.

Clearly one cannot have more air leaving the house via the ducts than indicated by the total air exchange rate, and so the results do indicate some inaccuracies in measurement techniques.

3.5.1 Discussion

The very high tightness of construction is confirmed by these results. Looking at both sets of carbon dioxide tests, it can be seen that in the absence of the duct system the window vents will only produce satisfactory air exchange rates when there is above average wind blowing - the stack effect alone is not sufficient.

It can be seen that the exhaust registers are throttling the flow, and so following these tests, that is, for the main results printed below, the registers were removed, so the ducts simply ended flush with the ceilings.

The introduction of the combination of the ventilation ducts (without the Bahco registers) and window vents appears to provide a very satisfactory system. With the window vents closed, most of the air leaving the building is via the ducts, with consequent re-routing of the air (confirmed by smoke tests) and under the typical winter's day conditions, flows were just below the minimum that would be acceptable. If the window vents are opened the overall ventilation rate is increased by about 50%, but apparently still with most of the air leaving the house via the ducts, continuing the beneficial conditions

for the removal of moisture at source. This is very different from the effect of opening window vents in the TRADA test house which caused a big increase in the amount of air bypassing the ducts - this may be because of the difference in air tightness of the two houses and to the different window (and window vent) positions.

Conditions of high wind were not encountered whilst the house was heated for the carbon dioxide tests: this is important as it is possible to have too high an infiltration rate for the house due to air bypassing the ducts under these conditions (significant over-extraction through the ducts themselves due to wind was not encountered - see Section 3.6.1). However, the first set of carbon dioxide tests showed an air exchange rate of 0.6 ac/h under high wind conditions with window vents open (ducts closed), so it does not seem likely that too high a total figure would be produced: it could again be argued that with high wind, the window vents are likely to be closed by the occupier, with a reduction of air exchange rate to 0.3 for the cross-ventilation without ducts.

3.6 Continuous Monitoring of Air Flows in the Ventilation Ducts

Monitoring took place over the winter period from September 1984 to February 1985.

As a result of failures of chart drives and air velocity probes (and the occasional collection of fluff on the air velocity sensor in the kitchen duct) incomplete sets of data were collected. Fortunately, the internal temperatures for the house remained fairly consistent throughout the period, as a result of the occupier leaving the main heater on 24 hours a day and controlling it with its thermostat and also because there was little direct solar gain.

3.6.1 9th March to 24th March 1985

A 16-day period has been chosen for evaluation assuming that the internal temperatures were as during the previous 22-day period, that is, downstairs at 20° C and upstairs at 16° C, both temperatures measured near to the duct inlets. During the 16-day period external temperatures varied from -3 to 14°C and wind from 0 to 10 m/s, and both duct sensors worked continuously and at the end of the period were checked and found accurate.

The most significant result from the monitoring is the overall consistency of the duct flows throughout the 16 days: an average 0.9 m/s in the kitchen duct and 0.6 in the bathroom duct representing 2.5 ac/h and 2.0 ac/h for those two rooms, and together representing 0.45 ac/h for the house.

If one takes lower limits of 0.6 and 0.4 m/s for the flows in the kitchen and bathroom ducts and upper limits of 1.2 and 0.8 m/s, corresponding to two-thirds and one-and-a-third of the average for the period, and which represents a range of 0.3 to 0.6 ac/h

for the house, flows were within these limits for 91% of the period; more than half of the remaining 9% was attributable to low flows in the bathroom duct on two particular days, which are discussed below. It must be remembered that the flows referred to are from the damped results: actual flows would be varying greatly over time periods of a few seconds but, provided that there are no undesirable side effects caused by the rapid fluctuations, it is the flows measured over time scales of a few minutes which are appropriate to removal of moisture.

An example of the results for 10th March is given in fig 9, which is typical, and is now discussed in detail: note that the time sequence is from right to left.

The pattern of variations of flow is the same in the kitchen and bathroom ducts, the flow being lower in the bathroom ducts almost certainly due to the shorter duct length, and hence smaller stack effect. Fig 9 also shows the corresponding wind results from Hurn and internal/external temperature differences.

Initially, flows in the ducts and the temperature difference are steady, and there is virtually no wind. As the temperature difference decreases flows start to drop, but then the wind starts to pick up, apparently having more effect than the continuing drop in temperature difference, as the flows in the ducts increase. Then the wind steadies, temperature difference continues to fall, and hence so do the flows. Temperature difference then starts to increase again but accompanied by a drop in wind, again the wind apparently predominating, with a continued (general) fall in flows. Then the wind again increases accompanying the increase in temperature difference and the flows increase again. The effect of the subsequent drop in wind is only really apparent in the bathroom duct flow.

The definite change at 09.00 hours from fairly steady flow to flows varying on the few minutes time scale, is almost certainly associated with reaching a certain level of wind, and there is some evidence throughout the results that this threshold value is higher the greater the temperature difference at the time.

There are a number of variations imposed on the general changes due no doubt to internal activities in the house, or local variations in wind and external temperature, but the patterns described above are generally to be found throughout the monitoring.

It was stated that a significant part of the period when flows were outside 0.3 to 0.6 ac/h for the house, was due to low flows in the bathroom duct on two particular days. The results for the worst day, March 12th, are given in fig 10. There was a dip in the kitchen duct flow, and the flow in the bathroom duct dropped significantly. The drop in performance corresponds to a low temperature difference of 6.5^{o}C and a below average wind of 3 m/s. However, the drop in flow in the bathroom duct is much greater than on 10th March, on which day conditions of 4.5^{o}C and

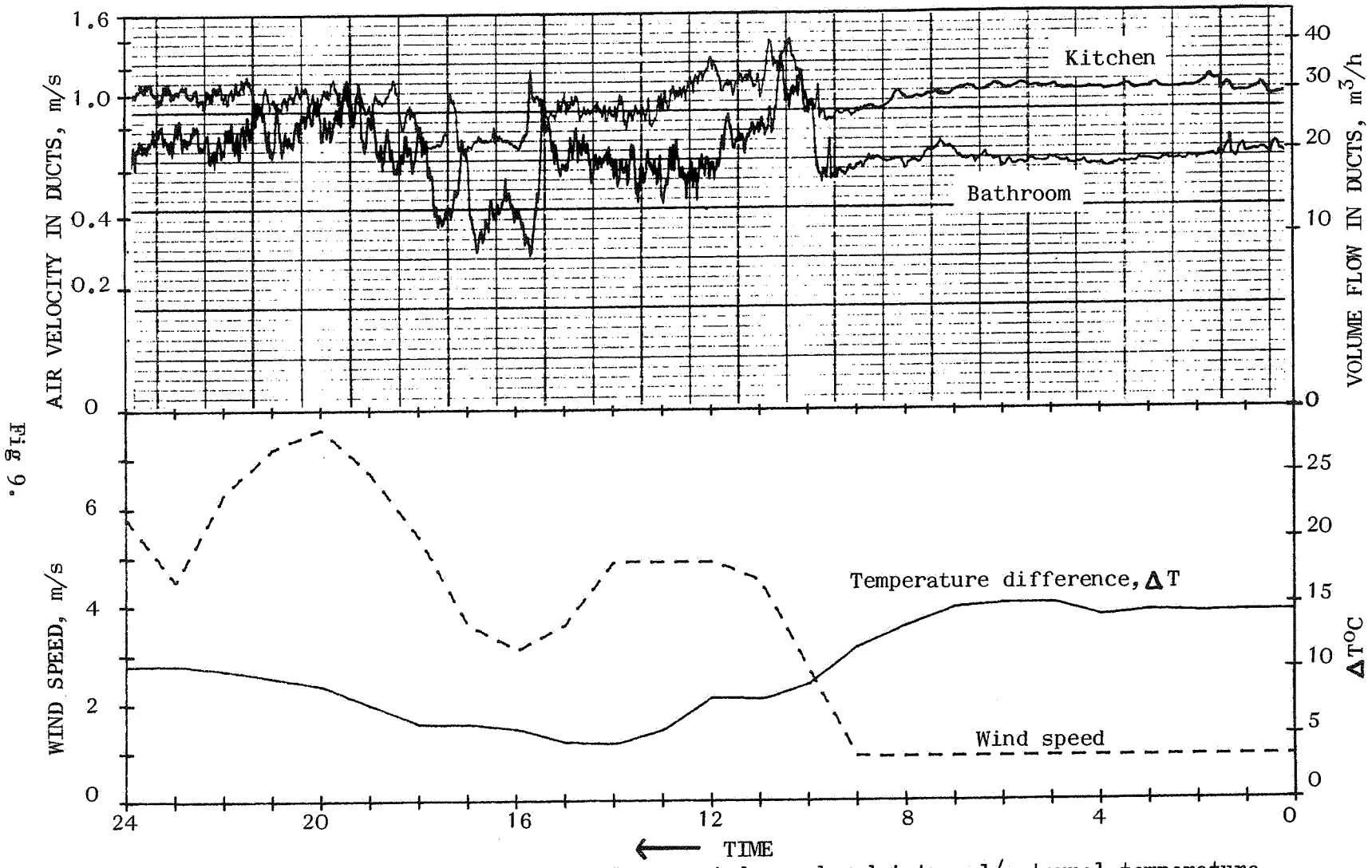


Fig 9. Flows in kitchen and bathroom ducts, wind speed and internal/external temperature difference (ΔT), 10th March 1985.

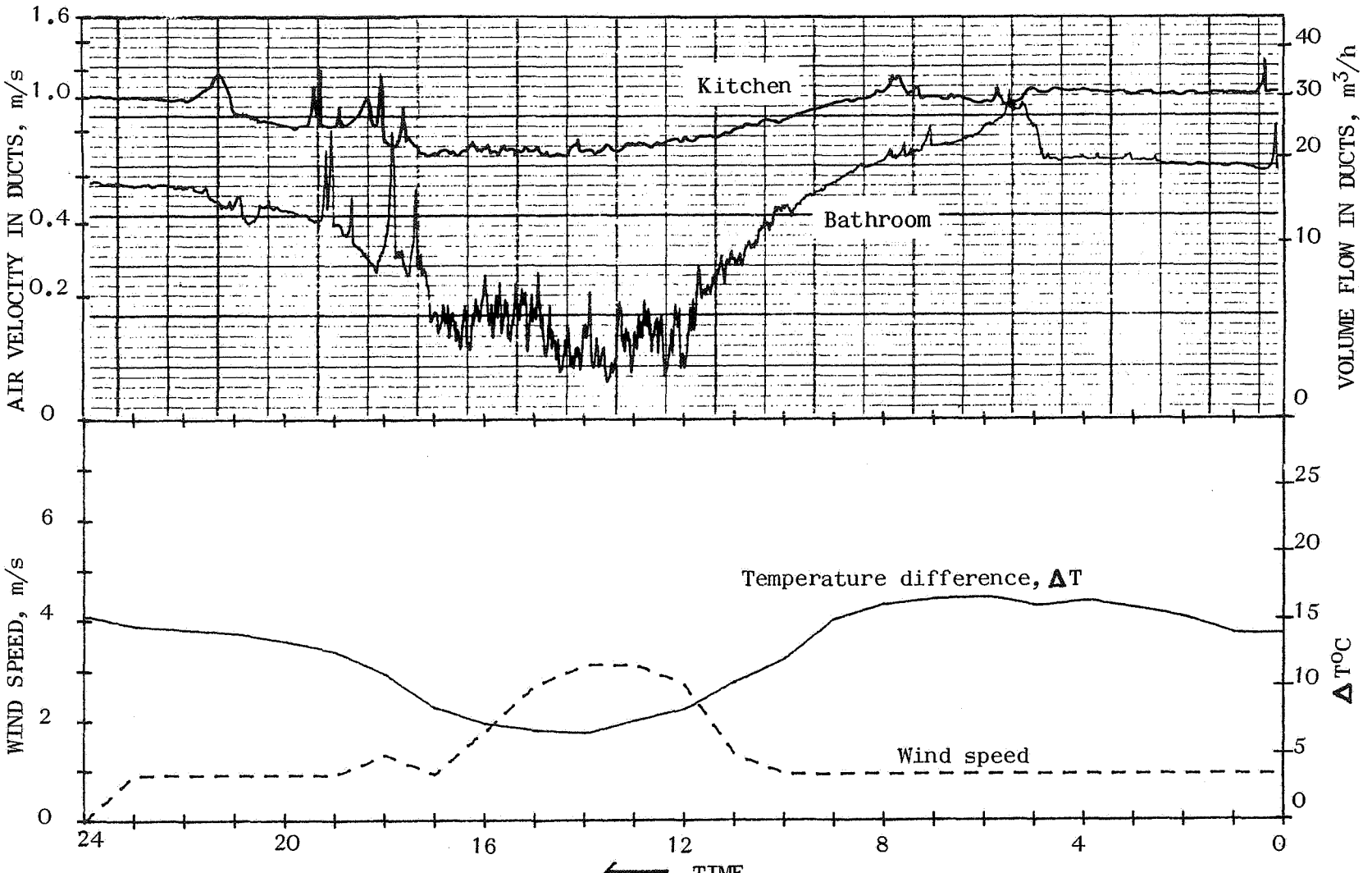


Fig 10. Flows in kitchen and bathroom ducts, wind speed and internal/external temperature difference (ΔT), 12th March 1985.

3.5 m/s were encountered. The known difference is the status of the window vents, open on 10th March and closed on 12th March, as part of the experimental programme and not under occupier control. Since generally over the test period no large difference was noticed in duct flows, whether window ducts were open or closed, the answer appears to be that the bathroom duct is particularly sensitive to the window vent status when both stack and wind driving forces are low - other low results seem consistent with this.

At the other end of the scale, the day with the greatest driving forces logged was 15th February (when only the kitchen duct was successfully monitored): the flows are given with internal/external temperature differences and wind data in fig 11. A temperature difference of 23.5°C combined with a wind of 7 m/s resulted only in the average flow in the kitchen duct - the status of the window vents is not known but it is likely that they were closed.

3.6.2 3rd May to 30th May 1985

A 27-day period in May was also successfully monitored. During this period flows in the ducts were reducing and, especially in the bathroom duct, becoming more variable. This corresponds to the much warmer weather but the data has not yet been evaluated. It is probably of much less practical interest, as windows are likely to be opened with the improved weather and, in any case, condensation risk reduces as winter is left behind.

3.6.3 Other Periods

The other data collected during the winter period, although not complete, is all consistent with the 16-day period and so overall the system appears to give a reliable background ventilation rate to the house. This must be due to the fact that usually at least one of the driving forces, stack and wind, is present. When both are reduced it will usually be mid-day and then only the bathroom ventilation is significantly affected, possibly only when the window ventilators are shut. A reduction in ventilation in this room at this time is not likely to have a significant effect on moisture spread and condensation problems.

The average flow recorded during high wind and large temperature difference is particularly interesting. The fact that extraction rates were not excessive confirms the prediction[3] that the system will self-throttle in a tightly constructed house (helped presumably by the decoupling of the pipes from the roof ventilator).

3.6.4 Short Experiments

A series of experiments was carried out to determine the effect of air inlets. Opening the window vents caused an increase of flows in the ducts of something like 20%. This is different

Fig 11. Flows in kitchen duct, wind speed and internal/external temperature difference (ΔT), 15th February 1985.

from that indicated during the carbon dioxide tests, and may be attributable to different stack and wind conditions. Subsequent progressive opening of windows caused increases of up to another 40%, mostly achieved on the night latch position, with little change thereafter. Opening the external door wide, in addition to all windows fully open, resulted in a duct flow from the kitchen of 1.2 m/s - the upper limit which was exceeded for only 2% of the time in the 16-day March period. Admittedly these short tests were carried out during low driving forces, but a picture does emerge of a system which has ducts which throttle at flows corresponding to about 0.6 ac/h for the house.

3.6.5 Doors

All the tests referred to were carried out with internal doors open. The effect of shutting the bathroom door (there was no kitchen door) was to decrease flows in the bathroom duct - say perhaps 10%. However, if the room window vent was also shut this had a marked effect on the duct flow in that room, especially during low driving forces. Under these conditions there would be little cross house ventilation through the bathroom, so moisture removal would still be quite effective. Indeed after baths or showers it should be noted that the passive system continues to extract, which will be more effective in practice than an extract fan, which runs only for a limited period, in clearing moisture left on tiled and bath/shower surfaces.

It is suggested that a kitchen door would act in a similar manner, but with less overall effect, due to the greater stack effect in the kitchen duct.

3.6.6 Cooking

Previous tests showed that the local heat from the cooker increased the extraction rate in the kitchen. It now seems likely that this effect would only occur under conditions of low driving forces: under high driving forces extraction would be high and already throttled.

3.6.7 Inlet Registers

The tests confirmed that the Bahco registers throttle the flows by something like one-third: a check on the dimensions showed that the free area through the register was only about half that of the duct area, so this is not surprising. It is still felt that some device is needed that will both collect any debris which may fall down the duct, and also which will positively shut the system in the event of fire. A redesign is therefore obviously needed here, such as an increase in duct end diameter to accommodate a larger register, or a redesigned register (the registers are designed for a mechanical system, so no criticism of the product is implied).

3.6.8 Dirt and Condensation

At the end of the tests a check was made for deposited dirt in the ducts: all that was found was a thin layer of dry dust on the walls of the kitchen duct.

No condensation was found on the roof tile, nor was there any evidence that there had been any. There were no signs of condensation having occurred in the ducts themselves.

3.7 Occupier Reactions

The overall reaction from the four households was that they had not really noticed or thought about the system until the interview which on investigation meant that they had rarely considered opening or shutting window vents or opening windows to reduce cooking smells or steam and that there were no significant annoying side effects: they had generally "forgotten" about the system - these are very encouraging comments.

In interpreting the views it should be remembered that in the three non-monitored houses the system was not working to full capacity because the inlet registers were restricting flows, and in two of those houses the ducts in the loft had a number of restricting bends which would also tend to reduce flows.

In detail it was apparent that window vents had generally been left open except during very cold or very windy weather following which the occupiers had reopened them. Just one window vent had caused problems - the one in the lounge had resulted in draughts to people whilst sitting, for example watching TV so this one was frequently closed. No back draughts had been noticed from the ducts nor had any dirt fallen or blown down. Some noise had been apparent: for example the occasional aeroplane had been noticed and heavy rain (presumably on the plastic of the tile vent) had been heard "through the kitchen duct" and there was a "whispering" noise during windy weather. However none of the occupiers had found these noises annoying and had only offered the information in response to the direct questions.

In particular they all thought that cooking smells and steam had cleared quickly (without window opening) with no musty smells in the bathroom after the room had been closed overnight. One pair of occupiers who smoked remarked on the quick clearance of smoke and lack of "stale tobacco" smell in the morning and commented that the clearance was much more effective than in their previous older and presumably leakier house.

Specific comments were received from the occupiers of the monitored house appertaining to certain test periods. They said they had noticed more condensation on windows during periods when the window vents had been shut (ducts open) and particularly when the ducts had been closed off. They commented on lingering cooking smells and "smokey" conditions with the ducts closed off whether or not the window vents were open.

Condensation had generally been encountered on the single glazed windows and in some cases had run off into pools on the sills: this would be expected during winter months due to the changing external environment.

3.8 Discussion

The simple passive ventilation system provided a continuous background ventilation rate averaging at about 0.45 ac/h during the winter conditions in a tightly constructed house which would have been otherwise under-ventilated. The driving forces for the system were the wind and the internal/external temperature difference, and it appears that in the winter there was usually sufficient of one or these to produce a reasonable extraction rate. If both driving forces were high, the extraction rate did not become excessive, as the ducts appeared to self throttle.

Window vents alone would have left the house under-ventilated except during strong winds, when they were likely to be closed anyway.

The effect of window vents in addition to the ventilation system was more complex. It appeared that if there was a good flow of air being extracted through the system due to one or both of the driving forces being high, then opening window vents had no effect or caused only a small increase in flows. However, the opening of the vents increased the natural cross house ventilation (as it would in the absence of the ventilation ducts) giving the occupier some control over the total ventilation rate. On the few occasions when both driving forces were low, air flows out of the house via the ducts dropped, especially that in the bathroom duct. Under those conditions it is thought that opening the window vents would tend to counteract this drop: both driving forces were low when it was relatively warm and calm in the middle of the day when ventilation levels in the bathroom least mattered.

Thus, if the occupier tends to close window vents in windy or cold weather and opens them during the better weather, the best from the system will be obtained. At worst, if the occupier leaves window vents shut all the time the house should still have, at minimum, an air change rate of 0.4 and so, with reasonable indoor activities, should not have too many condensation problems. There appeared to be no significant disadvantages and the occupiers were able effectively to "forget about" the system.

4. OVERALL ASSESSMENT AND CONCLUSIONS

The extent of the effect of fitting passive ventilation ducts into a house depends particularly on the basic tightness of that house.

If the house is very tight, as the monitored Laing house (about 0.1 ac/h) the introduction of the system is very beneficial.

It provides a continuous background ventilation rate, extracting from the moisture producing areas. If the window vents are kept shut this ventilation rate should be, for most of the time near to the minimum considered to be satisfactory, even when it is very cold with a strong wind blowing outside. If the window vents are opened the background ventilation continues but there is an increase in the total rate for the house: this will increase as wind increases, but is unlikely to be excessive, as the vents will probably be shut during strong wind to prevent draughts. During warm calm weather, flows in the ducts will reduce, especially that from an upstairs room (e.g. bathroom) but this reduction will be minimised if window vents are opened, which is probable under these conditions.

If the house is less tight, as the TRADA test house (about 0.4 ac/h) the introduction of the system is again beneficial. However, there will be higher cross house ventilation than if the house was very tight. The window vents will have the same effects, but the magnitudes will be different: overall there must be a tendency to higher ventilation rates than in the very tight house.

In an older type house with a basic ventilation rate of about 1 ac/h or greater, a passive ventilation system would still work, but the total levels of ventilation would be too high.

The idea of building tight houses and installing passive ventilation systems, similar to those described in this paper, to provide controlled background ventilation rates, is commended. The system would only be suitable for older property if extensive draught-proofing was carried out, and would only contribute to condensation control if the property was made thermally efficient and properly heated.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 5

INDOOR AIR QUALITY AND AIR EXCHANGE IN BEDROOMS

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SYNOPSIS

Measurements of natural ventilation rates in bedrooms during nighttime has been carried out in retrofitted apartments as part of a study investigating environmental data in relation to the results of preceeding epidemiological studies.

The meaurements indicate clearly that indoor air quality in bedrooms may be unacceptable in dwellings with a energy-efficient minimal ventilation rate. The air supply rates may be as low as 1 l/s/person in the median case of bedroom size, ventilation rate and two occupants. The carbon dioxide concentration will reach a level of 4000-4500 ppm in the morning depending on the length of the sleeping time in a closed room. The air humidity will be increased too, but depending on the accumulation and condensation of moisture in the room. However, users habits of living and housekeeping can increase ventilation rates in practice. The need of public information about indoor air quality and ventilation practice is therefore underlined.

INTRODUCTION

Regulatory requirements to thermal insulation in new buildings has been in force in Denmark since 1960, when specifications on maximal allowable k-values were given. These values have later on been upgraded, and the current demand is a k-value between 0.2 - 0.4 $W/m^2\ ^{o}C$ for various components of the building envelope.Windows have to be thermal windows and the total area of glass may not exceed 15 percent of the gross area of the building[1]. Airtightness standards similar to those in other IEA/AIC affiliated countries as reviewed by Jackman[2], have not yet been introduced in Denmark.

However new airtight window types, caulking and other measures designed to reduce heat loss by natural infiltration have besides been introduced in both existing and the new buildings, but normally without attention to ensure any lower health ventilation safe limit to be maintained. A safe limit is not only a minimal supply of oxygen for breathing, but a sufficient ventilation rate for dilution of airborne contaminants of any short-term or long-term significance to health and well-being.

A decription of the adverse health effects which can be associated with indoor non-occupational exposure are recently listed with reference to combustion sources and indoor air quality by the U.S. Department of Energy[3]. The knowledge available is based on clinical as well as epidemiological research.

The aim of the present study has been to investigate if such lower limits are violated in bedrooms in dwellings after change to tight thermal windows and retrofitting was carried out. The bedroom in the dwellings was chosen for field measurements and parametric calculations because this room is considered to be the most loaded indoor space with regard to continuous occupancy time and minimal volume ratio per person compared to the living rooms. Railio[4] has described this in particular as "the bedroom problem".

The exhalation of carbon dioxide and water vapour has been used as an indicator of human load of the indoor environment. This means that ventilation requirements to airborne contaminants from materials, household products, tobacco smoking, gas burning devices, cooking and unvented space heaters was not considered primarily.

MATERIAL AND METHODS

The measurements took place in the winter 1984-1985 in apartments which previously had been included in the study group of a prospective epidemiological study of the health and comfort changes among tenants after change to new airtight thermal windows and retrofitting of their apartments[5]. The changes to the new windows of PVC-frames had been executed in the fall of 1981. The ventilation rate in the dwellings before that time is not known, as environmental measurements were not performed in the buildings before the energy conservation measures took place.

The building types were medium rise brick buildings 3-4 storeys high built about 1950. All apartments were central heated and had a good maintenance standard. The kitchens had electric cooking, and laundry was supposed to take place in a separate common facility. Kitchens and bathrooms had openings to a passive exhaust ventilation stack to the roof. No homes had air conditioning units installed, as such units do not exist in private homes in Denmark. Living rooms and bedrooms were supplied with windows which could be opened for escape in case of fire and for airing. All measurements were performed with closed windows and doors in order to have the most reproducable condition and the worst condition in a contaminant build-up situation.

Outdoor weather conditions in terms of air temperature, humidity, wind velocity and wind direction were recorded from the meteorological station of Aalborg airport, located in a about 10 km distance from the housing areas.

The 29 investigated dwellings were of medium size, having separate kitchen and wc, one larger living room and one or two smaller bedrooms. The bedrooms were mostly used by 1 or 2 persons, but by

three persons in a few cases. The size of the bedrooms was between 18-43 m^3 with a median value of 32 m^3 (IQR 28-34).

Ventilation rates were determined with carbon dioxide as a tracer gas, and the decay from a initial level of 6-8000 ppm was measured continuously with a Leybold Heraeus/Binos 1 infrared gas analyzer. Uniform mixing was obtained by a table ventilator.

The room was unoccupied under the measurement, and the carbon dioxide concentrations in adjacent rooms were measured as well. The decreasing tracer concentration was measured within a 90 minutes period in order to obtain a 95% confidence level in the slope determination of the ventilation rate as stated by Kronvall[6].

The total ventilation rate of the dwelling as well as the room-to-room air transfer within the dwelling was measured in some cases.

Build-up of carbon dioxide and water vapour per kg dry air in the bedrooms during the nighttime has been calculated based on the values of air change rates and corresponding volume flow of outdoor air determined. The findings in field measurements will be described later on.

RESULTS

The ventilation rates in the 29 bedrooms were found to vary between 0.1-0.5 ach having a distribution with a a median value of 0.23 (IQR 0.17-0.31) and an arithmetic mean value of 0.25 ach (SD= 0.1). The related air volumes supplied from the outside depended on the room volume in each case and were found to vary between 1,0-3,7 liters/second, with a median value of 2.0 (IQR 1.5-2.8) l/s.

The distribution of air change rates and air supply rates is shown in table 1.

Outdoor temperatures were between 1.5 to 9.8 C with a median value of 5.0 C (IQR 3.4-7.6) and the wind velocities between 1.6-7.8 m/s with a median value of 6.2 m/s (IQR 2.6-8.2) on the days when measurements took place. Indoor temperatures varied between 16-22 C. Multiple linear regression analysis did not show any significant correlation between air change rates, wind velocity and temperature, certainly because air infiltration through the new window constructions are not that much influenced by outdoor weather conditions (Harrje and Mills[7]).

Analysis of means and moments of air change rate and air volume flows shows a tendency to a positively skewed distribution with respective skewness coefficients of 1.05 and 0.57. The difference between the two ventilation parameters is because of the tendency

to a lower air change rate in the larger bedrooms and a relatively higher air change rate in the smaller bedrooms.

Assuming an 8 hour continuous occupation of the bedroom of two resting persons exhaling 30 liters of carbon dioxide per hour, carbon dioxide concentrations in the morning are calculated in table 2 for the lowest, the mean and the highest air supply rates measured. The steady state concentrations of which 95% is reached within 6-30 hours at ventilation rates between 0.1-0.5 ach are shown as well.

These concentrations will exceed the recommended values of limits for carbon dioxide exposure in non-occupational environments which vary between 1000-2500 ppm (WHO Meeting Report[8]). The Threshold Limit Value of 5000 ppm for occupational exposure may even be exceeded in the worst cases.

The corresponding increase in indoor air humidity will depend on the adsorption of water vapour in the bedroom interior materials. The required volume of ventilating air to keep the air humidity below a certain level will, moreover, vary according to the humidity in the outdoor air, and therefore depend on the climatic conditions of the year round.

DISCUSSION

Apartment residents' evaluation of their health status and indoor climate perception related to the implementation of energy conservation measures in Danish housing has previously been described[5].

This showed the benefits of better insulation and a less draughty dwelling especially to the elderly, spending most of their time at home. Any immediate disadvantages of reduced natural ventilation on indoor air quality could not be demonstrated. This might be because it is less pronounced in 30-40 year old buildings where off-gassing from materials is neglible. In addition the households were usually small and did not include overpopulated dwellings, which in Denmark is stipulated to be more than two individuals older than two years per room.

The size of the population in the study was in addition not large enough to at random include a sufficient number of subjects suffering from allergic diseases. Those individuals should be first to respond on changes in indoor allergens caused by house dust mites, favoured by increased air humidity after sealing of the houses (Korsgaard[9,10]).

Therefore requirements for ventilation rates after retrofitting of the dwellings should still be considered from a health point

of view. It is most obvious to propose that the ventilation rates should fulfil the existing building code for new houses. This specifies an air change rate of 0.5 per hour to be obtained by the presence of a user-operable fresh air valve in each room with a 30 cm^2 free square [1]. Even better would be to agree with The Guidelines for Nordic building regulations regarding indoor air which has specified a fresh air supply of 4 l/s per person in bedrooms[11]. This equals a 0.9 ach in a average bedroom of 30-35 m^3 occupied by two persons, which is almost twice the prescribed value of 0.5 ach.

The present study has shown, that the air supply rates may be as low as 1 l/s/person in the median case of bedroom size, ventilation rate and two occupants. The carbon dioxide concentration will reach a level of 4000-4500 ppm in the morning depending on the length of the sleeping time. The air humidity will be increased too, but depend on the accumulation and condensation of moisture in the room. Becker[12] has described the problem of invisible condensation and mould growth in particular for housing in areas with high temperature differences between minimum night temperature and maximum day temperature with related variations in air humidity.

It is obvious that the user-operated ventilation is a most important parameter in practice. It has recently been shown by continuous measurement of ventilation rates in occupied homes, that the basic ventilation rate may be increased with a factor of 3-4 at the average (Kvisgaard, Collet and Kure[13]). The need for user active ventilation precautions has to be underlined in the case of bedrooms in energy efficient tightened building envelopes without controlled mechanical ventilation systems by public information. Field measurements in continuation including epidemiological studies can emphasize this need in further detail.

Acknowledgements

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TABLES

Table 1. Air change rates (h^{-1}) in bedrooms and corresponding air supply rates (l/s) according to room volume (m^3).

air change rate	number of dwellings	(%)	range of room Volumes	range of air supply rates
0 - 0,1	0	0%	-	-
0,1- 0,2	8	28%	33-37	1,0-1,7
0,2- 0,3	15	52%	21-43	1,3-2,7
0,3- 0,4	4	14%	18-33	1,8-3,1
0,4- 0,5	2	6%	27-28	3,1-3,7
0,5	0	0%	-	-

Table 2. Carbon dioxide concentration levels in bedrooms at air supply rates as measured. Background 350 ppm.

air supply l/s & p interval	number of cases	carbondioxide concentration levels ppm after 8 hours occupation	steady-state
0,5-1,0	15	5500-4300	8700-4500
1,0-1,5	10	4300-2900	4500-3100
1,5-2,0	4	2900-2400	3100-2400

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 6

EFFECT OF UNVENTED COMBUSTION APPLIANCES ON AIR EXCHANGE AMONG INDOOR SPACES

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SYNOPSIS

The effects of operating unvented appliances and opening windows on indoor pollutant levels and air exchange rates are being studied under the sponsorship of the Gas Research Institute. The study is being conducted in an instrumented, well-characterized bilevel house located near Washington, D.C. Air leakage due to window openings is characterized by pressurization measurements and the air exchange increment is characterized through tracer gas measurements. Two unvented space heaters, one radiant and the other convective, are operated singly and in combination with a gas cooking range.

When an upstairs heater is operating, there is rapid horizontal mixing of pollutants but little penetration to the downstairs area. When a downstairs heater is operating, there is rapid mixing throughout the entire indoor space. Results to date also indicate that effect of opening windows on pollutant levels and air exchange is quite variable. Simultaneous operation of two or more unvented combustion appliances results in peak concentrations that are greater than what would be expected by summing the peaks for each single-source case.

1.0 INTRODUCTION

In the United States, 40 percent of all occupied housing units in the country use natural gas as the primary fuel for cooking, according to the results of the 1980 Census of Population and Housing. The fraction of housing units using natural gas as the primary heating fuel is 53 percent; a relatively small proportion, probably about 2 percent, of housing units use unvented gas space heaters (UVGSHs) as the primary means of heating. As a general rule, UVGSHs tend to be used more often in areas of the country that have only a moderate heating demand, and more specifically in neighborhoods with housing units built predominantly before 1960.

As a product of the combustion, certain air pollutants such as carbon monoxide (CO) and nitrogen dioxide (NO_2) are emitted by unvented appliances into residential air spaces. The impact of these appliances on indoor air quality depends on the complex interplay among various types of factors such as size of the structure, number and type of unvented appliances and their patterns of use, the condition of the appliances, prevailing air infiltration rates, and ventilation practices by occupants. These ventilation practices include both mechanical ventilation, such as using a range exhaust fan, or natural ventilation, such as opening windows or doors.

During the past year, GEOMET has been performing investigations involving unvented gas appliances in an unoccupied test house under controlled conditions. This work, which has been sponsored by the Gas Research Institute, concerns the impact of unvented gas appliances on indoor air quality and the effects of different ventilation practices during appliance operation on air exchange

and indoor air quality. The focus of this paper is on results concerning UVGSHs but some results related to the gas range are also provided.

2.0 RESEARCH METHODS

The setting for this research is two unoccupied, bilevel houses that were built during the fall of 1982 as part of a new subdivision approximately 35 km northwest of Washington, D.C., in Gaithersburg, Maryland. The two houses were built side-by-side with a mobile laboratory between them that contains most of the analytical devices used for measurements and an automated data recording system. Since their construction, these houses have been used for various types of research on infiltration, energy, and indoor air quality. Parameters measured in these houses include air infiltration, various air pollutants, energy consumption, indoor and outdoor temperatures and relative humidity, barometric pressure, solar radiation, and windspeed and direction. A related paper[1] presented at this conference shows a picture of these houses and lists their construction characteristics.

Both of the houses have gas ranges and one of the houses was recently equipped with two UVGSHs--a 10,000 Btu/h convective unit located in the upstairs master bedroom and a 15,000 Btu/h radiant unit located in the downstairs living area. Figure 1 shows the floor plan including the locations of unvented appliances and three sampling points (X, Y, and Z) for CO, NO_2, and tracer gas (SF_6) in one of the houses. The upstairs zone is connected to the downstairs with a stairwell; the opening at the bottom of the stairs is 90 cm x 240 cm high and is without a door. The other house has an identical floor plan but has no UVGSHs and only one sampling line located in the upstairs living room.

Experiments concerning the impacts of UVGSHs and window openings were conducted during the 1984-85 winter; during each experiment, the house without a UVGSH was operated with its normal electric, forced-air furnace for comparison purposes. Each experiment was conducted between the hours of 9 a.m. and 4 p.m., during which one of the UVGSHs was operated for 4 h, shut off for 1 h, and then reoperated for 2 additional h. The specific sequence of events for each experiment is shown in Table 1.

The intent of the experiments was not to simulate any particular pattern of occupant use but rather to view the effect of intermittent UVGSH use in a repeatable way. During some experiments, the window nearest the heater was opened either 3.2 mm (1/8 in) or 19 mm (3/4 in). These rather narrow openings were expected to be typical of those that might be used in the coldest parts of winter. During a few of the experiments, the gas range was also operated during the last 40 min of the second period of UVGSH operation (see Table 1) so that the impacts of multiple appliances could be assessed; windows were not opened during any of the experiments that included the gas range. The choice of

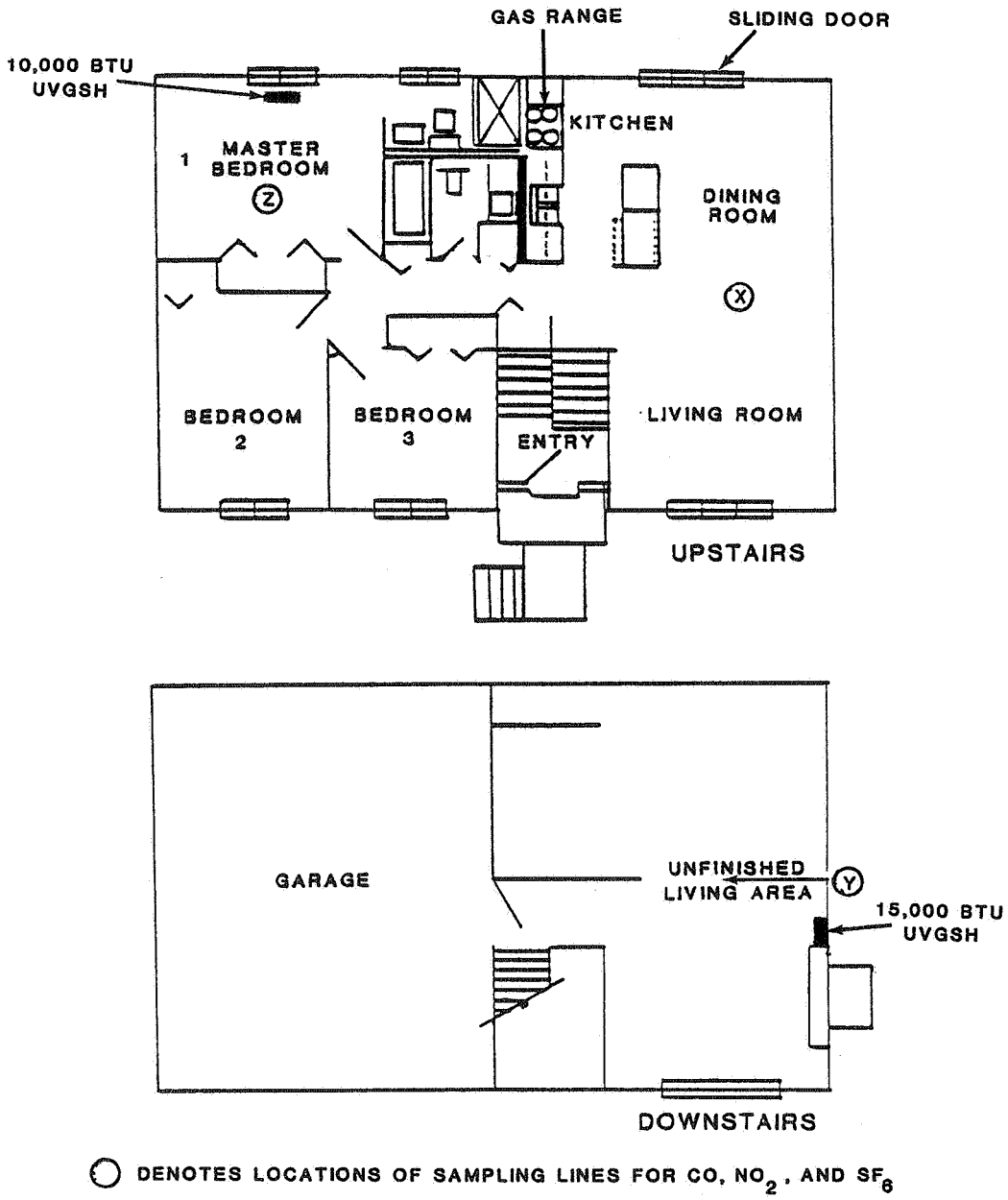


Figure 1. Floor Plans for the Test House Equipped with UVGSHs.

Table 1

SEQUENCE OF EVENTS FOR EXPERIMENTS CONCERNING UVGSHs

Time Period	Activity
8:00 to 8:30 a.m.	Inject and mix the tracer gas (SF_6) using the central air circulation system
9:00 a.m. to 1:00 p.m.*	Operate one of the UVGSHs at its maximum heat setting
1:00 to 2:00 p.m.	No source activity
2:00 to 4:00 p.m.*	Reoperate the UVGSH that was operated from 9:00 a.m. to 1 p.m.
3:20 to 4:00 p.m. (for selected experiments)	Operate the gas range with one burner fully on and the oven set at 175 °C

* For the experiments in which the gas range was not used, the window nearest the UVGSH was opened either 3.2 mm or 19 mm.

40 min for gas range operation was for compatibility with some previous experiments that concerned only the gas range.

Additionally, during the summer of 1984, experiments were conducted to examine the impacts of ventilation practices associated with the operation of a gas range on air infiltration and indoor air quality. The following ventilation practices were examined:

- Operation of a range exhaust fan
- A 15-cm (6-in) partial opening of a sliding glass door near the gas range in combination with the range exhaust fan
- Partial opening of the sliding door and additional windows to allow for cross ventilation.

For each experiment, the gas range was operated for a 40-min period. Some of the ventilation practices were concurrent with gas range operation whereas others began 20 min after the range was turned on; this latter mode of operation was chosen to represent the fact that some occupants might use ventilation only to reduce heat, odor, or smoke generated by the range and cooking. Another ventilation practice, continuous use of an air-to-air heat exchanger, was examined under a previous project[2] for the Electric Power Research Institute;

results concerning use of the heat exchanger during the period of range operation are also included in this paper.

3.0 RESULTS AND DISCUSSION

Results are presented in the next four subsections. First, the effects on pollutant and air-movement behavior when each UVGSH was operated without ventilation are examined. Second, the impact of opening a window nearest the UVGSH during its operation is discussed. Third, the effects of alternative types of natural and mechanical ventilation practices during gas range operation are shown. Fourth, the results of operating both a UVGSH and the gas range, with no ventilation, are provided.

3.1 UVGSH Operation with No Ventilation

Figure 2 shows CO concentrations during and after two periods of UVGSH operation. When the upstairs heater was operating (upper part of the figure), there was rapid mixing throughout the upstairs space but there was little impact downstairs; moreover, the peak CO concentration at the end of each period of UVGSH operation was slightly higher in the living room than in the bedroom where the heater is located. When the downstairs heater was operating (lower part of the figure), there was rapid mixing in both upstairs and downstairs or throughout the entire indoor space; the living room zone again had slightly higher peak concentrations than any of the other measurement zones and the bedroom had the lowest peak. It is also noteworthy that each time the downstairs heater was shut off the CO concentrations declined most rapidly downstairs. This greater rate of decrease is due to a higher rate of air infiltration downstairs; this higher rate, particularly during periods of cool weather, has been consistently demonstrated by tracer gas decay studies over the past several years[2] and has been verified recently by constant-concentration tracer gas measurements.[1]

NO_2 concentrations were also highest in the living room zone, regardless of the heater that was operating (Figure 3); it should be noted that the living room is directly above the room where the downstairs heater is located, as indicated by the floor plan (Figure 1). When the upstairs heater was operating, there was no evidence of NO_2 penetration to the lower level, as for CO. It also should be noted that the NO_2 concentration declined more rapidly than the CO concentration and that the rate of decrease appeared to be similar in all zones, in contrast to CO; this result is due to the fact that NO_2 is a highly reactive pollutant and its rapid rate of chemical decay overwhelms any dilution effects of air infiltration.[2]

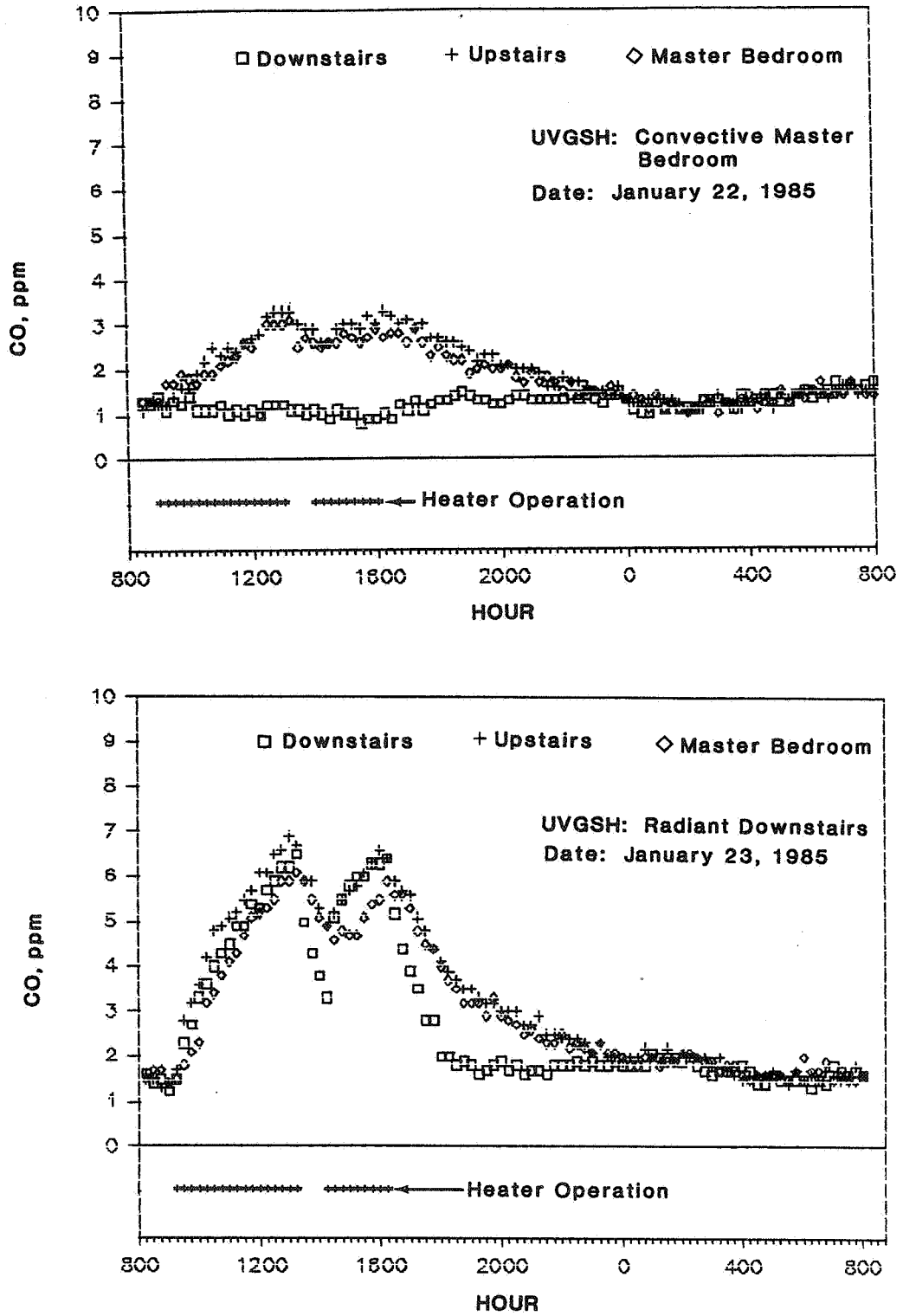
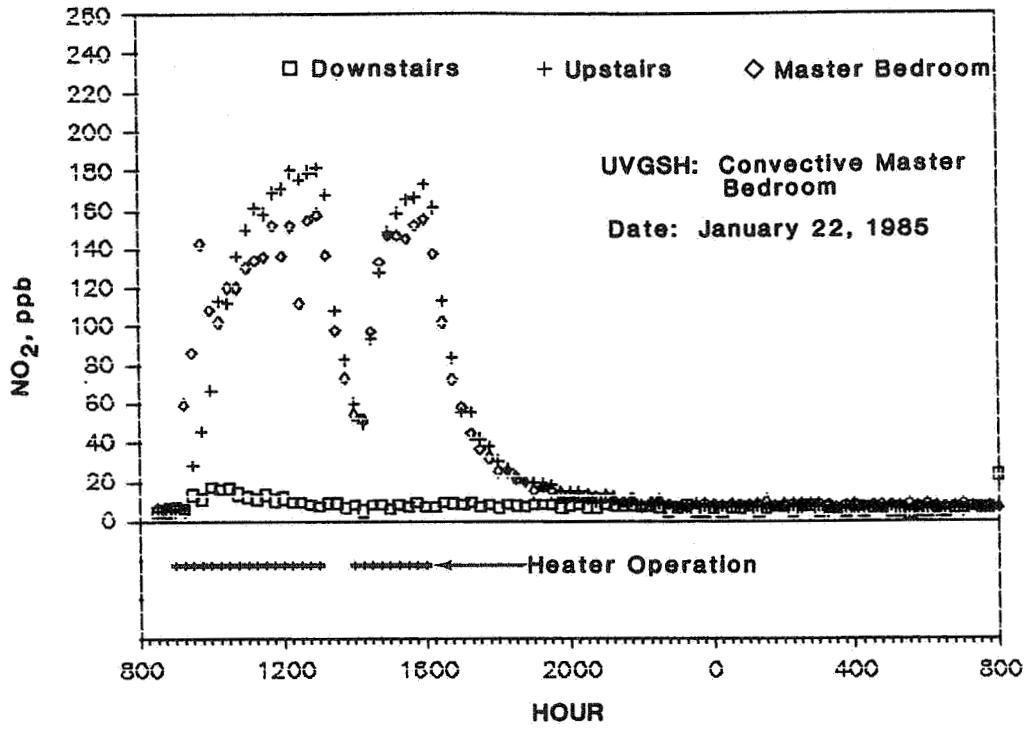


Figure 2. Carbon Monoxide Concentrations Resulting from Unvented Convective and Radiant Heaters.



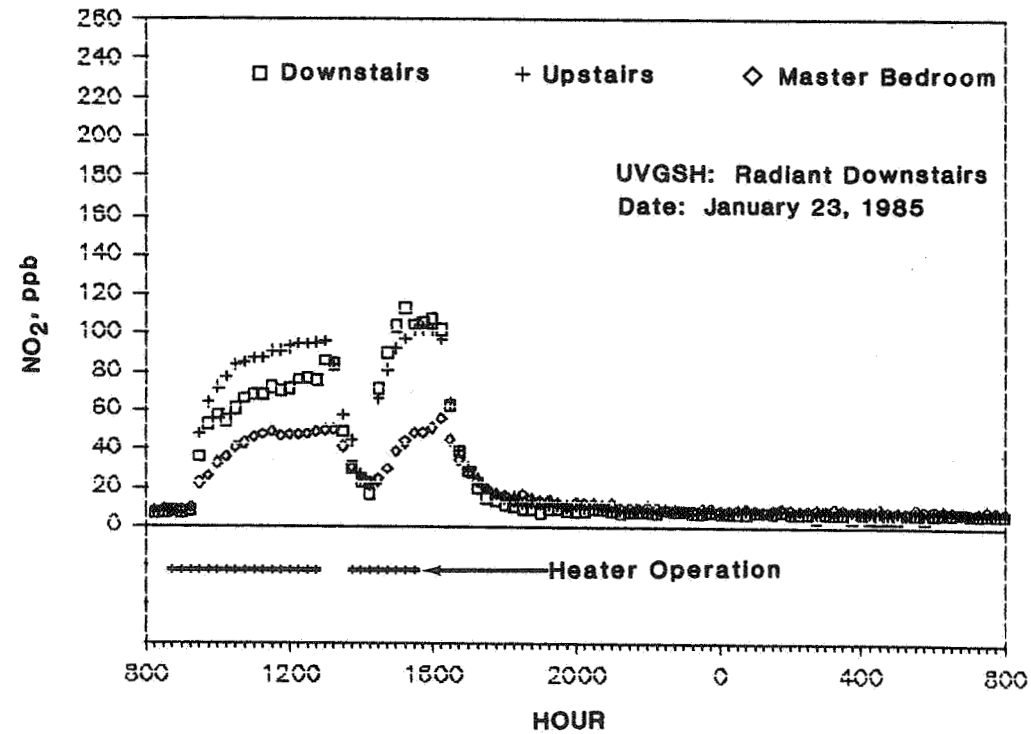


Figure 3. Nitrogen Dioxide Concentrations Resulting from Unvented Convective and Radiant Heaters.

3.2 UVGSH Operation with Opened Windows

Blower door measurements were taken to assess the potential impacts of narrow window openings on air infiltration rates. Pressurization and depressurization results at 50 Pascals are shown in Table 2. The narrow openings had a larger impact for the bedroom window than for the downstairs window. For a window opening of 3.2 mm, house tightness decreased by about 10 percent for the bedroom window and by less than 5 percent for the downstairs window. With an opening of 19 mm, the decrease in tightness was about 20 percent for the bedroom window and 15 percent for the downstairs window.

The effect of opening the master bedroom window during operation of the upstairs heater is shown in the upper portion of Table 3. With the 3.2-mm opening, there was no impact on peak CO or NO_2 concentrations. With the 19-mm opening, the CO peak was reduced by about 20 percent and the NO_2 peak by about 10 percent; however, in the case of CO, both the starting and outdoor concentrations were somewhat less than for the base case, such that the peak reduction was more on the order of 10 percent. The average air infiltration rates for these three cases were quite similar, but one of the major driving forces (ΔT or windspeed) was milder on the days when windows were opened. After an adjustment was made for weather conditions on the basis of a regression model developed from previous studies,[2] it was determined that the 3.2-mm opening increased the air infiltration rate for that day by about 0.05 ACH (11 percent) and that the 19-mm opening resulted in an increase of 0.15 ACH (33 percent). Thus, the increased air exchange seems to have brought about less than a proportionate reduction in peak concentrations.

The effect of opening the downstairs window during operation of the downstairs heater is shown in the lower portion of Table 3. Again the 3.2-mm opening had little impact whereas the 19-mm opening reduced the peaks by 10 percent. After adjusting for weather conditions the 3.2-mm opening increased air infiltration by only 0.02 ACH (5 percent) whereas the 19-mm opening caused an increase of 0.15 ACH (35 percent). It should be noted that the 3.2-mm opening had an apparent adverse effect on indoor air quality on day 713; however, this particular experiment took place on an unseasonably mild day, such that temperature and wind effects on infiltration were negligible. In addition, outdoor pollutant concentrations were somewhat higher on this day than in the other cases. A mass balance equation for indoor air quality, which accounts for the effects of indoor sources, air infiltration, and outdoor concentrations, was applied to CO concentrations for the two cases when the window was opened 3.2 mm. As shown in Figure 4, measured and modeled concentrations agreed very closely in each case; this finding means that the higher CO concentrations on day 713 can be confidently attributed to prevailing outdoor CO and temperature conditions rather than the fact that the window was opened.

Table 2

EFFECT OF SCALED WINDOW OPENINGS (3.2 and 19 mm) ON BLOWER DOOR RESULTS (ACH at 50 Pascals)

	Depressurized Conditions			Pressured Conditions			Average of Two Conditions		
	Window Closed	Window Opened	Percent Increase	Window Closed	Window Opened	Percent Increase	Window Closed	Window Opened	Percent Increase
Opening of 3.2 mm:									
Downstairs window	5.58	5.71	2.3	6.50	6.53	0.5	6.04	6.12	1.3
Bedroom window	5.43	6.04	11.2	6.44	6.97	8.2	5.94	6.51	9.6
Opening of 19 mm:									
Downstairs window	5.58	6.30	12.9	6.50	7.47	14.9	6.04	6.89	14.1
Bedroom window	5.43	6.78	24.9	6.44	7.56	17.4	5.94	7.17	20.7

Table 3

EFFECT OF WINDOW OPENINGS DURING UVGSH OPERATION ON CO AND NO_2 CONCENTRATIONS AND AIR INFILTRATION RATES

	Upstairs Heater (Convective)		
	No Opening (Day 22; 1/22/85)	3.2-mm Opening (Day 11; 1/11/85)	19-mm Opening (Day 58; 2/27/85)
CO (ppm)			
Initial*	1.2	1.6	1.0
Peak*	3.3	3.6	2.6
Outdoors	0.8	1.0	0.6
NO_2 (ppb)			
Initial*	5	4	5
Peak*	181	183	161
Outdoors	11	14	9
Infiltration Rate (ACH)†	0.46	0.42	0.43
Average ΔT (°C, in - out)	17.9	15.9	5.2
Average Windspeed (mph)	10.6	4.1	10.9

	Downstairs Heater (Radiant)			
	No Opening	3.2-mm Openings		19-mm Opening
	(Day 23; 1/23/85)	(Day 18; 1/18/85)	(Day 713; 12/13/84)	(Day 59; 2/28/85)
CO (ppm)				
Initial*	1.4	1.5	2.1	1.7
Peak*	6.9	7.2	10.0	5.6
Outdoor	1.0	1.0	1.6	0.2
NO_2 (ppb)				
Initial*	7	5	4	5
Peak*	96	83	109	86
Outdoors	13	13	28	10
Infiltration Rate (ACH)†	0.43	0.38	0.13	0.46
Average ΔT (°C, in - out)	15.6	12.3	0.7	8.8
Average Windspeed (mph)	5.5	2.7	2.5	2.8

* Based on measurements taken in the upstairs living room zone.
† Average air infiltration rate for the entire house during the period of UVGSH operation (0900 to 1300 in each case).

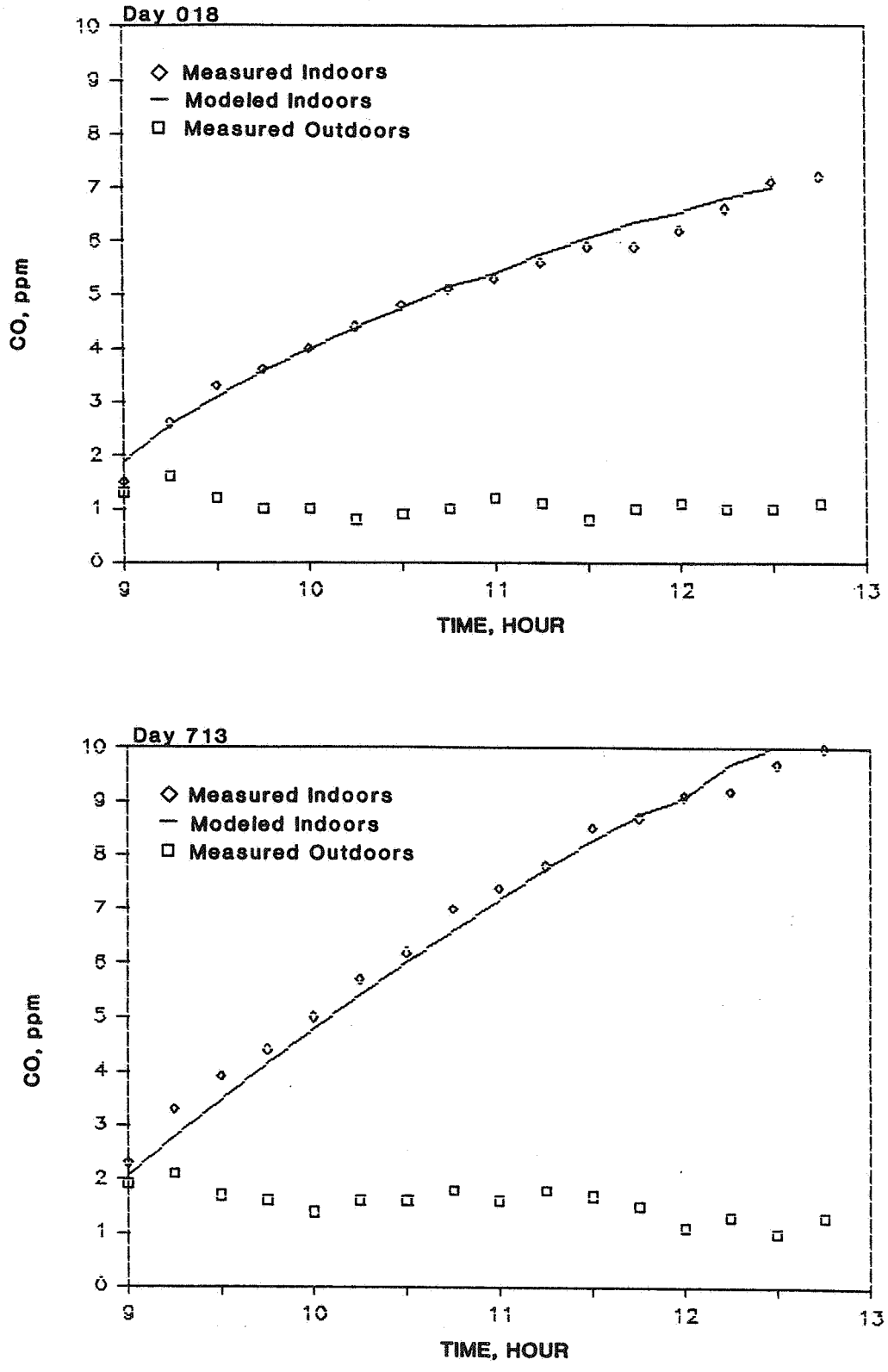


Figure 4. Measured and Modeled Indoor CO Concentrations with the Downstairs UVGSH Operating and a Window Opened 3.2 mm--Results from Two Different Days.

3.3 Ventilation Practices During Range Operation

The impacts of different natural and mechanical ventilation practices during the operation of a gas range are summarized in Table 4. In this case, the increment in air exchange due to each practice could be determined directly by comparing air infiltration rates during the 40-min period of range operation with rates before and after this period. A number of striking results are apparent:

- Operation of the heat exchanger had little impact on peak concentrations.
- The range exhaust fan reduced peak pollutant concentrations by nearly 50 percent when operating concurrently with the range but had little impact when its use was delayed by 20 min; results were similar whether the exhaust fan was operating in isolation or in combination with opening a sliding door near the kitchen.
- Opening the sliding door and one window in a remote part of the house had little impact on the CO peak and increased the NO_2 peak, even though air exchange was increased by more than 0.5 ACH.
- Opening the sliding door and all upstairs windows reduced the CO peak by about 30 percent but had no impact on the NO_2 peak, in spite of an air exchange increment of more than 1.0 ACH.

The effects of these practices on 8-h average CO concentrations were also examined; these are reported elsewhere.[3] The range exhaust fan had the greatest impact because it removes high-concentration air that is in the immediate vicinity of the emission source. One of the exhaust vents for the heat exchanger is located in the kitchen but the pollutant concentrations are already diluted by mixing with other indoor air by the time they reach this vent. Natural ventilation practices had variable effects because they result in unpredictable air movement patterns even though they increase air exchange. This is particularly true under summer conditions when stack forces are relatively mild.

3.4 Operation of Multiple Unvented Appliances

The results of operating the gas range during the last 40 min of bedroom heater operation are shown in Figure 5. There were marked increases in CO and NO_2 peaks, particularly in the living room zone. For example, when the gas range is the only source, our previous research[2] has shown that the usual CO peak in the living room is about 8 to 9 ppm. Similarly, when the bedroom heater is the only source, the CO peak in the bedroom or living room is about 3 to 4 ppm (Figure 2). For the

Table 4

IMPACT OF VENTILATION PRACTICES DURING GAS RANGE OPERATION ON AIR EXCHANGE RATES AND PEAK POLLUTANT CONCENTRATIONS

Type of Ventilation	Minutes Used with Gas Range*	Air Exchange Increment (ACH)	Peak CO Concentration (ppm)	Peak NO_2 Concentration (ppb)
None	--	0†	6.3	69
Air-to-air Heat Exchanger	All 40	0.33	5.9	62
Range Fan	Last 20	0.14	5.6	65
Range Fan	All 40	0.29	3.5	39
Range Fan and Sliding Door	Last 20	0.23	6.1	68
Range Fan and Sliding Door	All 40	0.56	3.1	36
Sliding Door and Window in Bedroom 2	All 40	0.63	5.9	96
Sliding Door and Windows in Living Room and All Bedrooms	All 40	1.24	4.4	65

* The gas range was operated for a period of 40 min in each case with one burner fully on and the oven set at 175 °C.

† Air infiltration rates during the period of testing were usually between 0.1 and 0.2 ACH in the absence of ventilation practices.

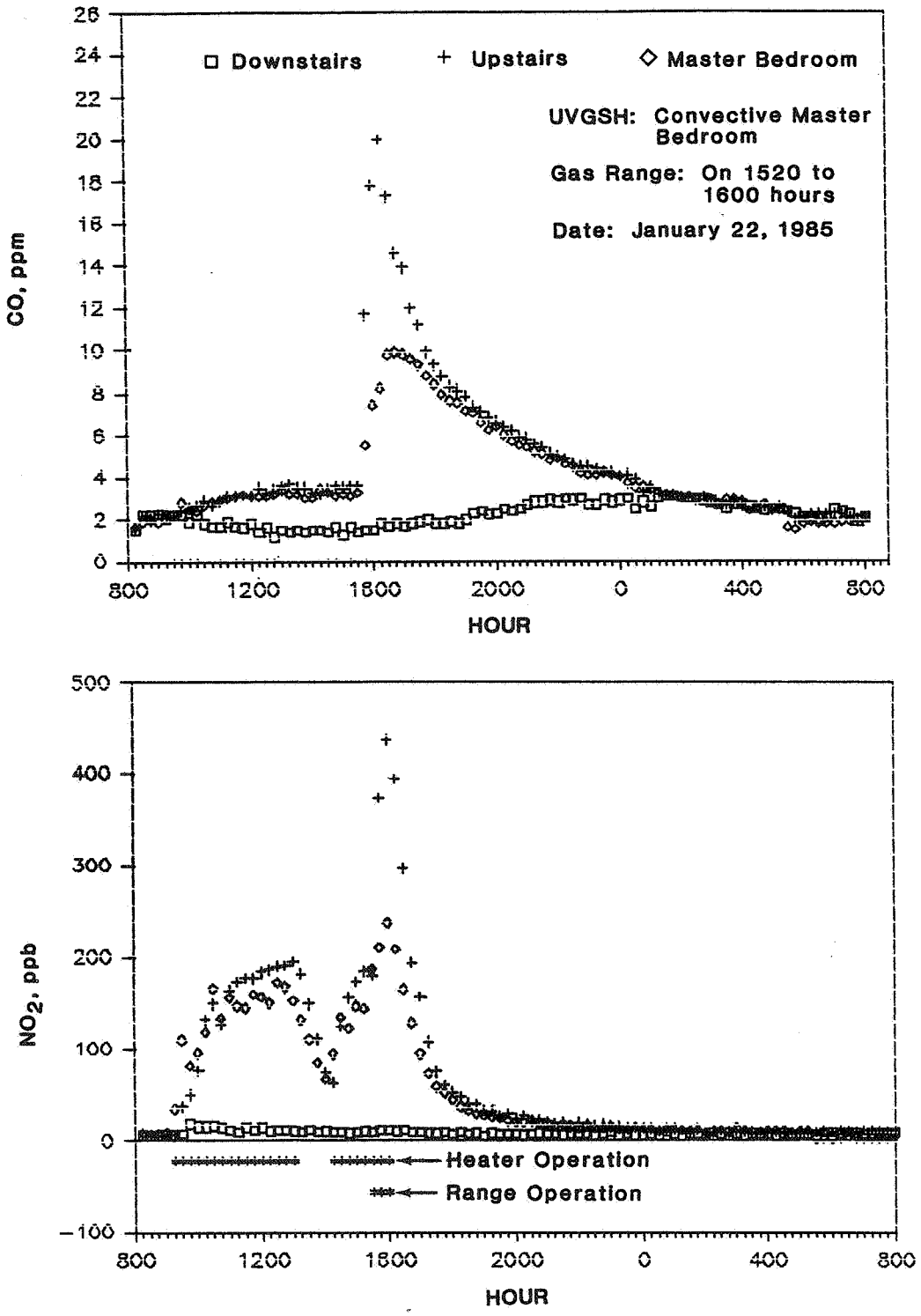


Figure 5. Effect of UVGSH and Gas Range Operation on CO and NO_2 Concentrations--Convective UVGSH in Master Bedroom.

case shown in Figure 5, the CO peaks in either zone are more than twice their values for the single-source case. A plausible explanation is that the convective forces that normally promote rapid horizontal mixing were restricted when the two heat sources were present. This would result in CO emissions from the range being confined mainly to the kitchen/dining room/living room area and CO emissions from the heater being confined mainly to the bedrooms and bathrooms, thus increasing peak concentrations. These high peaks last as long as 1 h after the heater and range are shut off, at which time the concentrations tend to equalize.

4.0 CONCLUDING REMARKS

This paper presents preliminary findings from research conducted in test houses. The findings include the following:

- Consistent with source emissions data[4] a radiant heater produces higher levels of CO than a convective heater. Similarly, as expected, NO_2 levels were lower for the radiant than the convective heater.

- Because of the buoyancy of combustion gases, concentrations of CO and NO_2 were higher than outdoors for only the upstairs area when the heater located upstairs was operating; the concentrations downstairs were similar to the outdoors under this situation. When the downstairs heater was operating the concentration on both floors were fairly well mixed, but those upstairs were somewhat higher than those downstairs.

- When windows were opened, there was a somewhat greater impact on air exchange due to differences in indoor/outdoor temperatures than the size of opening per se. Thus, the impact of opening windows to reduce levels of combustion contaminants was highly variable, particularly when the gas range was operating.

- For the gas cooking range, operating the range-hood exhaust fan during the entire cooking episode was most effective in reducing CO and NO_2 concentrations.

- Operating two unvented appliances created peak concentrations that were more than twice those of either of the single-source cases. It is presumed that this phenomenon was due to reduced air exchange between spaces.

The above should be considered tentative conclusions. More research needs to be conducted, especially on the last observation regarding multiple unvented appliances. This research would benefit from using multiple tracer studies as an integral part of the measurement approach.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 7

AIR EXCHANGE RATES BASED UPON INDIVIDUAL ROOM AND SINGLE CELL MEASUREMENTS

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SYNOPSIS

For more than two years a series of detailed air infiltration measurements have been conducted over the complete yearly weather cycle on two identical side-by-side test houses in Gaithersburg, Maryland, USA. These measurements have been part of a broad study of the interaction of air infiltration, indoor air quality and energy in tightly constructed, well-insulated homes. The standard method of collecting air infiltration data throughout the study has been tracer gas decay. Operation of the duct air circulation fans has transformed each house into a single well-mixed cell. Natural air mixing in the upper and lower floors, with the fan operated occasionally, results in two cell behavior. The present phase of the air infiltration portion of the study has been to use constant concentration tracer gas equipment to study the air infiltration in six individual zones. This has allowed comparisons between the two methods as well as looking at the air infiltration profile in a much more detailed way. For example, the average infiltration rates for the control house using the two measurement methods are quite similar, but detailed information is now available on individual zone air infiltration rates and the effects of mechanical systems and weather influences on the zones. This paper compares the air infiltration measurement method results in the well-documented control house.

1.0 INTRODUCTION

In determining the air infiltration levels in our housing stock, in many countries we are evaluating our primary sources of ventilation. In any building situation where quantification of these important air infiltration values is desired, there is a wide choice of measurement methods with an associated degree of measurement complexity and detail in the information provided.[1] Examples include single location, tracer gas decay measurements or perhaps an interpretation of pressurization information on the building, as the simplest ways to estimate air infiltration values. At the other end of the information and complexity scale are constant-concentration tracer gas (CCTG) systems which can sample each zone in the house or larger building. In addition, multiple tracer gases may be employed to document interzone air flows to complement the individual zone air infiltration/ventilation rates provided by the CCTG system.

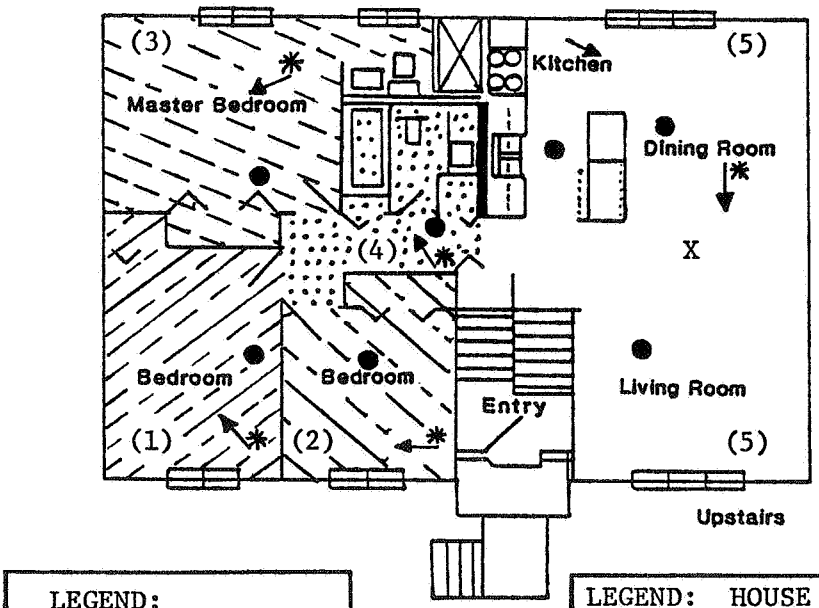
Is important detail on the air infiltration/ventilation rates being missed because of the choice of a simple measurement approach? The physics of the air movement within the house can greatly aid in making even the simplest air infiltration/ventilation measurements representative. Natural mixing of the air within the house is one factor that aids the investigator in collecting pertinent information. When we are dealing with more than one floor or where zones are separated by significant distances and/or closed doors, one can anticipate variations in the AI measurements depending upon location. Air exchange rates based upon individual zones (cells) and those based on limited cell measurements will be discussed in this paper.

Air infiltration was studied over a complete yearly cycle as part of an ambitious study into the interrelationships between energy use and indoor air quality (IAQ) in tight, well insulated residences.[2-6] The study, funded by the Electric Power Research Institute, followed a strategy using side-by-side identical houses which were closely monitored for indoor air quality, energy, local weather and air infiltration from a centrally located instrumentation trailer as shown in Figure 1. In addition, as part of the total experimental plan, the research included detailed testing of such other factors as: building envelope tightness over the seasons, insulation performance evaluated by infrared scanning, testing of passive detection methods to evaluate IAQ, and additional methods to measure the air infiltration rates in the individual zones of the houses. This paper discusses the results of the constant-concentration tracer gas measurements evaluating air exchange rates in six zones and how they relate to the extensive study of air infiltration in these houses using one or two cell tracer gas decay methods.



Figure 1. Test Site Showing Experimental and Control Houses with Mobile Laboratory.

The house floor plan is shown in Figure 2 indicating floor area and volumes. One path of communication between the various rooms and floors is the duct system that is used to distribute conditioned air in the heating and cooling seasons and can be operated continuously or intermittently ("auto setting"). Further details of the various aspects of the research conducted in these houses can be found in References 2-6. In many respects, the extended test period of more than two years has transformed the houses into valuable research laboratories for GEOMET Technologies. This was considered to be an ideal location to demonstrate the ability to evaluate individual zone air infiltration rates using the CCTG measurement system developed at Princeton University with funding from the U.S. Department of Energy.



LEGEND:
CCTG SYSTEM
* INJ. → FAN
●-SAMPLING PTS.
DECAY SYSTEM
X,Y-SAMPLING PTS.

LEGEND: HOUSE VOLUME
ZONES: (1)- 28.3m^3,(2)- 21.4,
(3)- 38.7,(4)- 19.9,(5)- 83.0
(6)- 121.2··· AREA - 145m^2

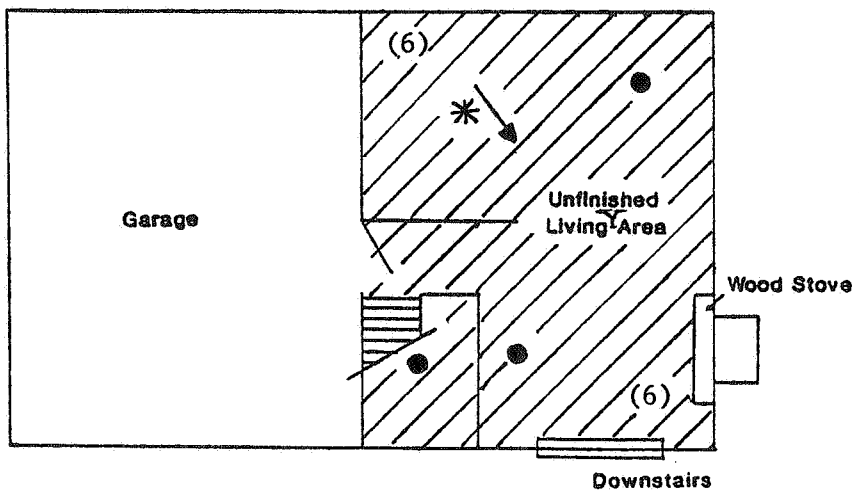


Figure 2 -
Floor plans, sampling points & fans, and volumes & floor areas of control house. Six zones evaluated for air infiltration by the constant concentration method are numbered.

Table 1

CONSTRUCTION CHARACTERISTICS OF STUDY HOUSES

GENERAL CHARACTERISITICS:

Exterior

Overall Dimensions	40 ft 5 in x 26 ft 8 in (12.3 x 8.1 m)
Foundation Wall	8 in cinder block extending 4 ft below grade
Exterior Walls	Aluminum siding above foundation knee wall
Windows	Metal frame, double-glazed
Sliding Door	Insulated glass
Doors	Steel with polyethylene foam core, doorsills with adjustable weather-stripping
Attic	Soffit vents and continuous ridge vent
Roof	Conventional asphalt shingle

Interior

Floor Area	1400 ft^2
Vertical Distance	16 ft 3 in (top of floor slab to main floor ceiling)
Walls	Wood studs placed 16 in on center, faced with gypsum board drywall

INSULATION/INFILTRATION BARRIER:

Attic	8 in of loose-fill between ceiling joists, R value equal to 30
Sill Sealer	Polyurethane foam between sill plate and floor surface
Walls	Unfaced 3.5 in glass fiber batts between joists, R value equal to 11
Vapor Barrier (Polyethylene)	From floor plate to ceiling, around windor and door openings, applied to ceiling joists extending 4 in from walls, overlapped at seams.

HVAC SYSTEM:	Rating
Air Conditioning--Electric Heat Pump	
Heat Pump Fan	1.2 A
Heat Pump Compressor	11.9 A
House Design Cooling Load	20,000 Btu/h
Heating--Electric Furnace	
Dual Circuits	40 A, 24 A
House Design Heating Load	24,500 Btu/h

2.0 THE HOUSES

The bi-level houses used in this study were built during the fall of 1982 as part of a new subdivision approximately 35 kilometers northwest of Washington, DC in Gaithersburg, Maryland. Two identical houses were constructed to somewhat relaxed building standards so that later retrofitting efforts could be made to improve the tightness of the building envelope. Table 1 summarizes important features of that construction. One of the houses, the experimental house, was subsequently retrofitted to achieve six air changes per hour (ACH) leakage rate at 50 pascals differential pressure, whereas the control house remained at 10 ACH @ 50 Pa throughout the period of testing.

3.0 DEPLOYMENT OF THE CCTG SYSTEM

The details of the constant-concentration tracer gas measurement system as used in these tests are to be found in Reference 7 and in the companion paper in this conference.[8] In order to make full use of the capabilities of the CCTG system it was necessary to carefully plan how it would be deployed in the control house at Gaithersburg. As Figure 2 points out, zones were assigned in the upper and lower levels of the house. Each of the six zones contained one sulphur hexafluoride tracer gas injection point (centrally fed by a plastic tube) located close to a small mixing fan necessary to circulate the air within that zone. Sampling in the smaller volume zones required only single sampling locations (as shown), whereas the larger zones such as the living room, dining room, kitchen zone (zone (5)) and the basement (zone (6)) required multiple point sampling. In each case, a single 1/8 inch diameter plastic tube was used to convey the zone air sample from the particular zone to the central control point of the CCTG system, but in the larger zones the tubing branched out to multiple sampling point locations. An additional fan was used in the larger zone (5) as noted in Figure 2.

The success of the operating CCTG system can be determined from its ability to maintain tracer gas concentrations within narrow bounds and thereby eliminate one zone from influencing the tracer gas concentration in adjacent zones. Table 2 is a printout of six hourly summaries of typical data recorded from the individual zones. The zones were actually sampled every ~~six~~ minutes

Table 2

HOURLY SUMMARIES OF CCTG DATA

```
Julian Day + fraction
20.9,12.2      Zone(1)          Zone(2)          Zone(3)          Zone(4)
89.4062,0.09, 150.1, 2.63,0.14, 149.9, 2.58,0.16, 150.1, 1.62,0.23, 150.6, 3.38,
0.08, 150.5, 3.53,1.00, 150.8, 3.17,0.46,5.7←Wind Speed(mph)
20.8,12.3 Zone(5)      Zone(6)          ↑—— AIave.(ACH)
89.4479,0.07, 150.5, 2.68,0.13, 150.0, 1.04,0.16, 150.0, 2.22,0.26, 149.6, 2.79,
0.08, 150.7, 3.26,1.03, 149.7, 3.10,0.47,6.8
20.6,12.2
89.4896,0.04, 154.7, 5.92,0.06, 151.6, 7.13,0.10, 150.9, 6.37,0.37, 149.9, 5.37,
0.04, 151.7, 6.28,1.03, 150.0, 7.45,0.45,6.1
20.5,12.1
89.5312,0.14, 149.1, 5.37,0.21, 149.6, 5.09,0.21, 149.9, 6.11,0.23, 151.5, 4.74,
0.13, 151.2, 6.34,1.12, 148.9, 4.06,0.54,7.1
20.3,12.0
89.5729,0.09, 150.8, 1.99,0.15, 150.6, 3.40,0.16, 150.6, 3.32,0.25, 149.8, 2.58,
0.08, 151.1, 3.34,1.10, 150.4, 5.98,0.50,6.4
20.2,12.0
89.6146,0.03, 152.0, 4.19,0.03, 153.3, 5.82,0.09, 153.7, 5.47,0.23, 152.2, 4.33,
0.02, 152.6, 4.22,0.89, 151.5, 5.23,0.38,5.2
```

Note Zone data includes:
AI rate (ACH), Concentration (ppb), Variation (ppb)

throughout each hour. The variation in tracer gas concentration, in hourly average, was held within approximately ±0.6% of the desired 150 ppb SF_6 concentration based upon a review of typical data, and over the hour the maximum tracer gas concentration excursion was approximately ±2.5%. These tracer gas concentration values insure a proper operation of the overall CCTG system based upon detailed error analyses. Again for additional CCTG system details see Refs. 7 and 8.

4.0 WIND AND TEMPERATURE DIFFERENCE PLOTS

The standard method of collecting air infiltration data in the two houses was through the use of SF_6 decay. Measurements were repeated every 15 minutes in each of the central locations upstairs and in the basements of both houses.[6] The locations X and Y are noted in Figure 2. It was observed that the magnitudes of the resultant air exchange measurements at the two locations tended to merge if the circulation fan in the air duct system was run continuously. This point will be discussed later.

To aid in the interpretation of the house air infiltration average data, the measurements were binned in narrow intervals of wind speed and velocity.[6] In all cases, as shown in Figures 3 and 4, a strong linear relationship between AI and the variables is apparent for both houses. The infiltration rate for the tighter experimental house is seen to be consistently lower than that of the control house.

To these original data plots has been added the information gathered using the CCTG system where the AI average is based upon volume averaging the individual air infiltration rates from the six zones. Comparing the results we observe that:

- The house AI average data, using the CCTG system, agrees closely with the infiltration rates for the control house using two zones and the SF_6 decay method.

- When the data sample sizes were comparable, the AI data scatter is noticeably reduced in the six zone averaging method with the CCTG system. Such comparisons, however, cannot be made in many of the bins because the March-April test window for the six zone testing was limited in temperature range.

5.0 AIR INFILTRATION DETAILS

5.1 Wind Direction

The CCTG data just discussed will now be reviewed for a case where adequate data points were available to allow discrimination between wind speed and direction over an extended range of wind speeds, as shown in Figure 5. Here the two sets of data points are for wind flowing from the direction of the neighboring experimental house vs. wind from all other directions. In the first data set, additional wind protection would be anticipated for the control house because of wind blockage by the experimental house and

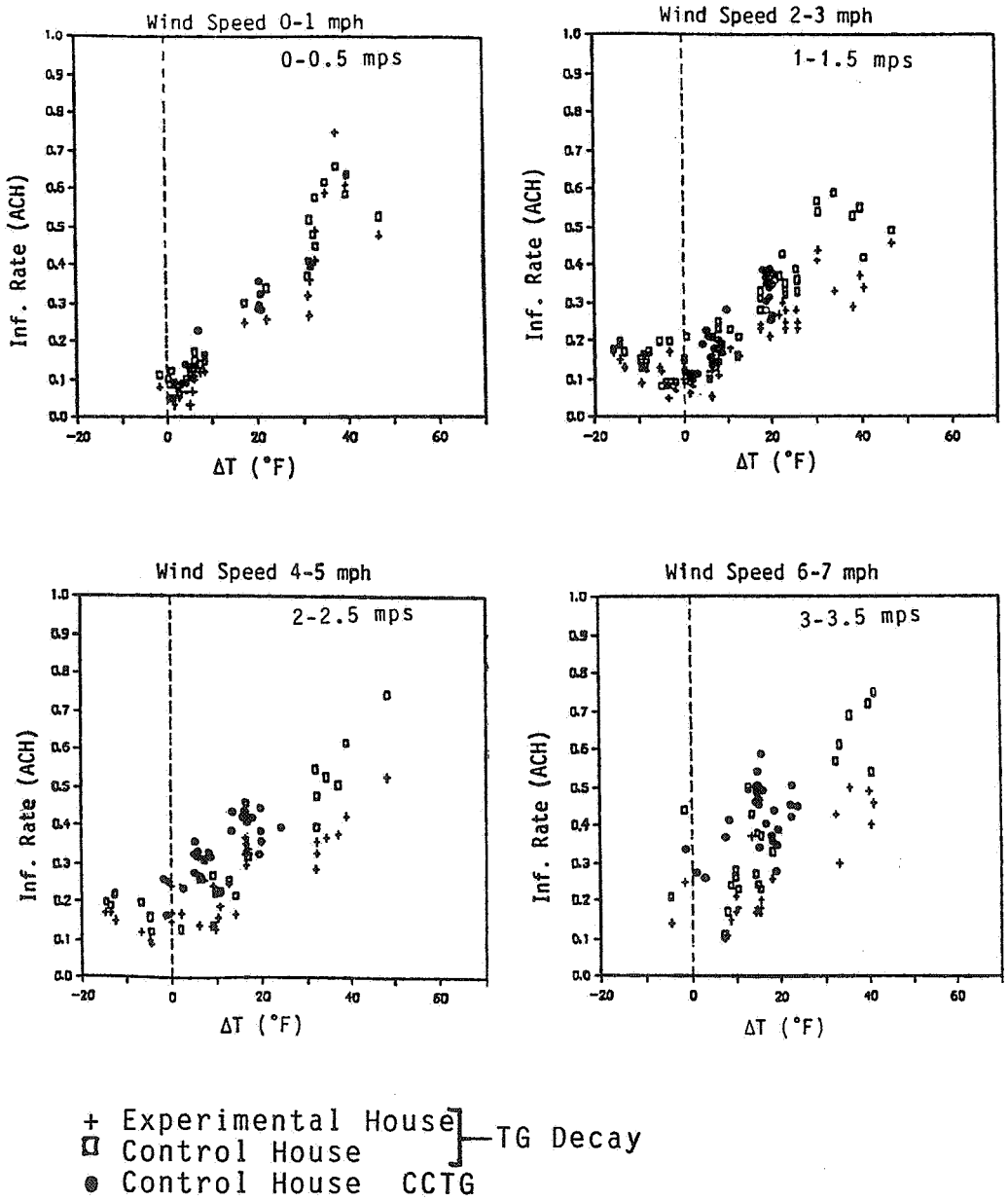


Figure 3. Binned wind speed data plotted to show the relationship of air infiltration rates to inside-outside temperature difference. Both tracer decay and constant concentration methods were used.

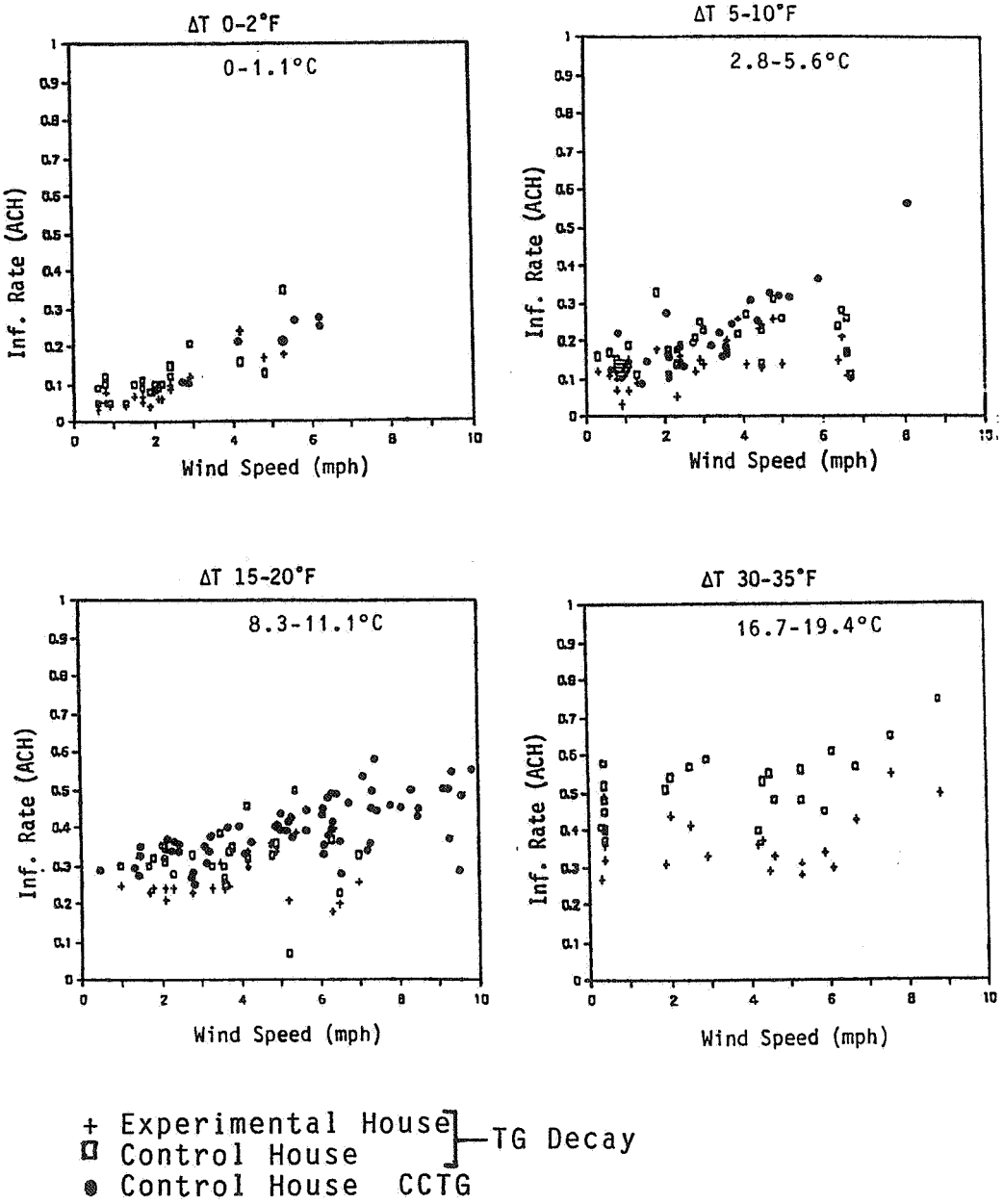


Figure 4. Binned differential temperature data plotted to show the relationship of air infiltration rates to wind-speed. Both tracer decay and constant concentration methods were used.

because the wind is impinging on the garage side of the control house (i.e., protecting the basement zone). Clearly the data indicate there is a wind directional effect; the average air infiltration drops in the control house for winds from that shielded direction, and the coefficient of determination (R^2) for the wind data from other directions is improved (R^2 increased to 0.8 from 0.66).

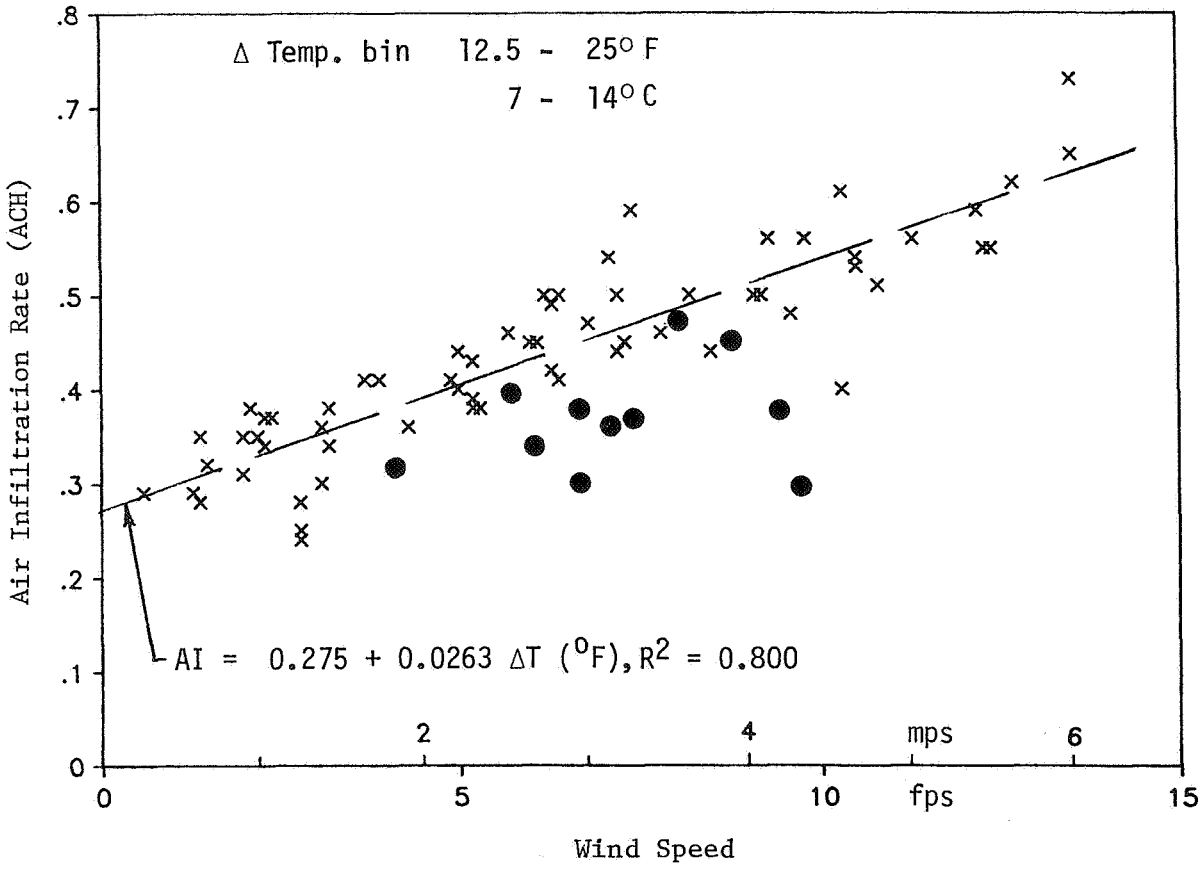


Figure 5. Binned temperature data showing the relationship of wind speed and air infiltration rate for wind direction. • Wind from "protected" direction; x All other wind directions.

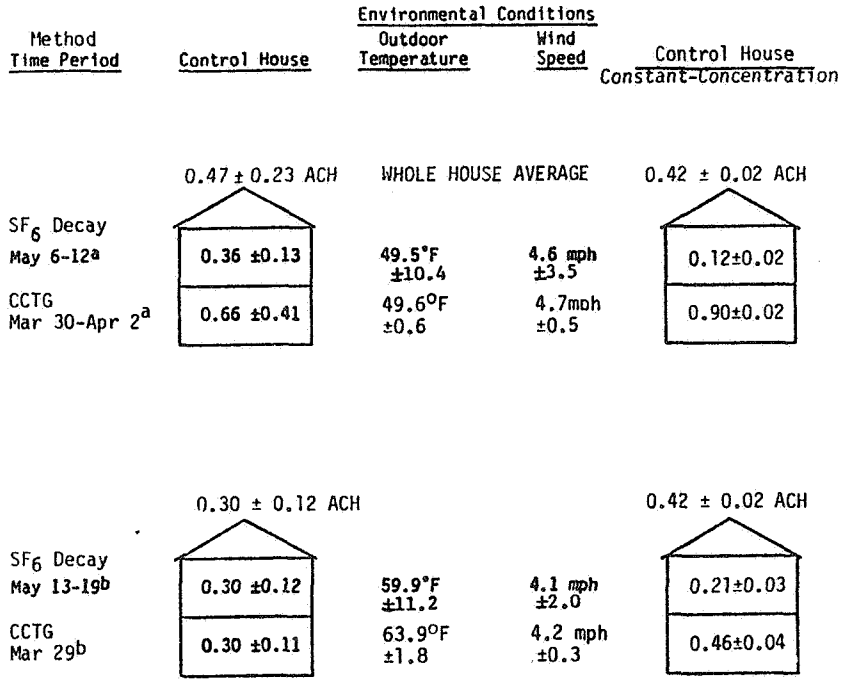
Spot checks were made of how wind direction (matching wind speed and temperature difference) can affect individual zone air exchange rates. For example, a 4.5 mps wind impinging on zone (5) raised the 0.14 AI rate to 0.33 ACH. At the same time the AI rate in zone (2) on the leeward side of the house dropped from 0.22 to 0.05 ACH. This is given as a typical example of what air infiltration changes can take place as a result of wind direction and that such changes should be of concern when considering whether or not individual room ventilation rates are being met. This point of ventilation adequacy was discussed with regard to ventilation standards in Reference 8 using the seasonal variations in air infiltration that have been documented in this research.

5.2 AI Rates in the Upper and Lower Floors of the Control House

Using the original SF_6 decay data to establish typical upper and lower floor air infiltration rates, it is evident in Figure 6 that noticeable differences are present, under the weather conditions specified, for the air circulation fan operated periodically and continuously.

Using those same specified weather conditions, but for a much narrower range of values, hourly data from the CCTG measurements have been used to form a similar average air exchange rate schematic for the upper and lower floors of the control house. Although the house average rates are similar to the original data, there are changes in the distribution. Upper level air exchange rates are reduced from 0.36 to 0.12 ACH for the periodic fan case, and correspondingly, the basement AI rates are found to be greater than the previous measurements.

In the case of the fan on continuously, the CCTG system was found to be capable of measuring difference in zonal air exchange rates although clearly these differences were substantially reduced from the fan being used periodically. Both the SF_6 decay and the constant concentration measurements point out that under continuous fan operation the upper floor and lower floor air exchange rates are no longer markedly different. These results point out that mechanical air movement, even without mechanical ventilation per se can help reduce weather dependence of the local ventilation rates.



[a]Circulation fan operated periodically.

[b]Circulation fan operated constantly.

Figure 6. Average upstairs and downstairs air infiltration rates determined by the tracer gas decay and constant concentration methods. Units are in ACH.

Perhaps the most dramatic illustration of the variations in air infiltration rates of the upper versus lower floor, and individual zones is found by plotting the air exchange over days of testing as shown in Figure 7. Variation between upper floor zones is of the order of 1 to 1 ranging to 5 to 1, between the lower and upper floors is as great as 10 to 1. Air exchange rates below 0.1 ACH are repeatedly shown to take place in many of the upper floor zones over the test period illustrated. This is best seen when the bedroom zones are plotted separately in Figure 8.

The variations observed between the measured air infiltration rates using the two tracer gas measurement methods is a result of eliminating the influence of tracer gas concentrations in adjacent zones. Such influences are particularly noticeable between the two floor levels causing a marked decrease in upper floor infiltration readings with the CCTG system.

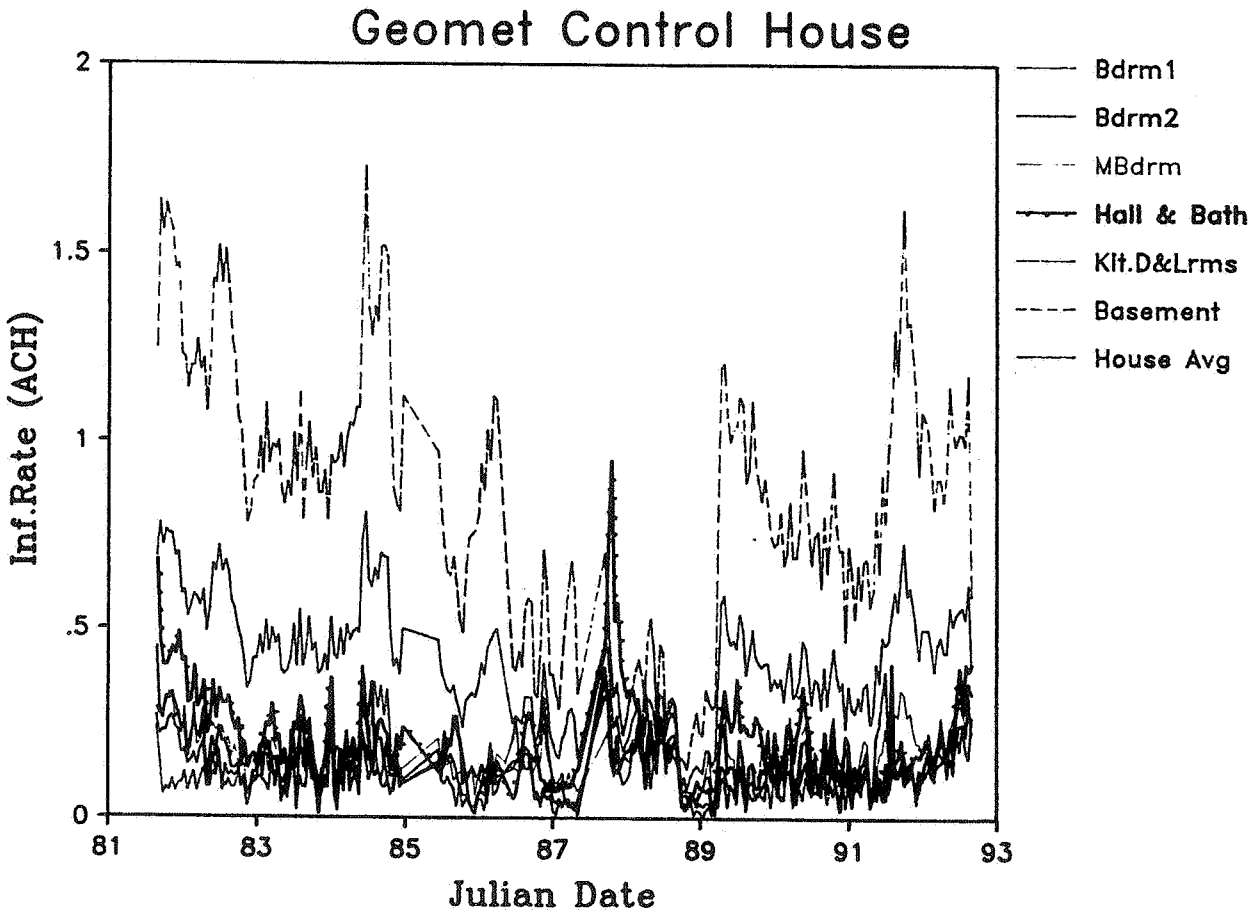


Figure 7. Detailed time history of 6 zones in the control house measured with the CCTG system at 10 minute intervals and hourly summary.

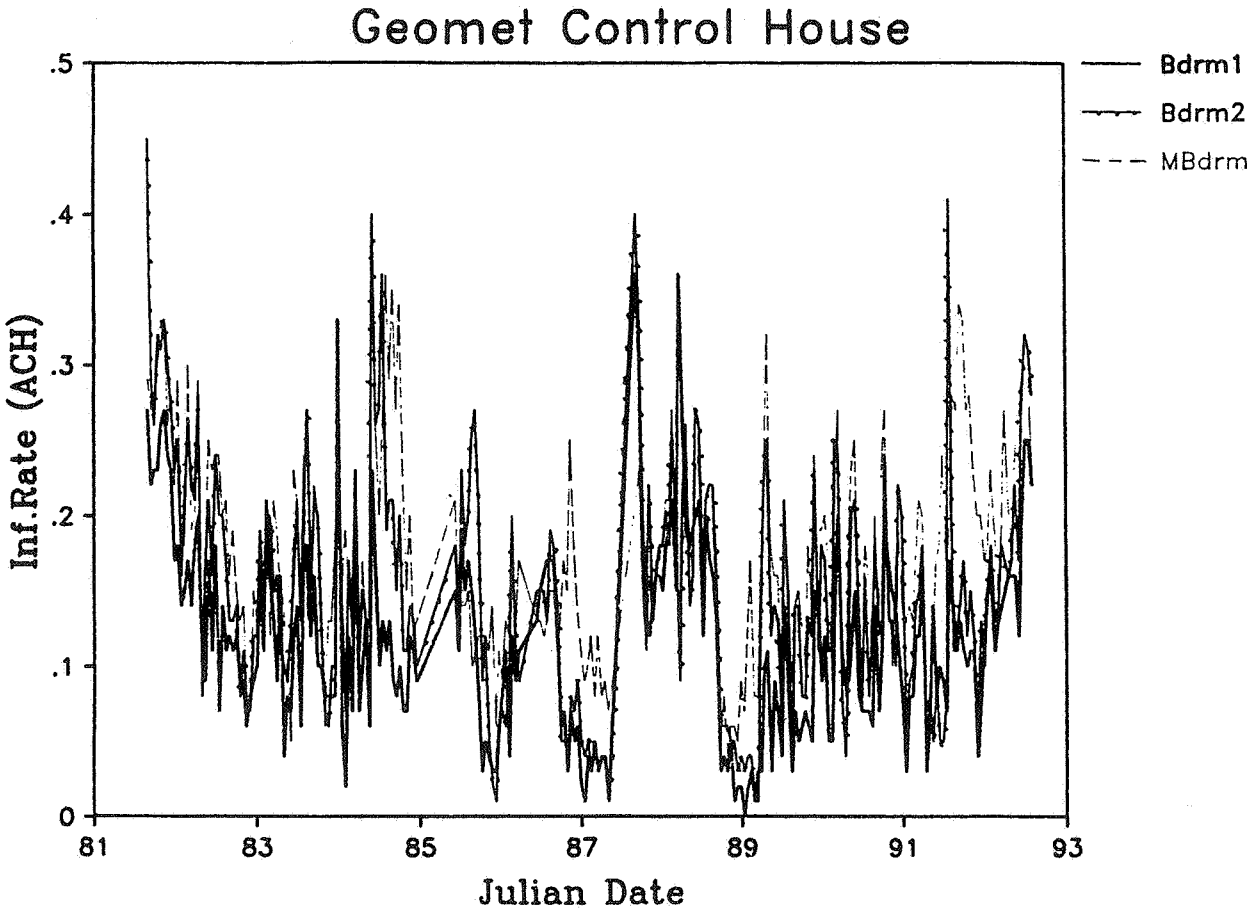


Figure 8. Air infiltration rates in the bedroom zones determined by the CCTG method.

5.3 Open Versus Closed Doors

As can be seen from Figure 2, door closure for zone isolation in these houses can only be achieved for the case of the three bedroom zones. Since the two floors are connected with an open staircase one cannot alter upper and lower floor communication. The doors were closed and data analysis was made over three hours before and after the closure, and again when the doors were opened. No significant changes in air exchange rates with the outside were observed, although exchange between zones would be expected to be reduced. Weather variations were taken into account in the comparisons.

6.0 CONCLUSIONS

The validity of the extensive documentation of air infiltration over the seasons in the GEOMET test houses using tracer gas decay was confirmed in the control house using the constant concentration method involving six individual zones of air infiltration measurement. Operation of the CCTG system was entirely successful and yielded additional air infiltration information on: individual zone variations, upstairs downstairs variations, and wind effects. These added ventilation rate details provide further data on the influences of weather and house system functions and thus prove useful in analyzing the impact on indoor air quality and energy.

7.0 ACKNOWLEDGMENTS

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 8

MULTIPLE CELL AIR MOVEMENT MEASUREMENTS

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SYNOPSIS

The multiple tracer gas technique developed at UMIST has been applied to the measurement of roof-space ventilation rates and house to roof-space air movement, for various types and combinations of roof-space ventilation. It has been shown that ridge tile ventilators, whilst increasing roofspace ventilation rates at low wind speeds, also significantly increase house to roof-space airflows over the whole range of wind speeds. This has implications not only in terms of energy wastage, but, more significantly, in terms of increased moisture rates to the roof-space. Methods of reducing air leakage to the roof-space are briefly discussed. The use of a kitchen extract fan is shown to reduce airflow from downstairs to upstairs to between 10 and 30 m^3/hr. It is pointed out that in order to be able to gain a better understanding of air movement within the building envelope, it will be necessary to make use of three and four tracer gas measurements.

MULTIPLE CELL AIR MOVEMENT MEASUREMENTS

1. INTRODUCTION

The energy crisis of the 1970's, and the resulting increase in the price of fuels, has shown that significant amounts of energy and money can be saved by the use of insulation. In the United Kingdom, approximately 30% of the total primary energy used is in the domestic sector[1], and it is clearly desirable that considerable savings are achieved here.

A popular method of energy saving has been the insulation of lofts. One of the effects of applying loft insulation is a general reduction of the structural roof temperature. The Building Research Establishment[2,3] have drawn attention to the danger of the occurrence of water vapour condensing in roof-spaces, with the consequent hazards of structural failure and ceiling damage. Sanders[4] has reported that typically, in still, cold conditions,30% of the air leaving a house does so through the roof-space. The increasing use of loft insulation, therefore, necessitates a greater understanding of air migration paths through the house and into the roof-space, which in turn provides indicators regarding the reduction of moisture transfer into the roof-space.

This paper briefly describes the multiple tracer gas technique used for ventilation and air movement measurements at UMIST for the case of two tracer gases, and its application to the determination of roof-space ventilation rates, house to roof-space airflows, and airflows between the upstairs and downstairs: in the latter case, the effect of a kitchen extract fan is demonstrated.

2. EXPERIMENTAL DETAILS

The multiple tracer gas ventilation and air movement measurement apparatus used at UMIST has been developed with three aims in mind: firstly, maximum portability and ease of use for site applications; secondly, rapidity of concentration/time data acquisition; thirdly, print-out of concentration/time data during the actual test period, so that any anomalies or faults can be noted and rectified immediately.

The apparatus used has been described in greater detail elsewhere[5]. Briefly, the system consists of a modified Analytical Instruments Model 505 gas chromatograph with electron capture detector. The chromatograph has been fitted (Figure 1) with two 4-port selector valves so as to permit the use of two matched chromatographic columns in parallel. This modification in effect doubles the number of samples that can be analysed in a given time, thus enabling air movement tests to be completed before recirculation of tracer gas becomes significant, and also minimises variations in data due to extraneous variables such as wind speed and wind direction. When used with two 8' long, 0.25" diameter 10% squalane separation columns, held at a constant 30°C in a thermostatically controlled water bath, it is possible, for the case of two tracer gases, (Freon 12 and Freon 114) to analyse a sample in 30 seconds. By careful conditioning of the chromatographic columns, their responses can be matched to within 0.5% for a given tracer gas concentration: furthermore, the use of the water bath at 30°C effectively eliminates problems previously encountered with baseline drift during ambient temperature use.

The concentration/time data obtained is analysed by the simplified analytical solution of the conservation of mass of tracer gas equations for two interconnected cells described in great detail in(5). This new analysis is superior to the Prony analysis previously used[6] on the grounds that it can cope more readily with random measurement errors, with the result that significantly less data has to be discarded as physically meaningless simply because of an inherent weakness of the mathematical analysis used. This is clearly of benefit in terms of efficiency.

The technique and new mathematical analysis have been validated in a series of tests carried out using two interconnected environmental chambers with controlled, measurable supply and extract rates[7]. The calculated inter-cell airflow values derived were within 10% of the measured values.

Site measurements were carried out in a three bedroomed, end-terraced council house of low energy design. (Figure 2). The house was built in 1981, and is of cavity brick/block construction, with insulation in the internal walls. The windows are double glazed. The roof is a 20 degree duopitch of cement tile and sarking felt underlay:

the ridge runs east-west. The roof-space of this house is insulated by 150 mm of loose-fill glass fibre insulation between ceiling joists. It is ventilated by a continuous 10 mm opening at the eaves level, (soffit ventilation) in combination with a ridge tile ventilator. (Figure 3). The bathroom, kitchen and lounge are fitted with extract fans. The house is heated by a solid fuel warm air heater.

3. RESULTS AND DISCUSSION

(a) Roof-space ventilation rates and house-roof airflows

Figure 4 compares the roof-space ventilation rates for the cases of all ventilators sealed, soffits only open, and soffits and ridge tile open, for the case of prevailing wind direction. For the case of soffit only open, the roof ventilation rate lies between 0.5 - 9.5 ach for wind speeds up to 5 m/s. Site observations show that soffit induced ventilation is relatively insensitive to changes in wind direction. In the case of the soffit/ridge tile combination, the presence of the ridge ventilator clearly has an effect on ventilation rate at low wind speeds (<2m/s): however, for wind speeds in excess of 6m/s, the roof ventilation rate tends to be the same value for both soffit only and the soffit/ridge combination.

Figure 5 shows the influence of different types and combinations of roof ventilator on house to roof air movement. With all ventilators sealed, 25 m^3/hr of house air escapes via the roof-space: this rate of airflow is relatively constant for wind speeds of up to 5 m/s. With a ridge tile open, the house-roof airflow lies between 25-60 m^3/hr for the same range of wind speeds. (It should be noted that the use of ridge ventilators with no openings at soffit level contravenes British Standard BS 5250: these results are included for experimental interest only). Ridge ventilators are highly sensitive to wind direction at low wind speeds. As wind speed increases, so the directional influence decreases, the velocity of the incident wind predominating.

House-roof airflows induced by soffit ventilators only can be seen to be between 16-34 m^3/hr for wind speeds up to 5 m/s: directional influences on soffit ventilators are generally small. For the same range of wind speeds, the use of the soffit and ridge ventilator combination

gives rise to airflows that are between 45-80 m^3/hr.

Figure 6 shows the same data expressed as a proportion of the total amount of exfiltrated house air. This graph implies that the soffit and ridge ventilator combination induces 25% more exfiltrating house air to leave via the roof-space than would be the case when using soffit ventilators only. It is suggested that this increased airflow is due to a greater house/roof pressure differential being induced when the soffit and ridge combination is used. (Figure 7).

(b) Effect of kitchen extract fan on air movement between downstairs and upstairs

Figure 8 and 9 show the effect of using the kitchen extract fan on the airflows between upstairs and downstairs, for the case of prevailing wind direction. With regard to air movement from downstairs to upstairs, it can be seen that switching on the fan decreases the airflow from 130 - 178 m^3/hr to 10 - 30 m^3/hr. The airflows with the fan on do not seem to be particularly sensitive to increasing wind speed. Airflows from upstairs to downstairs, however, whilst not apparently affected significantly by the kitchen extract fan at low wind speeds, show a tendency to decrease with increasing wind speeds. It is suggested that this effect may be caused by increased air movement to the roof-space, and an increased tendency for "cross-flow" ventilation in the occupied dwelling space at higher wind speeds.

(c) Calculation of water vapour transfer rates

Using the calculation method described by Sanders[4], the rates of water vapour transfer (both by diffusion through the ceiling and by air movement) were calculated for the combinations of different ventilator types used, assuming uniform temperature distribution and moisture content within the occupied zone, for the purpose of preliminary assessment of the likely rates of water vapour transfer to the roof-space. This data is presented in Table 1. For comparison, data due to Sanders[4] is included. Table 1 shows that, depending on the type of roof ventilation used, moisture input to the roof-space varies from 61.2 - 143.5 g/hr. This means that the type of roof ventilator used can approximately double the vapour transfer rate to the roof-space. The

water vapour transfer rates by air movement to the roof-space when ventilated by soffit vents and the soffit/ridge combination are 99.5 g/hr and 143.5 g/hr respectively. This implies that 44 g/hr of water vapour transfer into the roof-space can be ascribed to the ridge tile ventilator.

Water vapour transfer into the roof-space can be reduced by three principal methods. Firstly, by careful use of a vapour barrier at ceiling level, the water vapour input to the roof-space by diffusion could, in theory, be reduced to zero. In practice, however, there will be perforations in the vapour barrier caused by wiring and pipework entering the roof-space, and by poor jointing at the construction stage. Secondly, and most importantly, careful sealing of roof access hatches and pipework entries can reduce moisture transfer by air movement to the roof-space by as much as 75%. Finally, if the moisture generated in a dwelling can be removed at source using an extract fan, a lower house air moisture content is achieved. The decrease in pressure due to the fan also has the effect of reducing house to roof-space generally to below 10 m^3/hr.

4. CONCLUSIONS

Ridge tile ventilators, when used in combination with soffit ventilators, can be seen to increase roof-space ventilation rates by approximately 40% over the soffit only case at wind speeds of less than 2 m/s, when problems of roof condensation are most likely to occur. However, they also have the effect of inducing house to roof-space airflows which are approximately 25% greater. From the experimental work carried out so far, it is not possible to state categorically whether or not the benefit of the increased roof-space ventilation rate at low wind speeds is outweighed by the increased rate of moisture to the roof-space.

Current research involves the investigation of the effect of tile ventilators on roof-space ventilation and house to roof-space air movement rates, together with work on soffit vents in combination with more than one ridge vent. The new multiple tracer gas technique described in (5) and (7) has been refined and validated successfully for the case of three interconnected cells.[8] A mathematical analysis has been developed for the determination of ventilation and air movement rates between four interconnected cells. Calculations made from preliminary four tracer gas

site measurements have been encouraging. These improvements in airflow measurement techniques will enable house to roof-space airflows to be expressed in terms of relative proportions of air drawn from different areas of the occupied space, particularly those of high moisture production such as the bathroom and kitchen. This will enable the influences of specific types and combinations of roof-space ventilators to be more precisely ascertained.

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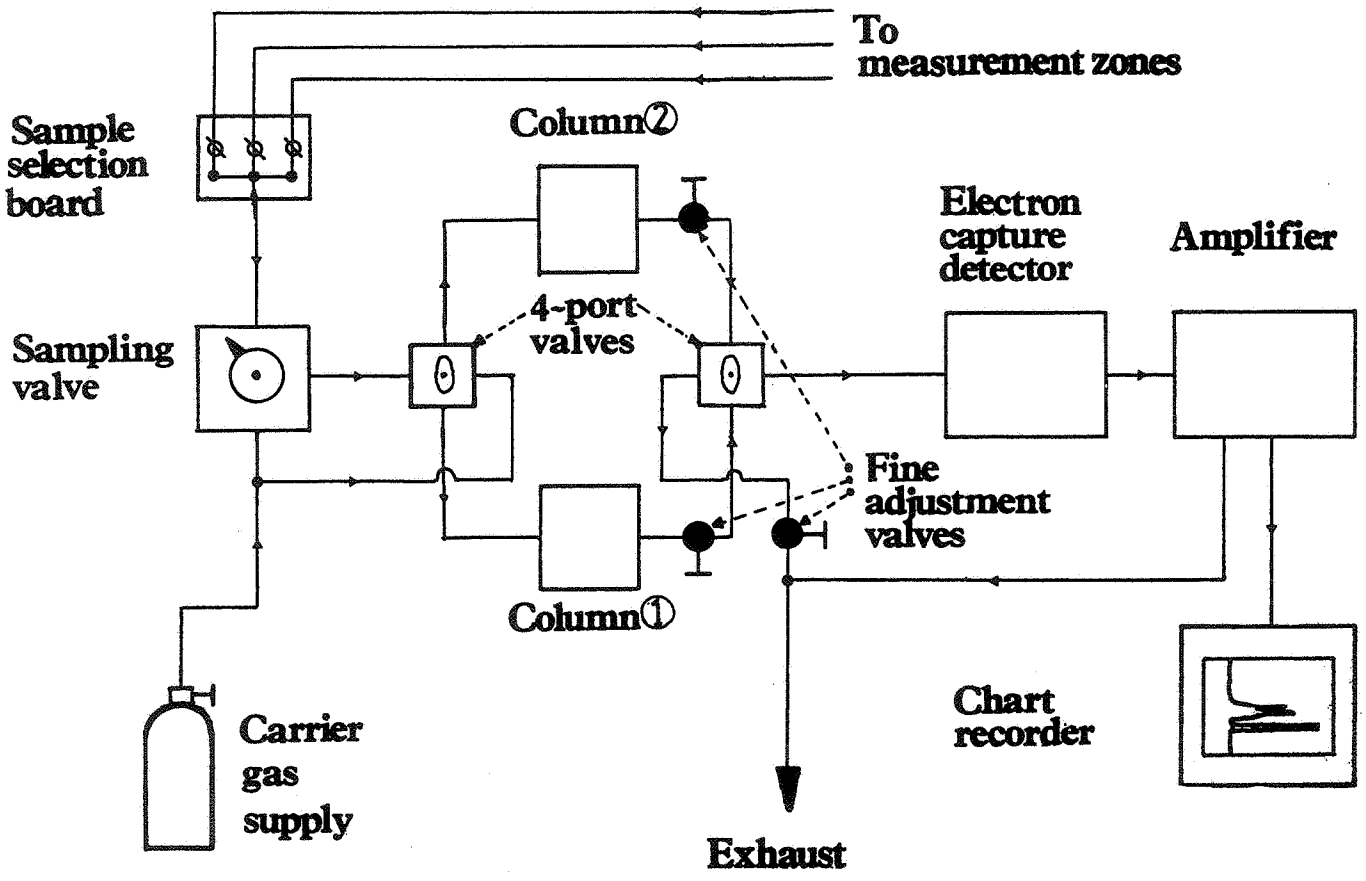
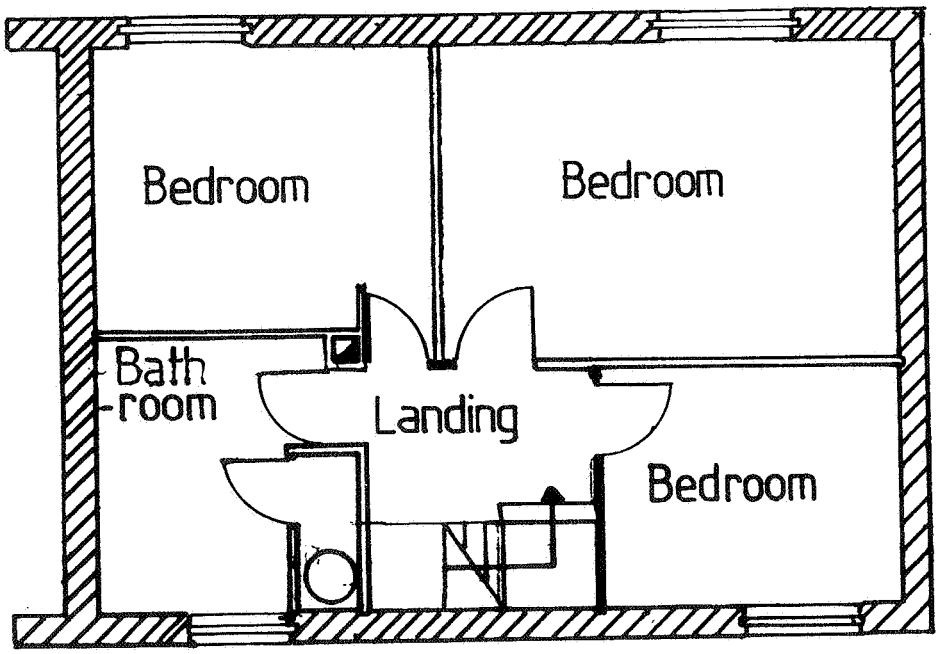
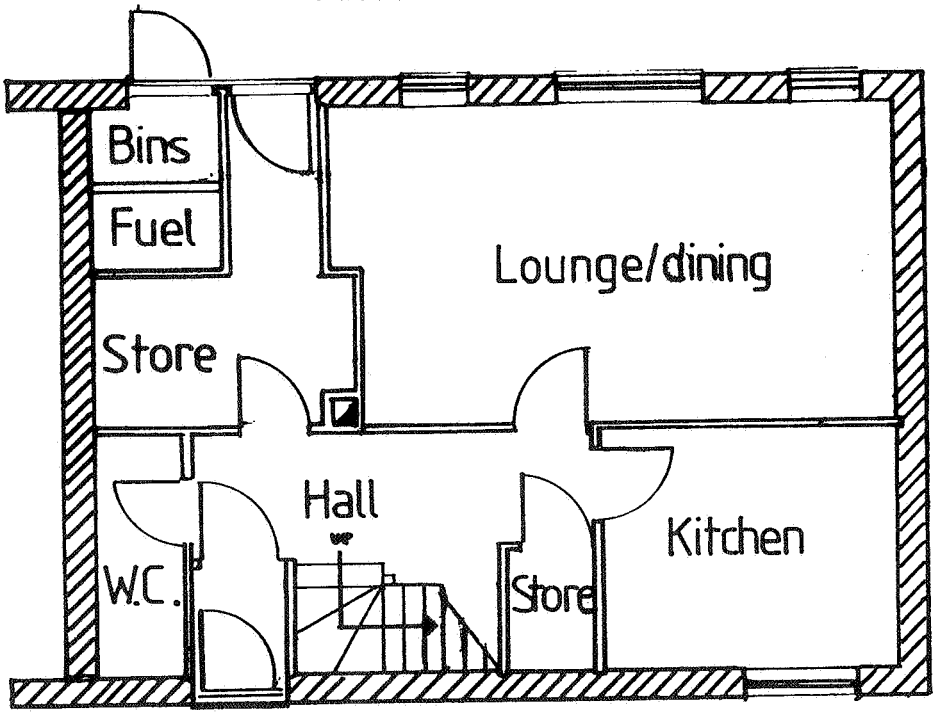

To
measurement zones
Sample
selection
board
Column②
Electron
capture
detector
Amplifier
Sampling
valve
4-port
valves
Fine
adjustment
valves
Column①
Chart
recorder
Carrier
gas
supply
Exhaust

FIGURE 1



FIRST FLOOR



GROUND FLOOR

FIGURE 2

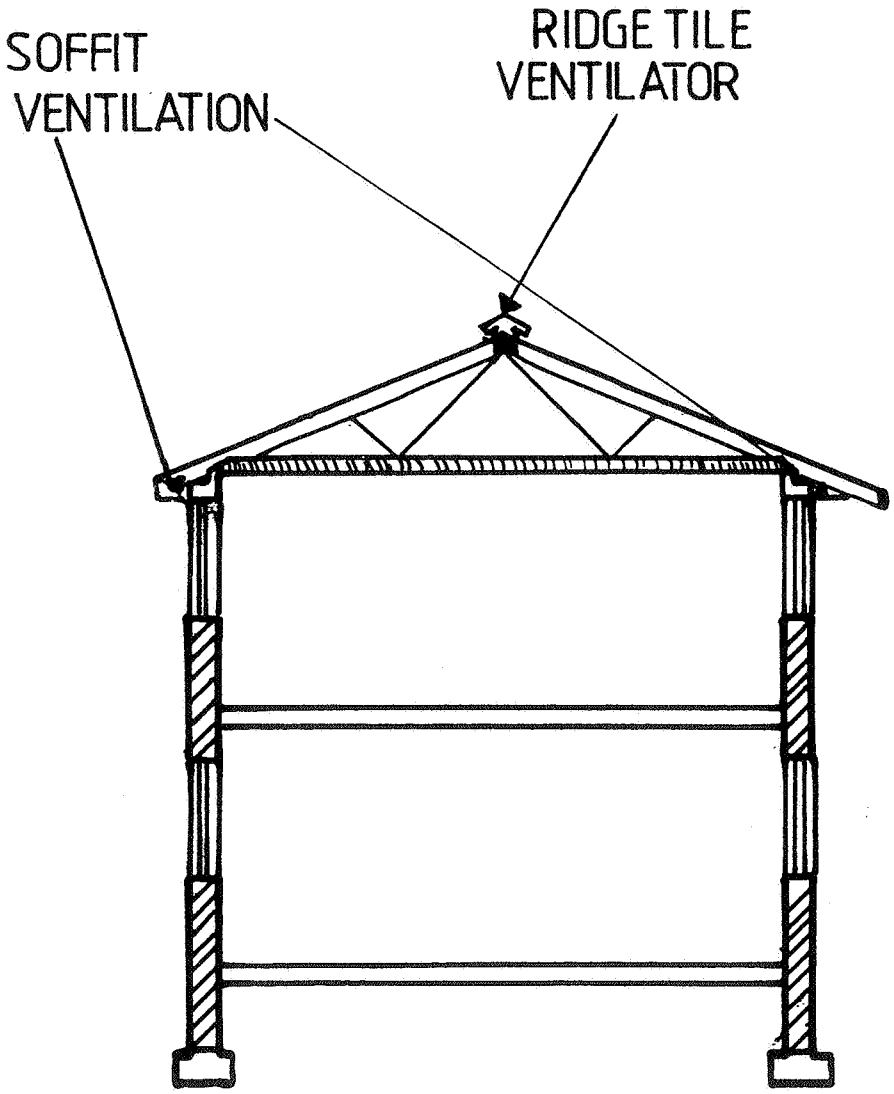


FIGURE 3

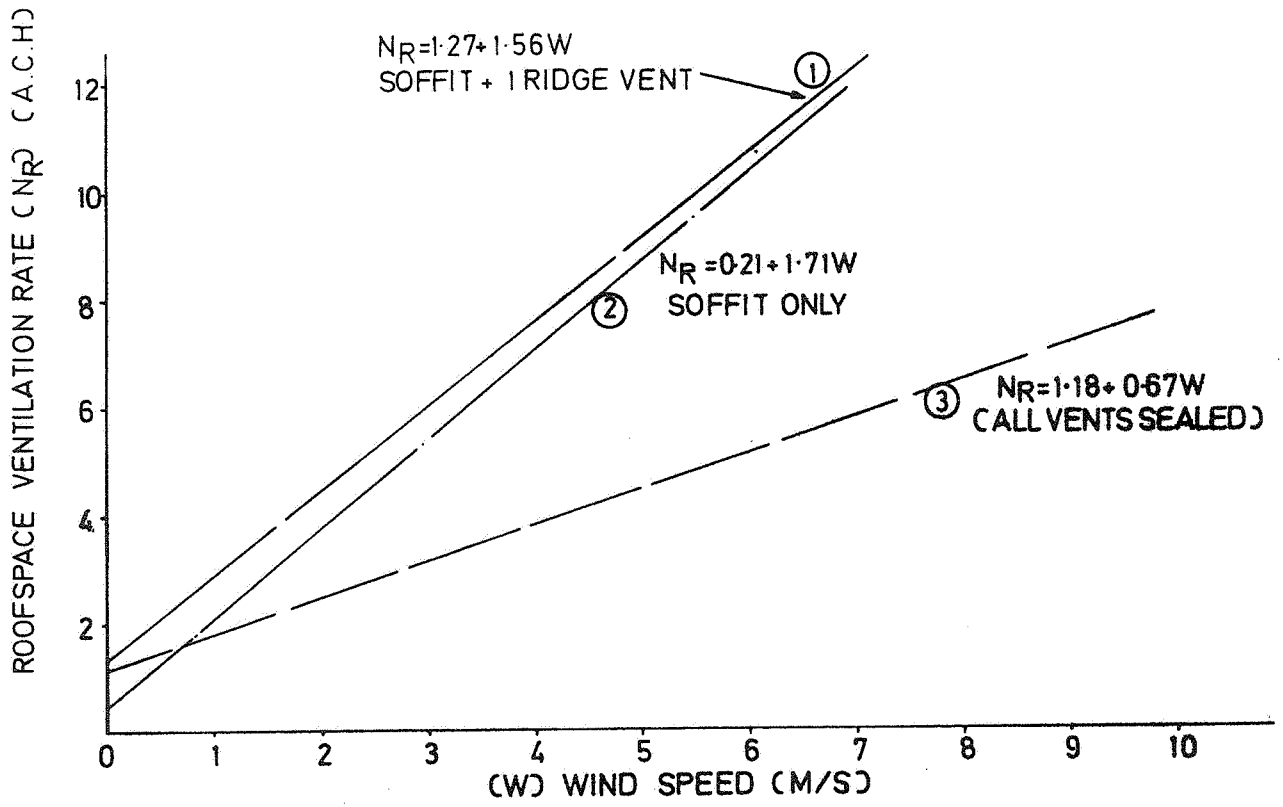


FIGURE 4 ROOFSPACE VENTILATION – SOFFIT AND RIDGE VENTS

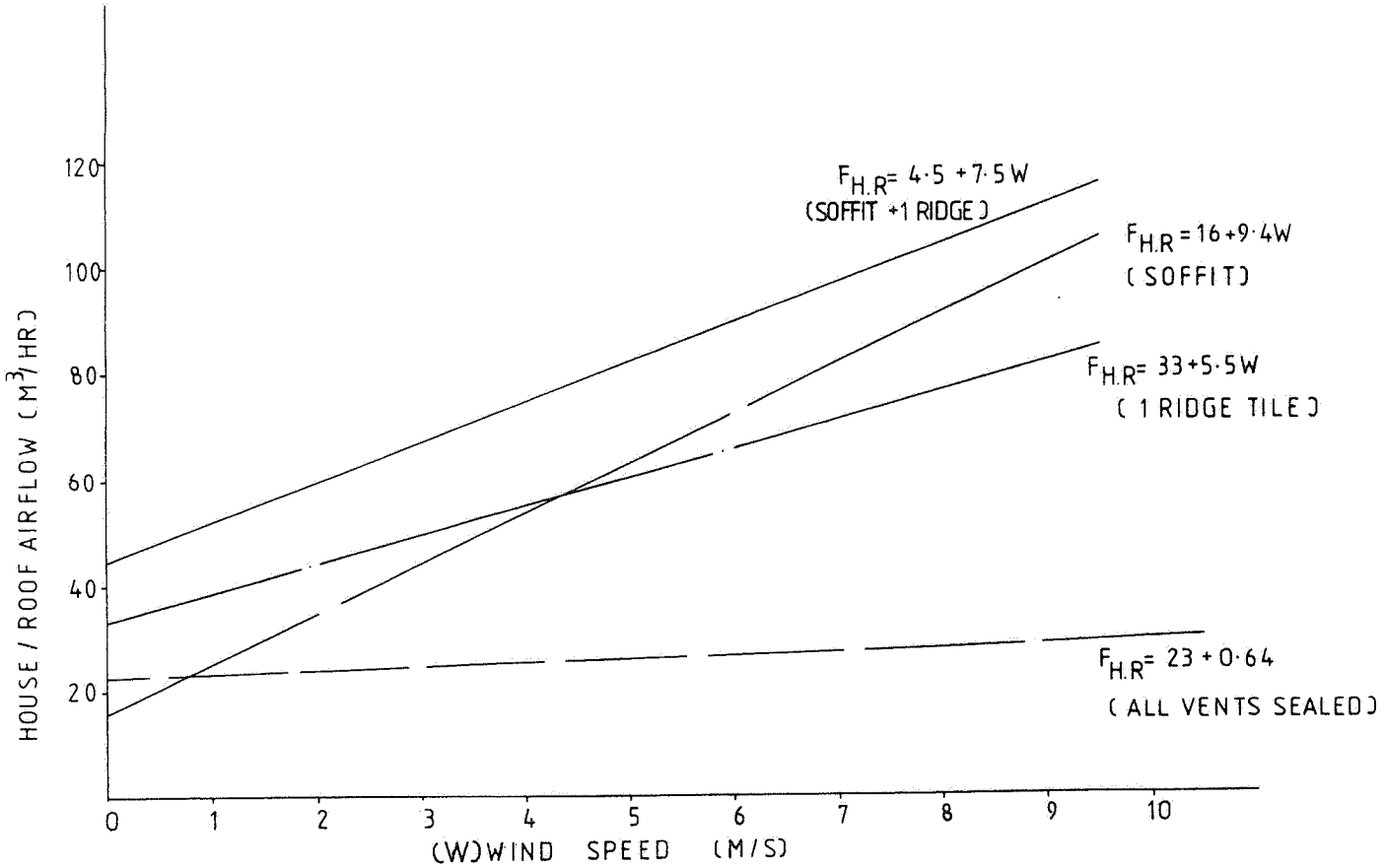


FIGURE 5 HOUSE TO ROOF AIRFLOW USING DIFFERENT ROOF VENTILATORS

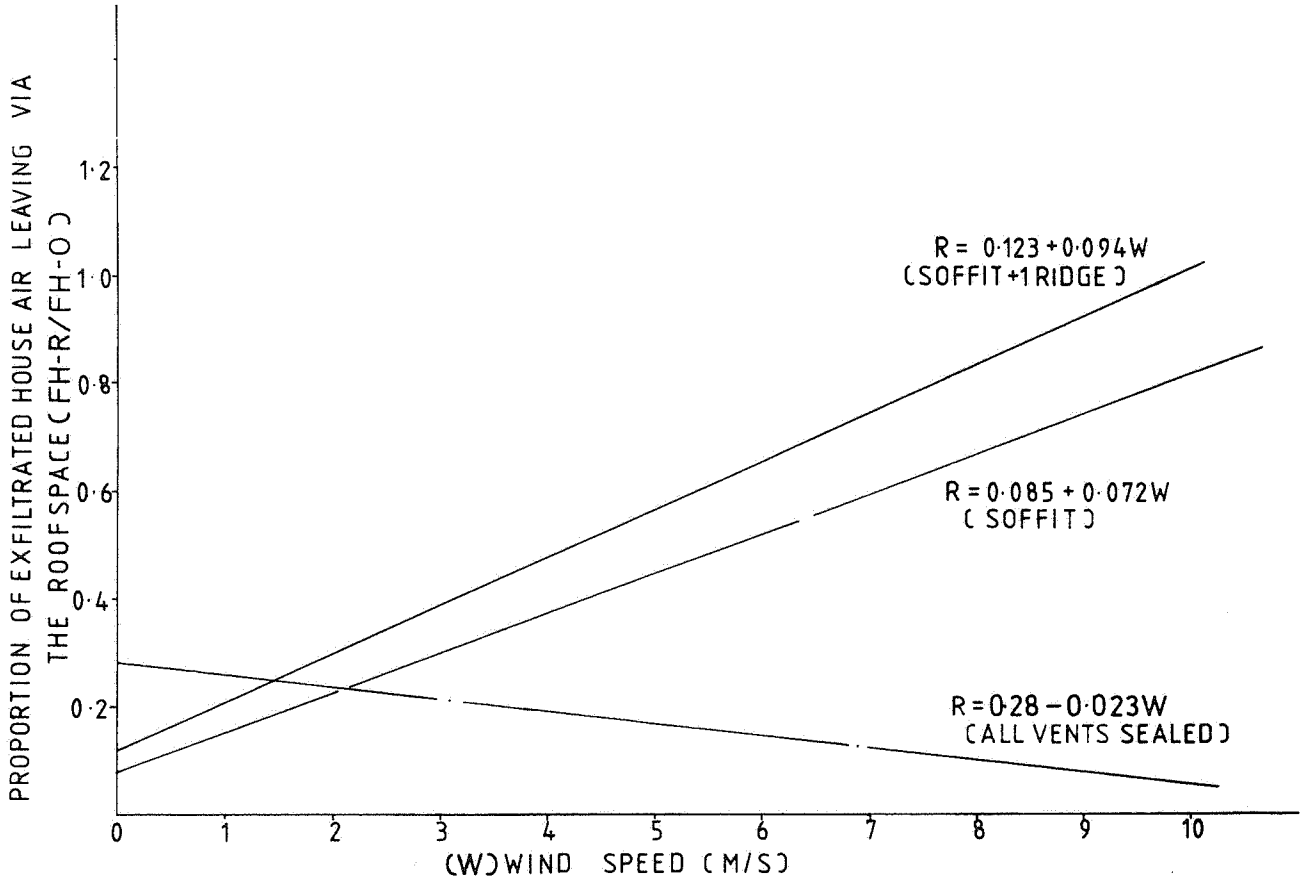


FIGURE 6 HOUSE TO ROOF AIRFLOW – EFFECT OF DIFFERENT ROOF VENTILATORS

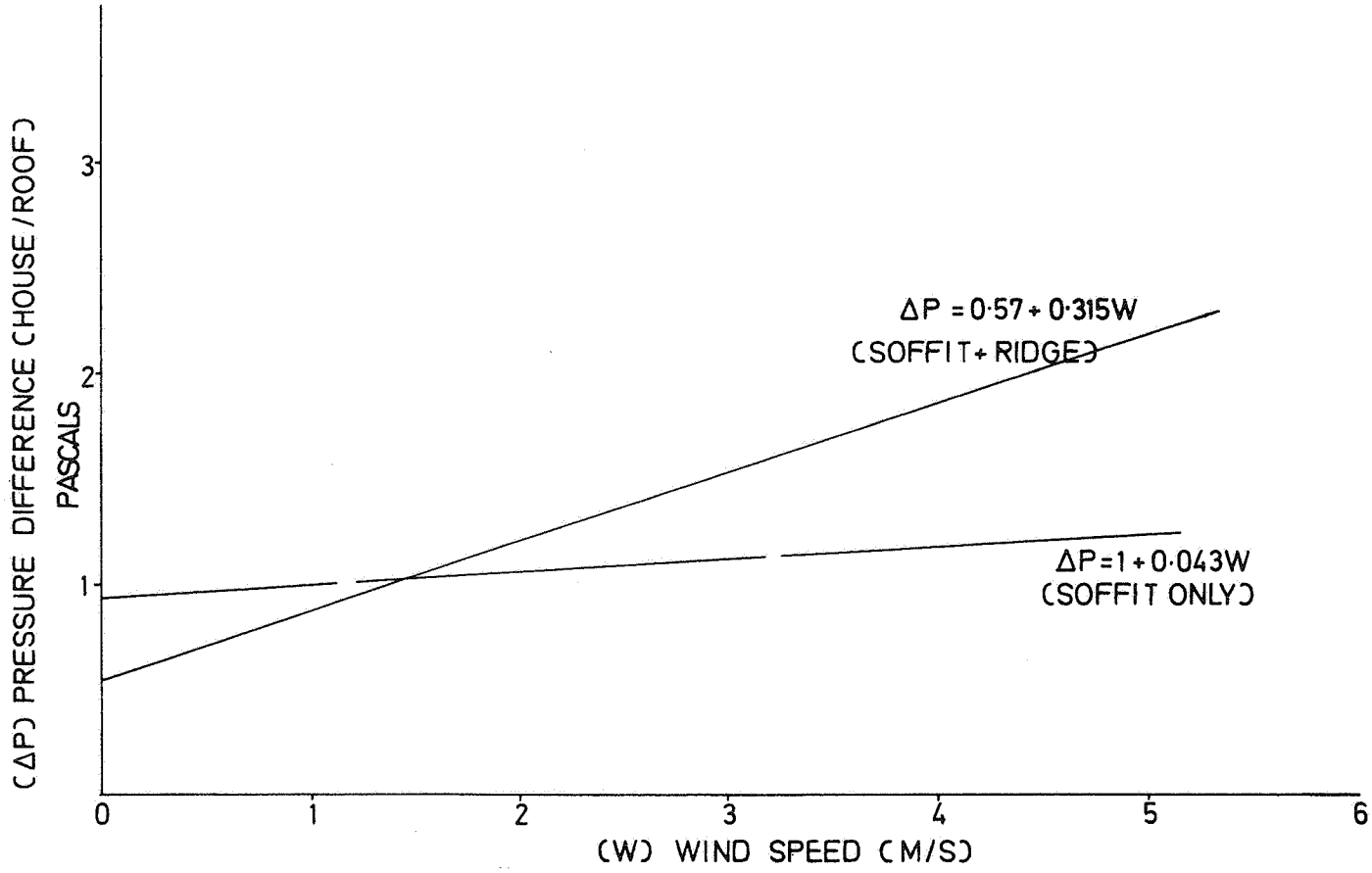
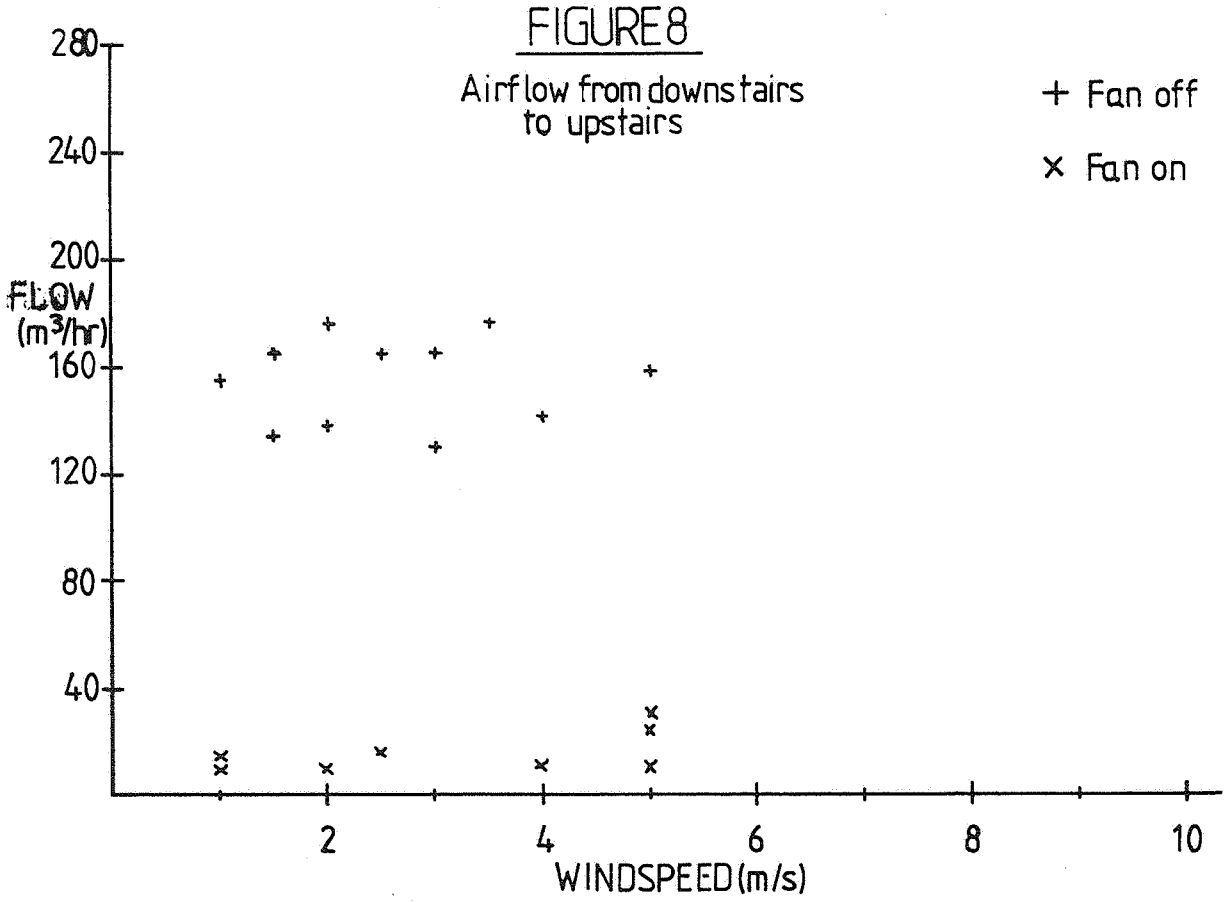
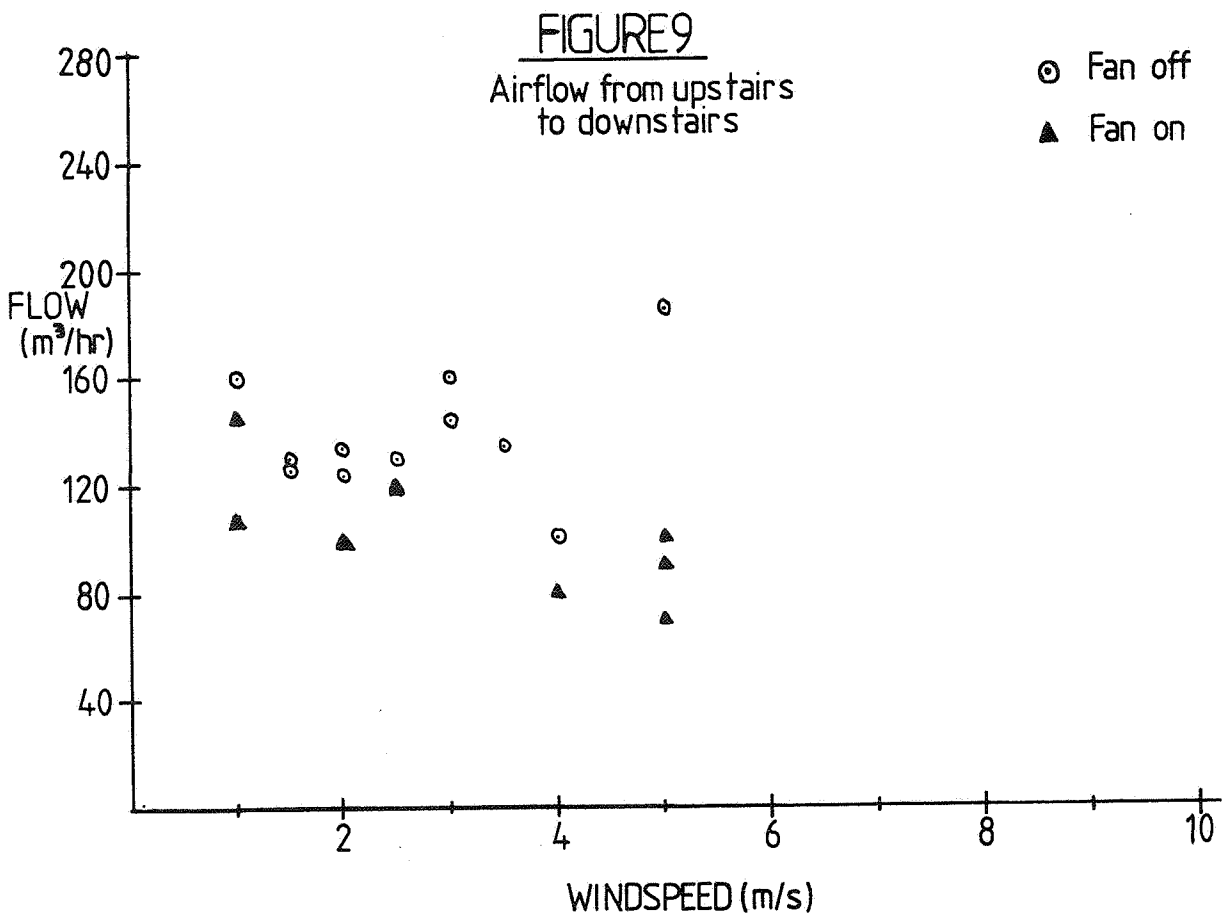


FIGURE 7 PRESSURE DIFFERENCE HOUSE / ROOF


FIGURE 8
Airflow from downstairs to upstairs
+ Fan off
× Fan on
280
240
200
160
120
80
40
FLOW (m³/hr)
2
4
6
8
10
WINDSPEED (m/s)


FIGURE9
Airflow from upstairs
to downstairs
Fan off
Fan on
280
240
200
160
120
80
40
FLOW
(m³/hr)
2
4
6
8
10
WINDSPEED (m/s)

TYPE OF ROOF VENTILATION	HOUSE TO ROOF AIRFLOW (m^3/hr)	ROOF VENTILATION RATE (ACH)	WATER VAPOUR TRANSFER BY DIFFUSION (g/hr)	WATER VAPOUR TRANSFER BY AIR MOVEMENT (g/hr)	TOTAL WATER VAPOUR TRANSFER (g/hr)
All ventilators sealed	25	2.8	13.3	61.2	74.5
1 Ridge Tile	47	4.5	12.7	110.6	123.3
Soffit ventilators	40	4.5	13.5	99.5	113.0
Soffit + 1 Ridge tile	70	5.1	11.0	143.5	154.5
Unknown*	30	2.0	22.7	64.0	86.7

* BASED ON INFORMATION IN REF (4)

TABLE1

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 9

CONTINUOUS AIR RENEWAL MEASUREMENTS IN DIFFERENT INHABITED BUILDINGS

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ABSTRACT

A Compact Equipment for Survey of Air Renewal (CESAR) was developed at the Ecole Polytechnique Federale de Lausanne in Switzerland. Controlled by a microcomputer, this apparatus uses tracer gas methods (decay, continuous flow or constant concentration). Up to ten different locations in inhabited rooms can be monitored simultaneously over extended periods of time, using mainly the "constant concentration" technique.

Several air renewal surveys were carried out on different inhabited buildings. During 1983/1984 and 1984/1985 heating seasons the following three main objects were investigated:

- an inhabited passive solar office building (LESO building)
- a three storey one family Swiss dwelling
- a low energy test greenhouse at the European Nuclear Research Center (CERN).

Following significant results were obtained:

- Air renewal measurements surveys were carried out in different inhabited dwellings over several weeks.
- Determination of actual outdoor-to-room and building-to-rooms flowrates were obtained in multi-chamber house configuration.
- Influence of inhabitants on the various air flowrates were determined.

Results of these surveys as well as a short descritpion of the developed apparatus are reported in this communication.

RESUME

Un dispositif compact de mesure du taux de renouvellement d'air (CESAR) a été développé à l'Ecole Polytechnique Fédérale de Lausanne. Contrôlé par une calculatrice de table, cet appareil utilise les méthodes à gaz traceur (décrément logaritmique, flux constant ou concentration constante). Jusqu'à dix endroits différents peuvent être mesurés simultanément et pendant de longues périodes dans des chambres habitées, en utilisant principalement la technique à concentration constante.

Plusieurs campagnes de mesure ont été effectuées sur différents bâtiments habités. Pendant les hivers 1983/84 et 1984/85 les objets suivants ont été mesurés:

- le Laboratoire d'Energie Solaire de l'EPFL, bâtiment solaire passif expérimental,
- une villa familiale de trois étages,
- une serre horticole expérimentale au CERN.

Les résultats suivants ont été obtenus:

- L'infiltration a été mesurée pendant plusieures semaines dans des bâtiments habités.
- Les infiltrations provenant de l'extérieur et du reste du bâtiment ont été déterminées.
- L'influence des habitants sur le taux de renouvellement d'air a été mise en évidence.

Cet article présente brièvement le dispositif de mesure et les résultats de ces campagnes.

INTRODUCTION

Improvement in the thermal performances of low energy buildings is concerned with precise air renewal measurements. In particular, great efforts are now dedicated to quantification of the occupants' influence on air change conditions. To attain this objective, measurement techniques must have the following characteristics:

- Allow continuous measurement over extended periods of time (several days or weeks) under varying air change conditions.
- Avoid presenting any health risks to living beings when exposed to prolonged measurement constraints.

The Compact Equipment for Survey of Air Renewal (CESAR) was developed at the Ecole Polytechnique Federale de Lausanne in Switzerland (1, 2). By use of an appropriate tracer gas technique with a non toxic gas at a very low constant concentration (100 ppm N_2O), the two criteria mentionned above can be attained.

Several air renewal surveys were carried out on the following three inhabited buildings (3,4) during 1983/1984 and 1984/1985 heating seasons:

- an inhabited passive solar office building (LESO building)
- a three storey one family Swiss dwelling (Roulet house at Apples)
- a low energy test greenhouse at the European Nuclear Research Center (CERN)

Results of these surveys as well as a short description of the developped apparatus are reported in this communication.



Figure 1: View of the Compact Equipment for Survey of Air Renewal (CESAR)

DESCRIPTION OF THE APPARATUS

CESAR is a compact and mobile installation for "in situ" measurements (Figure 1). This apparatus was designed for simultaneous analysis of up to ten inhabited rooms over extended periods of time. Three operating modes with different tracer gas techniques can be used: the "decay" and "continuous flow" methods and above all the "constant concentration" method (5,6). This last approach shows serious advantages when compared to the others; measurement of infiltration can be carried out even in inhabited buildings with varying air change rates.

Figure 2 shows a bloc-diagram of the developed apparatus. The overall equipment is integrated on a mobile rack shown in Figure 1.

Four main components constitute the overall apparatus:

- a monitoring microcomputer
- an infrared N_2O and H_2O spectroanalyser
- a ten channel gas sampling unit
- a ten channel programmable gas injection unit

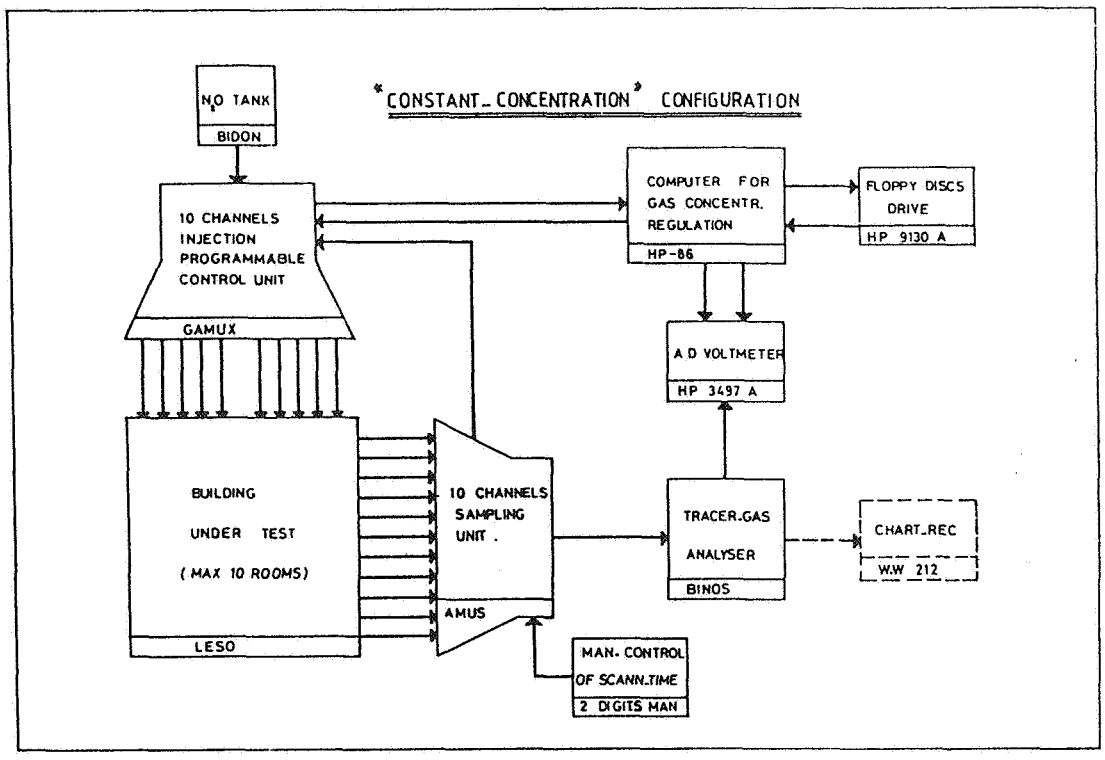
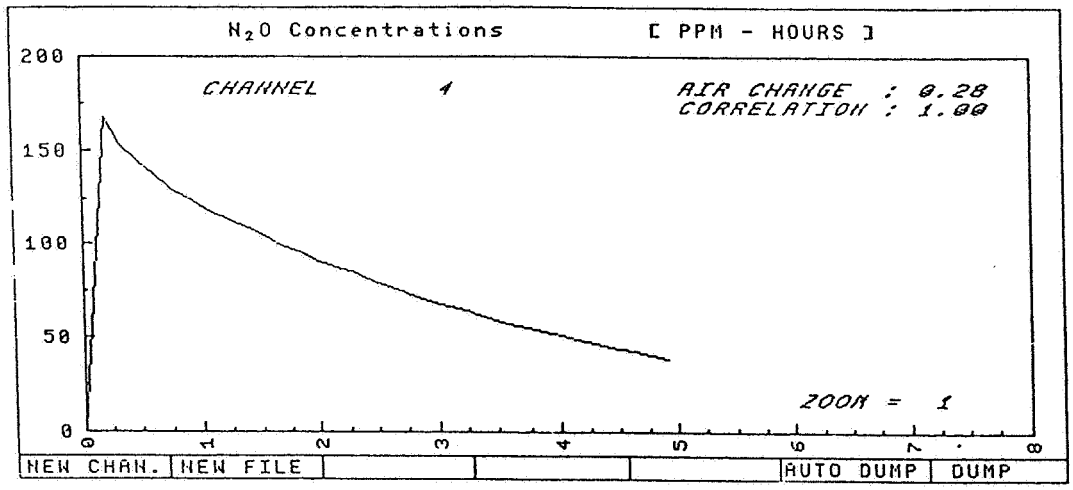


Figure 2: Bloc - diagram of CESAR

The following describes the main operations performed by these components:

a) Monitoring micro-computer

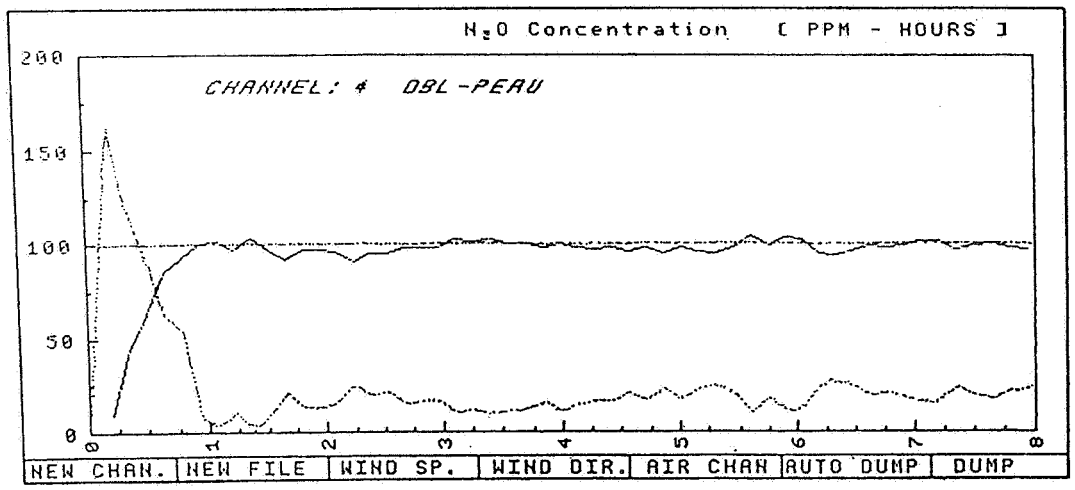
Acquired data is recorded on a magnetic support (floppy disc). Analysis of monitored data is done automatically by the computer at the end of the survey. Air infiltration rates and air flow rates as well as statistical parameters are displayed after each analysis. Figure 3 shows an example of a "decay" analysis delivered after treatment of the monitored data.



(MONITORING PERIOD OF 8 HOURS - FEBRUARY 1984)
VERTICAL AXES : CONCENTRATION (PPM). HORIZONTAL AXES : TIME (HOURS)

Figure 3 : Decay analysis delivered by the computer after processing the monitored data.

Figure 4 illustrates a "constant concentration" analysis done on an inhabited 86 m^3 room. The target level is maintained with a 4 to 8 % accuracy even for periods of several days. "Constant concentration" operation is controlled by the microcomputer, through the use of a proportional - integral - differential (PID) control. Air change rates obtained in a first "decay" experiment as well as room volumes were used as input parameters for the gas concentration control. The typical desired concentration level of 100 ppm N_2O can be achieved for rooms of up to 200 m^3.



ANALYSIS OF A "SOLAR UNIT" OF LESO BUILDING USING
"CONSTANT CONCENTRATION" METHOD

(MONITORING PERIOD OF 8 HOURS WITH OCCUPANTS - MAY 1984)
VERTICAL AXES : N_2O CONCENTRATION (PPM) (N_2O FLUX NOT SCALED). HORIZONTAL AXES : TIME (HOURS).

Figure 4: "Constant concentration" analysis made on an inhabited 86 m^3 room.
Solid line: concentration level. Dotted line : tracer gas flow.

b) Infrared nitrogen protoxyde and water vapour spectroanalyser

The nitrogen protoxyde (N_2O) concentration level is measured by means of a Leybold-Heraeus "BINOS" IR beam analyser. Since IR absorption bands slightly ovelap, water vapour disturbs the N_2O measurement. Measurement of the H_2O content is made simultaneously for automatic correction by the microcomputer. A high precision N_2O/N_2 gas mixture is used for periodical calibration.

c) Ten channel gas sampling unit

A Leybold-Heraeus "AMUS" unit performs the sampling of small amounts of air in up to ten different rooms. The scanning interval can be chosen between 10 and 1000 second. The typical scaning interval between two rooms is 50 seconds.

d) Ten channel injection programmable unit

This device was developed at our laboratory. Its purpose is to inject, under microcomputer control, known quantities of tracer gas in up to ten different rooms. Injection flowrate is stabilized by use of a high accuracy double stage pressure valve or a constant pressure dumper tank. Gas exhaust pressure is 200 kPa (2 Bar). Small fans provide dispersion of the tracer gas in the investigated rooms. The overall injection device was calibrated by use of a high precision (2 % accuracy) volumetric flowmeter.

LESO AIR RENEWAL EXPERIMENTAL SURVEY

The first infiltration survey was made on the LESO building during the 1983/84 heating season. Eight south rooms of the building, distributed over thgree floors and having various passive solar systems were investigated. Figure 5 shows the cross section of the building.

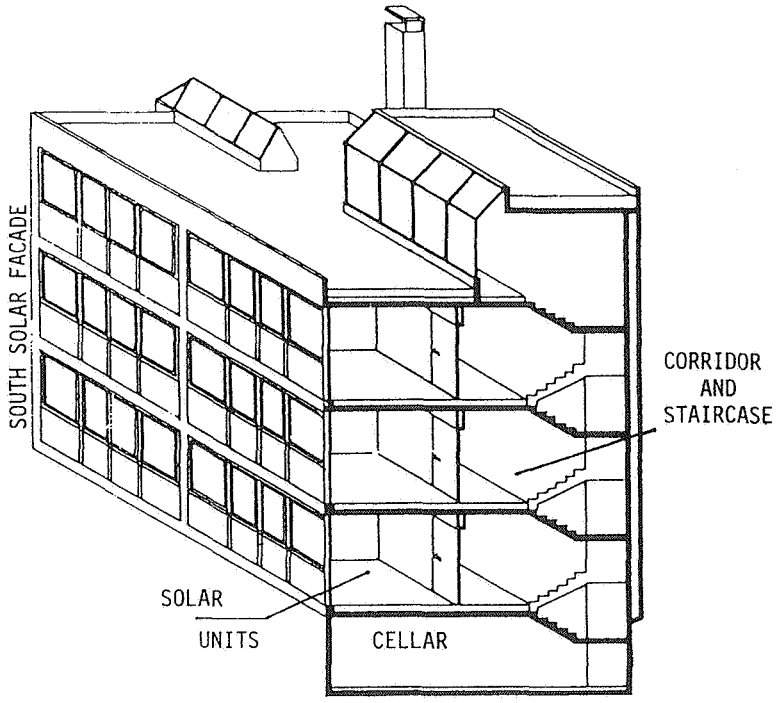


Figure 5: Representation of the passive solar office building (LESO building)

During this first experimental survey, the main effort was devoted to determining the outdoor-to-room and building-to-room (from the staircase) air flowrates. Precise evaluation of the south rooms' energy balances motivated this approach.

Fist, mean "decay" air change rates were determined for the 8 rooms. Figure 6 shows the measured values obtained over the February 1st to 29th period. Minimal and maximal values over the same period are also reported in the same Figure. Designation of the various passive solar systems, set up on the south facade of each room, are reported from bottom to top of the vertical axis in the same order as they were distributed in the building.

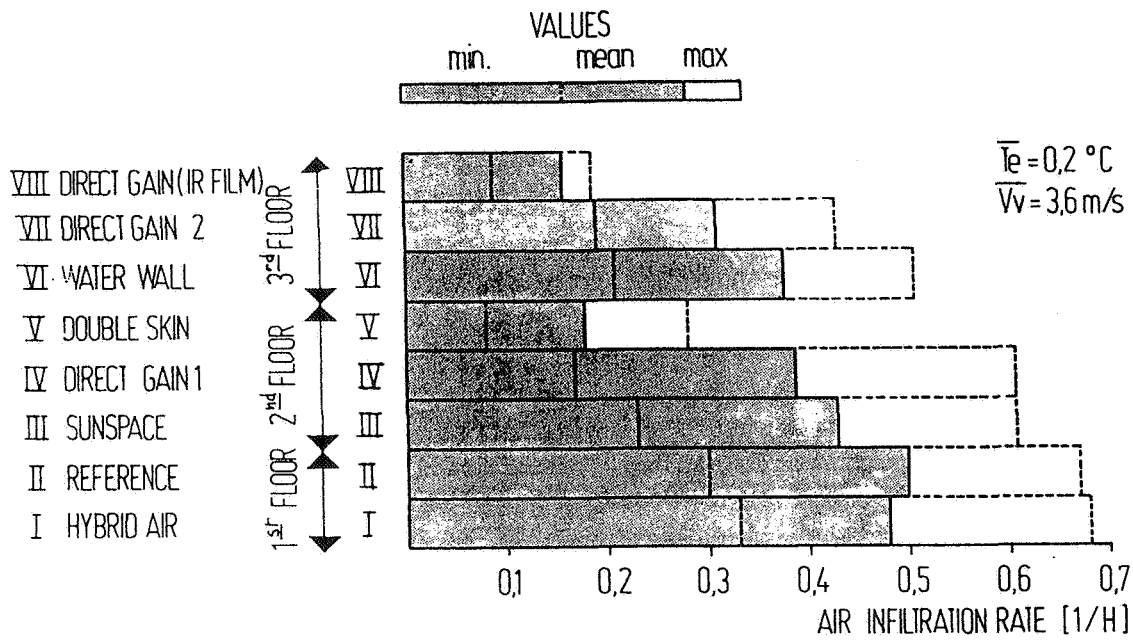


Figure 6: Minimal, average and maximal air change rates measured with the "decay" method from February 1st to 29th, 1984 on the LESO building.

Significant differences in air change rates have been found for the 8 investigated facades. New technology passive solar facades using double skin (V) or double infrared reflecting foils windows (VIII) have been shown to produce a drastic reduction in air infiltration, demanding a new air quality control strategy.

Total infiltration flowrates were also measured for each investigated room using the "constant concentration" technique, the tracer gas being injected only into the rooms.

Outdoor-to-room infiltration flowrates were determined for each south room by imposing the same desired N_2O concentration level over the entire building.

The mean building-to-room infiltration flowrates were obtained by substracting the mean outdoor-to-room air infiltration flowrates from the mean total infiltration flowrates.

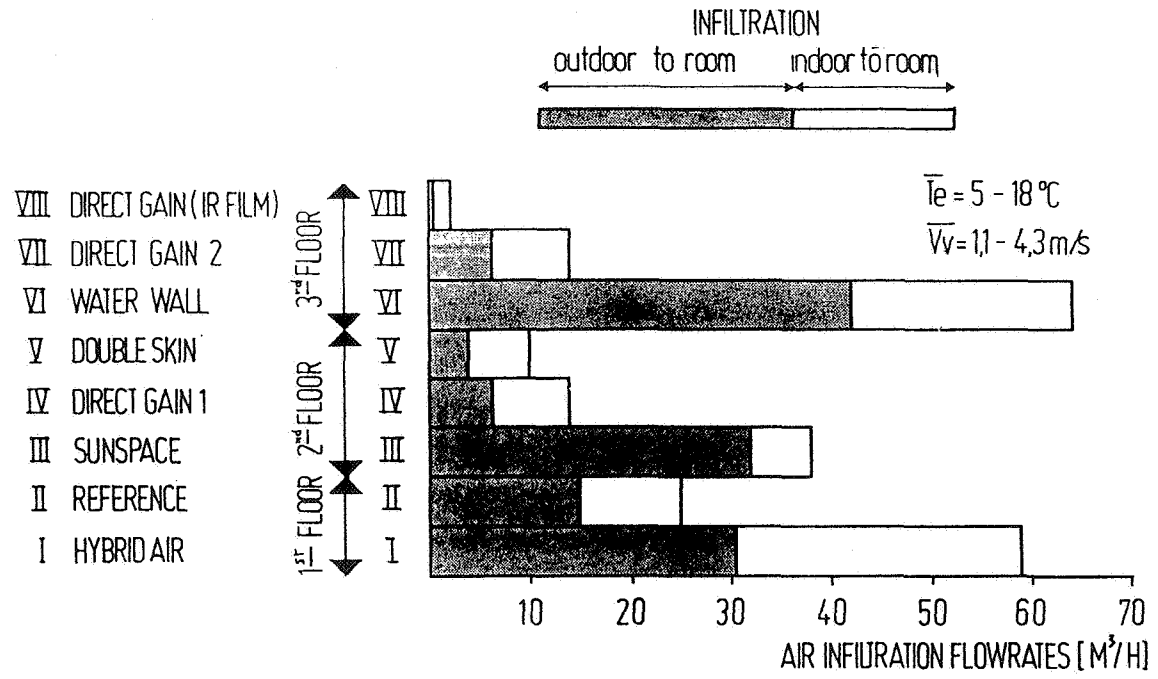


Figure 7 : Outdoor-to-room and building-to-room air infiltration flowrates experienced at the LESO on the March to end of May 1984 period.

Figure 7 shows outdoor-to-room air infiltration flowrates in grey, ranging from 1 to 40 m^3/h. Significantly low outdoor-to-room air infiltration flowrates were measured for the new technology facades. Building-to-room air flowrates of about 5 m^3/h were measured in unoccupied rooms having only one door connecting to the rest of the building.

A second air infiltration survey has been made on the LESO building during the 1984/85 heating season. The same south rooms, some of them having a new passive solar facade, were again investigated. The main effort this time was devoted to quantification of the occupants' influence. For this purpose, total air infiltration flowrates were measured for the 8 different south rooms over occupied and unoccupied periods. The "constant concentration" technique was used for this purpose. Total air infiltration flowrates were divided by the room's physical volume to obtain total air infiltration rates.

Figure 8 shows the measured air change rates obtained for the 8 different south rooms. Two different measuring periods (November 1984 and January 1985) are represented. Increase of air change rates due to colder meteorological conditions can be seen by comparing the results of the two months. The influence of occupants on the air infiltration rate is responsible for the air change rate increase measured for occupied rooms. Since windows were shut at all times, these increases were due only to door openings by the users. Mean values obtained for the overall 1984/85 heating season sho an 18 to 100 % higher value in air infiltration rates for inhabited rooms as compared to empty rooms.

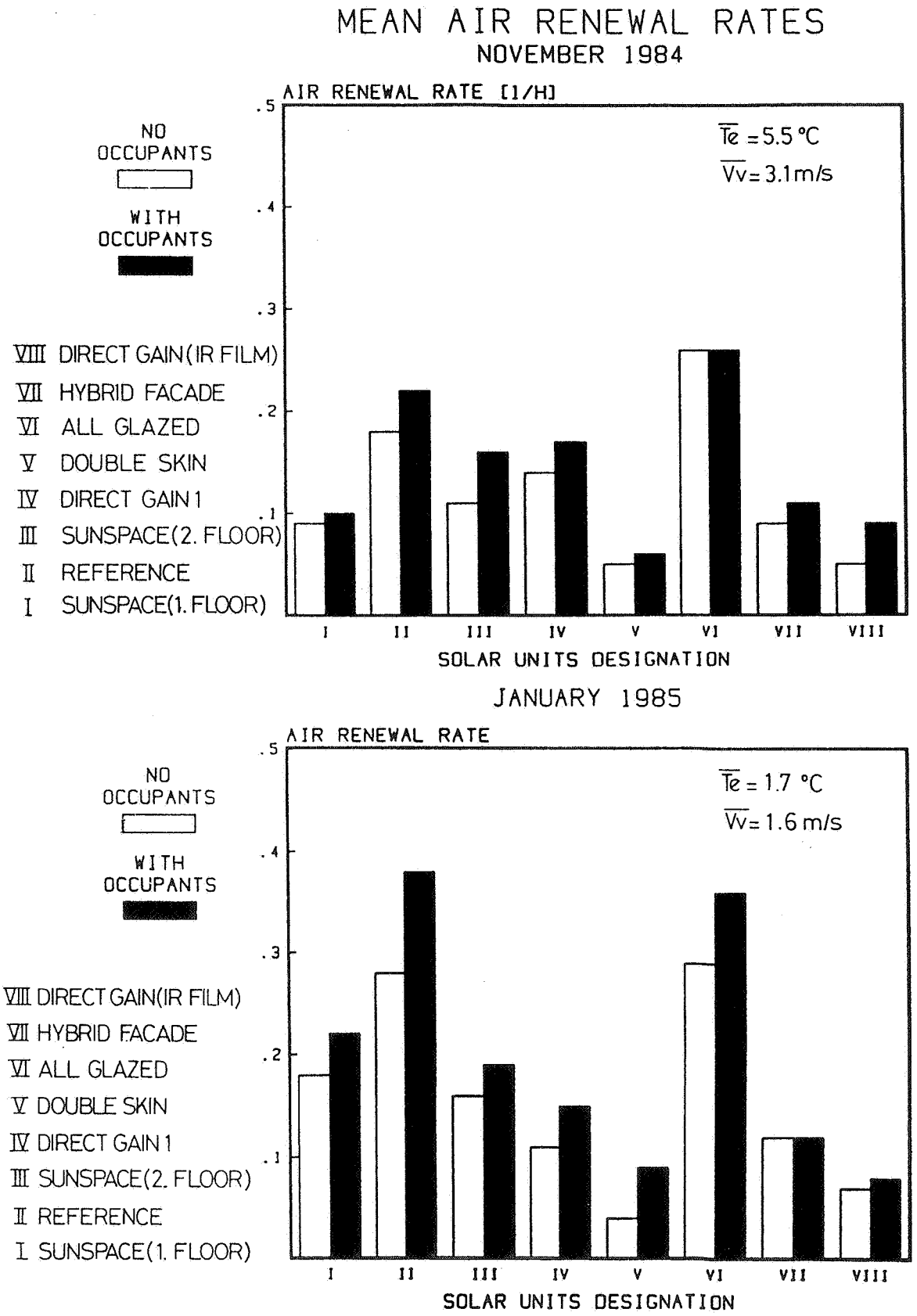


Figure 8 : Mean air change rates for two months with different outdoor temperature (January colder than November).
Black bars: with occupants White bars: without occupants.

AIR CHANGE SURVEY IN A ONE FAMILY HOME AT APPLES

Purpose of the survey and description of the building

A 12 day survey was made on a high one family home located in Apples, Switzerland; the main purpose being to test CESAR in the field. This home is built on 6 half levels (Figure 9). It has a heated volume of 530 cubic meter and 10 heated rooms which are interconnected with respect to air change. Air flows occur between the 10 rooms since they all open to the staircase.

The building has masonry walls with an external 4 cm fiberglass insulation, double glazed windows with weatherstripped wood frames and a frame wood roof including 14 cm fiberglass insulation. The toilets have ducts for natural ventilation and a fan is used in the kitchen when cooking. For the other rooms, natural ventilation occurrs through leaks and open windows.

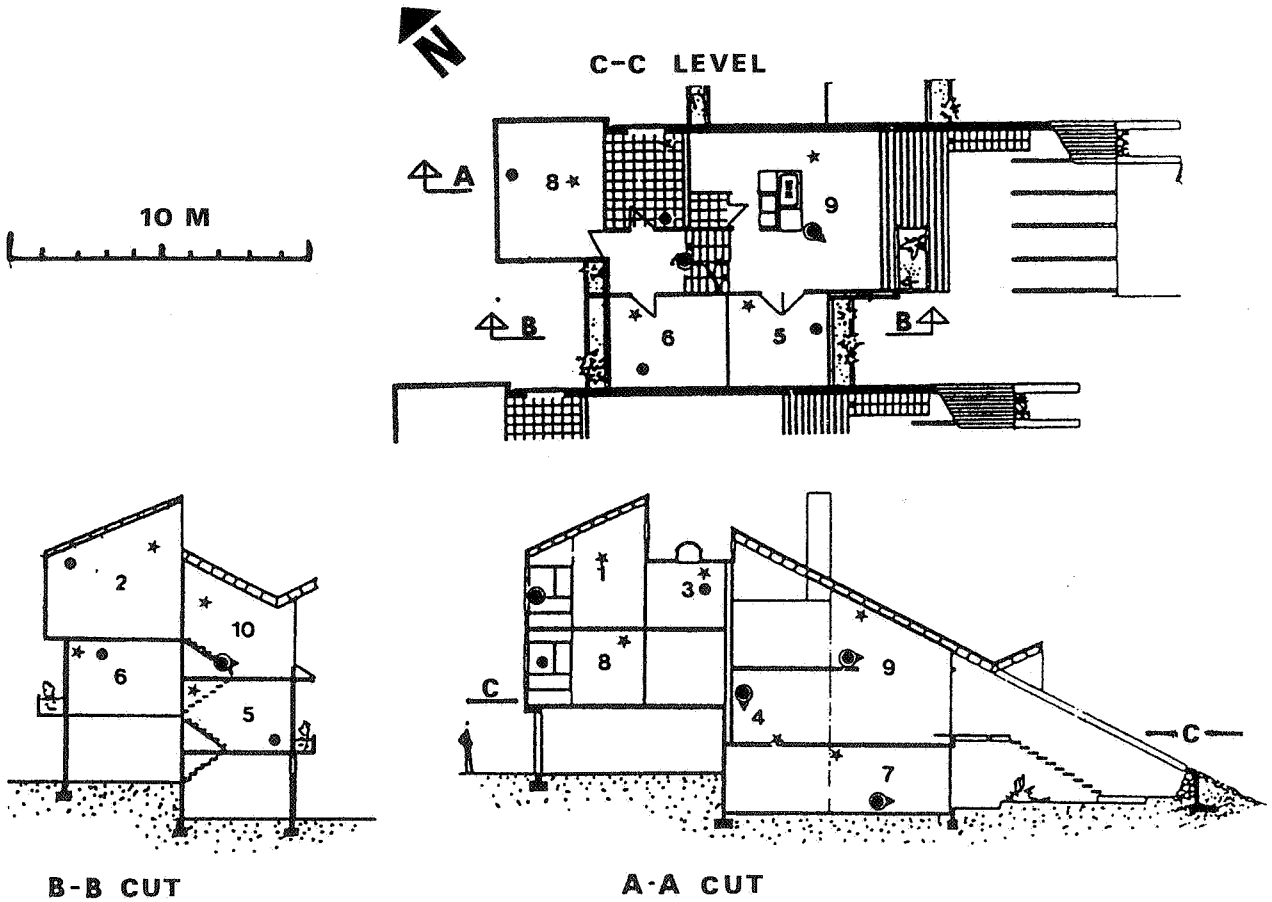


Figure 9 : Sketch of the middle level Apples family home and vertical cuts showing the inter-connected half levels.

1 Yve's bedroom	2 Parent's bedroom
3 Bathroom	4 Entrance and stairs
5 "Fumoir"	6 Knitting room
7 Friend's room	8 Kitchen
9 Living room	10 Guy's bedroom

● Tracer injection point ✱ Tracer sampling point

◀● Tracer injection point with fan. Arrow shows direction of the flow.

The building is occupied by 2 to 4 adults and their habits did not change during the survey. The structure of the building (high spaces, interconnected rooms) as well as the inhabitant behaviour (opening doors and windows) bring to this experiment some difficulties which are interesting for testing the apparatus and the monitoring software.

Measurements

The 10 measuring channels of CESAR were used for the heated rooms. Five other non-heated rooms such as the cellars were not measured. The air change between the heated space and the outdoor or unheated space was monitored.

Measurements were made using the "constant concentration" method between October 24th and November 7th, 1984. The data were recorded in 8 hour files on a floppy disk. During this period, the wind velocity was very low, between 0 and 3 m/s.

Because the large air change rate variations that occur in inhabited dwellings, it is quite difficult to maintain a constant tracer gas concentration level. Even with the sophisticated control system of the CESAR apparatus, small variations cannot be avoided. The measurements were then interpreted with the following equation (5), giving the volume Q of indoor air lost between the time t_1 and t_2:

$$Q = \int_{t_1}^{t_2} \frac{\dot{q}(t)}{C(t)}\, dt - V \left[\ln C(t_2) - \ln C(t_1)\right]$$

Where $\dot{q}$ is the tracer gas flow rate, C(t) the tracer woncentration level and V the measured volume. The integral is evaluated on the discrete measurement points by the trapeze method. One such equation was applied to each room, as if these rooms were independant and the total air lost quantity for the entire dwelling is obtained by summation. From this quantity, the mean air flow and air change rates can be easily evaluated. This interpretation method neglects the effects of the air changes between the rooms. In fact, these effects are negligible since the concentrations are nearly the same in every room.

Results

Figure 10 shows the mean air change rate for the entire dwelling averaged over 8 hours intervals. It is obvious that the behaviour of inhabitants can lead to very strong variations of the air change.

Separate sums of the air flowrates can be made for two different configurations: one when all the windows are closed, and another when only one or two windows, located in the bedrooms on the upper level are open (inhabitants sleep there with open windows).

The total mean air change rate, for the entire heated space during the whole survey is 0.5 /h.
This air change rate decreases to 0.37 /h for the time periods when all the windows are closed and increases to 0.56 /h if one or two bedroom windows are open. It is obviously larger when more windows are open.

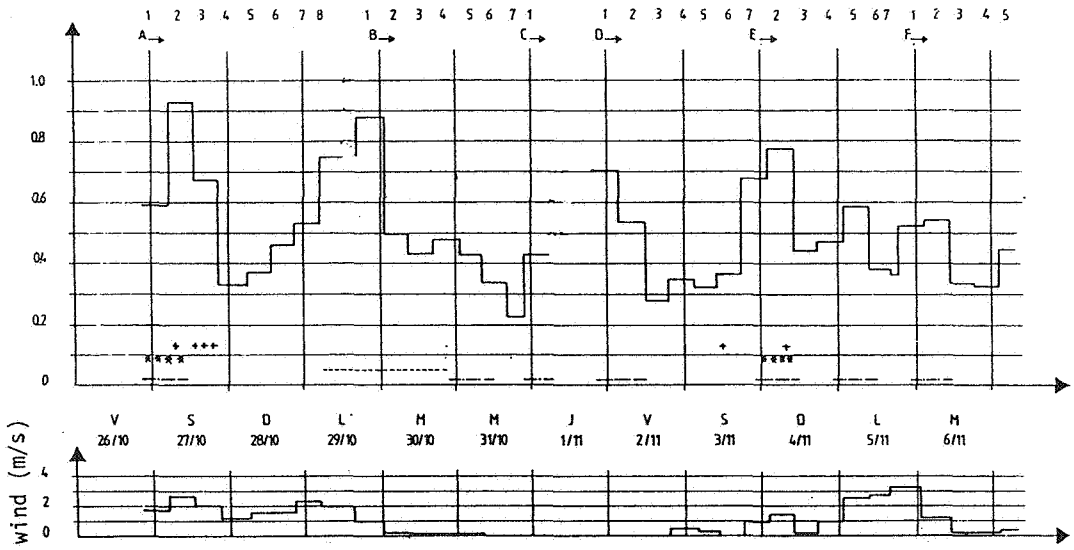


Figure 10 : Mean air change rate (ach) for the whole Apples dwelling obtained by the constant concentration method, averaged over every 8 hours interval. At the bottom, the wind speed is represented.

++++ : Large ventilation of the dwelling by opening kitchen and livingroom windows for 15 min.

**** : Window open in Yve's room.

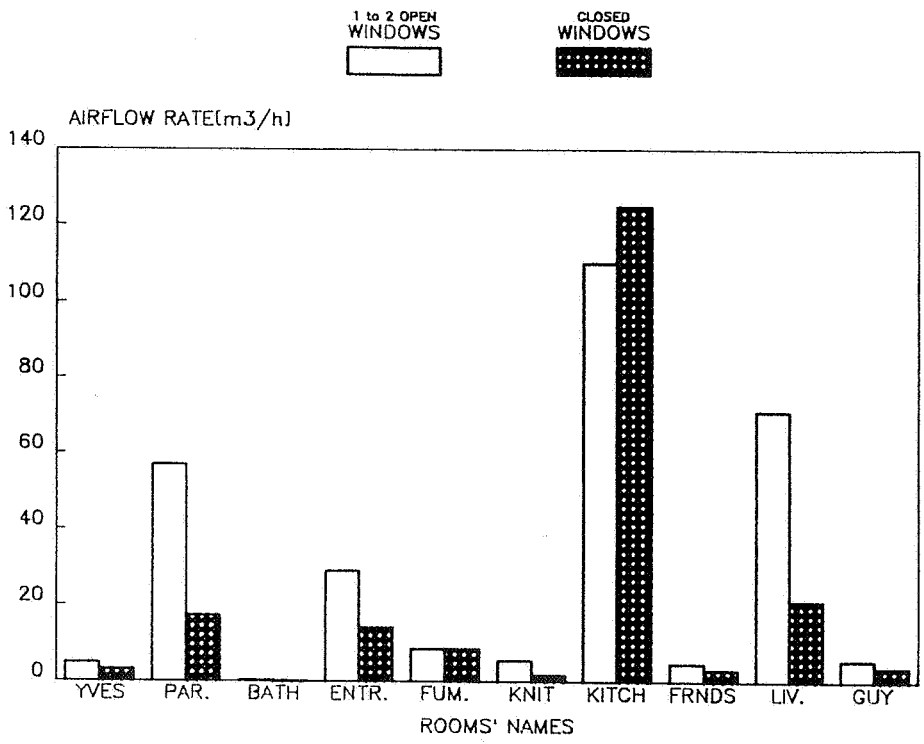
---- : Sky-window in the bathroom opened

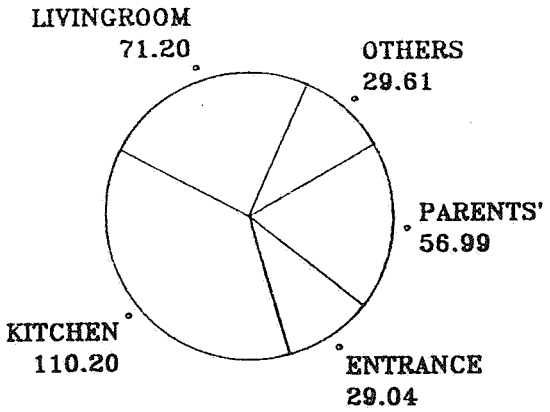
-.-.-: Parents' bedroom window open during the night.

Figure 11 shows the air infiltration flowrates for each room. The main infiltration occurs in the kitchen and the livingroom, which are on the lower levels and have large sliding glass doors. It is obvious that the fresh air is coming into the house mainly in these rooms. For example, the infiltration in the parents' room with open windows looks very low, since large quantities of indoor air, already containing the target concentration level of tracer gas, comes from the livingroom by way of the staircase and an untight door.

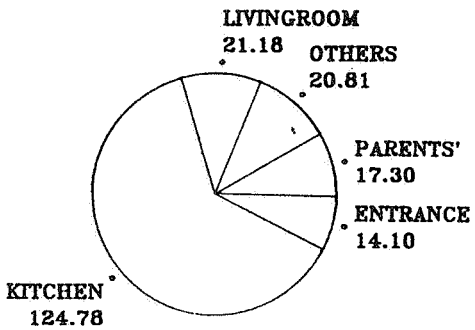
This total rising air flow is more obvious when looking at peculiar records, as in Figure 12. When closing the parents' bedroom window, effects can be seen in five other rooms located either at the same level as in the bathroom,(channel 3), at the lower level as in the kitchen (channel 7) and in between as in the staircase (4), the livingroom (9) and knitting rooms (6).

More developments on the tracer gas concentration control system will be made, taking into account the exchanges between rooms, to avoid the overshoots as those which can be seen on channels 2 and 7 in Figure 12.





1 TO 2 OPEN WINDOWS
TOTAL 297 m3/h



CLOSED WINDOWS
TOTAL 198 m3/h

Figure 11 : Comparison of the total air flows of each room. The windows which are open some time are in the bedrooms, on the upper level.

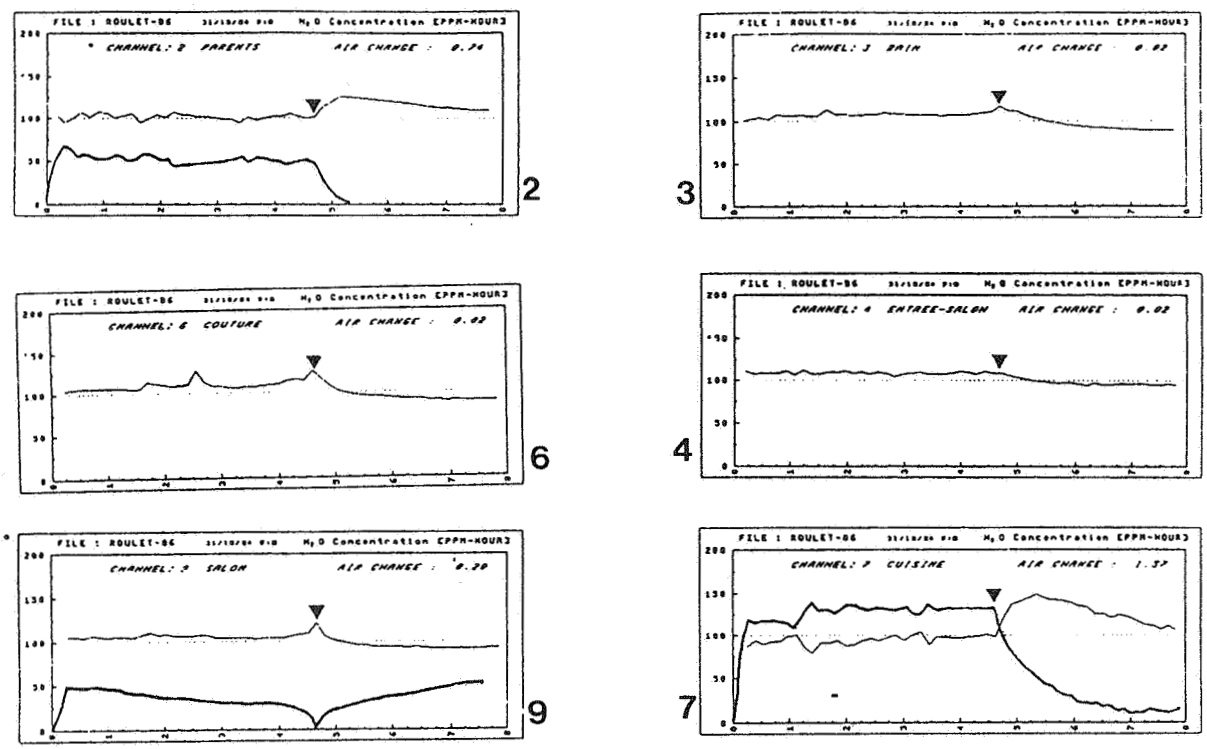


Figure 12 : Record of the tracer gas concentration (thin line) and of the tracer gas flow (thick line) in 6 rooms. This record shows the effect of closing the parents' room window (channel 2) on the air change in other rooms (arrows) and hence the strong inter-connections through the untight interior doors and the staircase.

AIR INFILTRATION SURVEY IN A LOW ENERGY TEST GREENHOUSE IN GENEVA

Purpose of the survey

In 1982, a research project was begun at CERN in Geneva to examine different methods of maximizing the solar energy contributions and minimizing heating costs in a greenhouse, using various heating systems and thermal screens.

The CESAR was used to study the fluctuations of air infiltration and particularly to quantify the influence of the following factors on the air change rate:

- the roof windows openings
- the use of thermal screens during the night
- the wind and the indoor/outdoor temperature difference.

It also provides an opportunity to test the CESAR on a large building (2670 m^3).

Description of the building and experimental setup

The greenhouse has an area of 668 m^2 and a total volume of 2670 m^3 (Figure 13). It is divided into five thermal zones separated by plastic films, each zone being equipped with a different low temperature heating system.

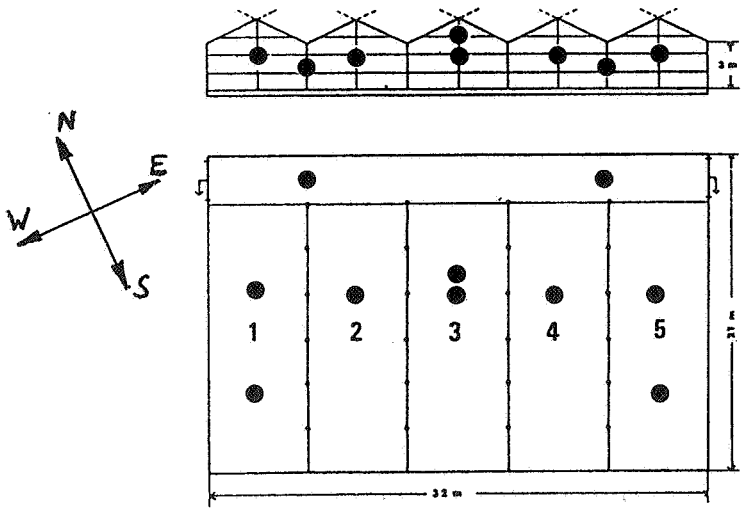


Figure 13: Top view of the CERN greenhouse with the 5 independant thermal zones. The dots show the tracer gas sampling points.

Two horizontal thermal screens were installed in the upper part of the greenhouse to reduce the night heat losses. The greenhouse has a single glazed roof and double glazed sides with aluminium frames. The airtightness of the greenhouse is improved by using rubber seals on the frame (Figure 14). During overheating periods (indoor air temperature over 24 °C) the control system opens the roof windows in order to create a natural ventilation. For more details see (6).

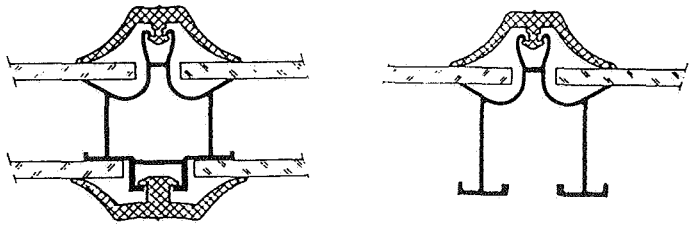


Figure 14: Detailed view of the frames and the rubber seals for the single and double glazing.

Measurements were made using constant concentration method from November 28th to December 14th, 1984 and from February 6th to 21st, 1985. The ten measuring channels of CESAR were installed and used for the entire greenhouse as shown in Figure 13. In addition, an automatic data acquisition unit allowed for detailed analysis of the climate and operating conditions of the greenhouse.

The method of analysis was similar to that used on the Apples survey but was directly performed using the total air infiltration flowrate and the mean concentration level for the entire greenhouse.

Results

Figure 15 shows the strong influence of opening the roof windows during overheating periods: even for a small opening of 5 cm, the air change rate increases from 0.2 - 0.28 /h (window closed) up to 0.6 - 1.5 /h.

During these periods, the tracer gas concentration level decreases down to 80 ppm because of the response time of the control. The effect of this on the results however is negligible considering the analysis method used.

One can also observe in Figure 15 that the thermal screens slightly reduce the air infiltration into the greenhouse by about 15 % (ach = 0.28 /h without screens, 0.22 /h with screens). This is confirmed in Figure 16 where, for similar wind velocity and temperature differences, air change is also slightly lower with screens than without.

Figure 16 shows the combined influence of the wind velocity (v) and the indoor to outdoor temperature difference. Note that during the measurement periods, the wind velocity was low ($v < 3 m/s$)

A multiple linear regression was performed on the data recorded with the screens, in order to determine the air change rate as a function of v and the temperature difference. The regression coefficients and their 90% confidence intervals are as follows:

$$ach = a + b\,v + c\,(\theta_i - \theta_e)$$

$$a = 0.104 \pm 0.04 \quad h^{-1}$$

$$b = 0.045 \pm 0.008 \quad s\,m^{-1}\,h^{-1}$$

$$c = 0.011 \pm 0.003 \quad K\,h^{-1}$$

Finally, one can note that, because of the frame rubber seals, this greenhouse is very tight. Its air change rate ranges from 0.15 to 0.4 /h as compared to approximately 1/h for a standard greenhouse.

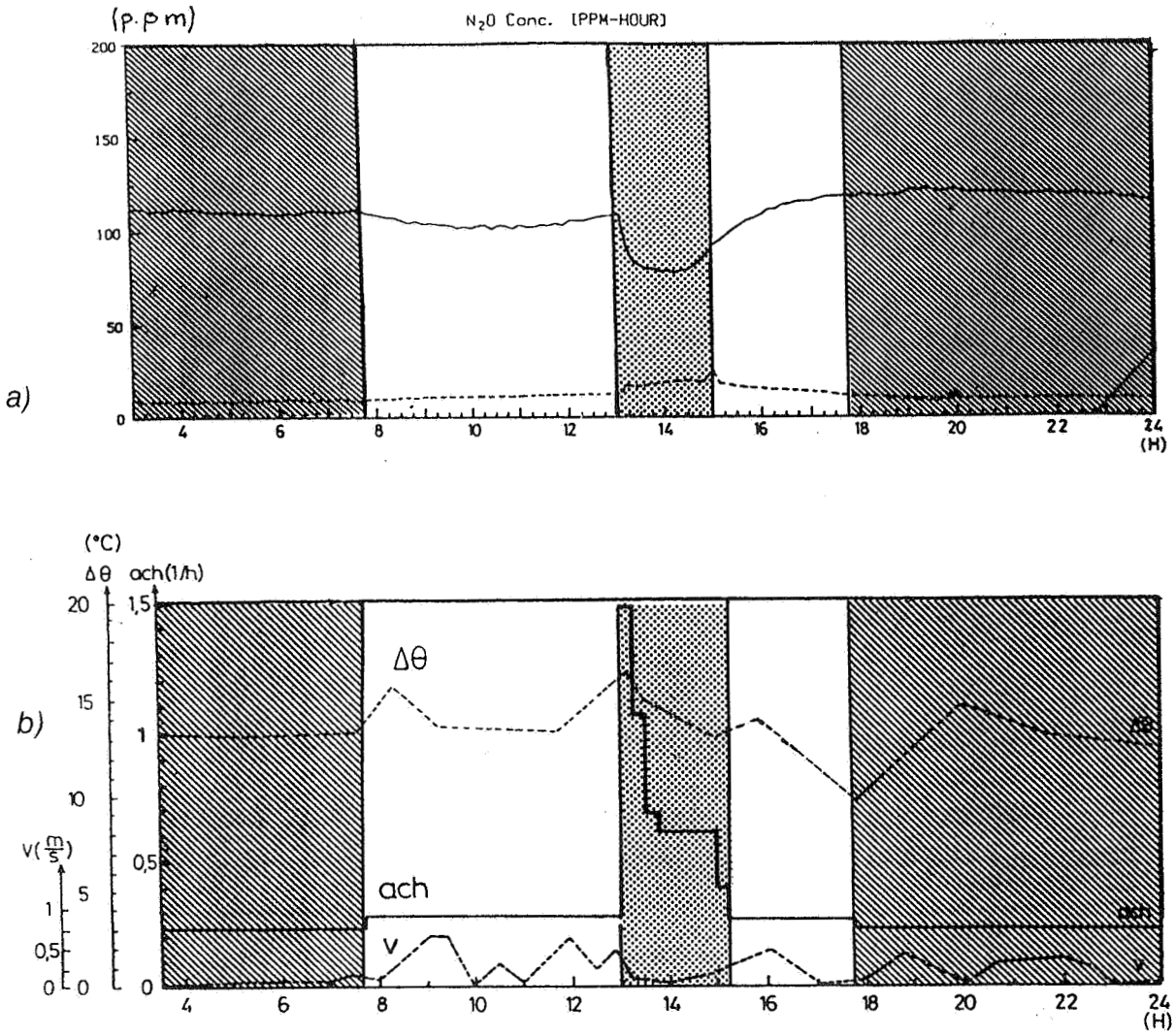


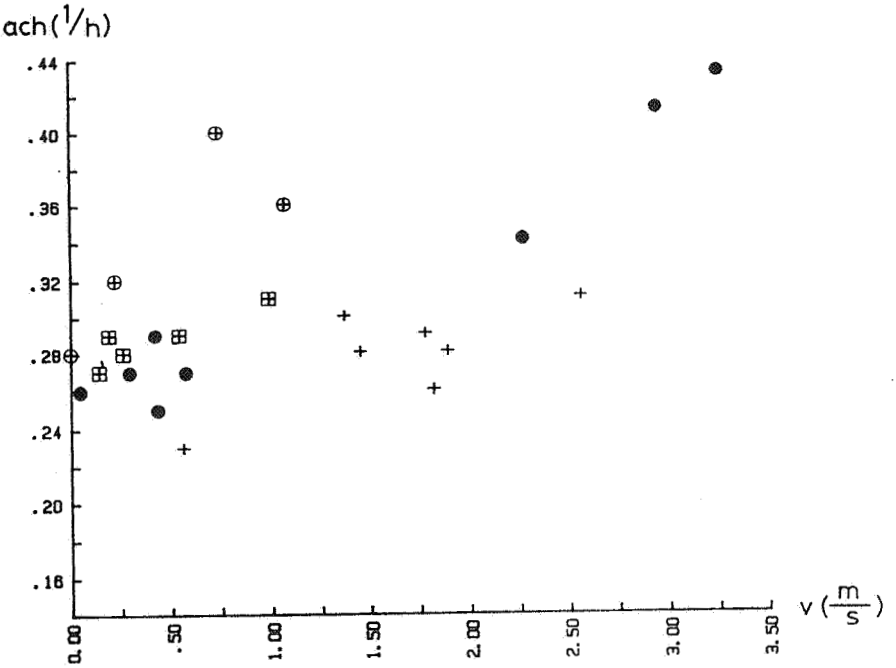
Figure 15: Measurements on the greenhouse during 24 hours:

a) Evolution of the tracer gas concentration (solid line) and the tracer gas flowrate (dotted line) for the entire greenhouse.

b) Evolution of the air change rate (ach), the indoor/outdoor temperature difference an the wind velocity (v)

Dotted zone : windows open. Hatched zone : thermal screen closed

a)



b)

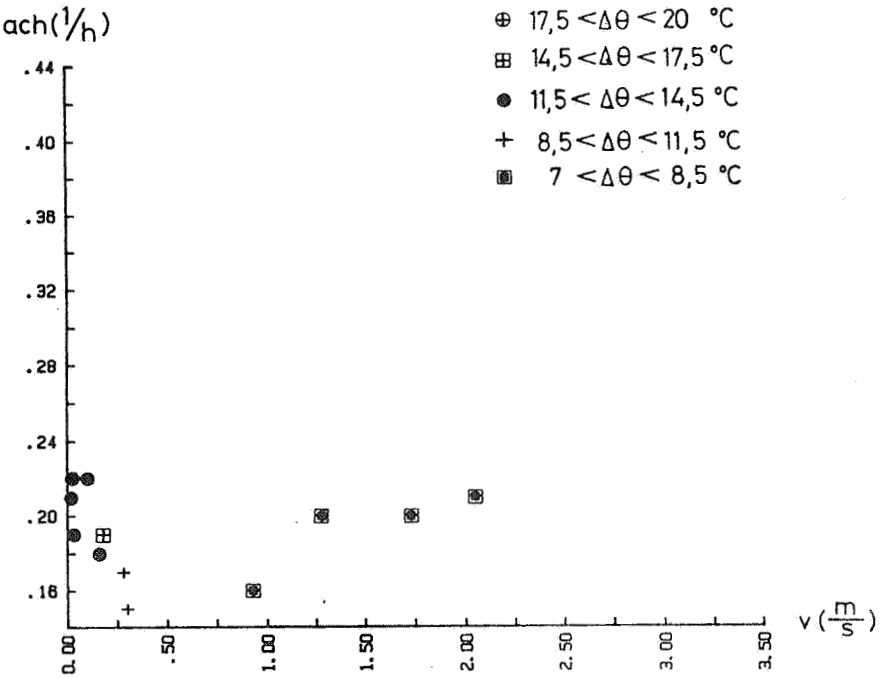


Figure 16: Air change rate as a function of wind velocity for different indoor/outdoor temperature differences. Mean values over 4 to 8 hours time periods where windows are closed.

a) without screens **b) with screen**

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 10

The Reduction of Air Infiltration in an Industrial Laboratory

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1. Abstract

As part of a programme to develop measurement methods for determining the ventilation rates of large buildings, we performed two series of tests in a single-celled laboratory with a volume of 600m^3. The first series utilised constant concentration, constant emission and rate of decay tracer gas techniques to determine the characteristics of the infiltration pattern in varying winds and external temperatures. We used both discrete and continuous injection and sampling methods. Pressurisation techniques were employed to determine the overall leakage of the building and the spatial distribution of the leaks with flow visualisation methods. The building was then draught proofed with commonly available materials and techniques before further pressurisation tests and thorough ventilation measurements were undertaken.

The experiment thus provided detailed comparisons of ventilation measurement methods and detailed performance characteristics of the building envelope in two states of leakiness.

The interaction between the changed leakage characteristics and the measurement methods is discussed together with a critical evaluation of the measurement methods themselves.

2. Synopsis

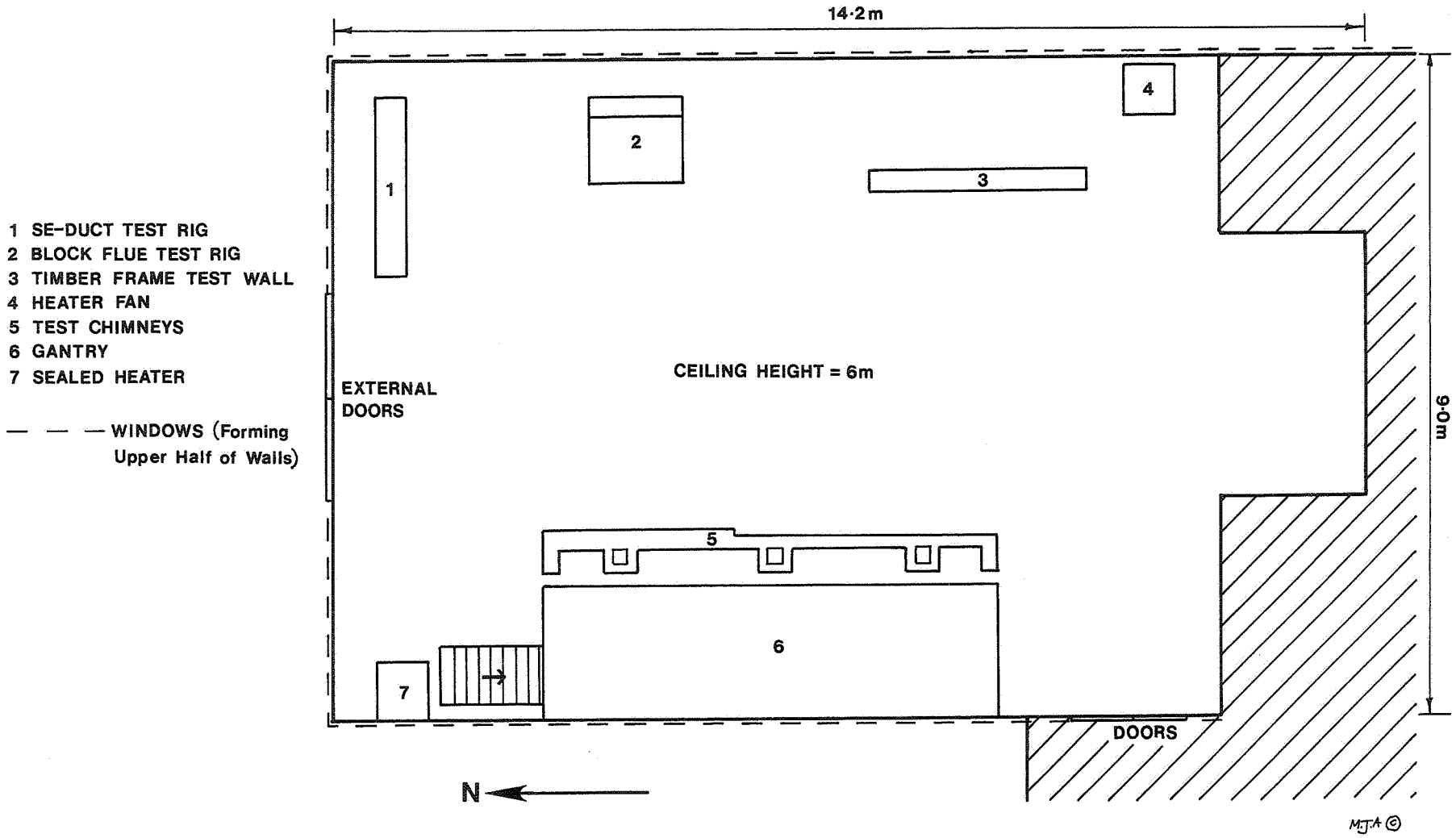
The current trend for the reduction of air infiltration in buildings must necessarily have an impact on the internal environment. If the internal environment is to be controlled to maintain a good standard of air quality, the reduction of air infiltration must also be controlled, particularly if supplementary fanned ventilation systems are not included in changes of design.

When considering the varying need for ventilation within a building, a minimum uniform ventilation rate may not be the most efficient alternative, especially if there are small areas which require high localised ventilation. When seeking to determine infiltration rates throughout a building, the interaction between the ventilation measurement techniques used and the ventilation characteristics must not be ignored. The errors in different infiltration measurement techniques (SANDBERG[1]) vary depending on the type of building considered. This is largely dependent on the individual nature of infiltration and mixing, which will change with building type, experimental technique, weather conditions, and that most fickle of variables, human behaviour.

In the practical application of the measurement of infiltration there are two important links which need to be rationalised:

a) The relationship between complex research techniques (which have by no means mastered the art of accurate infiltration measurement) and easily executed practical measurements. This link can be typified by the desire to obtain adequate information from building envelope pressurisation tests regarding infiltration characteristics which cannot yet be easily measured by direct infiltration measurement,

Figure 1 INDUSTRIAL LABORATORY–SEGAS CENTRAL LABORATORIES



and b) the relationship between the real infiltration and airflow patterns within a building, and the disturbing influence of techniques used to measure these characteristics.

The experiments described attempt to try and link some of these factors, and starts to look at the influence that they have on one another. In particular the limits of application of existing decay measurements are considered, by comparing the nature of concentration decay results in different building constructions.

3. Methodology

An industrial laboratory at Segas Central Laboratories has been used frequently to test and develop ventilation measurement techiques (see Figure 1). Consequently, a great deal of information has been collected about the ventilation characteristics of the building, including the distribution of "leaky" and "tight" areas around the perimeter of its 600m^3 volume. The main methods used have been 12 channel constant concentration, 12 channel decay, and various multichannel constant emission techniques including continuous instantaneous and discrete bag sampling methods (FREEMAN et al[2]) detailed analysis of the building's response to wind speed, direction, and stack was collected, along with many indications of primary infiltration sites and flow paths within the building. The variation in concentration of tracer gas in decay tests confirmed bulk air movement trends, and the finer constant emission methods identified specific areas of high infiltration (FREEMAN et al[3]).

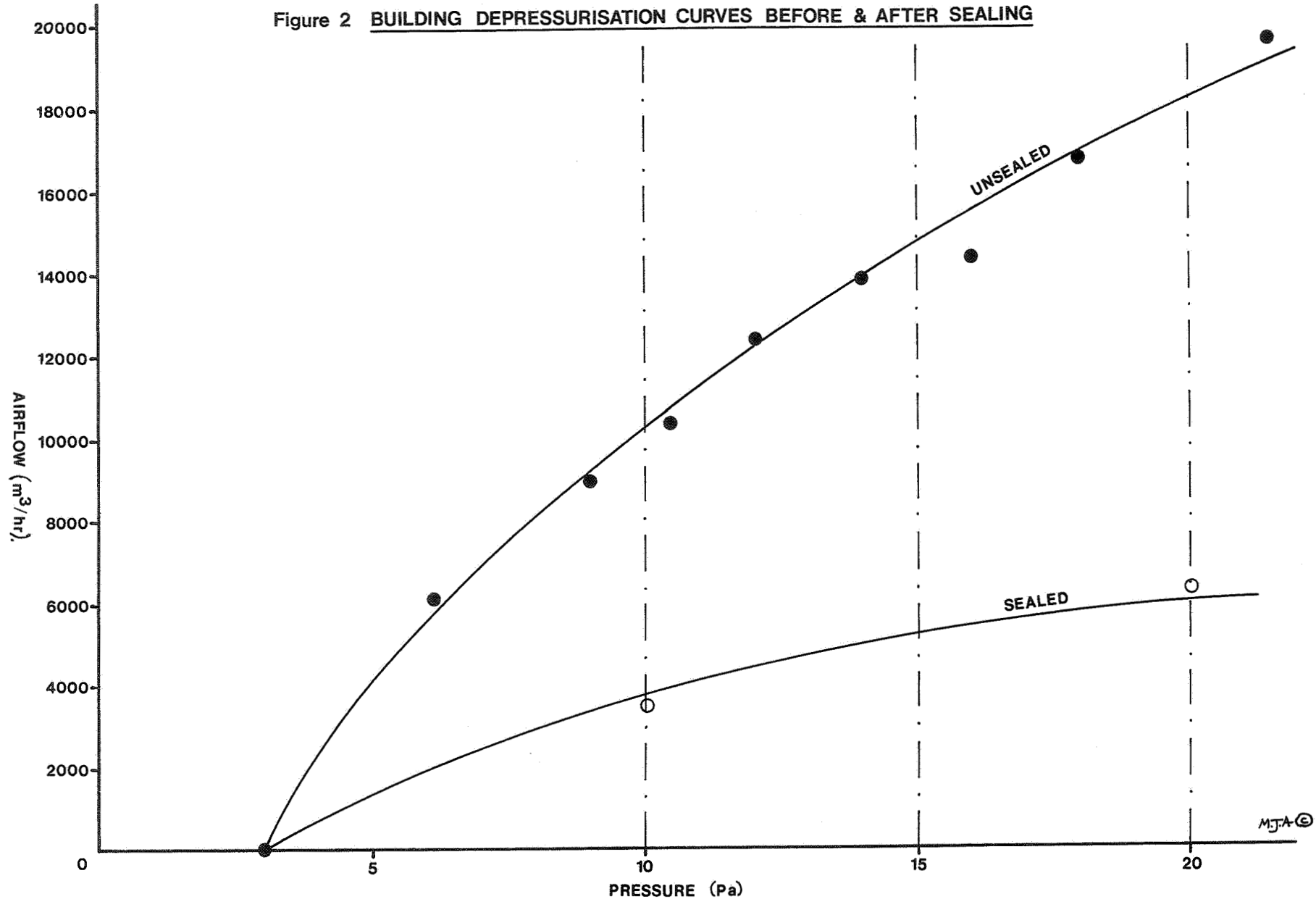
A depressurisation test of this relatively leaky building was then performed by connecting the outlet of a wind tunnel to the outside of the building, using a fabricated nylon tube connected to a false door. All the conventional leakage points were sealed including leakage through a partition wall and electrical ducting to an adjoining laboratory, doors and many disused flue vents in the roof. The largest single contribution to the leakage was through the cavity between the breeze block and metal clad wall, which had a loose fitting metal cover on. No draught proofing of the windows was performed as they were of a well-fitting metal construction. The depressurisation of the building (AL-NASSER[4]) could then be taken to -30Pa with respect to ambient, at a much reduced flow rate. (The extent of depressurisation was limited by the equipment used).

During the next heating season, further extensive ventilation measurements were performed, mainly using simple decay techniques, with a variety of injection and mixing methods.

By using this series of tests the relevance of different measurement techniques capturing different types of ventilation data could be determined, along with an understanding of the interaction of different techniques with the building's ventilation characteristics.

All the data, apart from the manually analysed constant emission bag samples, were collected and summarised by the 12 channel sampling Segas Autovent (a computer controlled integrated data logger and control system).

Figure 2 BUILDING DEPRESSURISATION CURVES BEFORE & AFTER SEALING



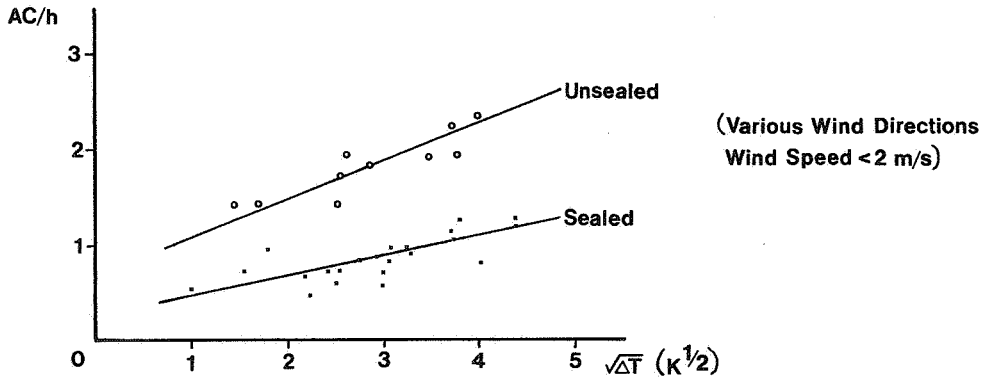
4. Results

4.1 Airchange Rates

The change in leakage flow/pressure charactertistics are shown in Figure 2. The flow rate reduction after sealing the building was consistent at 2.8 (± 0.08):1 at -10, -15 and -20Pa pressure differential.

Figure 3, below, shows the reduction in sensitivity of the building to temperature differential induced ventilation. This shows an approximate 2:1 reduction in ventilation rate after sealing.

Figure 3 REDUCTION IN BUILDING SENSITIVITY TO TEMPERATURE DIFFERENCE INDUCED VENTILATION RATE

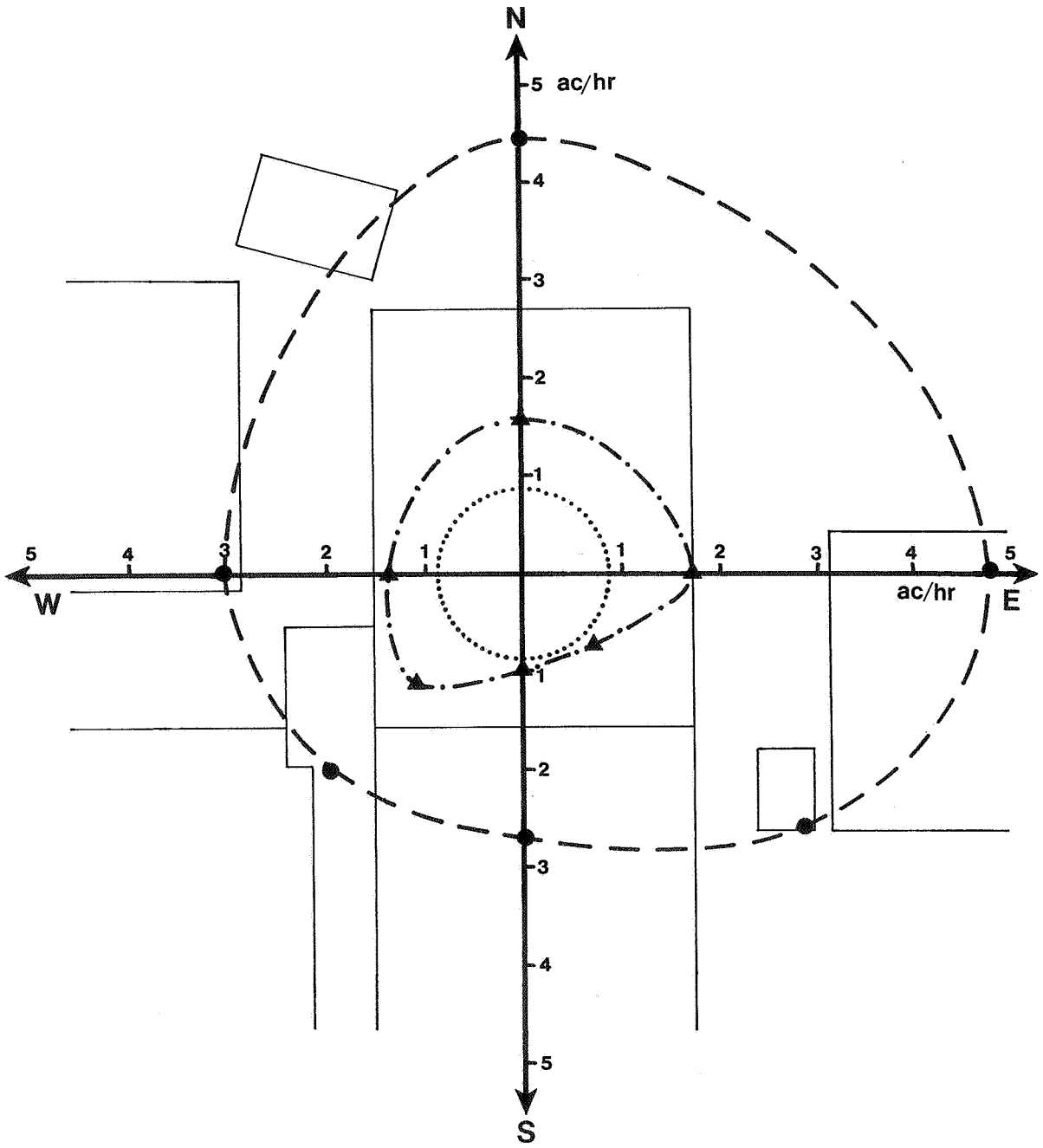


The sensitivity of the building to wind speed was also very much reduced, as was the sensitivity to wind speed on exposed or particularly leaky faces of the building. The polar diagram in Figure 4 shows the reduction in air infiltration at a wind speed of $3.5ms^{-1}$ with respect to wind direction. The ratios expressed in the figure show the reduction in infiltration that sealing effected for that particular wind direction. This ranges from 3.8:1 for south easterly winds' glancing impingement on the eastern face of the building (the southerly face being sheltered by an adjoining laboratory) to 1.8:1 south westerly winds, which are likely to be very turbulent as a result of the complex array of buildings to the windward of the laboratory.

4.2 Leakage Distribution

In the first set of ventilation measurements, concentration decay tests showed a distinct gradient across the laboratory with easterly and westerly wind directions. Areas of high infiltration could be determined by observing the sample points of lower concentration. These tests showed particularly high localised infiltration from the doors in the north wall, and the north-eastern corner of the laboratory in easterly and northerly winds. These results were endorsed by bag sample constant emission tests (FREEMAN et al[3]) and 12 point injection constant emission tests (FREEMAN et al[2]) which could identify these sites as points of predominant

Figure 4 POLAR DIAGRAM DEPICTING BUILDING SENSITIVITY TO WIND DIRECTION BEFORE & AFTER SEALING



— — — Before Sealing, 3·5 m/s, $\sqrt{\Delta T} = 3K^{1/2}$
— · — · — After Sealing, 3·5 m/s, $\sqrt{\Delta T} = 3K^{1/2}$
····· Stack Effect, $\sqrt{\Delta T} = 3K^{1/2}$

M.J.A©

exfiltration, (along with the roof) in westerly winds. When performing these tests, no mixing was employed apart from a small central fan in the constant emission The most effective method of injecting tracer gas into this intermediate sized volume without affecting the natural air flow paths was by bursting balloons full of the appropriate tracer gas (SANDBERG[7]).

When the pressurisation tests were performed, smoke tests showed that most the leakage was at a relatively high level. The only low level leakage was observed from the doors and a water drain in the laboratory floor. Leakage was concentrated high in the building around the top of the cavity between the metal cladding and breeze block wall, and from many cracks and holes in the roof around flue terminations and the loft hatch. The windows were well fitting metal windows which did not notably contribute to the leakage under depressurisation.

After sealing, the leakage distribution over the building envelope was very much more even, with no particularly dominant leakage sites.

4.3 Ventilation Measurements

Before the sealing of the laboratory was performed, decay, constant concentration and constant emission tests all indicated the spatial distribution of predominant leakage sites and as such the individual sample points had a wide range of standard deviation of the location ventilation rate from the mean. Using concentration decay tests from a constant concentration throughout the laboratory results similar, though less marked, were obtained to such tests performed previously in multi-roomed domestic dwellings (ETHERIDGE et al[5]). There, the localised ventilation rate is described in terms of the area underneath the decay curve. When larger, single-celled buildings are considered, there is a smaller variation in these areas, as would be expected, but the variations in wind speed and direction have a greater influence on different air paths within the volume, much increasing the errors involved in measuring the local infiltration rate. (A comparison of areas under decay curves for different building types is shown in Table 1). These errors reduce with the size of the building, and recent tests in a very leaky 10,000m^3 warehouse (ATKINSON[6]) clearly show the leakiest parts of the building dominating its ventilation charateristics. The most difficult task in doing measurements in this type of building is obtaining adequate mixing of the tracer gas on injection. Even the rapid evacuation of cylinders of tracer gas (DEWSBURY[8]) does not always produce a good initial distribution of tracer gas in these circumstances.

When the laboratory was sealed, the areas of predominant infiltration/exfiltration were removed, and the non wind induced mixing eddies within the building became much more dominant. The effect of this was to produce much more even and

TABLE 1

COMPARISON OF VARIATION OF AREAS UNDER DECAY CURVES FROM CONSTANT CONCENTRATION FOR FOUR BUILDINGS

2 STOREY TERRACED HOUSE (REFERENCE 5)(DOORS CLOSED)			UNSEALED SEGAS LABORATORY ($60Om^3$)			SEALED SEGAS LABORATORY ($60Om^3$)			LEAKY WAREHOUSE($10,000m^3$) (REFERENCE 6)		
ROOM	LOCAL DECAY RATE (ac/hr)	RELATIVE AREA UNDER DECAY CURVE (LOUNGE=1)	SAMPLE POINT	LOCAL DECAY RATE (ac/hr)	RELATIVE AREA UNDER DECAY CURVE (SAMPLE 10=1)	SAMPLE POINT	LOCAL DECAY RATE (ac/hr)	RELATIVE AREA UNDER DECAY CURVE (SAMPLE 1=1)	SAMPLE POINT	LOCAL DECAY RATE	RELATIVE AREA UNDER DECAY CURVE (SAMPLE 5=1)
LOUNGE	0.13	1	1	0.92	0.86	1	0.81	1	1	1.15	0.56
HALL	0.52	0.23	2	0.98	0.85	2	0.81	0.99	2	1.06	0.65
KITCHEN	0.31	0.43	4	0.91	0.92	3	0.87	0.99	4	0.92	0.91
BED 1	0.33	0.41	5	0.89	0.92	4	0.80	0.99	5	1.01	1
									6	1.44	0.96
BED 2	0.22	0.62	6	0.91	0.98	5	0.83	0.98			
BED 3	0.18	0.74	7	0.90	0.93	6	0.84	0.98			
LANDING	0.34	0.39	8	0.99	0.88	7	0.84	0.97			
TOILET	0.26	0.52	9	1.05	0.90	8	0.77	0.98			
BATH	0.27	0.52	10	0.89	1	9	0.97	0.98			
			11	0.96	0.93	10	0.80	0.97			
						11	0.82	0.97			
						12	0.83	0.97			
MEAN	0.28	0.54	MEAN	0.95	0.92	MEAN	0.83	0.98	MEAN	1.12	0.81
S.D.		0.225	S.D.		0.05	S.D.		0.01	S.D.		0.20

consistent local concentration decay curves and constant emission sample concentrations, and should produce better control in unmixed constant concentration experiments. Particular areas of infiltration were not identified, but the roof/window area was still identified as the main exfiltration area, due to the fact that concentration variations in all the tests reduced at high level, showing this area to contain tracer gas with the highest residence time in the building.

When decay tests were carried out after sealing, the length of time required to achieve an even tracer gas distribution for the decay did not appear to alter much. In tests in the leaky 10,000m^3 warehouse, the length of time to reach an even tracer gas distribution was considerably increased from 15-20 minutes for the laboratory to greater than 40 minutes in the warehouse. During this time, a considerable proportion of the tracer gas escaped, and an appreciable over-injection of tracer gas was required to obtain reasonably consistent rates of decay throughout the building.

Table 1 shows the variation in standard deviation of tracer gas decays from constant concentrations in four buildings. The large leaky warehouse and the terraced house, partitioned with walls and closed doors, have similar standard deviations of about 0.2 for the areas under decay curves in different sample positions. This shows that these two buildings have similar proportional variations in local ventilation. The characteristics of the buildings are obviously totally different, and the different mixing mechanisms in each demand due consideration when choosing a method for ventilation measurement.

The standard deviation in the areas under the curves of local sample points for the unsealed and sealed laboratory shows a reduction of 5:1 at similar mean airchange rates. This is due to the reducing importance of wind induced infiltration air streams, and the increasing importance of smaller natural internal eddy air flows in the sealed building, thus maintaining a more evenly distributed tracer gas concentration.

This implies that in practice, extract fans used to exhaust local areas of air pollutant are less likely to have their performance impeded by wind induced air streams. Also non-exhausted pollutants will mix evenly with the air in the building, rather than develop smaller "clouds" of higher concentration which migrate around the building whilst slowly dissipating.

5. CONCLUSIONS

The reduction in leakage under artificial pressurisation of the laboratory measured of 2.8:1 at 10 to 20Pa produced a reduction of ventilation sensitivity to stack induced infiltration of approximately 2:1. It reduced wind dominated ventilation between 1.8:1 to 3.8:1, dependant on wind direction. The measurement of

mean ventilation rates by the three major techniques available become easier and more repeatable after sealing as natural internal mixing eddies become dominant under the influence of less predominant ventilation pathways. Decay tests, in particular, developed much more even concentrations throughout the building, and the injection of tracer gas by balloon bursting was very successful in providing quick and reliable mixing with the least influence on the ventilation characteristics being measured.

The sealing of the building and removal of dominant ventilation paths implies that localised fanned extract ventilation would be much more effective for the removal of locally produced pollutants within the volume, without considerable dispersal to adjacent areas, subsequent dilution and high residence time.

The degree of leakiness, as well as the size of single-celled buildings has a great influence on the amount of information that can be derived from different ventilation measurement techniques. It may be useful to express the different information levels, available from different techniques, in terms of the infiltration volume throughout they can successfully measure. The larger and more leaky buildings become, the less useful are constant emission and constant concentration techniques without large increases in the power and capabilities of conventional automatic ventilation measuring instruments. Using any tracer gas technique, the larger and leakier the building, the more information is available about relative local ventilation rates, and the more difficult it is to produce mean ventilation rate measurements. Mixing for constant emission tests becomes excessive, or the need for many injection and sample points increases. This also applies to a lesser extent for constant concentration methods. Decay tests become more difficult or time consuming and wasteful of tracer gas, but for larger buildings, a greater amount of more reliable data can be obtained from simpler experiments. (Further work to investigate the usefulness of analysing concentration gradients in decay tests performed in larger leaky building is underway).

6. Acknowledgements

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 11

VENTILATION OF FACTORIES

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1. INTRODUCTION

In factories that are predominantly naturally ventilated, the heat loss associated with infiltration and ventilation can account for a large proportion of the total heat loss.

However, there is very little information available on the ventilation rates that are currently achieved in factories in practice and to what extent ventilation rates can be safely reduced in order to improve energy efficiency.

To provide such information was one of the objectives of the Welsh School of Archtecture's Factories Research Programme.* Part of this Programme is concerned with designing and constructing factories to have lower air infiltration rates in order to reduce energy running costs while at the same time maintaining adequate ventilation for occupants health and safety.

This paper describes a series of ventilation measurements carried out in two small factory units situated on an industrial estate in Newport, South Wales. One of the factories is typical of current design, and the other is designed to be of greater energy efficiency in terms of increased levels of insulation and reduced air infiltration rate. The factories were designed and are owned by the Welsh Development Agency.

The measurement programme was a collaborative venture involving the Welsh School of Architecture (R&D) and British Gas (Watson House).

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*The Welsh School of Architecture's Factories Research Programme consists of a series of Research, Development and Demonstration projects in factories, jointly funded by the Welsh Development Agency, the Energy Technology Support Unit, the Science and Engineering Research Council and British Gas, under the direction of Professor P.E. O'Sullivan

2. EXPERIMENTAL DESIGN

2.1 Description of Factories

Details of the two factories, which will be referred to as Factory 1 and Factory 2, are as follows:

Factory 1: The 'standard design' factory (i.e. designed to Part FF of the UK Building Regulations) (Ref. 1) has a production floor area of 230m^2 and a volume of 1300m^3. The wall and roof construction is of lightweight insulated cladding U-value 0.6W/m^2/°C, with an uninsulated roller shutter loading door. A ventilation rate of 2 air changes per hour was assumed for sizing the heating system.

Factory 2: The 'new design' factory with 'low energy' features, has a production floor area of 160m^2, and volume of 810m^3. The walls are of a solid construction and wall and roof U-values are 0.35W/m^2/°C. Particular emphasis has been placed on designing a relatively 'air tight' construction e.g. by eliminating cracks at wall and roof joints and by fitting a well sealed loading door. A ventilation rate of 1 air change per hour was assumed for sizing the heating system (an assumed 50% reduction from the 'standard design').

The design day heat losses for the two factories are given in Table 1.

Table 1 Design day heat loss (kW) (for an internal/external temperature difference of 20°C)

	FABRIC	VENTILATION	TOTAL
FACTORY 1	11.4	14.9	26.3
FACTORY 2	6.5	5.5	12.0

Figure 1 shows the floor plans of the factories and Figure 2 the site layout.

2.2 Project Objectives

The objectives of the project were as follows:

(i) to determine the infiltration rate of Factory 1 under a range of weather conditions

(ii) to obtain sufficient information for an assessment of the effectiveness of the improved sealing of Factory 2

(iii) to determine the influence of roof vents and sealing of loading bay doors on ventilation and infiltration rates.

2.3 Measurement Programme

The ventilation measurements were carried out by British Gas (Watson House) during one week in March 1984.

Two types of measurement were made in Factory 1 (ventilation rate and air leakage, see below), but only air leakage was measured in Factory 2. Both factories were unoccupied at the time. Factory 1 was heated with temporary electric convectors. Factory 2 required no heating.

The air leakage of a building is much quicker and easier to measure than the ventilation rate. It is simply a matter of pressurising the building to a specified level using a large fan. The flow rate required to achieve the specified pressure is the leakage at that pressure, and the leakage can be considered as an indication of the ventilation potential of the building. However leakage and ventilation rate are not simply related, because the former depends only on the size of the openings, whereas the latter also depends on the position of the openings and on meteorological conditions. Furthermore, to obtain acceptable accuracy leakages have to be measured at pressures which are much higher than those encountered with natural ventilation, which means that extrapolation of flow characteristics is required to relate ventilation rates to leakage. For these reasons the value of leakage measurements alone for drawing quantitative conclusions (as distinct from qualitative conclusions) about ventilation is still open to question. An example of the sort of problem which can be encountered will be seen in Section 4.4.

3. MEASUREMENT TECHNIQUES

3.1 Ventilation Rates

The Watson House "Autovent" system was used to monitor ventilation rates by the constant concentration technique. Although the system was originally developed for multi-cell dwellings, special tests carried out in the present factory and earlier in another building have indicated that it is equally suitable for large open-plan buildings (see Ref. 3 for a description of the system and the tests). Artificial mixing was provided by seventeen desk fans, six of which were placed at high level. The temporary electric fan heaters also enhanced the mixing.

Most measurements were made with N_2O as the primary tracer gas, but in some cases SF_6 was used (with somewhat less accuracy, see Ref. 3).

Internal temperatures, external temperature and wind speed and direction were monitored by the Autovent system. The wind anemometer was situated on a mast at a height of 10m within a few metres of Factory 1. This was some distance from the permanent UWIST weather tower (see Figure 2).

3.2 Air Leakage

Air leakage rates were measured using the Watson House Leakage Tester. This too was originally developed for houses, but it can be applied to larger buildings simply by using more than one unit. Three units were in fact employed to pressurise the factories, as shown in Figure 3.

Each unit consists of a cylindrical duct mounted on large wheels for manoeuvrability. The entrance to the duct is a bellmouth inlet followed in the downstream direction by a "Wilson" flow grid (Ref. 4), a honeycomb flow straightener and a variable-speed axial fan. The unit was specially designed for leakage measurements with the aims of achieving an instrument which could be used by inexperienced personnel, and which gave relatively high accuracy. An important contribution to achieving these aims is the choice of a proper flow measuring device,

rather than simply measuring fan speed. The flow grid has the additional advantages that it is relatively insensitive to upstream conditions, and has a large pressure output and a low pressure loss. The flow rate through the unit is obtained from a calibration curve supplied by the manufacturers.

A maximum flow rate of $1.0 m^3/s$ can generally be achieved, depending on the resistance of the flexible duct used to connect the unit to the opening in the building.

4. RESULTS

4.1 Infiltration rates of Factory 1

Figure 4 shows the infiltration rates measured in Factory 1 in its basic condition (solid symbols) as a function of the half-hour average wind speed $\bar{u}$. The ranges encountered of the average temperature difference ΔT and the wind direction ϕ are respectively 8.6 to 11.1°C and 25 to 90° (ϕ is defined in Figure 2).

The results show that the infiltration rate is strongly dependent on wind speed when it exceeds 2.5 m/s (and $\Delta T < 11°C$). Greater sensitivity is to be expected for wind directions in the range of 340° to 20°, because the north side of the factory is relatively exposed (see Figure 2).

The wind speed is continuously monitored by UWIST on the site and Figure 5 shows the frequency distributuon of $\bar{u}$ over a heating season (1984-85). Using these results it is possible to estimate the average infiltration rate over the period. For wind speeds greater than 2.5 m/s it is assumed that the infiltration rate is directly proportional to wind speed, and for lower speeds it is assumed that the infiltration rate is constant and equal to $1.25\ h^{-1}$. (This latter value is taken as the rate corresponding to a temperature difference of about 10 degrees Centigrade). On this basis, the seasonal average infiltration rate is approximately $1.4\ h^{-1}$, with infiltration rates exceeding $2.0\ h^{-1}$ for approximately 10% of the heating season.

4.2 Leakages of Factories 1 and 2

The leakages of the two factories in their basic form are shown in Figure 6. It is immediately apparent that the leakage of Factory 2 is much less than that of Factory 1, which indicates that the new design has a significantly lower level of infiltration.

It is not possible to evaluate precisely the difference in leakage between the two factories, because Factory 1 was so leaky that an air flow rate Q of $3m^3/s$ only produced a pressure difference Δp of about 6 Pa. Potential errors in Δp are therefore quite large, as indicated by the bars on the results in Figure 6. The uncertainty is mainly due to pressure fluctuations. When the same test was carried out under more windy conditions, a mean Δp of about 10 Pa was recorded, but the uncertainties are much larger and this result has not been included.

Nevertheless it can be said that the basic leakage of Factory 1 is very approximately four times that of Factory 2, and this value can be used for illustrative purposes. By making the common assumption that leakage and infiltration rates behave in the same way and taking into account the different volumes of the two buildings, the seasonal average infiltration rate can be estimated as $0.6\ h^{-1}$. This also assumes of course that the average wind pressure distributions on the two buildings are similar. In view of the similar orientations of the buildings and their surroundings (see Figure 2), this assumption might be reasonable. However, whatever the effect of this, one can still anticipate a large reduction of infiltration heat loss in the new design of factory.

4.3 Sealing loading bay door

In Factory 1 the effect of sealing the loading bay door was investigated with the Autovent system and the leakage tester. Figure 4 shows the substantial reduction in infiltration rate which was observed (~45%). The leakage results in Figure 6 are consistent with this observation, but for the reasons given

above, it is not possible to evaluate a figure for the reduction. It should perhaps be noted that the two results in Figure 6 are consecutive measurements (it took only a few seconds to remove the sealing) in order to minimise errors in their comparison. Visual observation of the door showed a large opening at the top with gaps down the sides and the door itself.

In Factory 2 only leakage measurements were made, but they are much more precise. It can be seen from Figure 6 that sealing the door reduced the leakage at 50 Pa by a small amount (~10%). This confirmed expectations from visual observations that the loading door of Factory 2 was much less leaky than that of Factory 1.

4.4 Effect of roof vent

The measured effect of the roof vent on the infiltration rate of Factory 1 is shown in Figure 7. The results were obtained during a single test period with the vent being open at the beginning and the end of the run. In this way the influence of the changes in weather conditions was minimised. Hence the observed increase in infiltration of 20% should be due solely to the effect of the vent under the prevailing test conditions ($\Delta T \sim 10.5°C, \phi \sim 38°$, $4 < \bar{u} < 6$m/s).

The effect of opening the vent on the leakage of Factory 2 is shown in Figure 6. At a pressurisation of 50 Pa there is an increase of approximately 12%. One would expect the percentage to be larger at the lower pressures, but this is difficult to detect in the results due to scatter in the measurements. This scatter is particularly significant, because we are dealing with the small difference of two large flow rates.

The different types of result obtained in the two factories are of interest, because the roof vents are nominally identical. Bearing in mind that Factory 1 is much leakier than Factory 2, one would expect the effect of the roof vent on the leakage of Factory 1 to be much less than 12% (the value observed in Factory 2). A value of less than 5% is probably to be expected, yet the observed effect of the vent on infiltration rate is much larger than this (20%). There are two likely explanations for this.

The first is that the flow characteristics of the vent and the remaining (adventitious) openings are considerably different. The vent will tend to follow a simple square law so that its relative contributions to the total flow will be greater at the lower values of Δp.

The second explanation is that the air vent is situated in a position which will maximise its effect on infiltration i.e. high negative pressures due to the wind (for all wind directions) and maximum height for buoyancy. The effect on leakage is of course not dependent on the wind or buoyancy.

It would seem therefore that the results are a manifestation of the importance of the leakage distribution to the determination of ventilation rate, at least as far as air vents are concerned. The results lend support to the arguments for treating air vents separately in prediction methods (even single-cell methods) as discussed in Reference 5.

5. DISCUSSION

Referring to the objectives of the ventilation measurement programme outlined in Section 2.2, the following has been achieved:

(i) The infiltration rate of Factory 1 has been measured under a limited range of weather conditions. The first objective can never be completely satisfied because of the wide range of possible weather conditions and the limited period over which it is practically possible to carry out the measurements. Nevertheless with modest temperature differences it has been established that wind speed is an important determinant of the infiltration of Factory 1. It is a pity that the wind direction did not change more during the measurement period because the directions of greatest influence were probably not experienced. The estimated seasonal average infiltration rate is 1.4 h^{-1}, and it can be deduced from Figures 4 and 5 that rates in excess of 2.0 h^{-1} can be expected to occur only about 10% of the time. The design value of 2.0 h^{-1} used by the

Welsh Development Agency for sizing the heating system is thus not unreasonable.

(ii) The overall effectiveness of the improved sealing of Factory 2 has been assessed from the ventilation measurements carried out in both factories. The leakage measurements indicate that the improved construction of Factory 2 has been very effective in reducing leakage. It is not possible to state accurately the reduction factor for the leakage, and there are greater uncertainties about the reduction of infiltration rate. It does however appear possible that the seasonal average infiltration rate for Factory 2 is about 0.6 h^{-1}. If so, the design value of 1.0 h^{-1} used by the Welsh Development Agency for sizing the heating system is again not unreasonable.

(iii) The influence of components, i.e. roof vents and loading doors, on the overall ventilation and infiltration rates has been measured. Much but not all of the reduced leakage is probably associated with the improved loading bay door. Complete sealing of the door in Factory 2 almost halved the infiltration rate, but it was not possible to determine accurately the effect on the leakage. This is unfortunate, because there is evidence from the observed effects of roof vents that changes in leakage and infiltration are far from identical. When assessing the cost-effectiveness of a sealing measure it is the reduction of infiltration rate which is important. Thus it is possible that the improved loading door of Factory 2 is much more cost-effective that the other sealing measures applied. This would certainly seem to be the case for Factory 1, because the cost of sealing the loading door would probably be much smaller than the cost of reducing the infiltration rate by sealing the fabric. One reason for this is simply that there were very obvious gaps in the door but no obvious gaps in the remaining fabric of the building.

6. CONCLUSIONS

6.1 The seasonal average infiltration rate of the standard design of factory (Factory 1) has been estimated as 1.4 h^{-1}. Infiltration is sensitive to wind speed and rates as high as 2.5 h^{-1} can be expected at wind speeds of about 6 m/s, but only infrequently. In view of this, the design value used by the Welsh Development Agency for sizing the heating system (2.0 h^{-1}) is not unreasonable.

6.2 The improved construction (see 2.1) of the new design of factory has been very effective in reducing the leakage. The reduction of infiltration rate has not been measured, but a very approximate estimate of the seasonal average infiltration rate of Factory 2 is 0.6 h^{-1}. This suggests that the design value of 1.0 h^{-1} used for sizing the heating system is also not unreasonable.

6.3 Sealing the loading bay door of Factory 1 reduced the infiltration rate by 45% and is potentially a very cost-effective measure. The gaps in this door were visually obvious, but the remaining gaps in the fabric of the building were not and effective sealing of them is probably more difficult.

6.4 There is evidence that the effect of a roof vent on infiltration rate is much larger than its effect on leakage. For Factory 1 the ventilation rate was increased by 20% whereas the estimated effect on leakage (at high pressure) is less than 5%. Thus although leakage measurements are much easier than ventilation measurements, care is needed in their interpretation. The basic reasons for this are given in Section 2.3

7. IMPLICATIONS

7.1 It is possible to successfully carry out ventilation measurements in factories of the size and nature as described in this paper using the Autovent technique.

Corresponding air leakage measurements become more difficult, in terms of maintaining accuracy, as the factory becomes relatively 'leaky'. To maintain the same level of accuracy in Factory 1 (a 'leaky' factory), as in Factory 2, air flow rates of up to $9m^3/s$ (3 x the current equipment maximum) would be required. This would mean either more fans or more powerful fans, both options involving practical implementation problems.

7.2 Large reductions in air infiltration rates can be achieved by using 'high performance' components e.g. well sealed loading doors. This information is important when designers are considering ways of reducing air infiltration. It is easier to specify a high performance component than it is to design an 'air-tight' construction.

7.3 With reduced infiltration rates adequate ventilation can be achieved by natural leakage together with a single roof ventilator, for factories occupied by light-engineering/service industry firms. During the summer ventilation rates can be increased by opening the loading door. For processes that produce excessive levels of heat/pollutants in winter and/or if the loading door cannot be left open in summer, then additional ventilation must be provided either naturally, using increased vent areas, or mechanically. It also important when using direct fired gas systems to comply with the regulations (UK Standards, BSI - BS5440) with regard to the provision of permanent ventilation.

7.4 It is important to differentiate between values of air change rate used to size heating systems and those used to calculate seasonal energy targets. Results indicate that the seasonal average infiltration rate of the factories is between 60 and 70% of the design value.

7.5 Care is needed when drawing conclusions about ventilation rates from leakage measurements alone. For acceptable accuracy it might be necessary to take account of additional factors, such as wind pressures.

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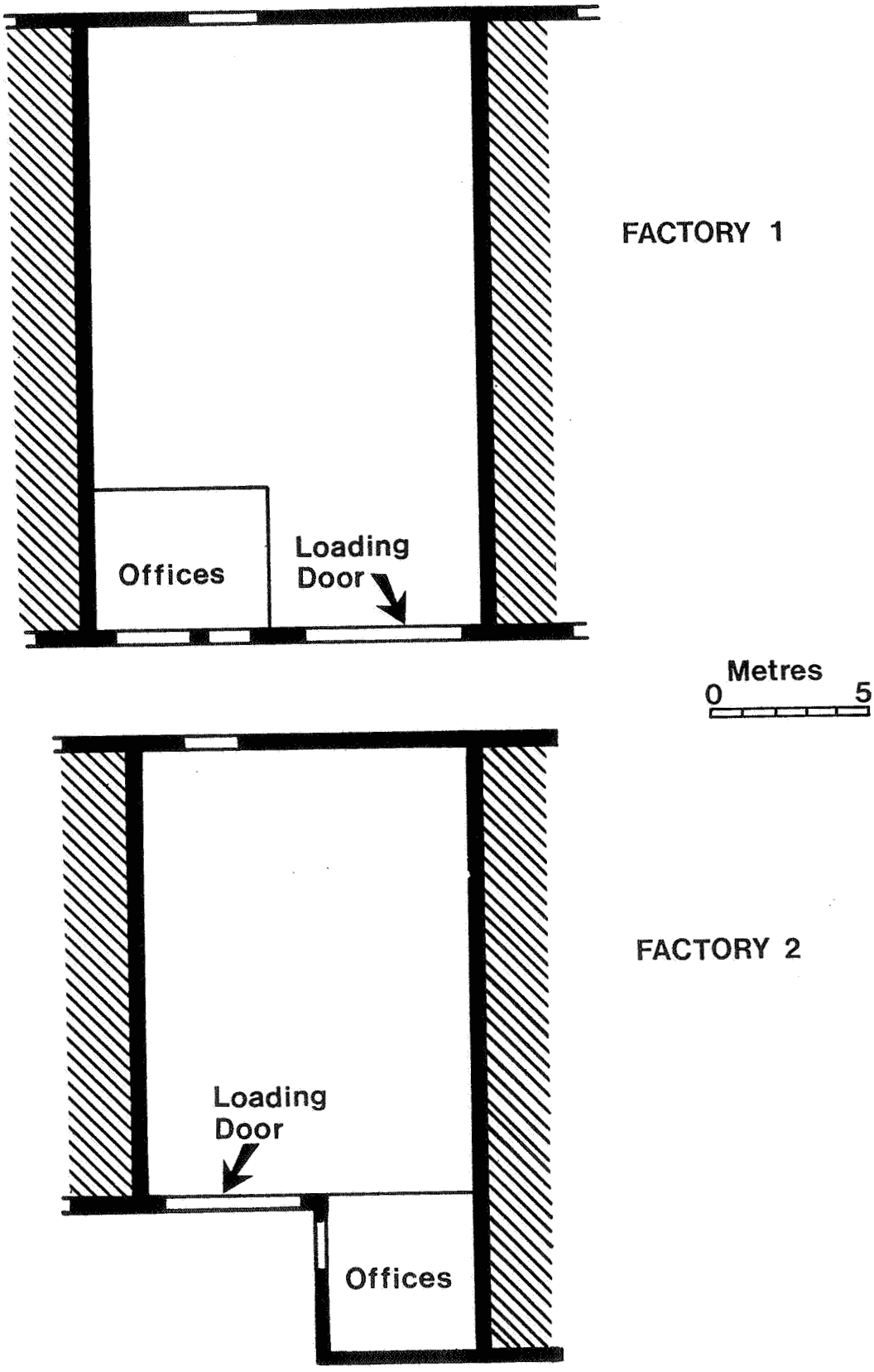


FIG. 1 FLOOR PLANS OF FACTORIES

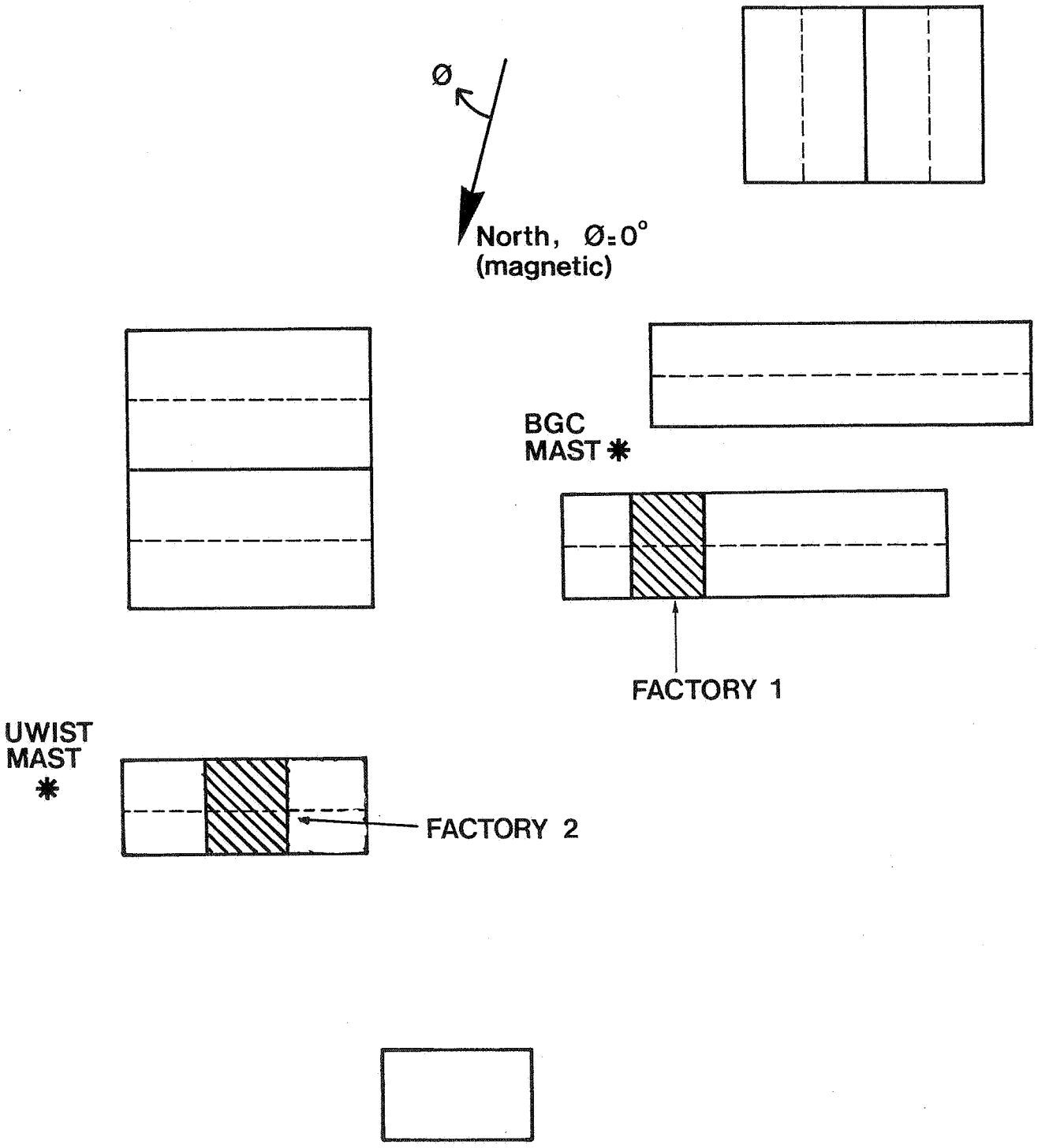


FIG. 2 PLAN OF SITE

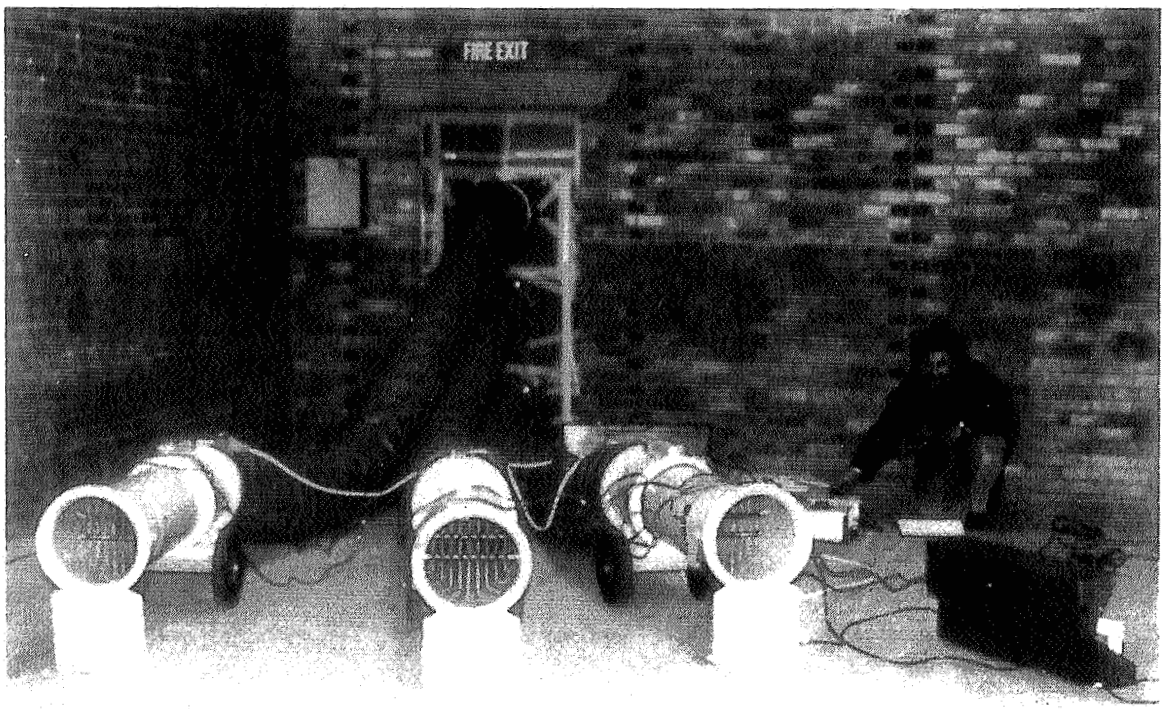


FIG. 3 LEAKAGE MEASUREMENT IN FACTORY 2

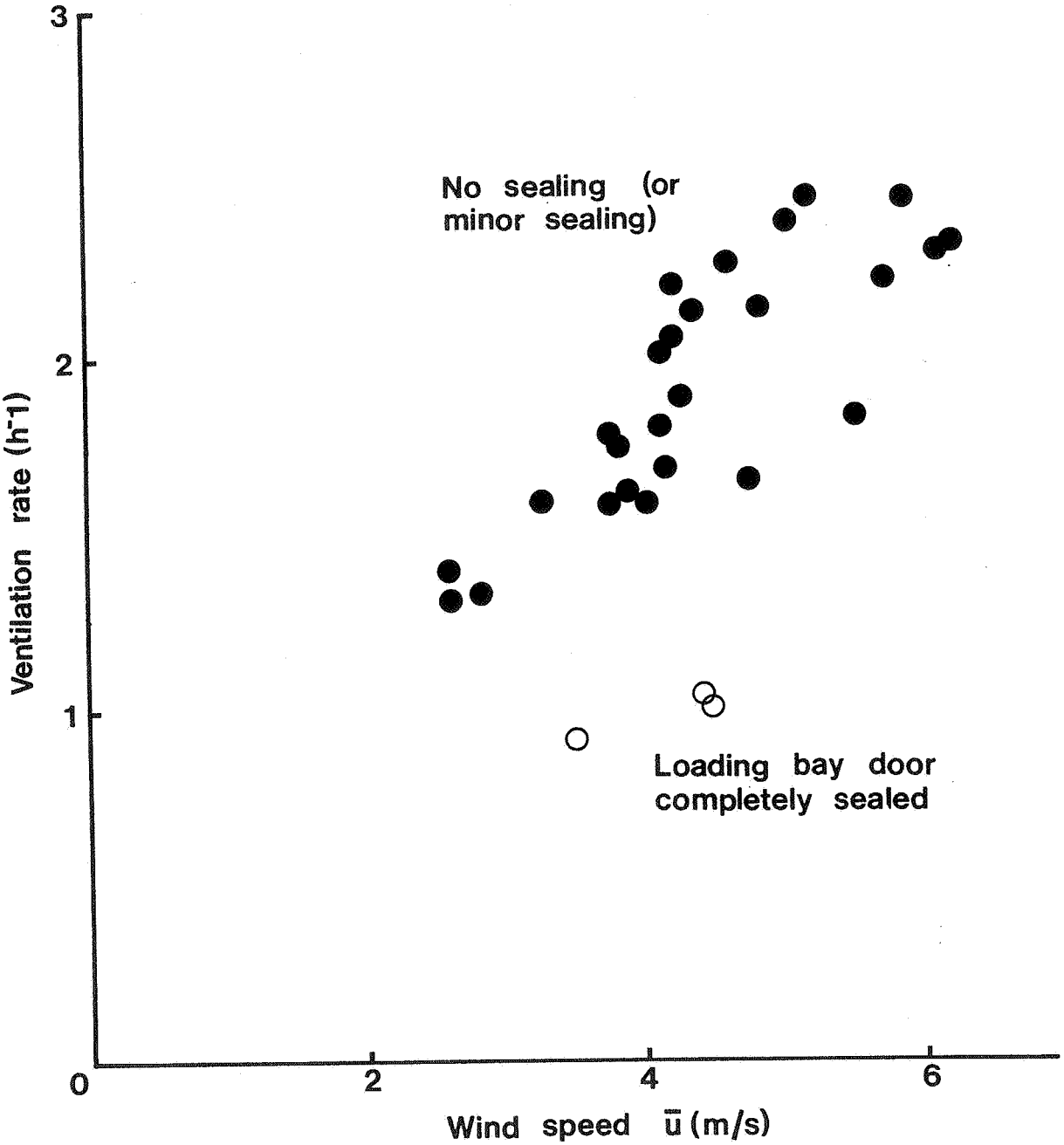


FIG. 4 MEASURED EFFECT OF SEALING LOADING DOOR OF FACTORY 1

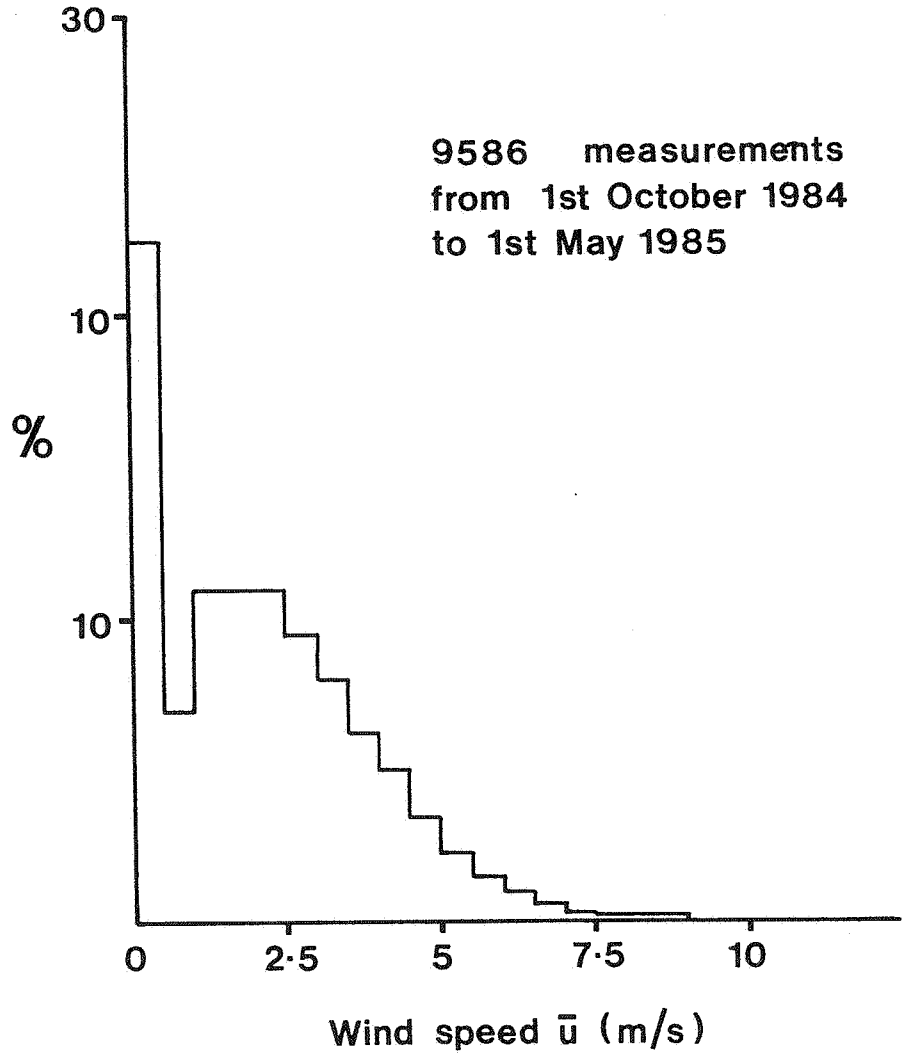


FIG. 5 FREQUENCY DISTRIBUTION OF HALF-HOUR AVERAGE WIND SPEED

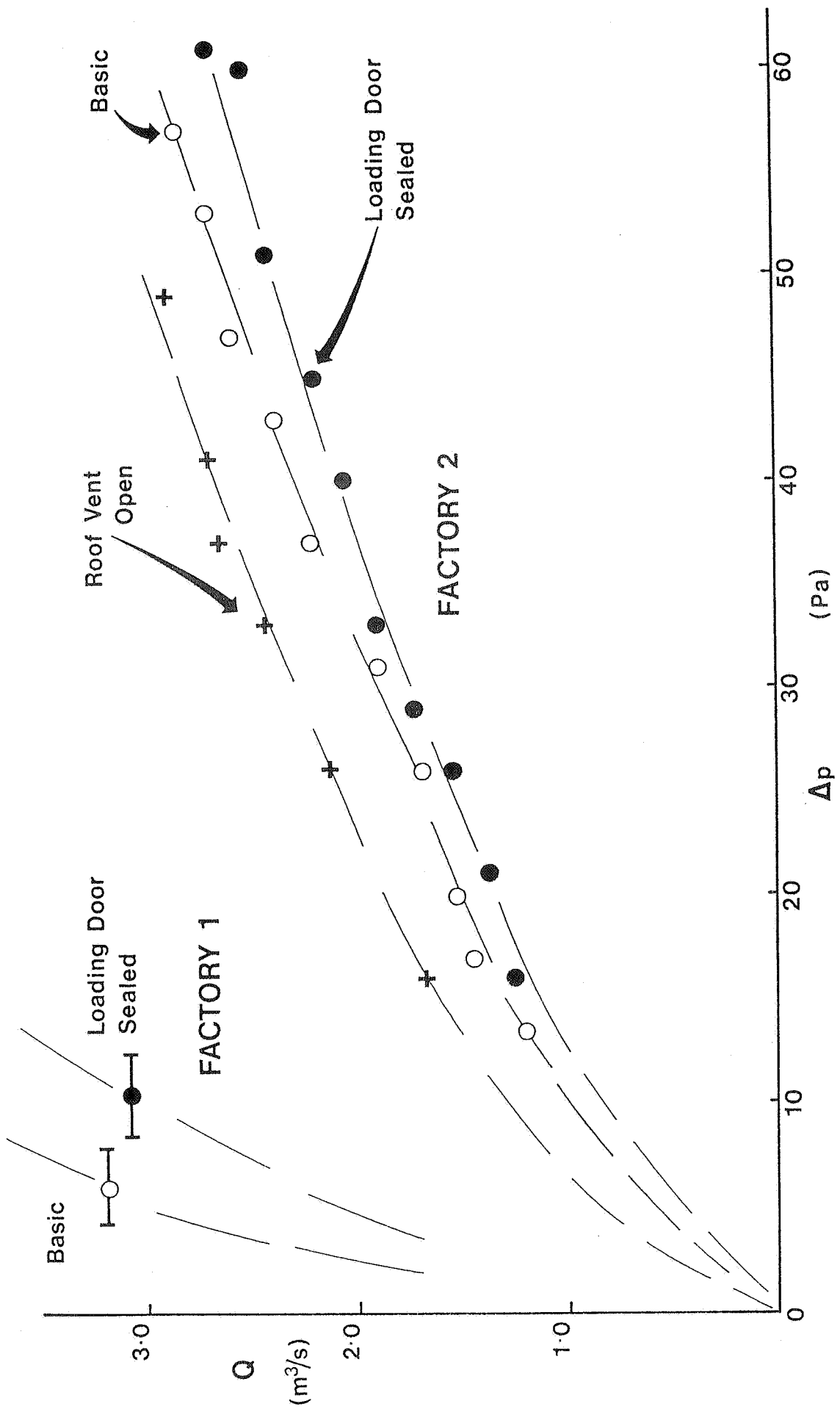


FIG. 6 AIR LEAKAGE OF FACTORIES 1 & 2

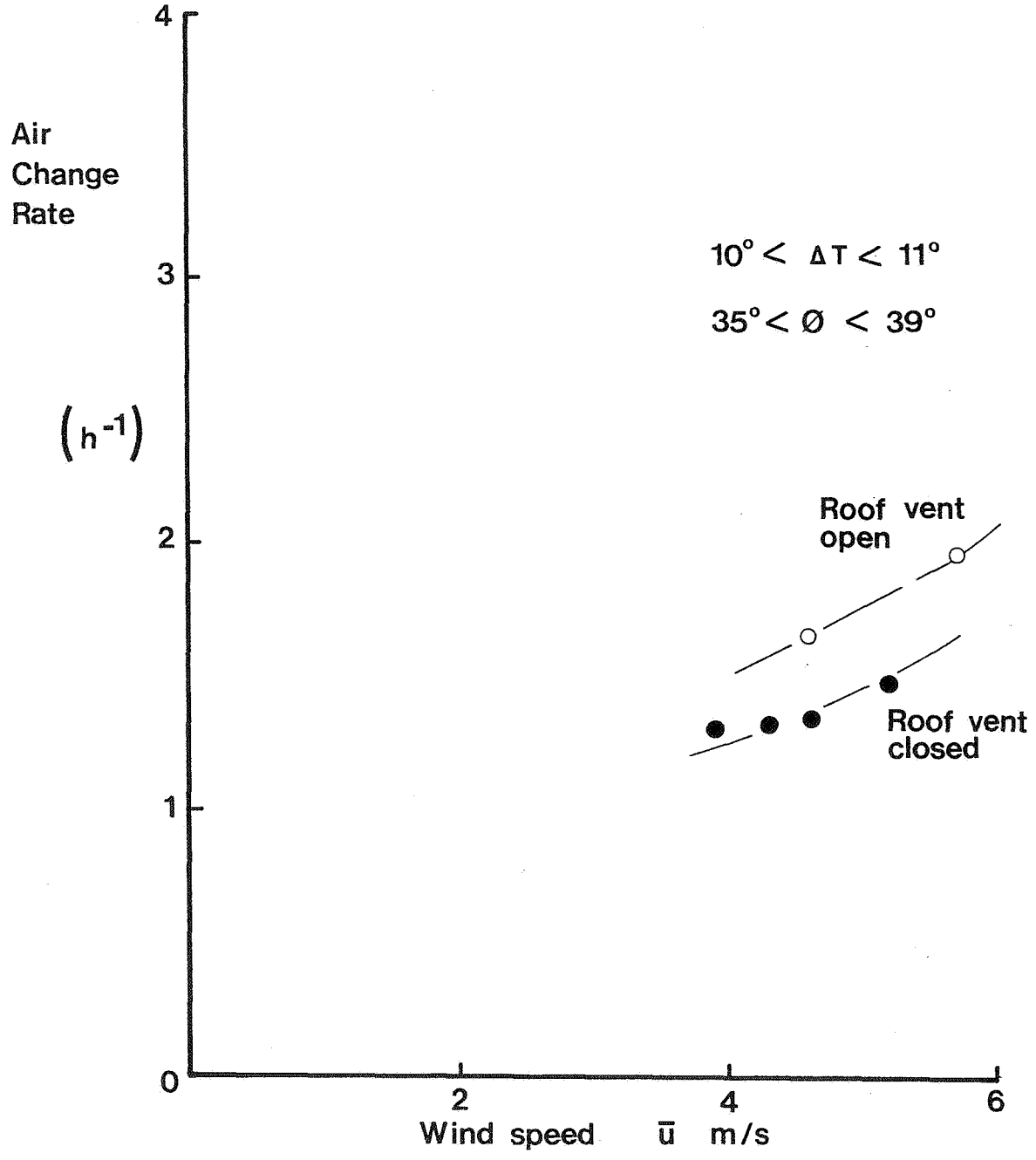


FIG. 7 EFFECT OF ROOF VENT ON AIR CHANGE RATE OF FACTORY 1

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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PAPER 12

ADVANCED ENERGY-EFFICIENT VENTILATION

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SYNOPSIS

It is often stated that advanced ventilation or air conditioning is expensive or energy-wasting. There are, however, several examples of highly energy-efficient air conditioning systems in industrial, commercial and public buildings.

Energy-efficiency can be achieved by
- optimizing air flows or demand-controlled ventilation
- avoiding simultaneous heating and cooling (except if "free")
- advanced automatic control system
- good operation and maintenance

The performance of ventilation and air-conditioning depends on several factors in the building process. The most important one is the "end user": inhabitant or other occupant. We should build ventilation for ordinary people who also should know what to require. Of course there are several persons or bodies who are responsible of the result: the owner of the building, the builder, the designer, one or several contractors and the maintenance personnel. If the end users become more aware of the elements of good indoor air and learn to require it, then it is obvious that the quality of ventilation systems will be improved.

1. INTRODUCTION

If we study the history of ventilation, e.g. (1), we learn to know that our indoor environment has almost continuously improved. The most recent exception has its origin in the energy crisis in 1973 and in addition to reductions in air flows the outdoor air quality deteriorated and new building and furnishing materials were taken into use. These all have caused general deterioration in indoor air quality. As there is no return to "good old times" we have to face greater challenges than ever before. "Natural" or "passive" ventilation alone is simply not able to meet today's requirements for indoor air quality and thermal comfort.

Many recent complaints make it necessary to study the history of ventilation more closely. In fact man started to make buildings some 9000 years ago in order to create an "artificial indoor climate". (And not for example in order to build "masterpieces of architecture", which came much later and has been until recent times a privilege of the rich. Before the industrial revolution, and in the developing countries even today, the great majority lived in extreme poverty.)

The so-called natural ventilation was a functioning ventilation system when it was connected to (or systematically integrated in) heating with local or large central fireplaces. The latter was generally a warm-air heating system introduced

in ancient Rome and widely applied in e.g. Finnish public buildings in the end of the 19th century. In warmer climates as in the Middle east many cooling systems were also constructed in earlier times (1). Earlier dwellings were generally heated by an (more or less) open fire but later on fireplaces were built with chimneys and a separate exhaust air duct was also introduced in the 17th century.

In the beginning of this century central distribution of heat with steam or water radiators began to gain popularity. Heating and ventilation were separated and the natural stack ventilation lost its main driving force.

2. IS GOOD INDOOR AIR EXPENSIVE

Everything is either expensive or cheap. But if we keep in mind that we build for indoor air it is not expensive.

The costs of HVAC (total) is about 15 % of all construction costs - respectively for air conditioning the cost is about 1 to 4 per cent.

The annual running costs of air conditioning (energy, operation and maintenance) are for an average office building about the same (per person) as the pay for a few working hours (indeed, not some working days or weeks).

We have for too long been calculating only the energy efficiency ignoring the influences on indoor air.

3. CAN WE BUILD ADVANCED ENERGY-EFFICIENT SYSTEMS?

Energy-efficiency is, in any case, necessary. Yet it is never an excuse for reduced air quality. There are cases where good indoor air quality has been achieved with very low energy costs but also cases where "energy-saving" has caused even health hazard.

Generally, mainly due to administrative problems, the intended performance is not completely achieved.

Some actual cases of high energy-efficiency are worth presenting:

1. Headquarters of an insurance company in Helsinki. Renovation of old part using induction units plus heat recovery. New adjustment of air flows. Reduction in energy consumption from 43 to 30 kWh/m^3a. Extension of the building was equipped with VAV system, exhaust air windows and heat recovery. Heating plus cooling energy consumption is below 10 kWh/m^3a.

2. Office buildings in Helsinki. In the care of a (today exceptionally) skilful maintenance company, newbuildings

provided with heat recovery have generally a very low energy consumption, between 19 and 30 kWh/m^3a.

3. Headquarters of a data processing company. Heat loads from computers require cooling almost around the year in daytime. Cooling is, except in summer, possible with outdoor air and variable air flows. This requires very good control systems as parts of the building should be heated in wintertime - and the whole building during the night and during weekends.

   Energy consumption is about 20 kWh/m^3a and could be reduced - e.g. for a planned extension no increase in heating effect will be necessary. Zero energy building cannot be constructed economically (requires heat pumps, thermal storage, additional control systems).

Results should be compared with the fact that the average energy consumption in fairly new office buildings was two-three years ago about 60 kWh/m^3a. Wrong measures (minimized outdoor air - maximal recirculation...) may result in low energy consumption but also in serious complaints - even in the "sick building syndrome".

4. ELEMENTS OF ADVANCED SYSTEMS

"Timing" of air conditioning: the full capacity is used during the hours of occupancy. For example in office buildings this generally means separate ventilation plants for space with exceptional occupancy (restaurants, ground floor shops etc.). Problems occur if the ventilation system is turned on right in the beginning of office hours. To avoid e.g. odour problems, it should start to run at full power at least one hour before.

Varying air flows according to actual demand: this demand can vary a lot because of cooling loads or air pollutants. VAV-systems (variable air volume) are common and a new approach is the CO_2-controlled ventilation. Individual control of one's indoor environment in large spaces is still to come (in fact, new applications of air diffusion are necessary) but it will be a success because of its great psychological effects.

Heat recovery from exhaust air is, at least in Nordic conditions generally very economical in large buildings. In addition to its importance in energy saving it should be pointed out that heat recovery also cuts the peak loads in heating plants, i.e. initial costs, space requirements - even power plants.

To understand the principles of automatic control is necessary. Unfortunately we often concentrate in how to control, not what or why - we overlook the actual demands or look only at the control components.

Recirculating or use of return air is very common and has a reputation of an energy saving measure. However, are we aware

of its disadvantages. (Who would like to use waste water again!!)

5. THE BUILDING PROCESS: CHALLENGES

Good indoor air is possible only with careful design, construction and commissioning. And, of course, only with planned and and systematic maintenance can the ventilation plant serve its users for the whole lifetime of the building, see e.g.(2).

The building process is not the same in all countries but similar problems may occur everywhere. Maybe everyone will find familiar "threats" in this Finnish example; it should be kept in mind that all the problems presented here can be avoided.

1. Objectives are not clearly determined. Do we want ducts and devices only or do we want certain indoor climate? We may agree that we want good indoor air but what is good indoor air? To find out the right characteristics of our indoor environment is the most important task in improving the reputation of ventilation! When we know what we want then it will be easier to get and also have a guarantee for it! Best examples of good ventilation are presented in industrial processes where the consequences of failures can be seen immediately.

2. The builder or the owner is not generally the "end user" of the building. If the end user does not have any specific requirements, the builder aims to minimize the initial investment costs.

3. Design: Good design is not good business if a cheap and less qualified designer gets the job. Maintenance planning is seldom included in today's design practice. Again the best examples come from industrial processes where good performance is necessary and where the end user has set his requirements clearly and is prepared to pay for good design.

4. Construction: The ventilation contractor generally gets his job by making the cheapest final offer; it is very common during construction to change equipment, materials and installations to cheaper ones in order to get better profit. The lack of proper control of workmanship and problems in keeping schedules are also hazards for gaining a proper functioning.

5. Commissioning: The time reserved for testing and adjusting the ventilation system is often too short. The control of the commissioning process is often completely neglected. In most cases the ventilation system is not completely "finished" when the occupants move in - ventilation becomes easily a scapegoat.

6. Operation and maintenance: In addition to neglected maintenance planning, difficult access to the ventilation plant and lack of skilful maintenance personnel is common. The owner of the building (who seldom is the end user) is not often prepared to pay for professional maintenance.

The ventilation problems, though common, are usually not serious (2). In Nordic countries the mechanical ventilation system is in very few cases the main reason to the so-called "sick building syndrome". For example in Finland with about 50.000 newbuildings every year and a stock of about one million buildings local health authorities have a few thousand complaints per year. A majority of these complaints concern formaldehyde - only a few hundred ventilation, in most cases the closing off of mechanical ventilation in blocks of flats.

It is, however, necessary to make strong efforts in order to avoid also the minor problems because every complaint has negative consequences as to comfort and productivity.

The philosophy behind the indoor air classification as a tool to present various objectives is presented in Fig. 1, (3).

How to avoid problems in construction process? In addition to technical development based on research work correct information is necessary. Owners, users etc. of buildings should, all become aware of the great importance of good indoor air.

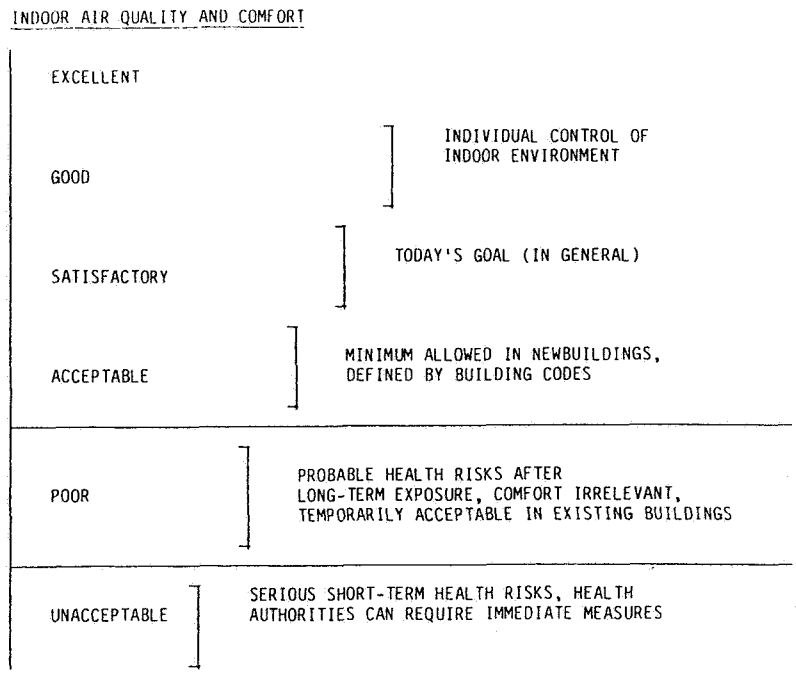


Fig. 1. Indoor air classification, principle

6. DEVELOPMENT IS NECESSARY

One chance, in addition to the clear objectives, is to develop a standard procedure for calculating the total costs of ventilation / air conditioning. Some ideas appear in e.g. ASHRAE Handbooks where also a method for system analysis has been presented, (4).

To analyze various alternatives for ventilation to a newbuilding only a small proportion of the total performance can be described in exact mathematical terms. All decisions must be made on certain "less scientific" estimation. Buildings are different, people are different!

These differences give the key to all system and product development. Individual control of one's own indoor environment has a great positive psychological effect. The simplest method is an openable window, almost as easy is to give everbody an individual room thermostat. The ventilation system should be designed so that one's individual ways of control is possible without disturbing the rest of the system! Most difficult it is in large spaces, e.g. landscape offices.

7. EXAMPLES OF AIR QUALITY CLASSIFICATION

It is important to give the owner (or the end user) of a building several alternatives of indoor air and ventilation so that he knows what he wants and what he gets, as was presented in Fig. 1.

The characterization of various "classes" for each parameter is not an easy task. We must again keep in mind that people are different - there will never be one certain indoor climate which is suitable for everyone. So, the degree of individual control of one's own indoor environment is a good parameter itself.

We are not prepared to present a complete list of indoor air classification - but we should at least give some examples to start the discussion.

Air temperature is one of the most important parameter. There is also some knowledge of its influence on comfort (or even on human productivity). Air velocity is a key parameter of draught. Air humidity is also important but there is no universal agreement concerning its effects on health and comfort. Concentrations of several pollutants shall be limited but here we must realize the difference: some people tolerate much higher concentrations than others.

An example on the characteristics and recommendations on air temperature, and formaldehyde concentration is presented in Table 1. Remember, this is no final suggestion, just one

possibility to discuss. Similar classification shall include all important parameters: air velocity (draught), noise level, humidity and its control, radon concentration, particles, odours etc. The recommended values can vary in different countries due to e.g. weather and building traditions.

8. SOME REMARKS CONCERNING EXISTING BUILDINGS AND RENOVATION

It is often said that natural ventilation should be used even in newbuilding, especially in housing, as well as in all building renovations. These statements have generally pointed out the trouble with and risks of today's mechanical systems, yet without understanding the history of natural ventilation as part of a fine integration: structure - heating - ventilation, which could work without mechanical forces, (1).

With today's higher requirements for air quality and working efficiency, higher rates of automation, declining outdoor air quality and central heating systems etc., it could be easily testified that it is uneconomical, if not impossible, to meet those requirements with pure natural ventilation. Of course we must avoid destructing old fine interiors but we still must keep in mind that buildings are made for people.

So, a good indoor environment is necessary even in old buildings. To guarantee this and to respect the "spirit of old architecture" simultaneously requires more skill than newbuilding. Some measures in ventilation systems are in most cases necessary because of several reasons:

Improved airtightness. Additional insulation, and especially the vapor barrier, makes the building envelope more airtight. In order to avoid draught, the windows are often re-sealed. In natural ventilation, improved airtightness always means a reduced air change rate and need for new supply air arrangements. In a mechanical exhaust system, these arrangements are needed as well because of less efficient ventilation the so-called "bedroom problem". The air always finds the easiest flow routes!

Removal of old local fireplaces. The integration of heating and ventilation (see the introduction) is broken if the old fireplaces are removed. Central heating with water radiators causes, of course, less work and is more comfortable, but who has paid any attention to the other part of this integration? The exhaust air ducts have often been closed off and even the still existing ones have lost most of their driving force previously created by the warm adjoining chimney.

Closing off the supply air vents. Vents in outer walls were earlier common as the supply air parts of natural ventilation. But since they are draughty in winter, the closing them off was a very natural consequence, leaving infiltration and airing the only ways of getting supply air in.

New building and furnishing materials (especially taken into use in renovations): The best-known of the several consequences is the increased emission of formaldehyde.

Changed usage or layout of rooms. This means almost always increased need for ventilation. In central Helsinki, for example, many dwellings have been changed into offices. A large room may have been divided into four small offices - three of them without any ventilation arrangements.

Modern working environment. This change often goes together with the previous one - more people, more machines. But increased office automation in itself has increased the load. In addition, the emissions from copying machines etc. must be taken into account.

Closed, leaky or otherwise useless ducts. The old ductwork, mainly masonry, may have been deteriorated in the course of time. E.g. during radical changes in usage (from residential to commercial) of a flat, many old ducts may have been cut off.

Deteriorated outdoor air quality. Most of the old buildings equipped with natural ventilation (except for the majority of one-family houses) are located in urban areas with highly polluted outdoor air. Therefore, air supply arrangements often must include air filtering and also noise reduction, which increase the flow resistance so that natural ventilation hardly can work properly under any conditions. In city centers, air intake from street facades should prefarably be completely avoided.

Increased energy prices. There is no return to cheap energy, and the health aspects do not allow any further reduction in ventilation rates. In the Nordic climate (and maybe also in milder climates), a good indoor air quality can be guaranteed in an energy-efficient way only if the ventilation is controlled and if heat recovery is included in the system.

Neglected maintenance. According to (2), up to 90 % of ventilation plants have lost some of their capacity in the course of time, mainly due to lack of maintenance.

As a summary, we shall again look at Fig. 1. Due to several reasons mentioned above, indoor air in existing buildings is often poor which can only be temporarily acceptable.

Before starting building renovations, a careful analysis must be carried out, with examining both the existing structures and building services (e.g. pressure tests of the ductwork), and the demands of the planned use of the building after renovations (generally various alternatives are to be evaluated).

The following two ideas are being developed and tested. They represent well today's efforts to make simple but efficient

improvements in existing buildings. Both can also be equipped with heat recovery, though the former only with exhaust air heat pump.

Low-pressure exhaust air ductwork. If the existing ductwork does not have any major leakages or if the leakages can be easily repaired, there is a simple and cheap way to convert the system into mechanical exhaust, as shown in Fig. 2.

Small ventilation units. In this alternative, further technical development is still needed, e.g. for small standard packages to serve a flat or a group of rooms. This kind of package, generally equipped at least with air filter, noise reduction, heating coil and fan can be integrated for example with an ordinary airing panel.

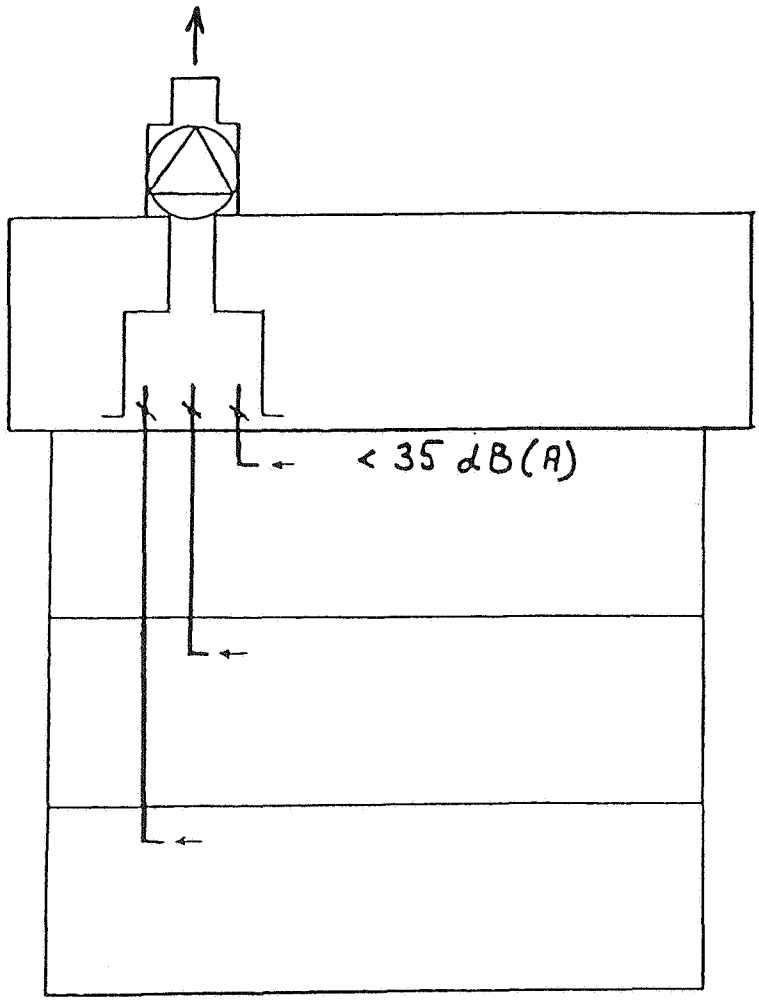


Fig. 2 Simple mechanization of natural exhaust. Existing ducts are cut and provided with adjustable dampers. An exhaust fan is installed and the new ductwork is provided with noise reduction.

It is possible to combine natural and mechanical ventilation, e.g. by installing a small ventilation unit for one room or for

one flat. If this unit has both supply and exhaust fan with (appr.) equal air flows, it can work under appropriate pressure conditions without disturbing the natural exhaust. But if exhaust only is applied, the natural exhaust ducts act as supply air ducts spreading e.g. odours from toilets when the kitchen hood fan is on! In that case serious problems can be avoided by using one-way dampers.

9. MUCH DEPENDS ON WHAT THINGS ARE CALLED

Many investigations are being made concerning the performance of natural ventilation though it has been, in many cases, testified that a good indoor air quality cannot be maintained with pure natural ventilation in a controlled and energy-efficient way. Some people still like it simply because it is called natural - something beautiful, something "green".

Mechanical ventilation has a more negative sound - especially because several indoor air problems and "sick building" complaints are connected to mechanical ventilation (which in fact is a minor cause for problems, though there is much to improve in ventilation only).

A more correct classification would be the following one, already used in some AIC papers:

- active systems: both air supply and exhaust controlled (e.g. air conditioning system in general)
- semi-active systems: supply or exhaust controlled (e.g. mechanical exhaust ventilation)
- passive system: neither supply nor exhaust controlled (e.g. natural stack ventilation)

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3. Railio, J., What is good indoor air - can we build and maintain it? EUROVENT General Assembly 1985, Helsinki, 6-7 June 1985.
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TABLE 1

INDOOR ENVIRONMENT CLASSIFICATION

	ACCEPTABLE	SATISFACTORY	GOOD
Objective	Serious problems shall be avoided. Ventilation shall be designed so that not more than 20 % of occupants can be dissatisfied in each parameter. Short-time dissatisfaction can be accepted (e.g. during high thermal load)	The percentage of dissatisfied will be limited as low as possible, the upper limit is generally 10 %. Efforts in limiting short-time dissatisfaction shall be carried out.	All indoor parameters are controlled so that comfort and productivity will be improved. The objective is that everyone will be satisfied. Also short-time dissatisfaction will be avoided.
Explanation (room air temperature as an example)	Winter temperature set-point is generally between 20 and 22 °C (with certain exceptions depending on the character of activity). No special limitations in summer indoor temperature though the highest outdoor air temperature shall not be exceeded by more than 5 °C.	Winter temperature set-point is selected carefully regarding the activities, generally 20-24 °C. High fluctuations shall be avoided and the summer maximum indoor temperature is related to outdoor temperature.	Each occupant shall be able to adjust his indoor temperature around given values within a range ± 2 °C.
(formaldehyde concentration as an example)	0,15 mg/m^3	0,1 mg/m^3	0,05 mg/m^3

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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PAPER 13

DESIGN FOR VENTILATION

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1. Introduction

Energy is used in buildings to provide a suitable environment for the processes carried out within their confines and to prevent deterioration of the fabric. In most cases the former means the provision of a satisfactory working environment for people, and the latter avoiding condensation. Thus it is usual (in the UK) to provide heating in winter and means of excess heat removal during the summer months. In addition, care must be taken to ensure adequate ventilation to remove excess moisture (and other internally generated pollutants) during the heating season and while this is of great importance, it will not be discussed any further here. This paper is concerned with the removal of excess heat.

The means taken to avoid excessive internal temperatures depend upon the form of the building, the surrounding environment (noise, atmospheric polutants) and the rent that can be charged. If the latter is excluded then the design process usually involves an assessment of the need for air conditioning or put another way the risk of high internal temperatures for a significant portion of the year. The common term for this is 'calculation of summertime temperatures', and a procedure is described in Section A8 of the IHVE (Now CIBSE, Chartered Institute of Building Services Engineers) Guide[1]. This method employs the concept of admittance[2] to represent the dynamics of the building fabric (for those unfamiliar with the method it is based on representing the response by the first term of a Fourier Series), together with an estimated air change rate. The type of result that can be obtained for a single room is shown in Figure 1, where a limit condition is reached at a fairly low number of air change rates. Thus if, as in this example, the designer can be sure of obtaining a minimum of 5 air changes from natural ventilation, then he can be reasonably certain of limiting the internal temperature to a maximum (depending on orientation and shade) of 4°C of the external. This leaves two questions:

(1) How can the minimum air change be guaranteed?

(2) What is an acceptable maximum internal design condition?

The usual answer to (1) is an open window will ensure at least 5 to 10 air changes, and to the second not more than (say) 3°C above the surroundings. These responses may well be correct but they will probably not satisfy a

fastidious client who will demand a more rigorous treatment. This Paper shows how one practice has approached the problem of designing two rather unusual naturally ventilated buildings. The first (see figure 2) is a deep plan office block located at Basingstoke and the second (Figure 3) an exhibition centre at Liverpool.

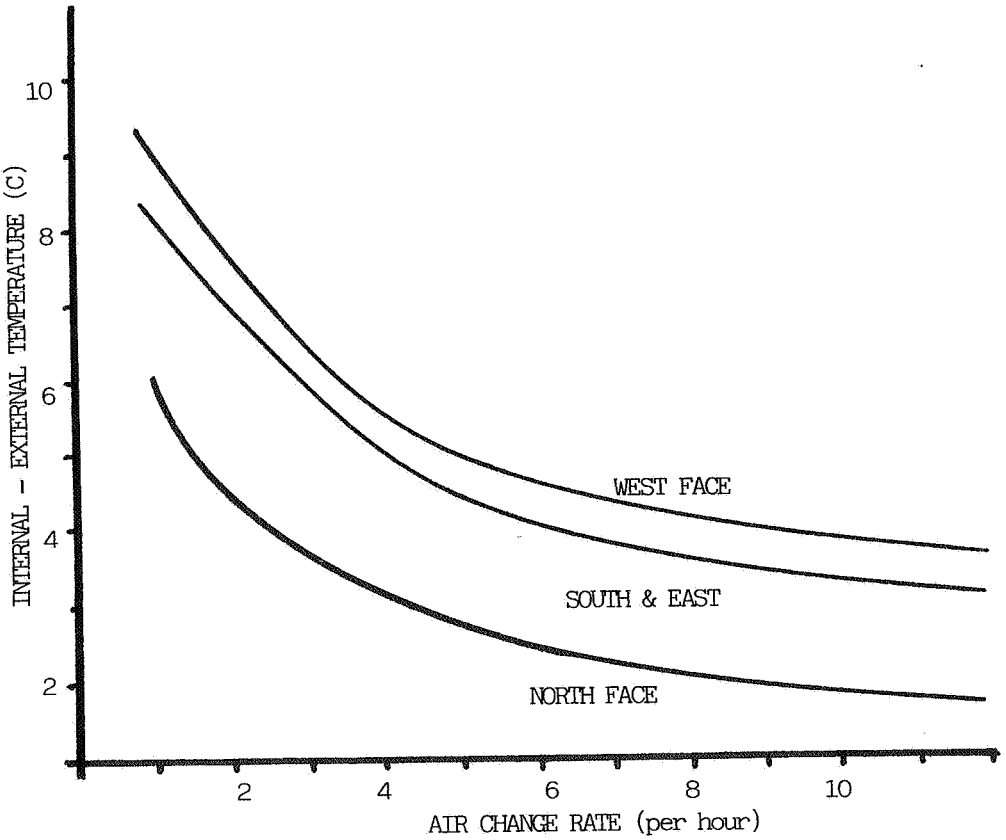


FIGURE 1. SUMMERTIME TEMPERATURE CALCULATION.

2. The Deep Plan Building

This building was to be constructed adjacent to the client's existing office premises, and be occupied by the staff of that building. The current building was to be let. In addition the client was very interested in energy conservation, having won a prize for achievements with the present air-conditioned office. Thus the major constraints on the new building would be low energy, and the capability to house the existing staff.

FIGURE 2. THE DEEP PLAN BUILDING

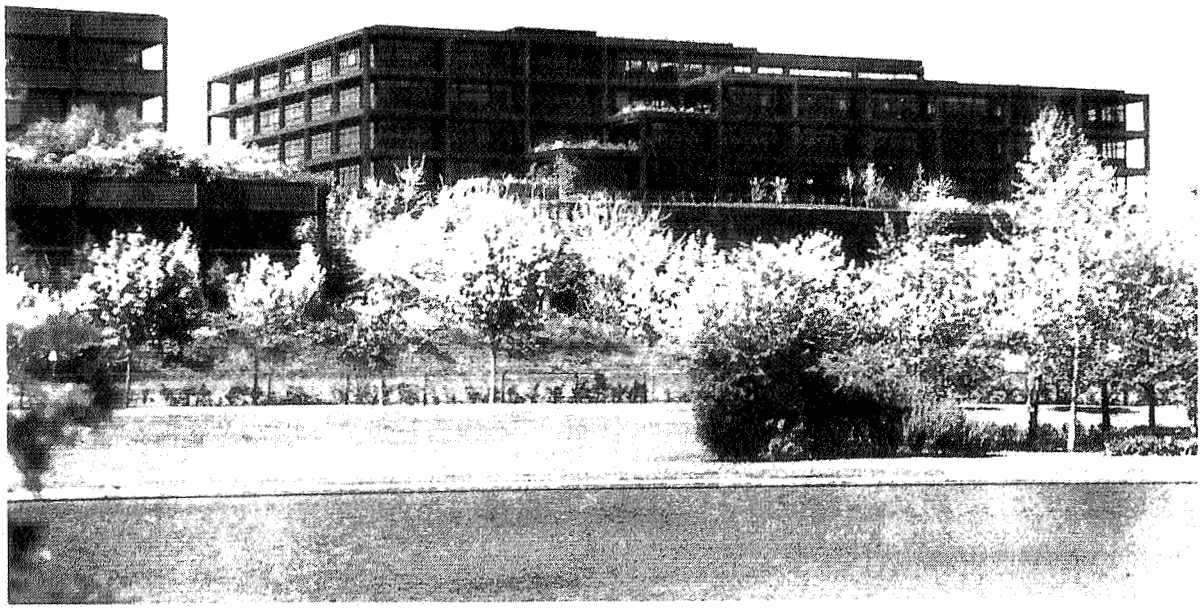




FIGURE 3. THE EXHIBITION HALL

The site available for development was roughly square, and consequently suggested a deep plan form. This would conventionally result in a requirement for air-conditioning which was thought not to be consistent with low energy (and first cost). Studies demonstrated, however, that sufficient floor area could be obtained with a 5 storey building with a light-well, that is constructed around a courtyard. The advantage of this form is that cross-ventilation is readily achieved and there is adequate daylighting. The disadvantage is the wasted space in the light well. If this could be covered over with a transparent roof then the daylighting might not be severely restricted and the floor area would become usable. The building would then unfortunately become deep plan, and might require air-conditioning. The designers believed however that provided care was taken, it should be possible to ensure that sufficient outside air passed through the building by means of windows in the perimeter wall and ventilation openings between offices and atrium (the covered light well) to prevent serious overheating. In addition the client required assurance that environmental conditions in the new building would be satisfactory. For the latter it was necessary to carry out an analysis of thermal comfort, whilst the former required a study of natural ventilation.

2.1 Comfort

This is not a paper on comfort, but it is necessary to make a few observations pertinent to the design of naturally ventilated buildings. Most designers base their analysis of comfort on fixed levels of clothing, for example a 'light business suit'. Thus it is implicit in the design that the environment is to be held constant because the level of dress will remain constant.

Now most buildings do not have a constant environment, but one that varies according to season and time of day, where the occupants are quite used to adjusting their level of thermal insulation to suit. It is therefore not unreasonable to expect the occupant of a new building to make similar adjustments, unless as in the present case they are used to an air conditioned environment.

Figure 4 shows some comfort criteria. It can be seen that discomfort is avoidable for a wide range of temperatures provided clothing levels are adjusted. This does not mean that the naturally ventilated building will always be comfortable but that it is possible to design for an acceptable failure rate.

The factors influencing the latter are weather dependent. Fortunately there is now a wealth of data available to enable a reasonable assessment of the risk.

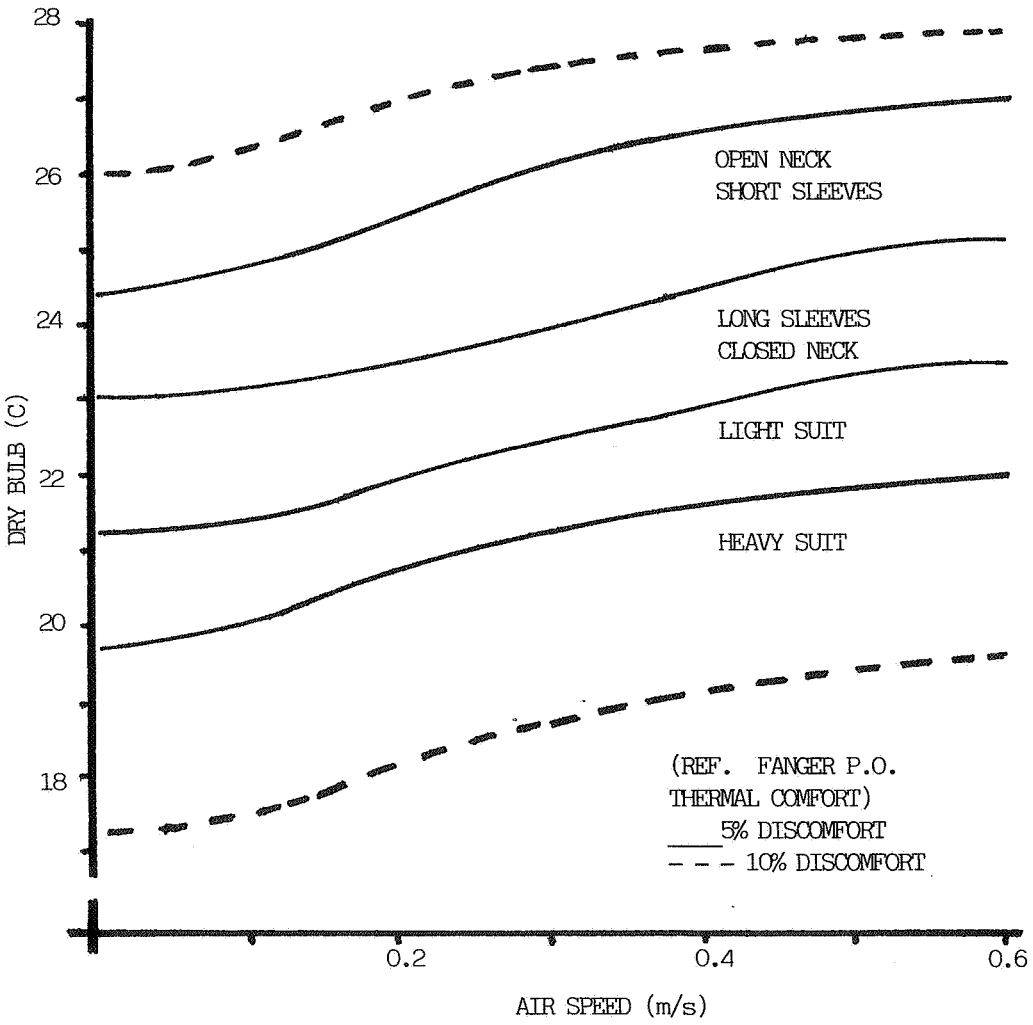


FIGURE 4. SOME COMFORT CRITERIA

Arguments of this nature were put to the client, and he agreed that such a building would be acceptable. More important he realised that, just as the staff had had to become 'acclimatised' to the air-conditioned building, there would be a need for a similar period of 'training' before they accepted the more traditional one.

2.2 Ventilation Design

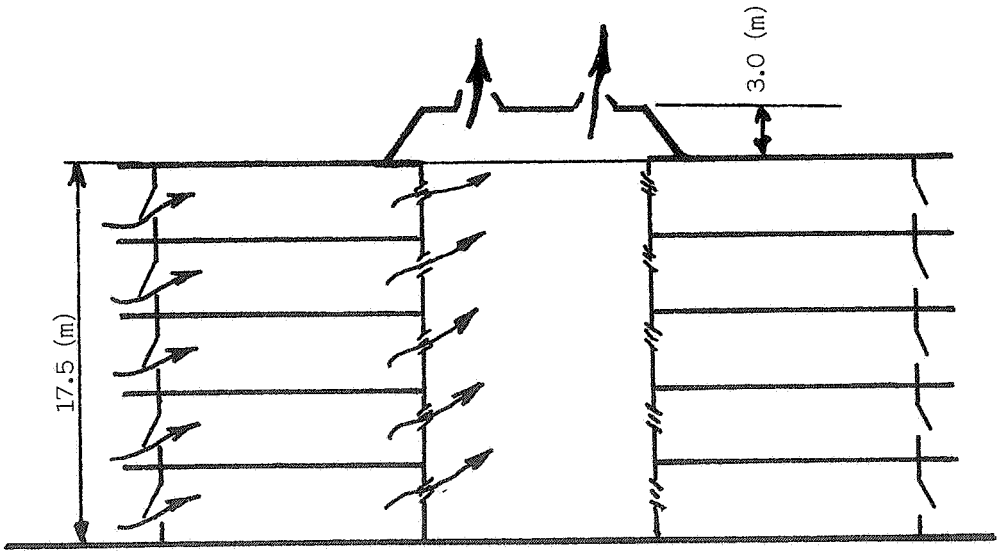


FIGURE 5. VENTILATION SCHEME

The design concept is indicated in Figure 5, where the central void or atrium is used as a 'tower of winds', causing air to flow into the building at all levels. The designer's main concern was that the height of the 'tower' was not much greater than the rest of the building. There were 4 main areas requiring study:

i) Was it possible to induce sufficient air through the building?

ii) What openings were necessary in both the atrium roof and offices?

iii) What temperatures would be likely in the offices and atrium?

iv) Which design conditions should be used?

Taking these in reverse order.

2.2.1 Design Conditions

Ventilation depends upon internal and external temperature and wind speed, so in theory it is necessary to determine the combination that is likely to cause failure. Internal temperature is also dependent upon the level of solar radiation and pattern of use, so an accurate determination of failure rate requires a

correlation between wind, sun and dry bulb temperature (and perhaps use). This was not seen to be practicable, so the design conditions would be based on experience.

The effect of solar radiation on the office environment had been minimised by shade and could therefore (See Figure 2) be considered a second order parameter. Any solar heating in the atrium would be of benefit because it should induce more air through the building. (Incidentally whilst probably not intended, this building has become one example of good passive solar design). In addition it was felt that there would never be any problem in achieving sufficient ventilation on windy days, and the temperature criteria could be satisfied by the difference between internal and external temperatures. Thus the design was based on a still day with high solar radiation.

2.2.2 Internal Temperatures

As already indicated, the standard calculation method for summertime temperature predictions involves guessing the air change rate. This is not the ideal. It is, however, a reasonable way to obtain the sensitivity of the building to changes in ventilation and to determine minimum acceptable values. The method described in the CIBSE Guide[1] is only applicable to an office or similar space, and consequently could not be used for the atrium. A special technique would therefore be necessary there.

The results of the standard calculation are shown in Table 1.

Table 1: Summertime Temperatures in the Office Areas

Condition - Sunny July day - maximum external temperature 25.5C.

Orientation	3 air changes (no lights on)	6 air changes (no lights on)
North	24.1	23.3
East	24.7	24.0
South	24.7	24.0
West	25.8	25.0

Note: the night time air change rate was 0.75/hr.

If the lights were to be switched on then all predicted temperatures would increase by about 4°C.

The low temperatures are due to the high thermal mass of the building, in particular a coffered ceiling of exposed concrete. Enclosing this within a false ceiling increases the predicted internal temperature in the south zone to 26°C (for 3 air changes).

This study demonstrated that if more than 3 air changes could be ensured then conditions in the offices should be acceptable. The atrium (See Figure 6) now had to be considered and whilst the philosophy of the standard method could be used a different theory was necessary.



FIGURE 6. THE ATRIUM SHOWING VENTILATION OPENINGS TO THE OFFICES AND THE UPPER WALKWAYS

The atrium was modelled as a box with a high mass base and a glazed top, with air injected at a known rate and temperature. A finite difference model was used to represent the floor slab, and the convective heat balance equation was simply:

$$\rho C_p V \frac{dTa}{dt} = \text{heat into air - heat out of air} \quad (1)$$

where

ρ	is the density of air
C_p	is the specific heat of air
V	is the volume of the atrium
T_a	is the air temperatures
t	is time

Heat in, and out, includes that from the ventilating air at office temperature and convection from the building fabric. The solar gain to the space was computed separately, and complicated by the presence of a slatted walkway just below the glazing (to allow access for maintenance), which provided some shading. The solar gain was modelled as follows:-

(i) Only direct transmission was considered. The convective gain was assumed to enter the air at the extract point, and the long wave radiant component would be mainly lost to the walk way and then to the extract air. In addition some of the short wave radiant energy would be absorbed at the walkway.

(ii) The short wave radiation that passed though the walkway was spread uniformly over all surfaces, that which fell on the ground floor forming part of the heat transfer temperature, whilst that at the walls was assumed to be converted to a convective gain. The radiation absorbed by the walkway would enter the extract air.

The appropriate weather data was considered to be that used in the standard calculations. The predicted leaving air temperatures are shown in Figure 7. Once again it would seem that, provided more than 3 office air changes are obtained, satisfactory conditions can be achieved, if there is a temperature gradient in the space of about 0.5°C/m.

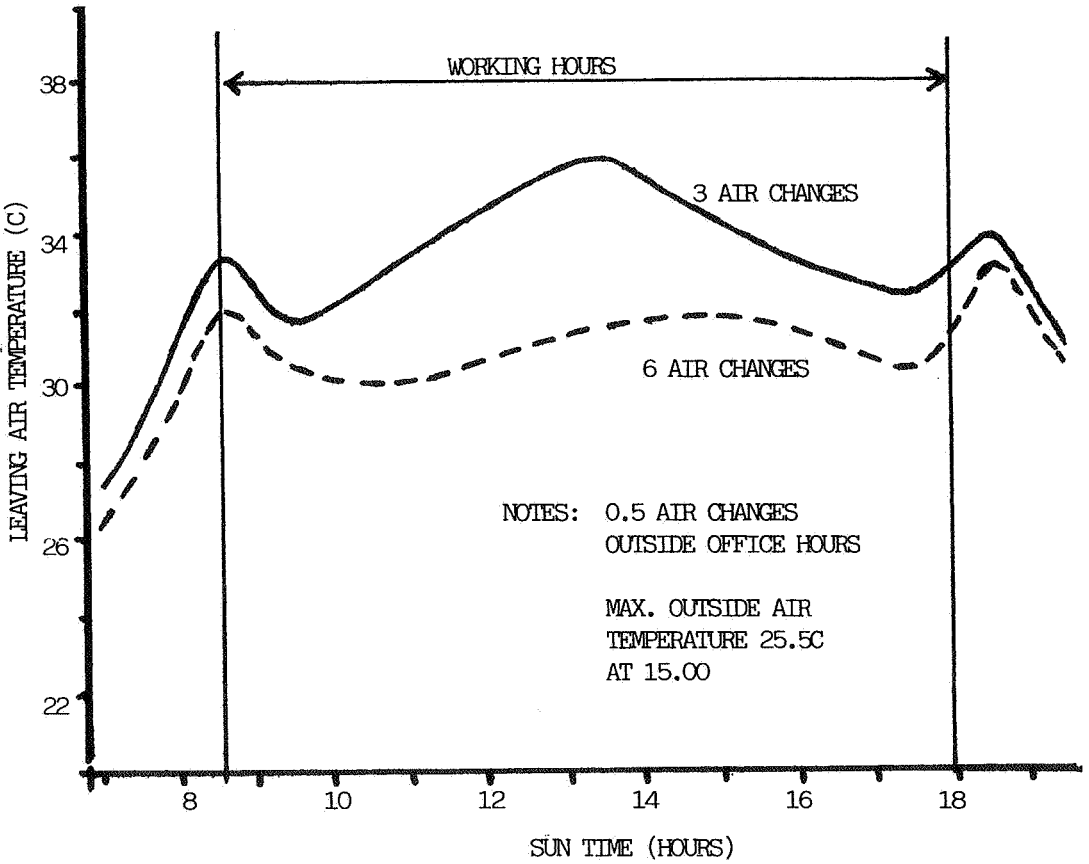


FIGURE 7. PREDICTED TEMPERATURE OF AIR LEAVING THE ATRIUM

2.2.3 Distribution of Ventilation Area

This type of building can be idealised to that shown in Figure 5 and, if all internal temperatures are assumed to be the same, then the simple conceptual model shown in Figure 8 becomes valid, where each A_n is the combined effective area of external open and internal open window area. The effective area at each floor is calculated in the following way (assuming the required air change rate has been specified).

With reference to Figure 8, the flow through opening 1 (Q_1) is:

$$Q_1 = A_1((Po-h_i g\rho_o) - (P_B-h_i g\rho_i))^{\frac{1}{2}} \qquad (2)$$

The base pressure P_B is given by:

$$P_B = P_3 + h_T g\rho_i \qquad (3)$$

and

$$Q = A_T(P_3 - P_4)^{\frac{1}{2}} \qquad (4)$$

where $P_4 = P_o - h_T g \rho_o$ (5)

and ρ_o = external air density (kg/m³)

ρ_i = internal air density (kg/m³)

g = acceleration due to gravity (m/s²)

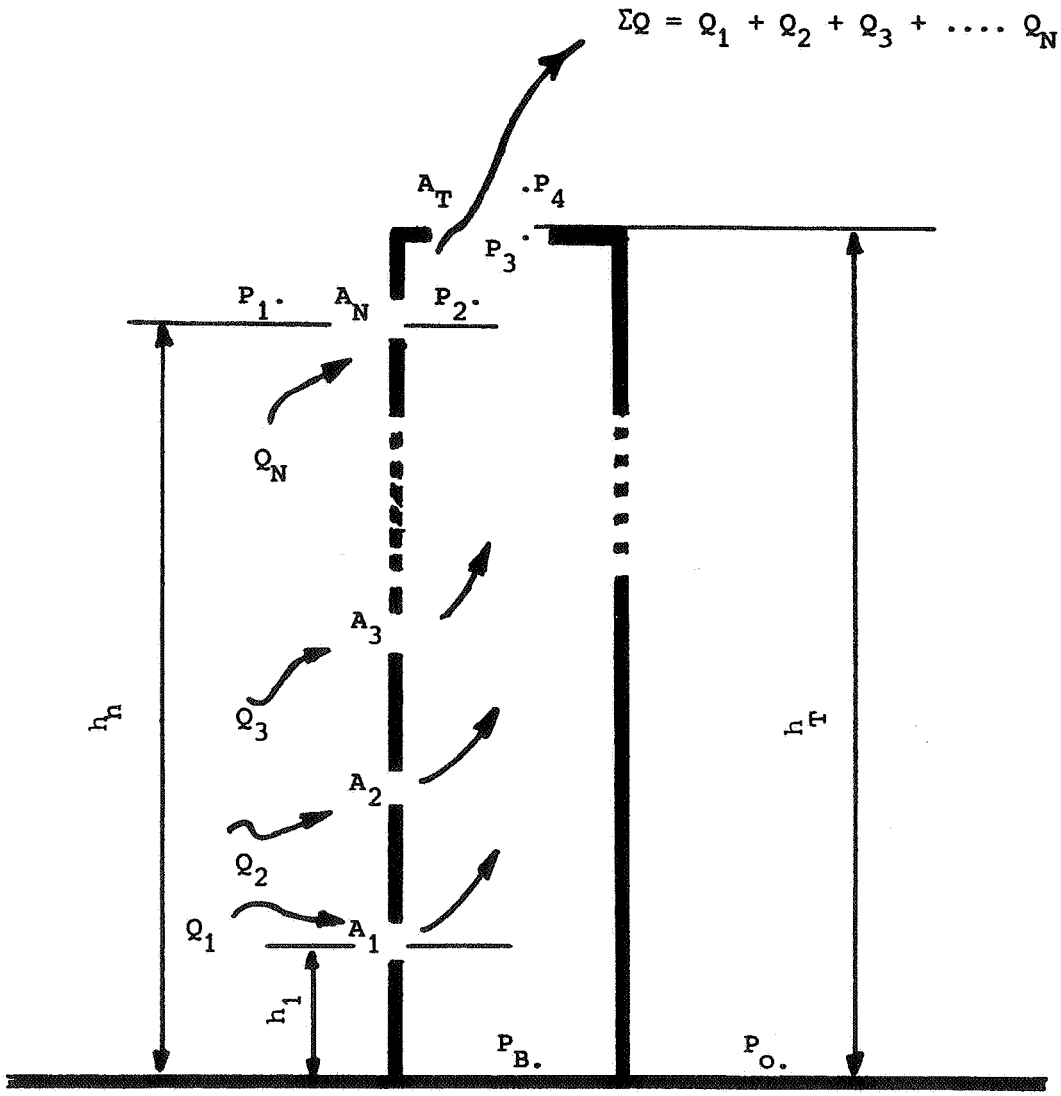


FIGURE 8. CONCEPTUAL BUILDING

If A_T is specified, then back-substitution will yield P_B and hence A_1 and then A_2 etc. The only practical difficulty is in the value of A_T. The most useful approach is to determine the minimum value which will ensure air flow into the building at the highest opening. This will be A_{TM} the area corresponding to an infinite A_N, which means that:

$$P_2 = P_1 = Po - h_N g \rho_o \quad (6)$$

and $$P_3 = P_2 - (h_T - h_N) g \rho_i \quad (7)$$

and with the flow through A_T given by (4), the minimum value of A_T is:

$$A_{TM} = \Sigma Q / (g(\rho_o - \rho_i)(h_T - h_N))^{\frac{1}{2}} \quad (8)$$

These equations were used to calculate the values in Table 2, which were given to the client to demonstrate how window opening should be controlled.

TABLE 2.

Predicted open areas of windows for self balancing arrangement.

Floor	Required air changes/hour	% open area External window	% open area internal atrium windows
1	3	10	-
2	3	14	14
3	3	17	17
4	3	22	20
5	3	25	11
1	6	19	-
2	6	29	29
3	6	37	37
4	6	48	45
5	6	58	26
1	8	25	-
2	8	39	40
3	8	50	50
4	8	66	61
5	8	100	43
1	10	35	-
2	10	49	50
3	10	63	63
4	10	84	78
5	8	100	55

The figures in Table 2 are all based on conditions to be expected on a hot, still, summer's day and assume that the atrium roof windows are fully opened (123m² opening area).

2.2.4 Prediction of Whole Building Ventilation Rates

The calculations in the previous sections were based on the assumption that there would be no difficulty in obtaining the required amounts of ventilating air, and indeed there was no good reason for thinking otherwise. It did, however, seem prudent to take the desk study a little further and examine what might happen with indis criminate use of windows. This was done using a multi-cell ventilation model.

The computer program started life in 1979 as a very simple single cell model to study infiltration in the National Exhibition Centre at Birmingham, and has been subject to continuous development. The version used in the current study, in common with most multi-cell models, was capable of taking both wind and stack pressures into consideration. In addition each cell could have an assigned temperature and, where appropriate, the simultaneous in flows and outflows which occur at large openings between internal cells and between cells and the outside being assessed. The non-linear equation set is solved directly via the secant method[3]. Two flow balances are required, one for each room and a second for the whole building. The result of the latter is used to generate an overall pressure correction, which is applied to individual room pressures after each complete iteration. This ensures that the solution satisfies conservation of mass flows both internally and externally.

The objective of the current study was to examine the effect of window opening and size on the distribution of ventilating air in the building. In addition it had been suggested that mechanical extract ventilation might be of some benefit in the atrium. The building was divided into 25 cells for the calculations; this was so that stair wells and some smaller separated areas could be modelled. Some sample results are presented in Table 3 and, while these indicated that it might be useful to fix stops to the windows to prevent excessive opening on the lower floors, this was not done and, in the light of experience seems unnecessary.

Table 3 Summary of Multi-Cell Predictions

Conditions: Wind Speed Zero
External dry bulb 25°C
Internal dry bulb 27°C (29°C in atrium when marked*)

Note: Mechanical extract in atrium equivalent to 4.5 air changes.

% Percentage of windows open,
Ac air change rate (hr^{-1}).

Atrium Conditions		Office Ventilation									
Open roof vent (m^2)	Mechanical Extract	Floor No. 1		2		3		4		5	
		%	Ac	%	Ac	%	Ac	%	Ac	%	Ac
0	Yes	100	18	100	15	100	5	100	0	100	0
0	Yes	80	14	60	8	40	0	20	0	10	0
0	Yes	10	2	20	4	40	7	60	7	80	0
102	Yes	100	22	100	20	100	15	100	1	100	0
102	No	100	21	100	18	100	13	100	0	100	0
200	No	35	9	40	10	60	13	85	17	100	8
200*	No	35	13	40	14	60	19	85	24	100	11
102*	Yes	35	12	40	14	60	17	85	20	100	0
102	No	35	12	40	13	60	16	85	17	100	0

These results show that natural ventilation is a more effective than limited mechanical extract. The mechanical extract rate and the 102m^2 ventilation area were both related to requirements for smoke extract. The final selection of ventilation area (123m^2), was the largest practicable area.

2.3 Discussion

The designers' greatest worry, that the building would not work, was relieved soon after completion. While the occupants had some difficulty initially with the new environmentm they 'settled in', and found it comfortable. There are, of course, days when the lack of air-conditioning is noticed - when it is very hot outside. Measurements taken on a very hot still day are shown in Tables 4 and 5. The design objectives were achieved, although it is unfortunate that no air-change measurements could be made (There is still a small chance that this might be done).

One result of these measurements was to recommend that the windows are left open during the night to obtain more structural cooling. In many buildings this would not have been possible for reasons of security. This problem had already been considered and the design of the external windows was such that they only opened sufficient for ventilation. It would not be possible to enter the building - nor to fall out by them. No experimental data are available to demonstrate the value of night time ventilation.

TABLE 4 Temperatures on 13 July 1983

WEATHER - SUNNY, VERY NOT, NO BREEZE

LOCATION		12.00hrs. deg.C	14.15 deg.C	15.15 deg.C	16.15 deg.C	17.00 deg.C
External-Ground		30	31.5	31.5	31.75	30.5
Atrium Level	1	29	30	30	30.75	30
	2	29	30	30	30	30
	3	29	30	30.5	30.5	30.25
	4	29	30	31.25	31	31
	5	30	31	31.5	31.5	31.5
Roof Walkway		36	37.5	37.5	36	35
Offices Level	2S		30	30		
	3S		29.5			
	5S		30			
	5N		30			
	5W			30.5		
	4S			30.5		
	3N			30		

These observations (Tables 4 & 5) indicate a slight improvement in office temperature when comparing the measurements with the predicted values, being 1°C to 1.5°C below the ambient.

TABLE 5. Comparison between predictions and measurement

LOCATION		Predicted Temp. deg.C	Predicted Temp. deg.C	Measured Temp. deg.C
External		25.5	31.5	31.5
Atrium - Level	1	25	31	30
	2	26.3	32.3	30
	3	27.5	33.5	30
	4	28.8	34.8	30
	5	30	36	31
Roof Walkway		32.3	38.3	37.5
Offices	N	24.1	30.1	30
	E	24.7	30.7	30
	S	24.7	30.7	30.5
	W	25.8	31.8	30.5

In addition to demonstrating the usefulness of ventilation prediction techniques, the project also demonstrated a defficiency in the program - ventilation and thermal analysis had to be carried out separately. An initial response to this has been to modify the program to:

(a) trace the passage of air through the building - this means that the concentrations of neutral density pollutants can be determined.

(b) given heat gains to the space calculate corresponding air flows and temperatures.

The final step of linking the ventilation program to a finite difference thermal model is almost complete, but there are some problems associated with handling the large amount of input data necessary.

3. The Exhibition Centre

This building (Figure 3) was to form the centrepiece of a Garden Festival to be held at Liverpool during the summer of 1984. The use as an exhibition hall was seen to be only transitional, and for the summer months. Future use as a sports hall was envisaged. The basic design requirement was to prevent overheating without recourse to mechanical plant, which of course would probably not be suitable for the future. It was therefore decided to make use of natural ventilation, and as with the atrium of the previous building a special computer program was necessary so that the design options might be studied.

3.1 Analytical Approach

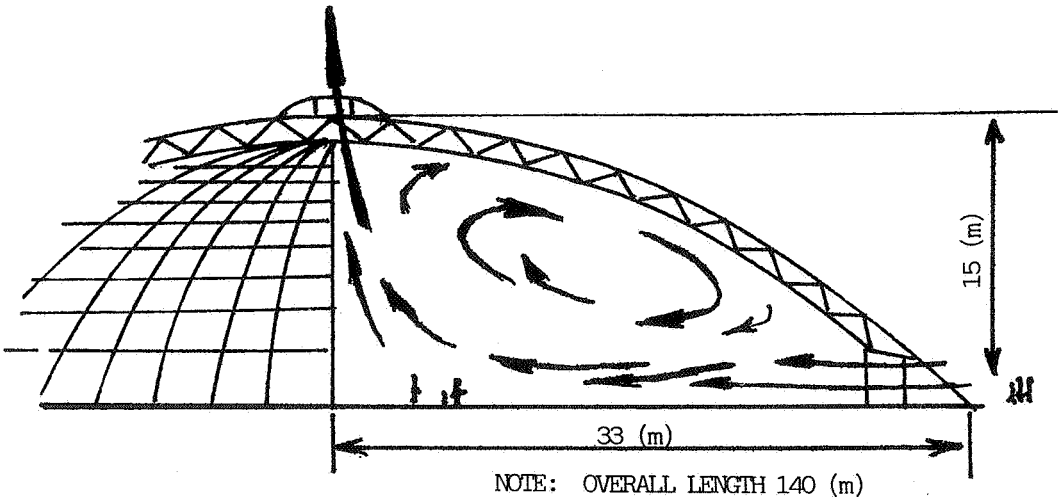


FIGURE 9. SECTION THROUGH EXHIBITION HALL

There is little difficulty in predicting the general pattern of air flow within the building (see Figure 9). The amount of air that might be expected to flow through the building is a little more difficult to guess. The main requirement expressed by the designer was, "how large does the top opening need to be?". The pragmatic reply of "at least as large as that at the bottom" was of little help, the building would have looked awful. The solution was to compute the thermal loads on a design day and simultaneously determine the induced ventilation. Once again a design day would be a still, cloudless one, and the objective to limit temperature rise. An additional demand was to investigate the possibility of condensation on the inside of the roof.

The calculation would therefore involve:

i) Solar gains

ii) Storage in the ground slab

iii) Internal heat gain

iv) Surface temperature predictions

v) Air flow rate prediction

vi) Water vapour flow prediction

Only an outline of the solution technique is possible here, with each item taken in turn.

3.1.1 Solar Gains

These comprise the major load on the structure (see Figure 10). To enable a reasonable analysis, the transmitted and absorbed portions were to be calculated from the optical properties of the roofing material. In practice this proved to be difficult because a double skin 'plastic like' material was used. The surface was assumed to behave as clear glass. Discomfort would arise because of high roof surface temperatures and direct radiation. The latter would cause only local problems and its effect (in the sense of impact on occupants) was ignored.

3.1.2 Storage in the Ground Floor Slab

Modelled by finite difference equations, the floor is the only significant storage component in the structure. The main load is the direct solar gain, and some care was taken to estimate the amount of internal shade given by exhibition stands and occupants.

3.1.3 Internal Heat Gains

These have two sources, occupants and lights. Both sensible and latent components of the former were represented as functions of temperature[4], and the latter was split into its radiant and convective parts.

3.1.4 Surface Temperature Prediction

The most likely mechanism for the transfer of heat from the upper to lower regions of large spaces is radiation. So that a reasonable representation might be attempted, the radiosity matrix[5] is solved at each calculation step. The surface temperatures resulting from combined radiant and convective transfers then are used to predict the mean radiant temperature "seen" by the occupants.

3.1.5 Air Flow Rate Prediction

The air flow pattern has already been suggested (Fig 9). The quantity of air depends upon internal and external temperatures and the available openings. The flow pattern suggested that a mean internal temperature be used (in practice the difference between leaving and entering air at the previous time step).

The conventional stack equation was used to determine the pressure difference across the building and hence the induced flow. The convective heat balance was represented by Equation (1), with a slight modification. The hall was divided into two sections;

i) A lower, occupied area, where it could be assumed that people were standing in the airjet from the openngs (see Figure 9).

ii) The upper volume where the thermal capacity of the air is significant.

In the case of the former an instantaneous convective heat balance was used with gains due to occupancy, low level lighting and the floor surface. A dynamic solution (Equation 1) was appropriate for the upper section with heat gains from the roof and high level lighting.

3.1.6 Moisture Balance

An approximate dynamic relationship for the flow of water vapour can be postulated on the basis of a first order system with a time constant equal to the reciprocal of the air change rate. This enables an elementary model of the flow of moisture and prediction of surface condensation. The effect of variable internal moisture content on air density was not considered. In this case it was assumed (but not checked) that the large space volume would mean that internal/external density variations due to water vapour would not be significant.

3.2 Results

A large number of design options were studied. These covered the effects of:

Occupancy patterns
Internal lighting
Single and double roof skins

and of course ventilation strategies, in particular the effect of varying the high level open area and duration of opening. Some results are shown in Figures 10 and 11.

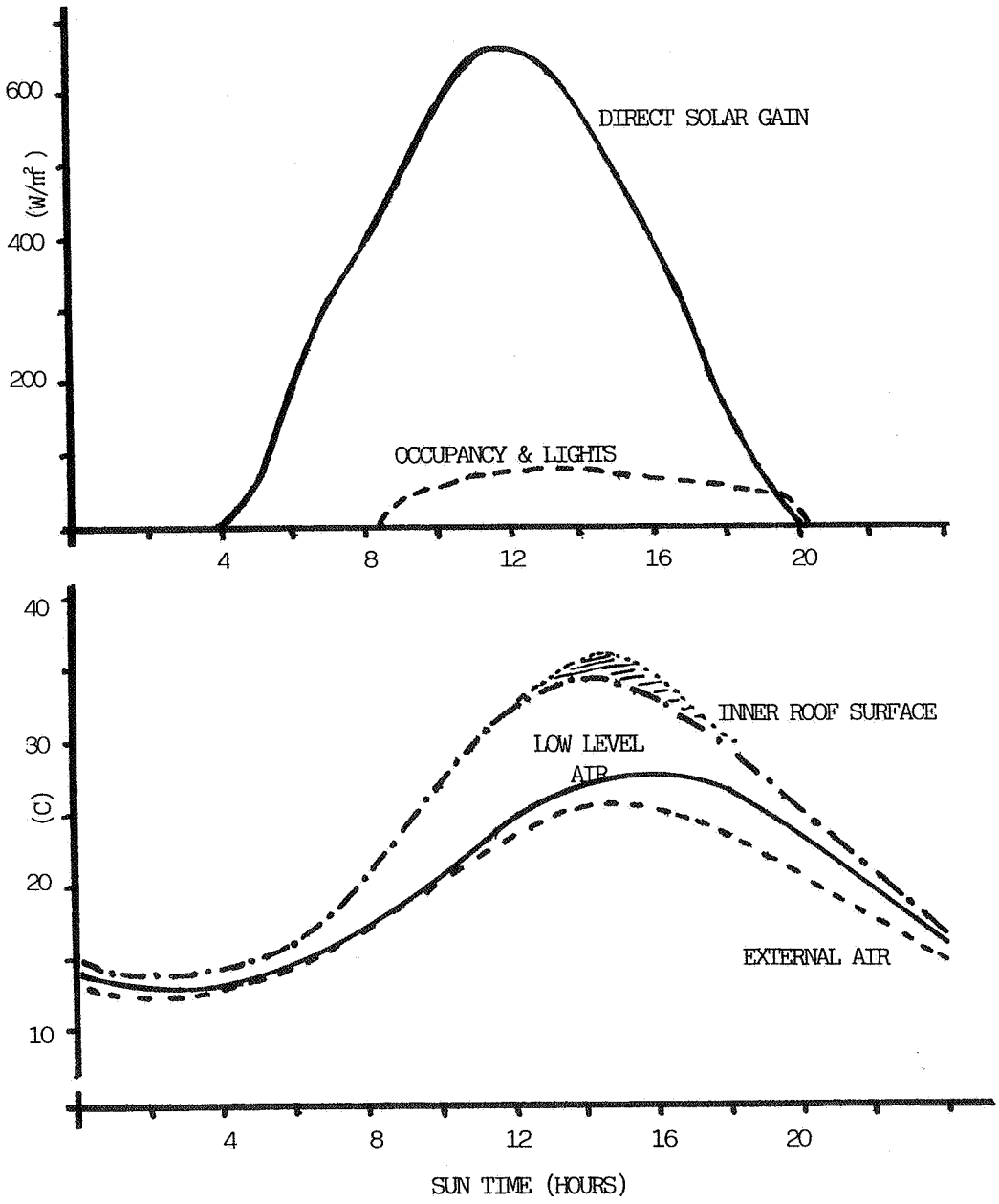


FIGURE 10. TEMPERATURES AND HEAT GAINS

3.3 Discussion

It was intended to monitor the performance of the building, but the unusual nature, and short life, made arrangements difficult. The performance could therefore only be judged subjectively. (There is still a slight chance of some measurements in the future). A visit on a hot day showed that the building was not generally uncomfortable, but there was a significant sensation of direct radiation from the sun. Thus, whilst the program had probably over-predicted the average internal comfort condition, it was about right for persons standing out of the shade offered by exhibition stands.

The computer model used to analyse the design has since been further developed to include high mass surfaces and mechanical ventilation, and has been used on a number of projects. A further enhancement would be to include the effect of water vapour upon the buoyant forces. This would seem to be a phenomenon which merits further study, especially where there is an high occupation density.

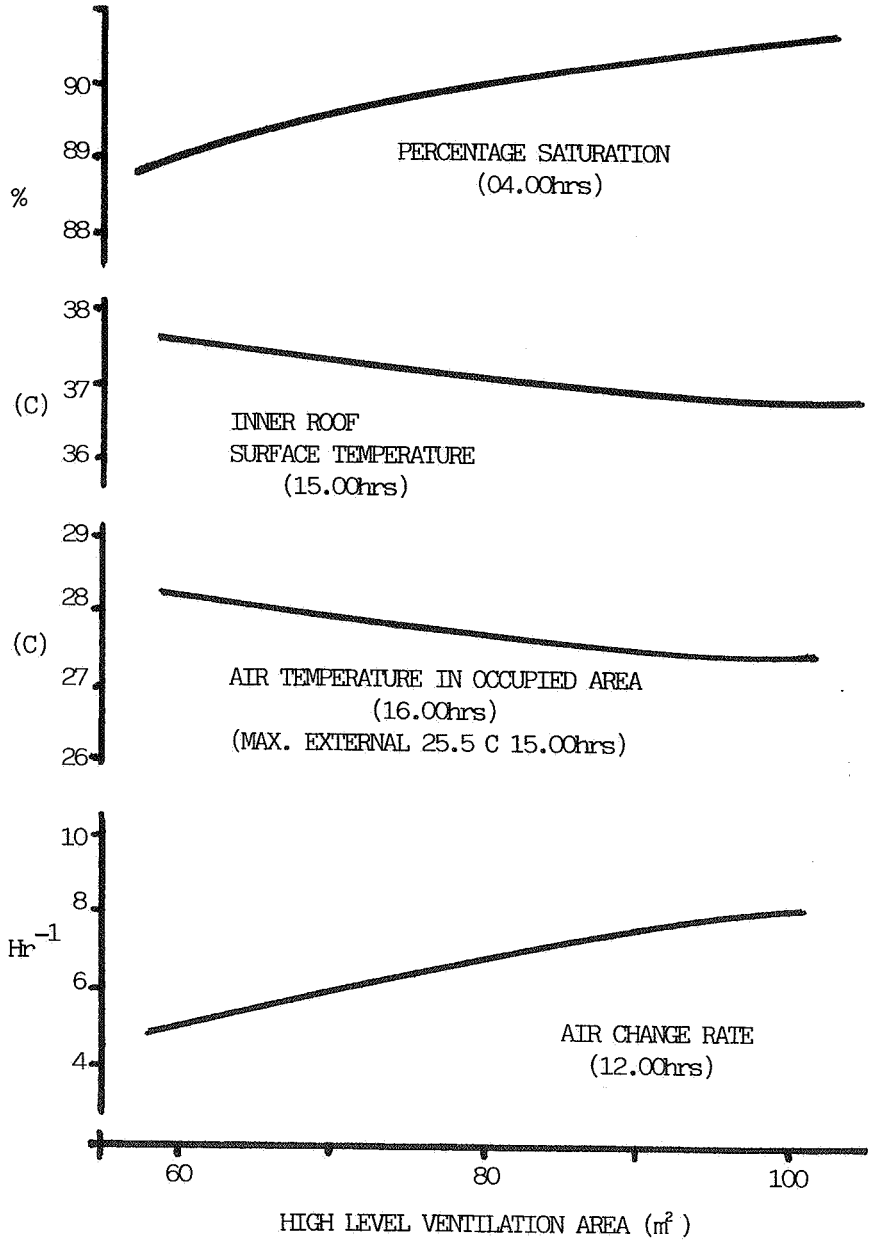


FIGURE 11. MAXIMUM VALVES OF SOME DESIGN PARAMETERS

4. Conclusions

There is little doubt that the designers' objectives for both buildings were achieved. Whether the analytical and design tools have been proven is perhaps open to question. If the only proof required is that the internal conditions expected were achieved, then the measurements presented in Tables 4 and 5 are perhaps just sufficient. Closer examination of Table 5 will, however show that whilst a linear vertical temperature gradient was assumed, in practice a step jump occurred just above the walkway. There is published data that suggests this[6], but conventional wisdom (with some justification) has always assumed a temperature gradient.

More experimental data would be useful. The same applies to air change rates. Although not measured they would seem about right, but again a closer look, in this case at Figures 1 & 11, might suggest otherwise, because room temperatures are not very sensitive to air-change rate. What is needed is detailed monitoring of all predicted parameters over a number of days. This, even if the money were available, is not a simple task in occupied buildings.

Regardless of the preceding observations the design techniques presented here were valuable and have been used on a number of other occasions. The main problems now faced by the designer of this type of building are to ensure that the client does not insist on a large number of small offices at the perimeter (and so restrict ventilation in the core areas), and the installation of additional electronic office equipment. Experience shows that the electrical load in offices is increasing (design figures of 5w/m² some 5 years ago are now perhaps 25W/m²). It may soon be impossible to avoid the use of air conditioning in the general office.

Acknowledgement

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 14

AIR QUALITY AND ENERGY CONSERVATION BY DIFFERENT VENTILATION STRATEGIES

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SYNOPSIS

The increasing awareness that indoor air quality aspects may restrict energy conservation by infiltration and ventilation measures has led to extensive investigations of different ventilation strategies. Aiming at a reduction of energy consumption air infiltration and ventilation rates have to be minimized. But in order to maintain healthy, safe and comfortable conditions for the inhabitants and to avoid damages to the building fabric the outdoor air supply should not remain under minimum ventilation rates.

To find out advantages and disadvantages of various ventilation systems, to assess the role these systems will play in different ventilation strategies and for defining ventilation standards in the Federal Republic of Germany in 1980 the main activities of a r & d programme "Air Infiltration and Ventilation in Residential Buildings" had been started, supported by the Federal Ministry for Research and Technology.

First results show that the conflicting requirements energy conservation and adequate indoor air quality in many cases best are met by mechanical ventilation and heat recovery. In unoccupied test houses as well as in occupied buildings the total energy consumption coul be reduced by 10 to 20 %. Inhabitant's behaviour and functional deficiences of the systems can decrease these effects in practice.

1. INTRODUCTION

The basic aim of the German r & d programme "Ventilation and Air Infiltration in Residential Buildings"[1] was to identify possibilities for reducing ventilation heat losses. Therefore emphasis had been laid on investigations of different ventilation systems in unoccupied test houses as well as in occupied buildings. From the beginning it was evident that aspects of indoor air quality had to be incorporated because reducing ventilation rates resulted in higher levels of indoor air pollutions' concentration. Of importance in this connection are the activities of Annex IX "Minimum Ventilation Rates"[2] of the International Energy Agency. To maintain healthy, safe and comfortable conditions for the inhabitants on one hand and to conserve energy on the other the various ventilation systems will play different roles in ventilation strategies being of importance for residential buildings.

Table 1: Reasons for ventilation and measures for acceptable indoor air quality

	minimum ventilation rates*	ventilation strategy	primary measures
i) avoid damage to building fabric	0.8 ach**)	basis ventilation	ventilation
ii) decrease annoyance	0.6 ach	add. ventilation dependent on number of persons	ventilation
iii) minimize health risks	> 0.5 ach	add. ventilation supporting other measures	reducing or prevent emission (covering, elimin. materials etc.), air cleaning

*) order of magnitude, assumption: floor area 70 m^2, 3 persons

**) climatic conditions and building construction typical for Germany

In table 1 only a rough idea will be given about necessary air change rates and measures. It was and is one of the objectives of Annex IX "Minimum Ventilation Rates" and the German standard DIN 1946 "Wohnungslüftung" to define and to give reasons for ventilation rates in more detail.

Important is that building physics, inhabitants' health and annoyance demand minimum ventilation rates[5] above 0.5 ach. Possibly in Germany moisture aspects dominate and minimum ventilation rates in the order of 0.8 ach have to be recommended[6].

2. SOME ASPECTS OF INDOOR AIR QUALITY

The principles of improving indoor air quality by ventilation are based on dilution and removal of contaminants. Known for decades the discussions on fundamental problems still continue:

- definition of the term "sufficient indoor air quality"
- outdoor air rate needed to ensure this indoor air quality
- ventilation strategies which are most appropriate for an effective contaminant removal (ventilation efficiency).

Most of the national ventilation standards are confronted with these questions. In Germany e.g. activities are going on to modify existing standards, having in mind air quality as well as energy conservation.

There are three reasons of different kind for the observance of minimum ventilation rates in buildings and dwellings:

i) to avoid damage to the building fabric

typical indoor pollutants: moisture and humidity

ii) to decrease annoyance of the inhabitants

typical indoor pollutants: odours, body odour, carbon dioxide etc.

iii) to minimize health risks

typical indoor pollutants: tobacco smoke, radon, organic vapours and gases, formaldehyde etc.

The first reason is nearly independent of the number of persons living in the dwelling. That speaks for the definition of a "basis ventilation". In the second case the number of persons is to a great extent correlated with the degree of annoyance. Carbon dioxide e.g. may be used as an indicator for body odour. Influencing the emission rate is nearly impossible. So the required ventilation rate will be dependent of the number of inhabitants. Besides, Berg-Munch et al.[3] could show a different sensitivity of persons to body odour and carbon dioxide. Therefore the minimum ventilation rate will be also dependent of the percentage of persons accepting a certain air quality level. In the ASHRAE Standard 62-81[4] acceptable air quality is defined as an indoor air condition which is accepted by at least 80 % of the inhabitants.

For the definition of minimum ventilation rates in the third case a risk assessment has to precede. Apart from the question which risk level could be accepted, for decreasing pollutants' concentration ventilation only can support, independently from the number of inhabitants. In table 1 some of the statements of interest are summarized.

3. VENTILATION SYSTEMS AND STRATEGIES

The ventilation systems under consideration, their ventilation functions on principle and energy aspects had been presented in several papers[1,7]. The investigations covered

natural ventilation:

windows, devices for "controlled" natural ventilation

and mechanical ventilation:

central or decentral systems for exhaust fan ventilation or for both supply and exhaust fan ventilation, in two multiple dwellings combined with heat recovery.

The main types of ventilation systems and characteristics being of interest are summarized in table 2.

Table 2: Ventilation systems and some of their characteristics

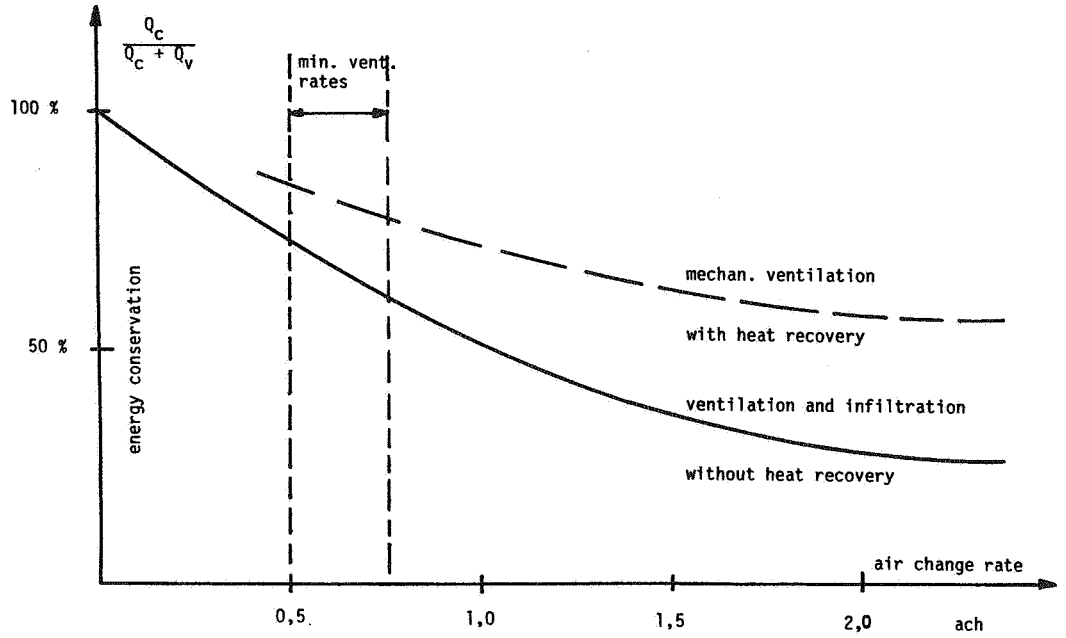
	control of ventilation rates	main influencing factors	auxiliary energy
natural ventilation	extremely variable	inhabitants, wind velocity, temp. differences	no
controlled natural ventilation	control in practice not yet proved	inhabitants	no
exhaust fan ventilation	good	almost independent	for fan operation and heat recovery
supply and exhaust fan ventilation	very good	almost independent	for fan operation and heat recovery

From the viewpoint of energy conservation the air change rates should be as low as possible, independent from other factors as wind velocity temperature differences, inhabitants behaviour etc. and controllable. For reasons of indoor air quality they should be high enough, not remain under values in the order of 0.6 to 0.8 ach, but also not affected by other factors and adaptable to changeable inner pollution concentration levels.

Comparing with the system's characteristics in table 2 mechanical ventilation systems obviously meet these demands best. For the example of a multi-story residential building different ventilation strategies and their consequences are illustrated in figure 1.

Figure 1: Energy conservation by different ventilation strategies

multi-story building with A/V = 0.7 m^{-1}, U = 0.5 W/m^2K,
Q_V: ventilation heat loss, Q_C: conductive heat loss

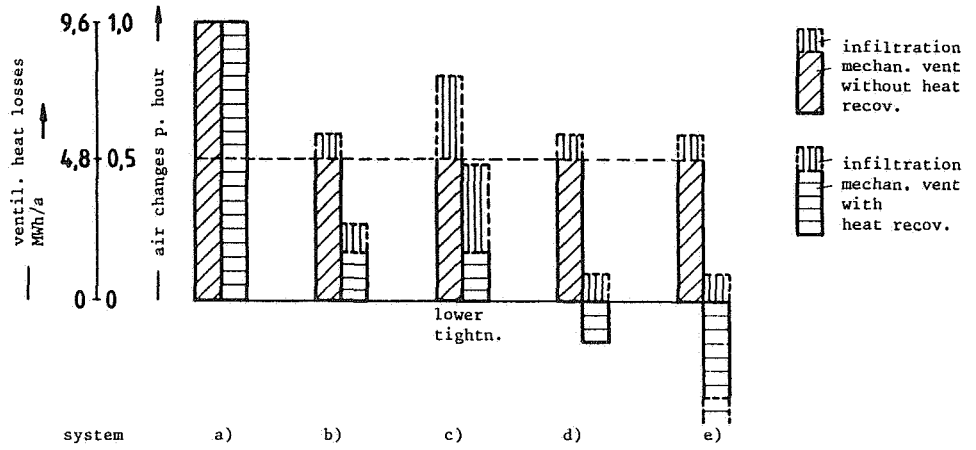


For low air change rates as e.g. in the case of tight building envelopes and tight windows energy conservation is comparatively high. However, indoor air quality can raise problems. Air cleaning devices or other measures decreasing emission rates could make such strategies to an alternative.

Higher inner loads may require air change rates far above 0.7 ach. Heat recovery is the only way to conserve energy, especially if the system's ventilation efficiency is low. In figure 2 common systems are compared.

Figure 2: Typical air change rates and heat losses by ventilation[7]

single-family dwelling, volume ca. 450 m³
a) reference, window ventilation
b) + c) supply and exhaust ventilation, heat exchanger
d) supply and exhaust ventilation, air/air heat pump
e) supply and exhaust ventilation, heat exchanger, heat recovery from exhaust gas



High air change and infiltration rates result in high energy losses (2a and c). If these rates are necessary for indoor air quality reasons heat recovery influences positively the energy balance.

4. CONCLUSIONS

In principle supply and exhaust fan ventilation links indoor air quality and energy conservation most promizing. Ventilation heat losses can be minimized by heat recovery if the building is tight and the outdoor air flow controlled. The mechanical ventilation gives the possibility to adapt air change rates to varied situations, e.g. higher indoor or outdoor pollutant levels. These systems can be developed to pollution controlled ventilation systems.

But in ventilation strategies also other aspects have to be considered: elimination of pollution emissions, air cleaning devices, ventilation efficiency etc.. Further important factors are reliability of these technical systems, maintenance and finally acceptance by the inhabitants. So, in ventilation strategies also other system variants will play a role.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 15

EXPLORATION OF VENTILATION STRATEGIES IN DOMESTIC HOUSING. THEORY AND EXPERIMENTAL RESULTS

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SYNOPSIS

The performance of whole-house mechanical ventilation systems was explored in an full-scale indoor test house (volume 176 m^3). A range of parameters were monitored:

* The pressure distribution
* The inflow of outdoor air to each room, the mean age of air in each room and the air-exchange effectiveness
* The spread of a 'contaminant' released respectively in the kitchen and in the bedroom.

The tests were undertaken both with the internal doors closed and with the internal doors open. Both mechanical extract system and balanced (combined) systems were tested. The tests were undertaken for a specific flow rate equal to 0.5 house volumes/hour (total flow rate 88 m^3/h). The fundamental concepts used are defined at the beginning of the paper. The concepts are in accordance with those currently proposed in Scandinavia. In particular the relevant meaning of the concept air-exchange rate is discussed. Then follows a short description of the test house and the measuring procedures adopted. Finally, the results obtained are given.

1. Purposes of a ventilation system

The most general purposes for ventilating a dwelling with 'fresh' air are:

* The removal of 'contaminants' originating from the building fabric and from people and their activities.
* Temperature control.

Only the first task will be considered in this paper. For a given 'contaminant' source the concentration attained at an arbitrary region in the whole house is governed by the following two factors:

* How much of the 'contaminant' that passes through the region.
* How much 'fresh' outdoor air that passes through the region.

The transfer of a 'contaminant' and 'fresh' air to a region can be more or less related to each other. The degree of relation depends on the type of 'contaminant' source we have. At one extreme end of the state we have a passive 'contaminant' generated everywhere in

the house, and with the same and constant rate. In this case the 'contaminant' levels are fully controlled by the distribution of the air. At the other extreme end we have a point source releasing a 'contaminant' with e.g. a density that differs from the density of the air. In the closest neighbourhood of the source the spread of the 'contaminant' is more or less independent of local air motions. However, when the 'contaminant' has become sufficiently diluted with air it will start to follow the local air motions.

In domestic housing, unlike the situation in industrial premises, there is seldom any specific 'design contaminant' with known characteristics. Therefore the designer of a ventilation system for a residential building does not normally know in advance which pollutants the ventilation system is to remove.

In our approach to the evaluation of the performance of different ventilation schemes we have chosen the following criteria:

* The efficiency in the distribution of the supplied air and the air-exchange efficiency.
* The concentration levels caused by a uniform source in the kitchen and in the bedroom respectively.

2. Terminology and theoretical background

We will make a distiction between the total flow rate of outdoor air entering a house, and the infiltration. Infiltration is the difference between the total flow rate of outdoor air entering a house, and the flow rate of outdoor provided by a mechanical ventilation system.

The nominal time constant, τ_n, of a ventilation system is defined as:

$$\tau_n = \frac{V}{q^t} \qquad (1)$$

where:

q^t = The total flow rate of outdoor air entering the house

V = The total volume of the house.

The physical meaning of the nominal time constant is limited to be equal to the average residence time in the house of the air supplied. That is to say, that each unit of volume of the supplied flow rate q^t will on average stay in the house for a time period equal to the nominal time constant. However, this does not imply that the air present in the room is replaced (exchanged) at the same rate. The time, $\bar{\tau}_r$, it takes on average to replace the air present in the room is equal to (Sandberg and Sjöberg[1], equation 69).

$$\bar{\tau}_r = 2 \cdot \langle\bar{\tau}\rangle \qquad (2)$$

where:

$\langle\bar{\tau}\rangle$ is the mean age of the air in the room.

The reciprocal of the nominal time constant

$$n = \frac{q^t}{V} = 1/\tau_n \qquad (3)$$

is often called the air-exchange rate.

In view of equation (2), this is a misleading terminology. The physical meaning of n is, as is literally expressed in the right-hand side of equation (3), the total volume of outdoor air (m^3/h) per total volume (m^3). Therefore, there is in Scandinavia a proposal to call n the specific flow rate. SI Units for n is ($m^3/h/m^3$) or (room volumes/h).

The air-exchange effectiveness is defind as:

$$\varepsilon_a = \frac{\tau_n}{\bar{\tau}_r} \times 100 \qquad [\%] \qquad (4)$$

The theoretical upper limit for the air-exchange effectiveness is 100%. Complete mixing of air gives rise to an air-exchange effectiveness equal to 50%.

The following relation holds between the stationary room-average concentration $\langle C(\infty)\rangle$ and the mean age of the 'contaminant', τ_e^C, when it leaves the room (turn-over time)

$$\langle C(\infty)\rangle = \tau_e^C \frac{\dot{m}}{V} \qquad (5)$$

where:

$\dot{m}$ is the 'contaminant' production rate.

The ventilation efficiency, $\langle\varepsilon\rangle^C$, is defined as ($C_e(\infty)$ = conc. in the extract):

$$\langle\varepsilon\rangle^C = \frac{C_e(\infty)}{\langle C(\infty)\rangle} \times 100 \qquad (6)$$

The right-hand side in the above relation may be expressed in terms of the turn-over time for the 'contaminant' time constant as:

$$\langle\varepsilon\rangle^C = \frac{\tau_n}{\tau_e^C} \times 100 \qquad (7)$$

3. Description of test house

3.1 General

All the tests reported in this article were carried out in the test house shown in figure 1a. The house is located in the laboratory hall at the Institute. The house has five 'rooms' (see figure 1b), a total volume of 176 m^3, and the floor area is 70.2 m^2. One short wall of the house consists of the existing south wall of the laboratory hall. Against the short wall at the opposite end of the house there is a cooling chamber. The air temperature in this chamber can be reduced to -25^{o}C. Both above and below each internal door there are adjustable gaps. The air movement in the doorways is shown by releasing smoke. To enable inspection from outside there are several strips of glass in the building envelope. The house is heated by electric radiators, or by heating the supplied ventilation air. Pressurization of the house to 50 Pascal pressure difference gave rise to a specific flow rate of 0.8 house volumes/h through the building envelope.

3.2 Flow rates and ventilation systems

The tests were carried out at a nominal flow rate q_n^t equal to 88-89 m^3/h, which corresponds to a nominal time constant of 2.0 hours, and a specific flow rate equal to 0.5 house volumes/h.

The air was always extracted from the kitchen (about 68% of the total), and the bathroom. When the extract system was in operation

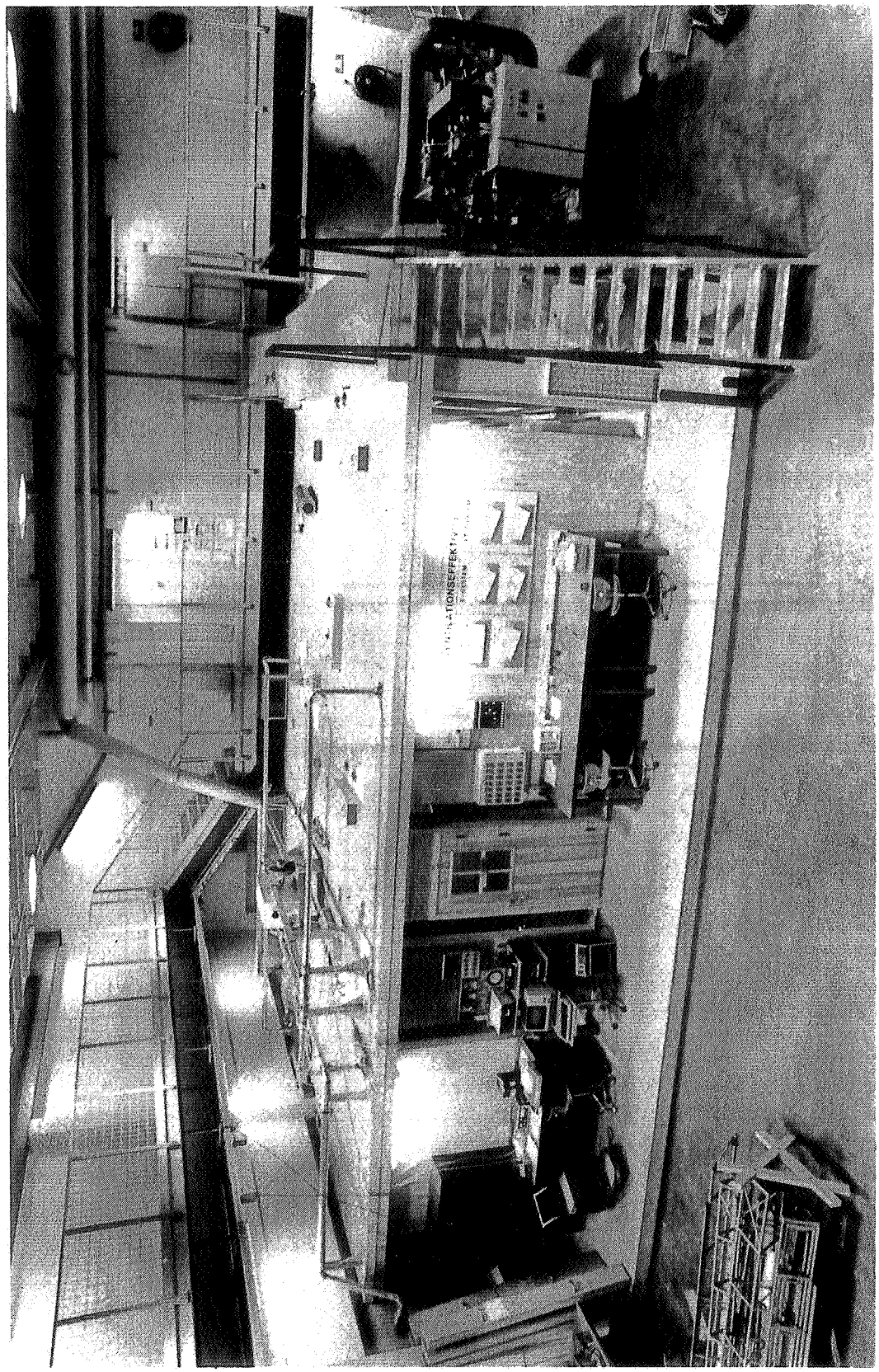


Figure 1a. The test house

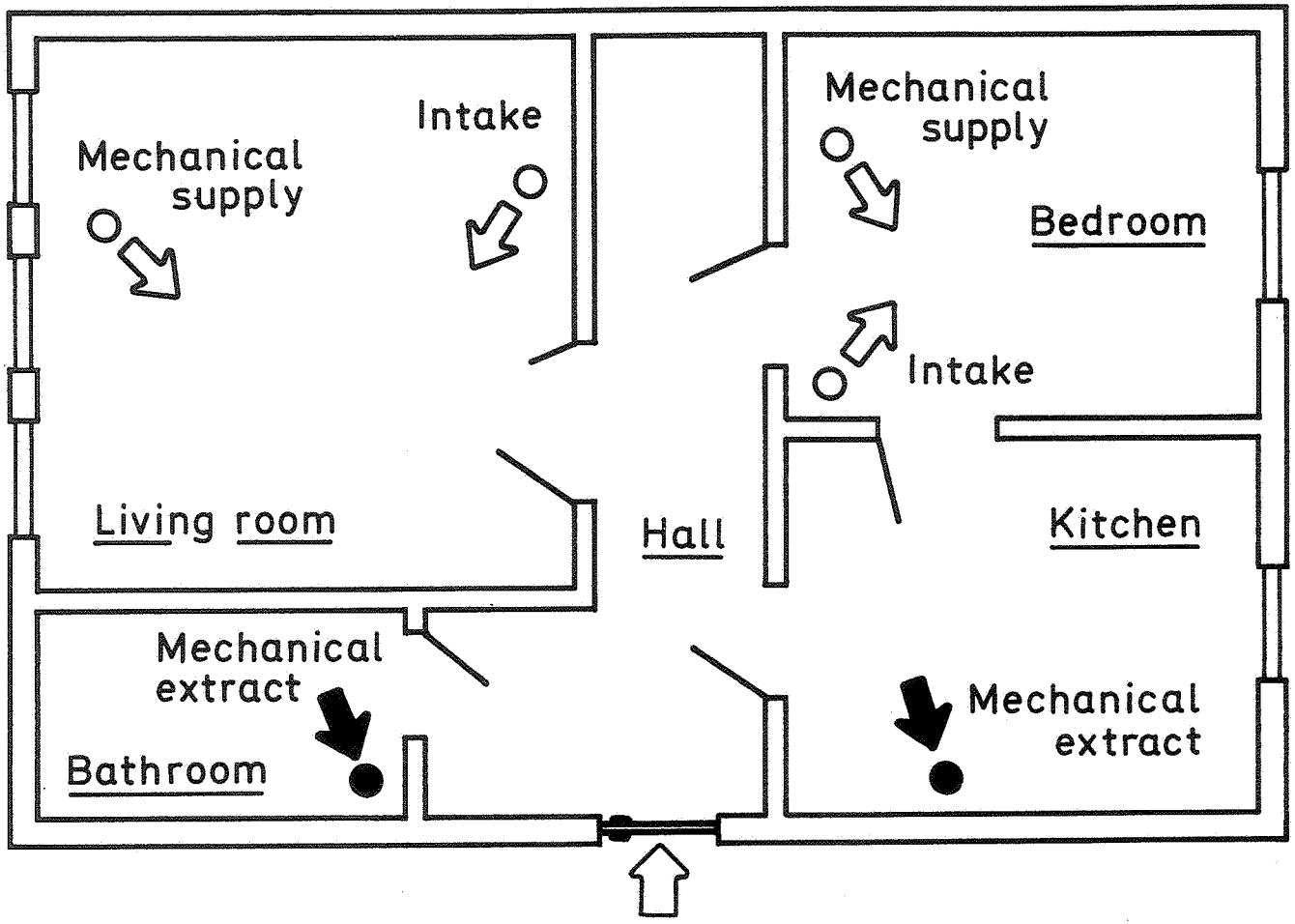


Figure 1b. Plan of test house

two 100 mm diameter intake holes in the ceiling were opened. One intake was in the living room ceiling, and the other intake in the bedroom ceiling (see plan of house in figure 1b). When the balanced ventilation was in operation the air was always supplied to the living room (about 54% of the total), and to the bedroom. The points of supply are indicated as mechanical supply in figure 1. The supply air was always taken from the laboratory hall while the air extracted from the test house was dispersed outdoors.

4. Experimental procedure

The following quantities were monitored in each room:

* Room air temperature at 0.2 m above the floor, and 0.2 m below the ceiling
* The pressure (relative to the laboratory hall) in the middle of the room
* Gas concentration in the middle of the room.

Tracer gas (N_2O) was released in each room directly into the air stream created by the mixing fan. The temperature in the laboratory hall and the outdoor temperature was continously monitored. The pressure difference between outdoors and the laboratory hall was also recorded. Three runs were made for each situation. The measuring and control sequence in each run was as follows:

1:st run:

1. Temperature
2. Pressure
3. Start of mixing fans and release of gas into each room
4. Constant concentration method to determine the flow rate of outdoor air to each room
5. Stop of gas-release and mixing fans
6. Decay of concentration to determine the mean age of in air in each room and the mean age of all air present in the house
7. A repeat measurement of temperature and pressure.

2:nd run:

1. Temperature
2. Pressure
3. Release of 3.6 liter of tracer gas in the kitchen (during the whole release period the mixing fan in the kitchen is running and the door to the kitchen is closed)
4. Recording of gas concentration to determine the transfer of 'contaminants' to other rooms
5. A repeat measurement of temperature and pressure.

3:rd run:

The same procedure as in the 2:nd run except that now 3.6 liter of gas is injected into the bedroom.

In order to check the zero drift of the analyzer the gas concentration in the ambient air was recorded before and after each run.

From the concentration readings during the decay of concentration in the 1:st run, the mean age of air in each room, $\bar{\tau}_p$, is calculated by taking the total area under the curve and dividing it by the initial concentration. The mean age of all air present in the room $\langle\bar{\tau}\rangle$ is calculated by taking the normalized first moment of the concentration readings in the extract duct.

From the concentration readings during the 2:nd and 3:rd run, the total dosage, D_p (= the time integrated exposure), of the gas in each room is calculated. From the concentration readings in the extract duct, the mean age, τ_e^C, of the 'contaminant' when it leaves the room is calculated.

From the pressure measurements, an equivalent pressure difference, Δp_e, across the building envelope is calculated as:

$$\Delta p_e = \sum_i \left(\frac{A_i}{A}\right) |\Delta p_i| \qquad (8)$$

where:

Δp_i = Pressure difference across surface no i of the building envelope

A_i = Area of surface no i of the building envelope

A = The total area of the building envelope.

The flow of air between the rooms through the doorways is visualized by releasing smoke around the doorways.

5. Results

5.1 Extract system

Figures 2a-2b (Case: Internal doors open) and fig 3a-3b (Case: Internal doors closed) show the results from the extraxt system. Fig 2a and 3a give the results concerning the supplied air and internal pressure distribution. First is given the inflow of outdoor air (q_m) to each room as predicted by the constant concentration method. The result is presented as a percentage of the nominal total flow rate, q_n^t (the flow rate set by the mechanical system). The internal pressure distribution is given as the pressure difference between each room and the pressure recorded in the hall, ($p - p_{hall}$). The pressure distribution presented constitutes an average of six repeated measurements. The equivalent pressure difference, Δp_e (see equation (8)), across the building envelope is also presented. Finally, the mean age of the air, $\bar{\tau}_p$, in each room is given as a percentage of the nominal time constant.

Figures 2b and 3b give respectively the results obtained from releasing a 'contaminant' in the kitchen and in the bedroom. First is given the integrated exposure, D_p, recorded, divided by the integrated exposure, D_s, in the source room. This ratio is equal to the ratio between the equilibrium concentrations we should, under identical release and air flow conditions, have obtained with a continous release of 'contaminant'. On the right-hand side part of the figures is given the fraction (m/m_s) of total amount of 'contaminant' released (m_s) extracted from the kitchen and bathroom respectively.

In figure 3b, case source in kitchen, this fraction has not been presented because the predicted amount of 'contaminant' that left the house was greater than the released amount of 'contaminant'. This effect can probably be explaned by an offset of the baseline caused by a drift of the gas analyzers zero level.

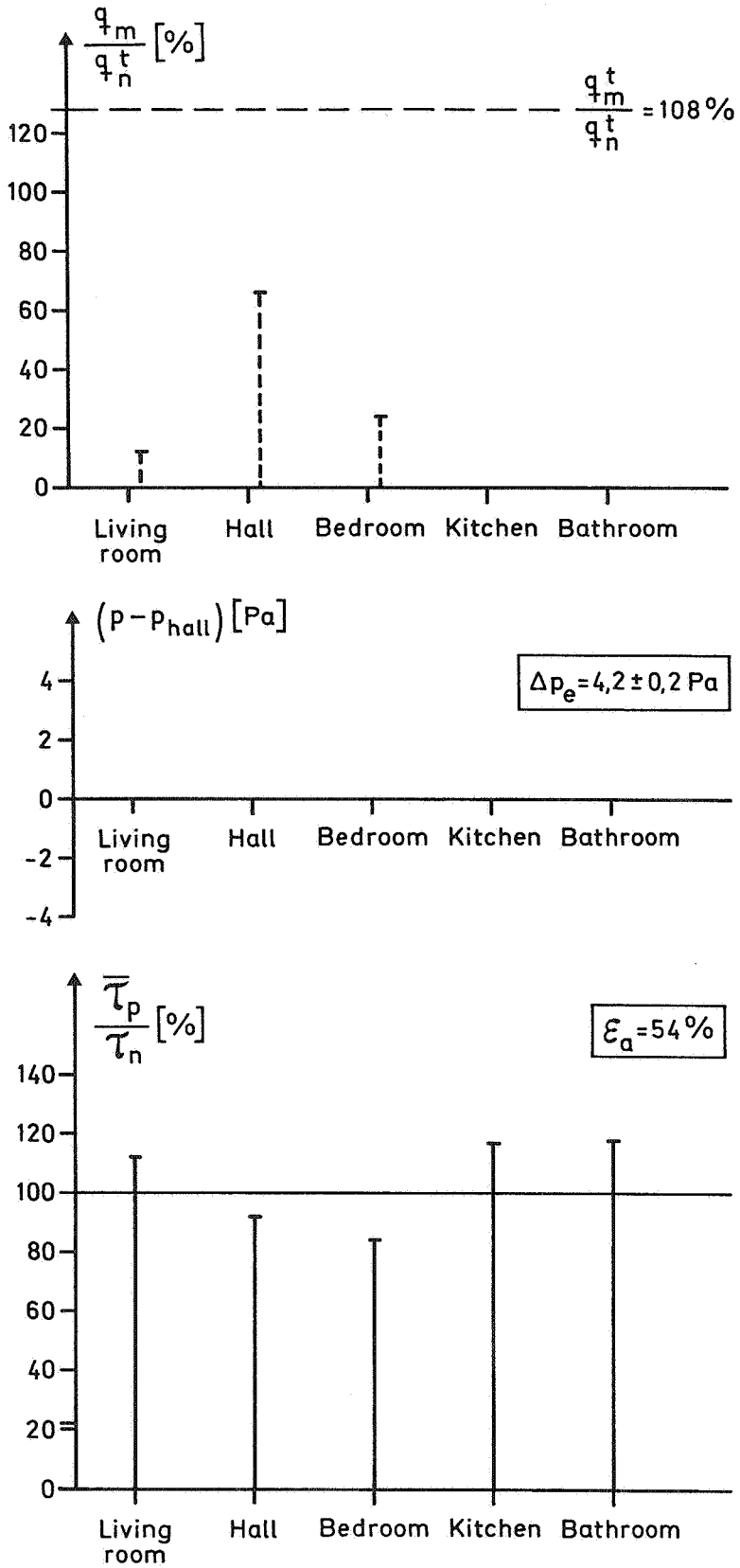


Figure 2a. Extract system and internal doors open. Supplied air, pressure distribution and mean age of air.

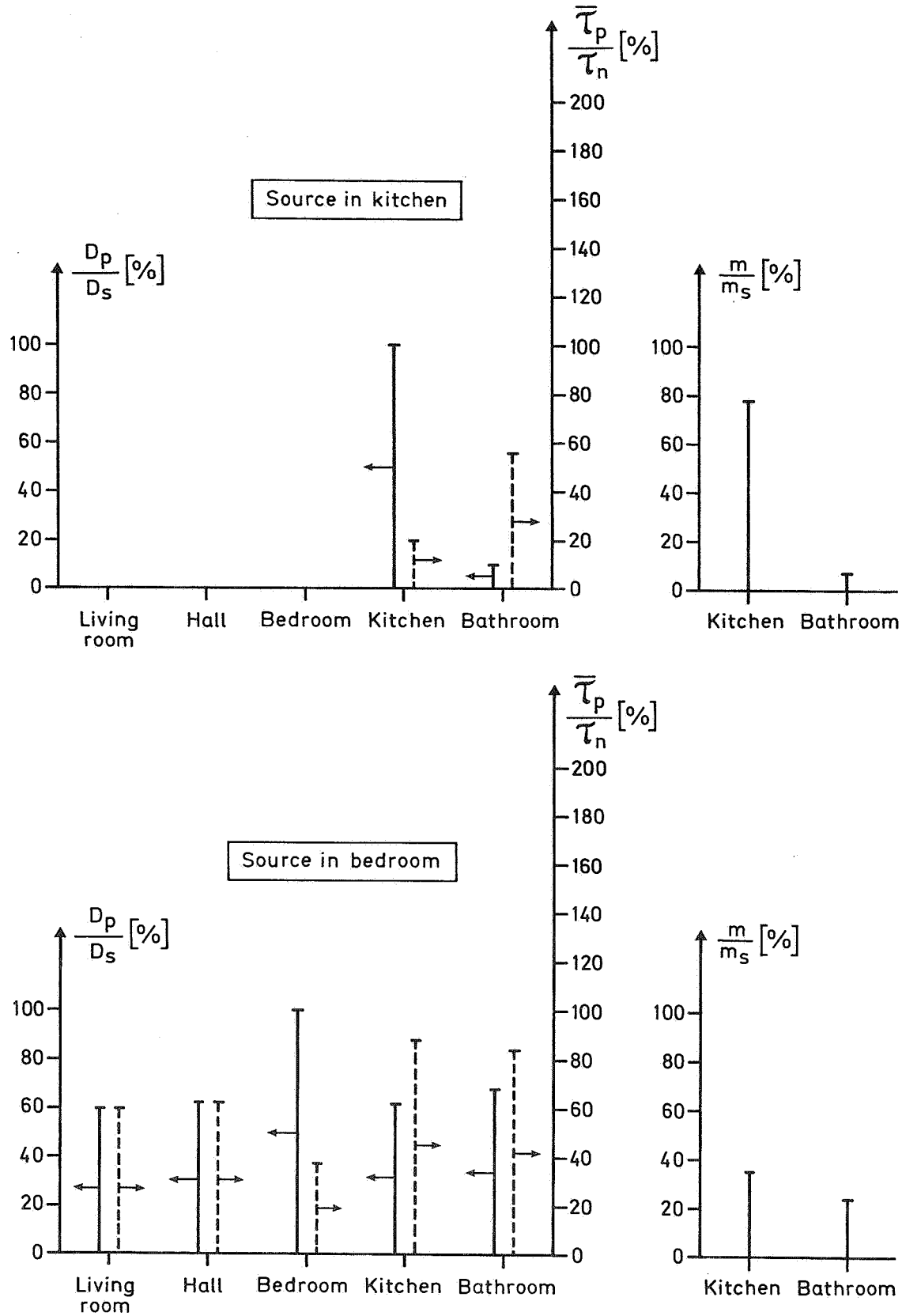


Figure 2b. Extract system and internal doors open. 'Contaminant' exposures and mean age of 'contaminant'.

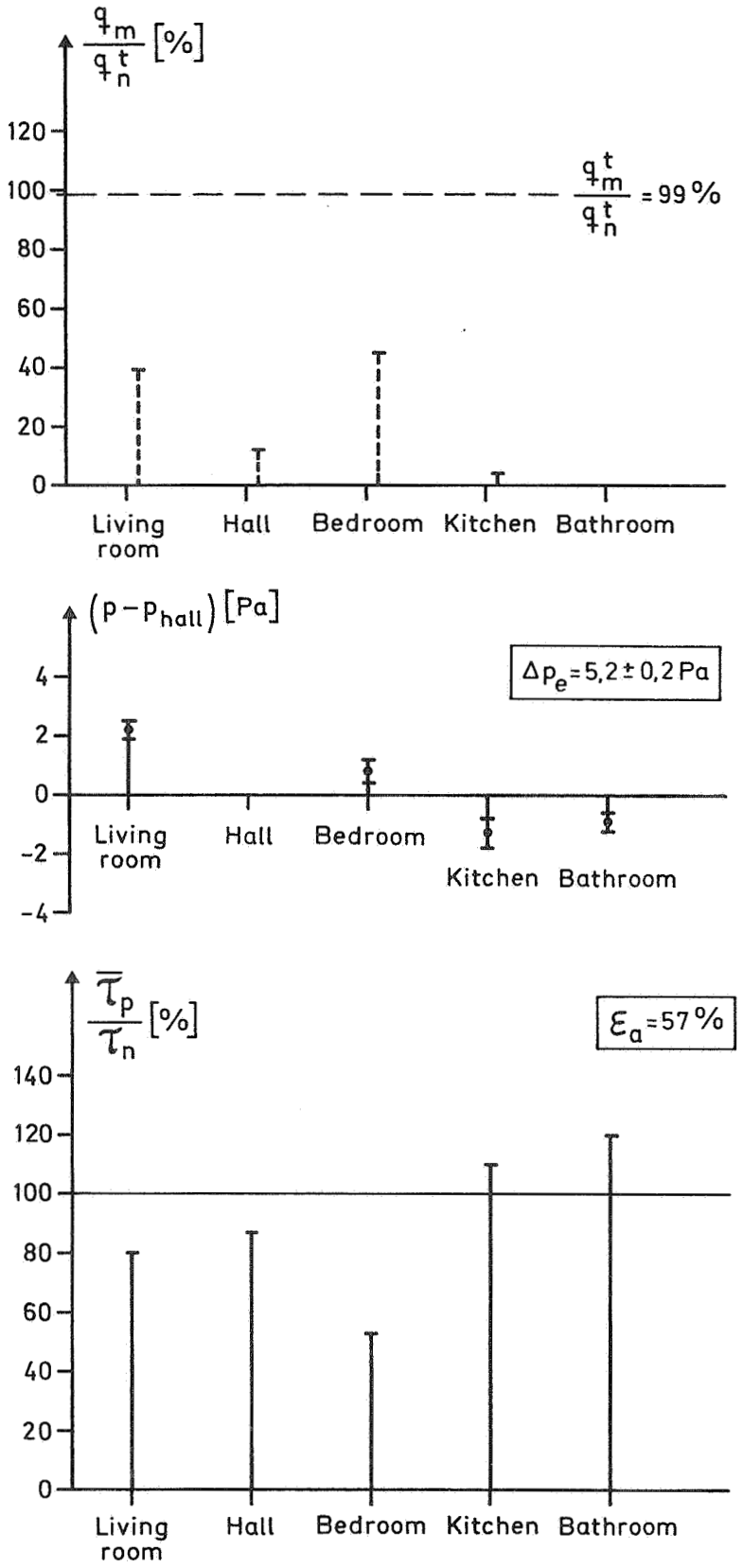


Figure 3a. Extract system and internal doors closed. Supplied air, pressure distribution and mean age of air.

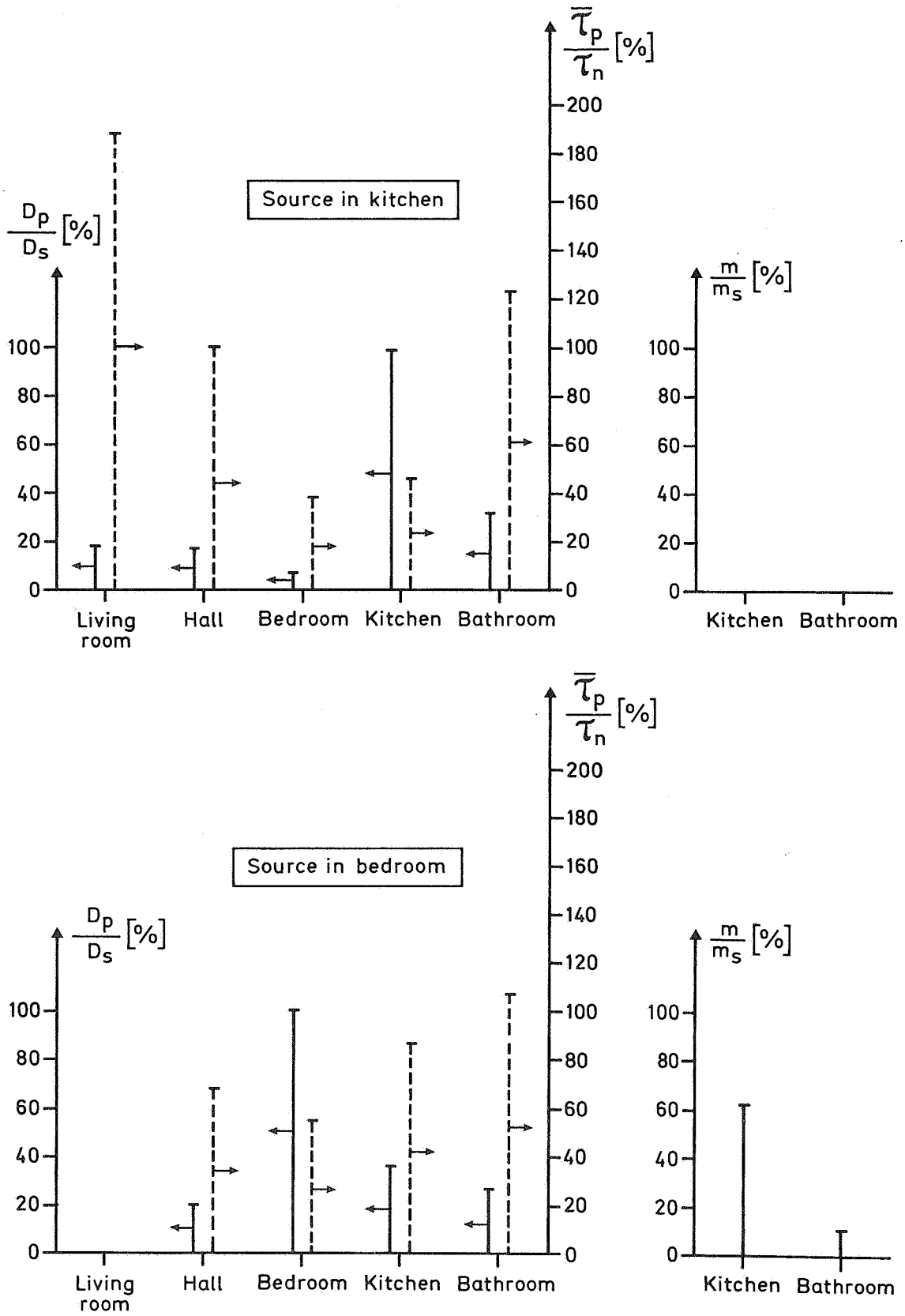


Figure 3b. Extract system and internal doors closed. 'Contaminant' exposures and mean age of 'contaminant'.

This focuses on the problem of making absolute measurements with this pulse technique.

First, concerning the results on the air distribution, we see that closed internal doors give rise to a slight increase in the air-exchange efficiency compared to the case with the internal doors open. This is in accordance with results reported earlier from experiments in a small two room test house, see Sandberg[2].

With the internal doors open quite a large inflow of outdoor air to the hall (64% of the total flow rate) is predicted. When the doors are closed the predicted inflow of air to the hall drops to 12% of the total inflow. This is fully in accordance with the properties of the constant concentration method, see discussion in Sandberg and Blomqvist[3]. The constant concentration method essentially predicts the inflow of 'fresh' air to each room. 'Fresh' air can come to a room from the neighbouring rooms and not only directly from outdoors. 'Contaminant' released in the kitchen is less dispersed than 'contaminant' released in the bedroom. This is what one should expect since air is extracted from the kitchen. Even when the doors are open almost all 'contaminant' released in the kitchen is also extracted from the kitchen. The rest of the 'contaminant' flows direct towards the bathroom. No concentration is recorded in the middle of the hall. This is due to the layout of the house with the bathroom located directly opposite the kitchen.

4.2 Balanced system

Figures 4a-4b (Case: Internal doors open) and figures 5a-5b (Case: Internal doors closed) shows, in similar manner as in section 4.1, the results from the balanced system.

We see from the figures that qualitatively we have the same results as for the extract system.

4.3 Comparison between the extract and balanced system

If we have a very low infiltration rate through non-purpose provided openings, that is to say a very tight building envelope, then we should not expect any greater differences in internal air move-

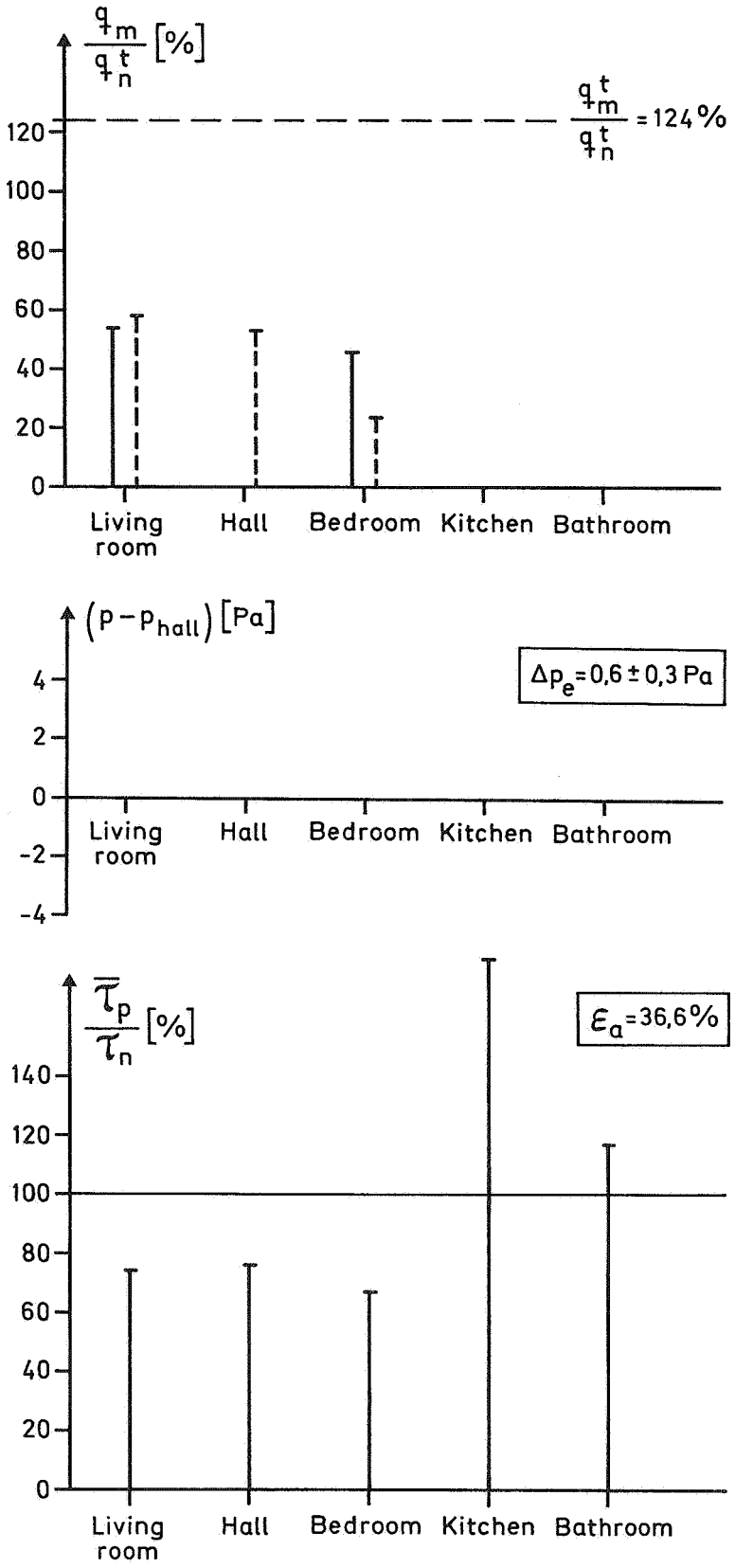


Figure 4a. Balanced system and internal doors open. Supplied air, pressure distribution and mean age of air. The mechanical supply is denoted by (———).

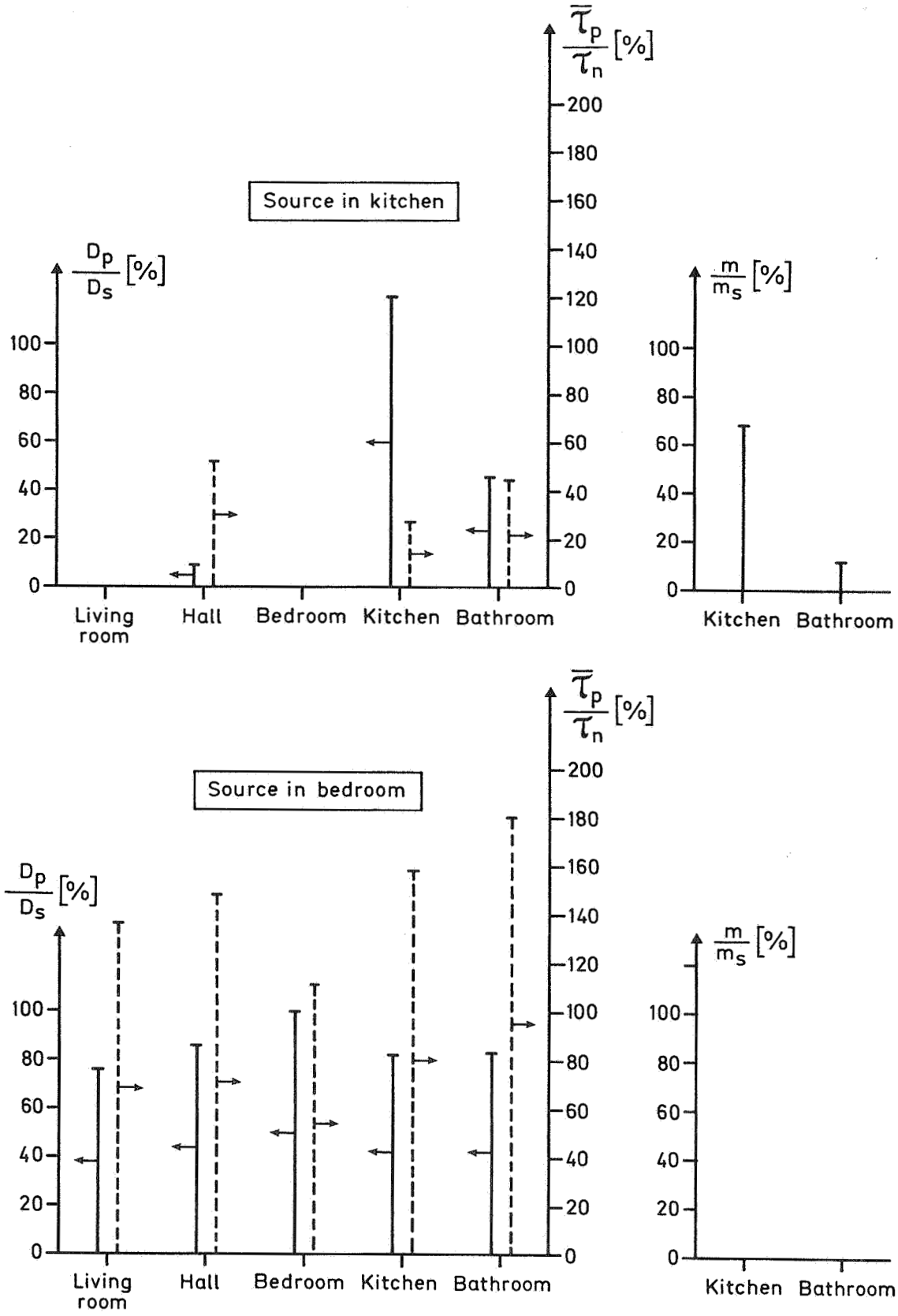


Figure 4b. Balanced system and internal doors open. 'Contaminant' exposures and mean age of 'contaminant'.

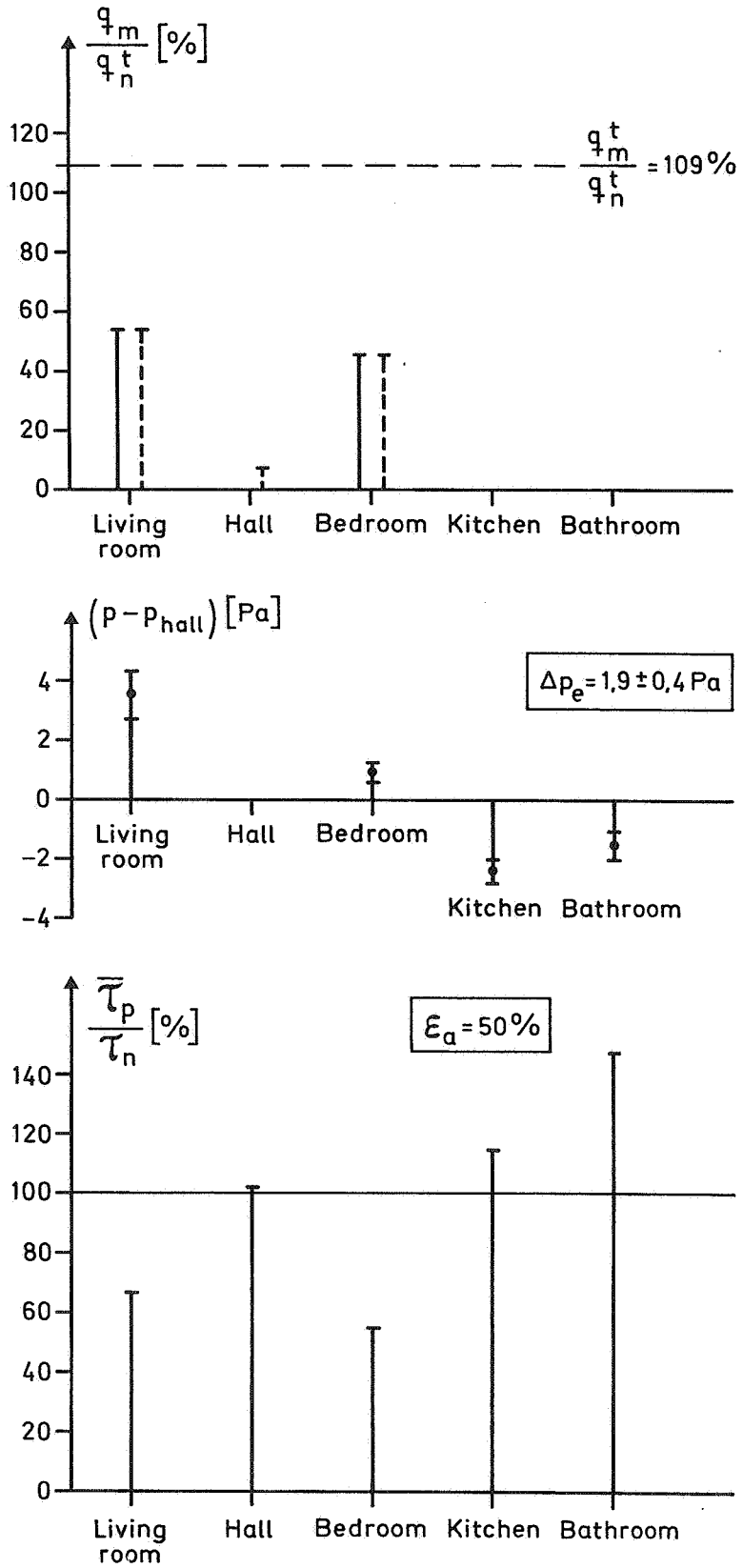


Figure 5a. Balanced system and internal doors closed. Supplied air, pressure distribution and mean age of air. The mechanical supply is denoted by (———).

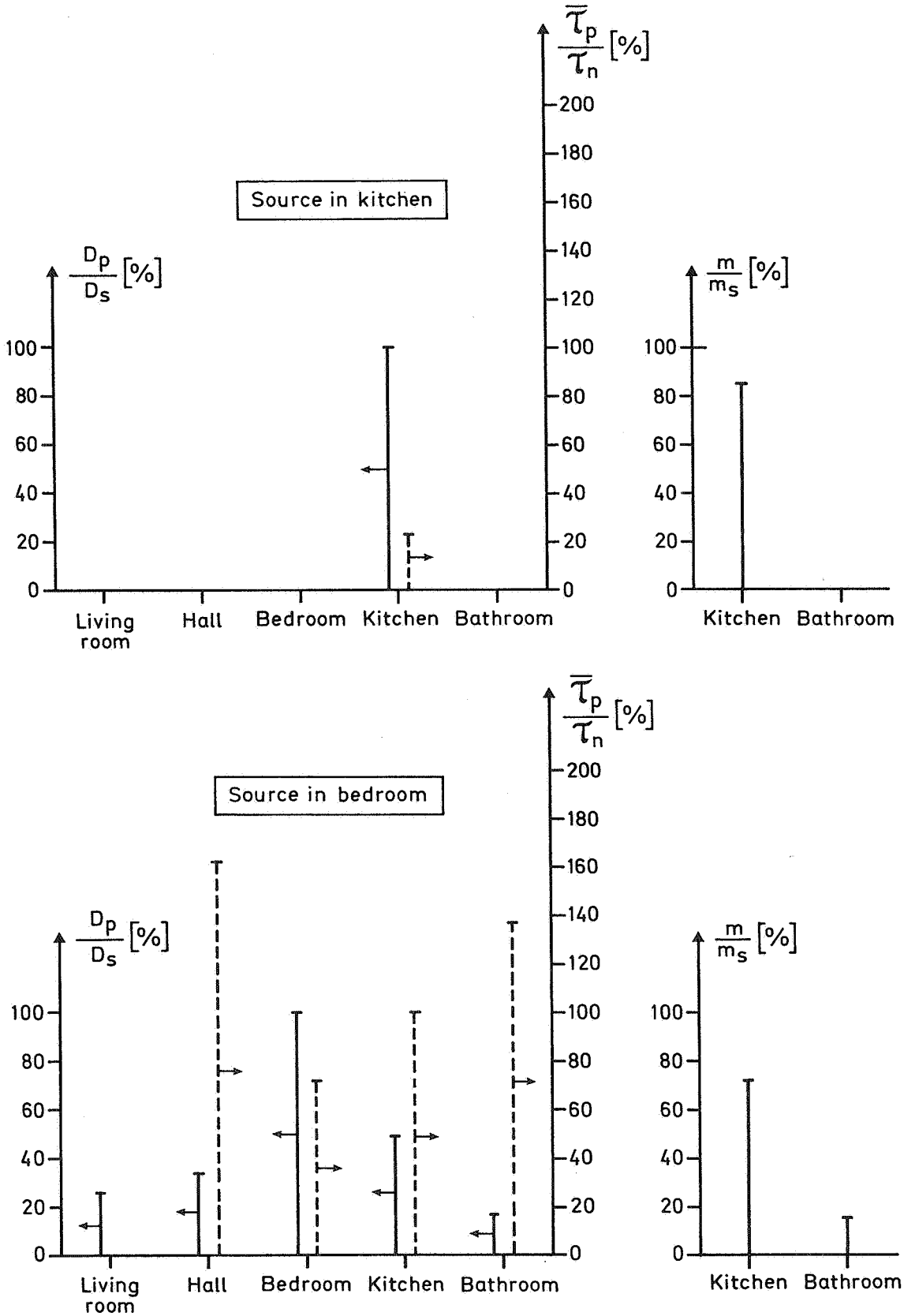


Figure 5b. Balanced system and internal doors closed. 'Contaminant' exposures and mean age of air.

ments due either to mechanical extract system or balanced system. The prerequisite for this statement to hold is of course that we have the same nominal flow rate, that the intake and the supply points are at the same location, and that the air is extracted from the house at the same points on both occasions. The most pertinent data of performances recorded is summarized in table 1.

TABLE 1. Comparison between ventilation systems.
Parenthesis indicate closed door cases.

	Air-exchange effectiveness	Source in kitchen		Source in bedroom	
		Ventilation efficiency	Mean age of contaminant	Ventilation efficiency	Mean age of contaminant
Extract ventilation	54% (57%)	380% (199%)	0.39 h (0.91 h)	123% (109%)	0.71 h (1.12 h)
Balanced ventilation	37% (50%)	389% (406%)	0.53 h (0.46 h)	58% (93%)	2.20 h (1.42 h)

The mean age of the 'contaminant' in the source room is a measure of how fast the 'contaminant' is evacuated from that room.

From table 1 we can see some differences between the systems. For a 'contaminant' released in the kitchen in a closed door case, the average ventilation efficiency becomes higher with the balanced system in operation. A possible explanation for this behaviour is that a somewhat greater positive pressure difference (see figure 5a) between the supply air room and the kitchen is created with the balanced system in operation. This prevents the spread of the 'contaminant' to rooms with a higher pressure. This gives rise to a low average 'contaminant' exposure in the whole house.

The difference in air-exchange effectiveness between the ventilation systems when the internal doors are open is difficult to explain. When the balanced system is in operation the mean age of the air in the kitchen becomes very great, see figure 4a. A repeat test with a balanced system and an open door case gave an air-exchange effectiveness equal to 51%. Even in this test the mean-age of air in the kitchen is much larger than in other rooms.

5. Conclusions

At the tested flow rate no greater systematic differences in performance between a balanced and an extract system could be found. This is what one should expect for a house as tight as the test house. For both systems the closed door case gave a slight higher air-exchange effectiveness.

'Contaminants' released in the kitchen in a closed door case were somewhat less spread to other rooms with the balanced system in operation compared to the case with the extract ventilation system in operation. This is probably an effect of somewhat greater pressure drop between rooms with the balanced system in operation.

With the doors open and release of 'contaminants' in the kitchen, the bulk of 'contaminant' (70-80% of the total) is extracted from the kitchen itself. The rest is only spread to the bathroom.

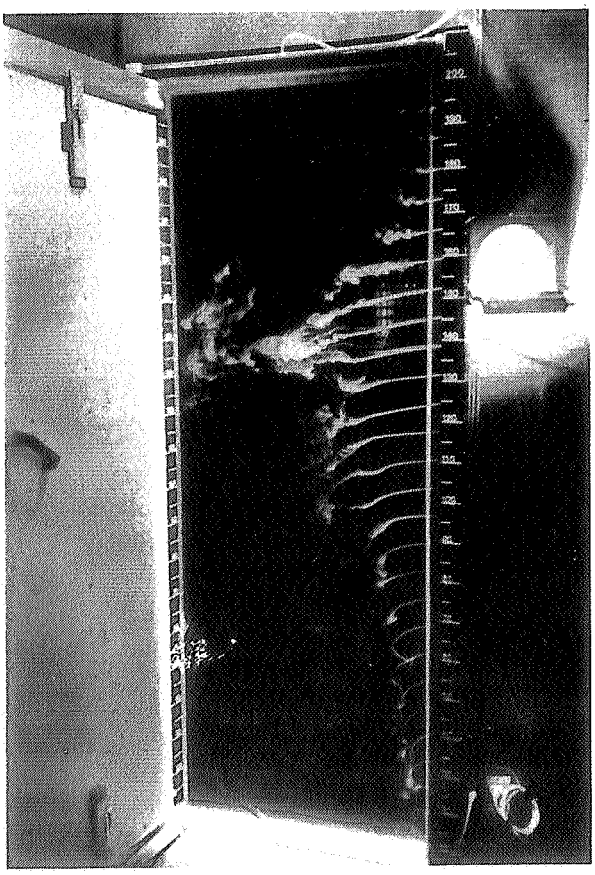
The tests reported here were undertaken for only one flow rate. Further tests at other flow rates must be undertaken in order to interpret the results obtained and to gain a better understanding of the properties of different systems. The balance between individual extract points and supply points should also be systematically varied.

Regarding the experimental technique, it was found that, even in a controlled environment such as the laboratory, it is often difficult to make estimates of absolute quantities such as e.g. the amount of 'contaminant' from different extract points. Drift of the analyzers zero level is one source of error.

6. References

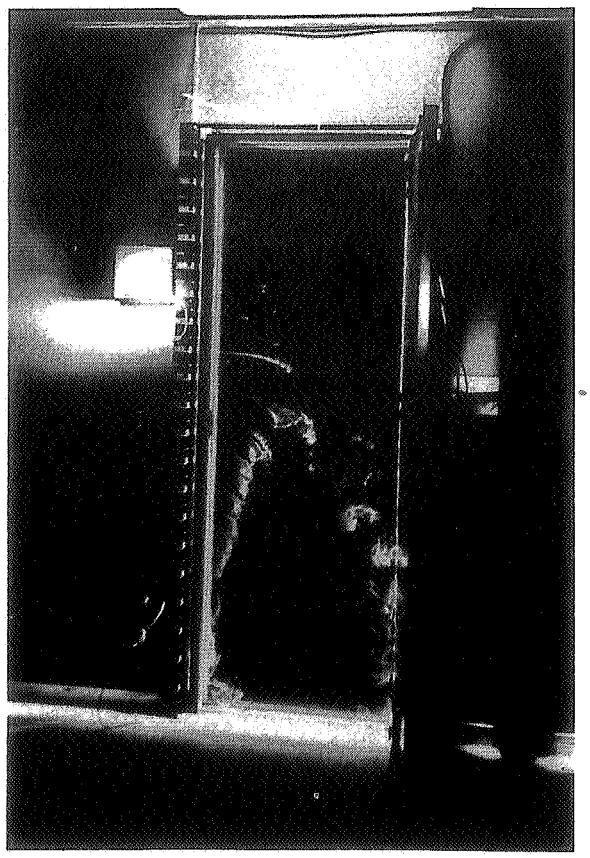
1. Sandberg, M. and Sjöberg, M. 'The use of moments for assessing air quality in ventilated rooms'. Building and Environment, UK, Vol 18, 1983, pp 181-197.
2. Sandberg, M. 'The definition of ventilation efficiency and the efficiency of mechanical ventilation systems'. Proceedings 3rd AIC Conference, 1982.
3. Sandberg, M. and Blomqvist, C. 'A quantitative estimate of the accuracy of tracer gas methods for determination of the ventilation flow rates in buildings'. To appear in Building and Environment, UK, 1985.

APPENDIX



Flow visualization. Balanced ventilation. All pictures taken from the hall.

Door between hall and bedroom

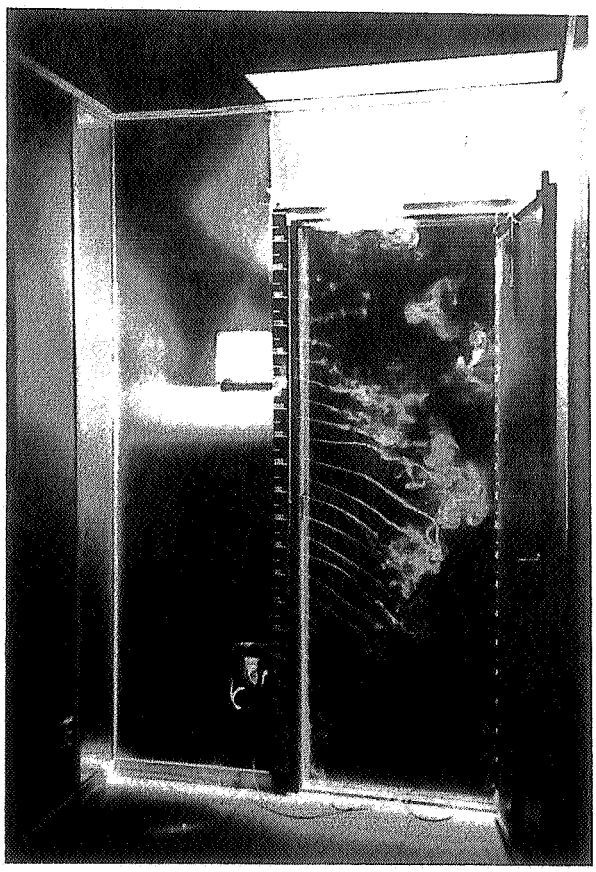


Door between hall and kitchen



Flow visualization. Balanced ventilation. All pictures taken from the hall.

Door between hall and living-room



Door between hall and bath-room

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 16

MECHANICAL VENTILATION SYSTEM REQUIREMENTS AND MEASURED RESULTS FOR HOMES CONSTRUCTED UNDER THE R-2000 SUPER ENERGY-EFFICIENT HOME PROGRAM

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SYNOPSIS

The R-2000 Super Energy-Efficient Home Program is a co-operative industry/government initiative sponsored by Energy, Mines and Resources Canada (EMR) and delivered by the Canadian Home Builders' Association. The program supports building industry development, training of builders and the construction of energy-efficient houses incorporating high levels of insulation, a well sealed air barrier and mechanical ventilation systems with heat recovery.

In 1983, with assistance from the Buildings Energy Conservation Sub-Committee (B.E.C.S.), EMR embarked on a field monitoring program which included air quality and ventilation system testing of approximately 300 R-2000 super energy-efficient demonstration homes and a sample of control homes that reflect conventional building practice. B.E.C.S. is responsible for general federal funds allocation in the area of energy conservation research and development.

This paper reviews the ventilation system requirements for R-2000 Homes and compares these requirements with ASHRAE Standard 62-81, the measured airflow capacities of the installed heat recovery ventilators and the average air change rates for homes using the Capillary Adsorption Tube Sampling (CATS) procedure. The CATS procedure, developed at the Brookhaven National Laboratory, uses a passive tracer gas source that emits a perfluorocarbon tracer (PFT) gas and a passive air change sampler that collects the emitted tracer gas during a 30 day test period.

The paper concludes that the response to the program is favourable; R-2000 Homes are generally performing within the tolerances of the program criteria and air quality in R-2000 Homes compares favourably with conventional homes. Formaldehyde levels in R-2000 and control homes were identical and well below the Health and Welfare Canada guideline of 0.1 ppm. The average air change rates were 42% higher in R-2000 Homes then in control homes. On average, the measured capacity of ventilation systems met program criteria but the systems generally were not balanced.

Further refinements to technical criteria and compliance requirements are under development to ensure quality assurance and to provide maximum flexibility to accommodate a variety of ventilation strategies.

1. INTRODUCTION

In 1980, Energy, Mines and Resources Canada in cooperation with the Canadian Home Builders' Association (CHBA) established the R-2000 Super Energy-Efficient Home (SEEH) Demonstration Program for the construction of homes to the R-2000 energy performance target and technical criteria. The initial demonstration program was recently extended to 1990.

R-2000 Homes are characterized by high levels of insulation, controlled air leakage through improved air barrier techniques, mechanical ventilation coupled with heat recovery, improved heating systems and, where possible, utilization of passive solar energy. Program emphasis was placed on industry development, training and education programs for the industry, public awareness and monitoring and evaluation.

Since 1980 the R-2000 Home Program has become an important catalyst in the evolution of energy-efficient housing technology through: the development of standard performance requirements; the development of consensus standards for products and equipment; the establishment of improved inspection and compliance procedures; the implementation of field monitoring activities; and, the support of laboratory testing of products and equipment in order to provide quality assurance for R-2000 Homes.

These activities have also provided direction for improvements to areas of housing technology that apply to conventional housing. In particular, the program has chosen to deal with ventilation and air quality issues that also apply directly to conventional housing units. Although current standards and guidelines indicate desired ventilation rates for all residential buildings, few new conventional residential buildings in Canada consistently comply with recognized ASHRAE Standard 62-81[1] minimum ventilation requirements or have the capability to provide an adequate intermittent maximum ventilation capacity when demanded by occupants. This is not surprising, since residential building codes do not require the continuous operation of whole house mechanical ventilation systems or require that ventilation air be supplied throughout the house. The R-2000 Program Technical Criteria include such requirements.

To date, there are only 400 registered R-2000 demonstration homes built across Canada despite the fact that there is considerable public interest and many builders want to build a greater number of units. Large volume construction will not proceed until adequate inspection, testing and quality assurance procedures exist throughout the industry.

2. TECHNICAL REQUIREMENTS FOR R-2000 HOMES

The R-2000 Program Technical Criteria[2] are basically performance-oriented and not prescriptive. The energy consumption target can result in a 50 to 80 percent reduction in energy consumption as determined by the HOTCAN computerized energy analysis program developed by the National Research Council of Canada[3]. The performance approach encourages builders to treat the whole house as a system using the best combination of features and options to suit their particular circumstance.

The technical criteria also include the requirement that the airtightness of the building envelope not exceed 1.5 air changes per hour (ACH) at 50 Pascals pressure difference when tested in accordance with the R-2000 test procedure. This procedure is based on the preliminary Canadian General Standards Board draft standard for testing the equivalent leakage area of homes[4]. This provision helps protect the building envelope from potential moisture damage and permits the efficient operation of balanced Heat Recovery Ventilators (also known as air-to-air heat exchangers).

Other specific technical criteria were established primarily for health and safety reasons. In particular, these requirements include provision for a controlled mechanical ventilation system which ensures adequate air quality; selection of combustion appliances which prevent accidental backdrafting; and, provisions to provide replacement air for appliances such as clothes dryers, central vacuums, kitchen fans and combustion equipment which exhaust air to the outside.

As the program evolves, considerable effort is being devoted to the refinement of these criteria by providing support for the establishment of consensus standards through existing national standards writing organizations such as the Canadian Standards Association (CSA) and by supporting the development of the products, equipment and skills necessary for quality assurance.

3. VENTILATION REQUIREMENTS FOR R-2000 HOMES

Given the lack of standards or experience in Canada regarding mechanical ventilation requirements for residential buildings, the Swedish standard of 0.5 ACH was adopted as the R-2000 criterion for the minimum installed mechanical ventilation system capability required in all R-2000 Homes[5].

The technical criteria require the house ventilation system to maintain a neutral pressure - neither forcing household air into the wall structure nor drawing products from the building structure into the air of the occupied space.

Although negative pressures are frequently viewed as beneficial with respect to avoiding moisture problems in structures, they can influence the diffusion of pollutants from the building structure or from soils into the basement. By operating the house close to neutral pressure and by installing a continuous air barrier, potential problems are minimized.

In order to ensure neutral pressure at all times, make-up air must be provided to replace air exhausted by central vacuum cleaners, kitchen exhaust fans, clothes dryers, and other air-exhaust appliances whose operation may induce negative pressures in the house. This must be done separately from the central mechanical ventilation system.

Figure 1 represents a recommended installation for a whole house ventilation distribution system installed in a home with perimeter radiant heating while Figure 2 illustrates a typical system using an existing forced air distribution system.

As a result of the initial field monitoring and laboratory testing of the Heat Recovery Ventilators (HRVs) which are used in virtually all R-2000 Homes, significant refinements continue to be made to the initial criteria to ensure quality assurance. Refinements under development, beyond the initial specification for a minimum installed capacity for a ventilation system, include the establishment of a minimum continuous ventilation rate of 5 l/s to be delivered to each room based on ASHRAE Standard 62-81.

Specifications are being developed for acceptable manual or automatic control strategies to increase ventilation rates to maximum capacity to handle moisture and contaminants sources when the need arises. The revised specifications would also permit greater flexibility when installing ventilation systems, including the possibility of dual or separate ventilation elements (one for continuous minimum operation and one for intermittent maximum capacity) within the system.

The Program is also considering a requirement for permanently installed airflow sensors in the ventilation system to provide a simple means for balancing, inspecting, monitoring and maintaining the ventilation system.

Recent refinements include a provision that no longer permits naturally aspirating space and water heating equipment to be installed in R-2000 Homes, in order to avoid potential problems concerning backdrafting or spillage of combustion products.

Support has also been provided to Canadian Standards Association (CSA) for the development of preliminary standards for testing and rating the performance of HRVs[6] and the development of HRV installation guidelines[7]. Support includes the testing of HRV equipment against the preliminary CSA standard by the Ontario Research Foundation (ORF)[8]. The results of both the CSA and ORF work have already been incorporated into the R-2000 Program requirements.

A national training program for installers has been developed and implemented by the Heating, Refrigerating and Air Conditioning Institute (HRAI)[9] to train contractors to design and installation of HRV systems according to the new installation guidelines.

A national technical advisory committee representing interested and concerned groups has been established to refine program criteria to ensure that R-2000 Homes continue to represent a high quality product which meets or exceeds all accepted good building practice.

The following represents a summary of results from a number of field monitoring activities related to the performance of ventilation systems installed in R-2000 Homes.

4. MONITORING PROCEDURES

4.1 Background

In 1983, Energy, Mines and Resources Canada and the Buildings Energy Conservation Sub-Committee (B.E.C.S.), which is composed of representatives from Health and Welfare Canada, National Research Council of Canada, Public Works Canada, Canada Mortgage and Housing Corporation, and Indian and Northern Affairs, established an advisory committee to review and approve funds and monitoring procedures for an extensive R-2000 field monitoring program for 1983-84 and subsequent years.

The initial monitoring program was general in scope, concentrated on indoor air quality and ventilation testing which included all R-2000 Homes and a sample of conventional control homes. Further detailed monitoring studies will be defined and undertaken during subsequent years depending on the initial results of the general field monitoring program.

The control homes were recently constructed by R-2000 builders using similar building materials as R-2000 Homes but not constructed to R-2000 insulation, airtightness and ventilation requirements.

The monitoring activities were implemented by technicians in EMR regional offices located in each province and territory in Canada. Individuals from each of these offices were trained in the specifics of air quality testing, questionnaire completion and energy metering. Laboratory and field support was provided by the Ontario Research Foundation (ORF), regional engineering firms and several laboratories in Canada and the U.S.A.

Field equipment was selected after laboratory evaluation and field testing products for ease of use, accuracy, response time and sensitivity, field durability and cost.

An extensive 200 page monitoring manual has been prepared for field technicians on all aspects of the monitoring program including administrative procedures, home occupant liaison, questionnaire completion, air quality monitoring procedures, ventilation system testing, energy metering and procedures for remedial measures.

A micro-computer based technical data base has been developed and is linked to a statistical program to analyse all program technical information.

Detailed background information for each R-2000 Home was provided by the builder upon completion of the home. This included a set of construction plans. Builder final reports described the building envelope characteristics, mechanical systems, incremental costs of construction, consumer response and attitudes, and airtightness test results. In addition, a HOTCAN computer energy analysis was performed on each home to predict monthly energy consumption for each dwelling. House surveys by regional technicians provided supplementary information during site visits. Where possible, similar information was gathered on a sample of comparative control homes.

Table 1 provides general information on the construction characteristics of both R-2000 and control homes.

4.2 Ventilation Compliance Testing

The required ventilation capacity for all R-2000 Homes was determined at the building plans examination stage where the interior heated volume of the house (including any basement area) was calculated and the required ventilation capacity was determined according to the program requirement of 0.5 ACH.

All R-2000 Home construction plans were reviewed and the minimum ASHRAE ventilation rate calculated based on 5 l/s per habitable room. Combined rooms such as living/dining or dining/kitchens were regarded as individual rooms. For basement and utility areas 10 l/s was used for the calculation since these areas were not specified in ASHRAE 62-81.

HRV testing included the measurement of airflow rates and static pressures to determine compliance with the R-2000 program ventilation criteria of 0.5 ACH and to identify and document installations, equipment sizing and control settings.

Airflow tests were performed on both the supply air stream and the exhaust air stream using a TSI Model 1650 Air Velocity Meter. External static pressure measurements were performed using a Dwyer 2000-0 Magnahelic Differential Pressure Gauge and Probe. These were used to derive airflows from specific fan curves for each HRV.

The HRV testing was conducted at the normal homeowner operating settings and at the high speed capacity of the unit. The measurements provided only a general approximation of the ventilation system performance and were not be used for any rating purposes concerning the thermal performance of the different HRVs.

4.3 Air Change Rate Monitoring

The average air change rate of the house over time was determined using a technique developed at Brookhaven National Laboratory, known as the Capilliary Adsorption Tube Sampling (CATS) procedure[10]. The technique was developed to monitor the air change rate in residential buildings over a prolonged period of time. Calibrated air change sources emit a perfluorocarbon inert tracer (PFT) gas while passive air change samplers collect the emitted tracer gas.

Four sources were installed on exterior walls and four samplers were installed on interior partition walls for a 30 day test period when all houses were operated under normal conditions. Gas chromography of the collected tracer gas was conducted upon each of the samplers and information obtained on temperature, house volumes, and wind conditions during the test period was used to determine the air change rate of the home.

Sulphur hexafluoride (SF6) measurements were completed in a limited sample of R-2000 and control homes as a further indicator of the average air change rate in the homes and as a cross reference to the CATS 30 day average air change rate measurement results. The SF6 measurement procedures conformed closely to those described by Tamura and Evans of the National Research Council of Canada[11].

The SF6 tracer gas was injected into the forced air distribution system or directly into the air space. Floor fans were utilized for tracer gas mixing to minimize the length of the test and to aid in distributing the gas.

Three sampling sites were required for each home: basement air space, ground floor main living area and second storey area (second ground floor point for bungalows). Six air samples were collected at ten minute intervals at each sample site.

The SF6 testing was conducted while the ventilation system was operating at maximum capacity and all exhaust fans/equipment operating; while the ventilation system was operating at normal setting (low speed) or exhaust fans were operating in such a manner as determined by the homeowner; and, with all ventilation and exhaust fans/equipment shut off except for furnace recirculating fans if the system was designed to operate continuously.

4.4 Formaldehyde Monitoring

Formaldehyde gas monitoring was performed in R-2000 and comparative control homes approximately six months following construction to determine the impact of the ventilation systems upon the concentrations and distribution of formaldehyde gas.

The EMR regional office technicians installed dosimeters purchased from Dupont de Nemours (Wilmington, Delaware) in a living and sleeping area in each of the R-2000 and control homes built by R-2000 b ilders.

The formaldehyde dosimeters were installed during the early spring months when wind induced natural ventilation is reduced and building materials are thawing (thereby possibly releasing increased quantities of moisture and formaldehyde).

Three formaldehyde dosimeters were installed in each home for seven days: one in the bedroom, one in a central location and one remaining unexposed to serve as a laboratory control unit. Temperature and humidity measurements were taken at the three installation locations to determine the initial environmental conditions of exposure. The dosimeters where then sent to I.E.C. Beak Laboratories, Mississaugua, for laboratory analysis after the seven day exposure period.

5. MONITORING RESULTS

5.1 Ventilator System Compliance Testing

The R-2000 Program requires that the house ventilation system be capable of supplying 0.5 ACH capacity. Approximately 98% of the builders selected a ventilation system with sufficient design airflow capacity to meet this specification, based on manufacturers' product information. All R-2000 Homes incorporated an HRV as the prime ventilation system. Only one comparative home had a continuous ventilation system.

Table 2 indicates that on average the measured installed ventilation capacity in R-2000 Homes did meet the program criteria. The measured mean mechanical ventilation system capacity was equivalent to 0.50 ACH for field installations.

The addition of natural air leakage of .05 ACH based on the average airtightness of 0.85 ACH at 50 Pascals for R-2000 homes increases the average ventilation capacity to beyond the program's requirement of 0.5 ACH. There was significant variation around the mean.

Generally, smaller size homes met the program requirements while some larger homes failed to meet the 0.5 ACH target. This result reflected the lack of HRVs with sufficient capacity to meet the requirement for an installed capacity of 0.5 ACH in large homes.

The mean measured capacity was 43% higher than the minimum recommended air change rate based on ASHRAE Standard 62-81 which averaged 0.35 ACH for the R-2000 Homes. The measured capacity of ventilation systems exceeded the ASHRAE minimum ventilation rate in 95% of R-2000 homes (273 out of 283 homes). The average ASHRAE recommended minimum ventilation rate for all R-2000 Homes was 50 l/s.

The results also indicated a potential conflict between the R-2000 Program requirement for 0.5 ACH capacity and the ASHRAE 62-81 per room minimum ventilation requirements. Larger homes that were sized to the 0.5 ACH capacity far exceeded the average minimum air change rate based on ASHRAE requirements of 0.32 ACH.

Proposed changes to the ventilation requirements would permit the installation of ventilation equipment for continuous minimum operation based on ASHRAE which could be separate from the equipment required to provide intermittent capacity (0.5 ACH) in large homes. The availability of improved "third generation" ventilation equipment should also resolve most problems of system capacity compliance in large homes.

Table 2 also presents comparisons of the measured ventilation capacity for R-2000 Homes heated with electricity and homes using fuel-fired heating and indicates that the results are similar. The ventilation capacity of homes with electric heating systems measured 11% higher than those with fuel-fired heating systems. The majority of the fuel-fired heating systems were forced-air gas heating systems.

The results should not be surprising since many electric baseboard heated homes used HRV equipment, ducting and installation procedures similar to those HRVs installed in homes using forced-air heating systems to distribute air.

Initially, many baseboard heated homes supplied ventilation air to the basement or to one point in the living area and relied on natural convection to distribute air throughout the house.

These strategies are no longer permitted in R-2000 homes since ventilation air must now be delivered to each room of the house in accordance with ASHRAE 62-81. This will result in more ductwork and higher external static pressures for HRVs installed in electric baseboard homes since the HRVs must now distribute air to each room of the house.

Table 3 indicates that only 16% of ventilation systems were balanced within the 10% range as required in the R-2000 technical criteria. This was determined by comparing the amount of supply air entering the ventilator to the amount of exhaust air leaving the ventilator.

It was apparent that the majority of installers did not carry out field balancing on the system. Less than 15% of the installations contained balancing dampers. This should not be surprising since most installers did not have access to balancing equipment or were not aware of potential problems due to equipment imbalance.

High negative pressure conditions could increase the level of pollutants such as radon entering the home through cracks in the building foundation, and could also induce combustion appliance backdrafting. Conversely, a high positive pressure condition may tend to force moisture into the building shell. As well, any HRV imbalance may affect the heat recovery efficiency and increase energy consumption for space heating.

Except for the issue of balancing, the above results indicate that on average the installed capacities of units are within the tolerances of the program criteria and above minimum ASHRAE ventilation requirements. However, there was considerable variation around the average values, with some homes experiencing significantly higher or lower ventilation air change rate capacities.

Monitoring activities indicate that measured results were dependent more upon the quality of the installation than the airflow capacities of many HRVs. It was evident that poor duct design, excess use of flexible duct materials and use of 125 mm diameter and smaller ducts resulted in a significant reduction in airflow in some units. Most of these problems can be attributed to lack of experienced and trained installers.

Balancing of mechanical ventilation systems would normally involve installing a simple damper in the duct with the highest airflow in order to reduce the airflow rate to balance the system. Reducing the higher airflow may result in a lowering of the system capacity below R-2000 requirements. Extensive changes may have to be made to the ventilation equipment and ductwork in order to provide minimum ventilation capacities when measures are taken to balance existing systems.

Although very few of the home occupants expressed any concern over the comfort levels experienced in their homes, steps are being taken to ensure that all units are balanced and meet minimum airflow requirements. The R-2000 monitoring program will continue to test all R-2000 homes to verify that the ventilation requirements are being provided.

The R-2000 Program is preparing revised guidelines for the installation of whole house mechanical ventilation equipment which make it mandatory to measure airflows and balance units at the time of installation. National training courses for installers will greatly improve compliance with program criteria.

5.2 Measured Air Change Rates

The CATS air change rate monitoring results provide information concerning the operation of the mechanical ventilation systems by occupants and the effect of air infiltration, door openings, combustion air and supplemental ventilation and air exhausting equipment operation (range hoods, clothes dryers, etc.) over a 30 day period. The results in this paper were based on 123 R-2000 homes and 40 control homes.

Since the CATS procedure is relatively new, initially, some comparisons were made between the CATS perfluorocarbon test procedure and sulphur hexafluoride (SF6) spot measurements in 9 homes.

Table 4 indicates that, on average, there was a good comparison between the SF6 and the 30 day CATS measurements even though the SF6 testing was only a spot measurement completed at the time the CATS dosimeters were installed.

Additional work is underway to validate the CATS procedure in a number of homes which are being monitored using continuous tracer gas techniques. This activity will commence in the fall of 1985.

The analysis indicates that the CATS average air change rate of .37 ACH in R-2000 homes was 26% lower than the measured capacity of the mechanical ventilation system. This is to be expected since many units were run continually at a low speed setting and since some occupants operated units intermittently (see Table 5).

The CATS average air change rate of in R-2000 homes was 42% higher than the average of .26 ACH in control homes. This is not unreasonable since measurements were taken in the spring when wind and stack effects are minimal, windows have not yet been opened and the control homes do not have mechanical ventilation systems.

A possible explanation for lower results in some control homes may have been the lack of precise information on house volumes since construction plans for control homes were not available for examination. Builders and field technicians were relied upon to supply this information.

The CATS average rate of 0.37 ACH for R-2000 Homes was slightly higher than the calculated ASHRAE air change rate of 0.35 ACH, Table 2, indicating that R-2000 Homes are performing in accordance with ASHRAE minimum requirements.

Air change rates based on ASHRAE were not available for control homes but it appears that the average CATS air change rate of .26 ACH for control homes may not meet ASHRAE minimum requirements.

Factors such as house type and size, space heating distribution systems, ventilation supply air discharge and measured air exchange rates were examined and presented in Table 5. Most analysis was conducted only on R-2000 Homes, since only one control home was equipped with a mechanical ventilation system.

Houses with volumes less than 500 m3 and homes with slab-on-grade or crawlspace foundations exhibited higher average air change rates. This is likely a reflection of the capability of the HRVs to provide a higher air change rate in smaller homes even at low speed settings.

Table 5 indicates that the mean measured CATS results for R-2000 homes heated with electricity where identical to those homes with fuel-fired systems but the CATS air change rates for control homes heated with electricity were substantially lower than for control homes with fuel-fired systems. Most of the control homes that were heated with electricity used baseboard heating systems.

R-2000 homes with electric baseboard heating had CATS average air change rates of 0.32 ACH as compared to those homes with forced-air heat distribution systems which averaged 0.39 ACH.

Control homes also exhibited much lower average air change rates for homes with electric baseboard heating with average CATS measurements of only 0.18 ACH as compared to 0.30 ACH for forced air heating systems. The lack of an active chimney flue may be a contributing factor for low air change rates in electric baseboard homes.

Analysis of the results based on the type of ventilation air discharge strategy indicates that the CATS air change rate results were 15% lower for R-2000 Homes where ventilation air was discharged into the basement rather than the living space.

Results for houses where the ventilation air was discharged into the return air duct of a forced air system were lower than expected. This may be due to to the small sample size and the possibility that many furnace fans were not operating continuously during the spring period when the measurements were conducted.

These results indicate that R-2000 homes have higher air change rates than control homes and that air distribution strategies have an impact on the whole house ventilation rates and ventilation efficiency for both R-2000 and control homes.

The CATS results will also assist in determining appropriate air change rates to be used when determining the thermal performance of R-2000 homes.

5.3 Preliminary Formaldehyde Results

The following formaldehyde results are based on 248 R-2000 homes and 62 control homes. The Health and Welfare Canada indoor air guideline of 0.1 ppm is used as a benchmark when comparing the results for the R-2000 Homes with the control homes.

Testing was performed in the spring months, concurrent with the CATS monitoring activity when formaldehyde offgassing is expected to be at an elevated level due to increased ambient temperatures, reduced wind induced ventilation and increased moisture content in building materials.

Table 5 presents results of measurements taken in the bedrooms of each home. Both bedroom and living area measurements were similar in R-2000 and control homes.

The test results indicate that both the R-2000 and control homes have identical average formaldehyde concentrations of 0.06 ppm. The average levels were well below Health and Welfare guideline of 0.1 ppm with only 8% of R-2000 Homes and 9% of control homes exceeding 0.099 ppm.

Relationships were hypothesized between formaldehyde levels and various contributing factors such as house type, space heating distribution systems, ventilation air discharge and measured air change rates. Most analysis was conducted only on R-2000 Homes, since only one control home was equipped with a mechanical ventilation system.

The results in Table 5 indicate little difference according to house size, volumes less than and greater than 500 m3 but slab on grade and crawlspace homes exhibit levels 26% lower than average. It should be noted that the sample size was quite small.

Baseboard electric homes on average exhibited a mean formaldehyde concentration of 0.066 ppm or a 15% higher level than those homes with forced air heating systems. This result was consistent for bedroom and living room measurements in R-2000 and control homes.

The results also indicate that formaldehyde levels in homes that simply discharged supply air into the basement and relied on natural convection to circulate air to the upper portions of the home were 0.066 ppm or 18 % higher then the average levels for houses using other ventilation air discharge strategies.

Analysis of only those homes with both CATS and formaldehyde test results, Tables 6, indicates that although the CATS air change rates were 40 % higher in R-2000 Homes, the average formaldehyde levels were not any lower then in control homes.

Preliminary formaldehyde results from repeat testing of 134 R-2000 homes and 22 control homes in the spring, 1985, indicates that control homes have average formaldehyde levels 23% higher than R-2000 homes. These new results may indeed indicate that lower air change rates are in resulting in higher formaldehyde levels in control homes. These new results will be analyzed shortly.

Table 6 also indicates that the average CATS air change rates were lower and the formaldehyde levels higher for R-2000 and control homes with electric baseboard heating systems.

R-2000 homes where ventilation air was discharged into the basement and natural ventilation was relied upon to distribute ventilation throughout the house also exhibited higher formaldehyde levels and lower air change rates than homes where the fresh air was discharged in the living area.

Additional analysis of the 17 R-2000 Homes that exceeded Health and Welfare Canada guidelines, indicates that not one home had CATS air change rates in excess of ASHRAE minimim requirements which were equivalent to 0.32 ACH for these homes. The CATS average air change rate for these homes was 0.16 ACH or 57% lower than the average of 0.37 ACH for all R-2000 Homes although the average measured capacity of the ventilation systems was 0.46 ACH.

Air distribution problems may have been a major contributing factor given that electric baseboard heating systems were in 70% of these homes and 47% discharged ventilation air into the basement. Other factors such as poor controls, intermittent operation and occupant behaviour may also be factors for such low air CATS air change rates and high formaldehyde levels.

These results indicate that both total air change rate and ventilation air distribution efficiency are major factors in controlling formaldehyde levels. Current program criteria now require that ventilation air be distributed, continuously, to each room of the house at the ASHRAE minimum of 5 l/s per room.

Measures are also being taken to reduce formaldehyde levels in the small group of homes that exceeded Health and Welfare Guidelines and formaldehyde monitoring will continue during the 1984/85 monitoring period on all R-2000 and control homes to determine if levels have dropped over time.

6. CONCLUSIONS

The overall response to the program is generally favourable and the R-2000 Program is showing that well-sealed homes can be constructed to provide air quality at least comparable to conventionally built homes.

The R-2000 Technical Criteria concentrate on ventilation and indoor air quality issues. The program criteria currently require a balanced mechanical ventilation system capable of 0.5 ACH and an air distribution system that supplies the ASHRAE minimum of 5 l/s per room. Installation guidelines have been established to ensure that equipment has been installed correctly and that replacement make-up air is provided for all equipment exhausting air from the house.

The monitoring program results indicate that the R-2000 homes appear to be performing within the tolerances of the program criteria. Air quality and ventilation rates compare favourably with those of conventional homes with the average formaldehyde levels identical for R-2000 and control homes and well below Health and Welfare Canada guidelines. R-2000 Homes had average air change rates that were 42% higher than control homes. On average, ventilation systems were sized to the program criteria of 0.5 ACH but the systems generally were not balanced to program requirements.

Further program refinements are being considered to ensure quality assurance for future increased numbers of R-2000 homes. These refinements include revisions to program technical requirements, inspection procedures, and national standards to address concerns or issues raised during the monitoring phase.

In particular, current requirements for ventilation system capacities and the delivery of air throughout the house need to be expanded to address issues related to system control strategies. Occupants need to be better informed about the correct operation of their ventilation systems and the systems must be designed in a manner that ensures that occupants will in fact operate them.

The R-2000 Program is supporting a large number of activities related to ventilation and air quality by including field monitoring, laboratory testing, standards development, and industry development activities. The program is at the forefront of residential ventilation and air quality activities in Canada.

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FIGURE 1

HRV INSTALLATION WITH BASEBOARD HEATING

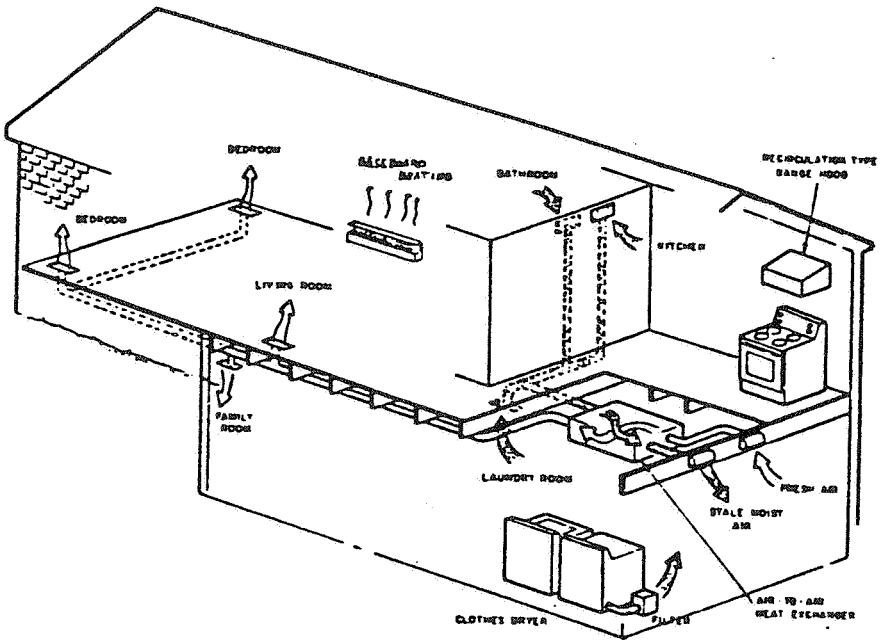


FIGURE 2

HRV INSTALLATION WITH FORCED AIR HEATING SYSTEM
WITH CONTINUAL FURNACE FAN OPERATION

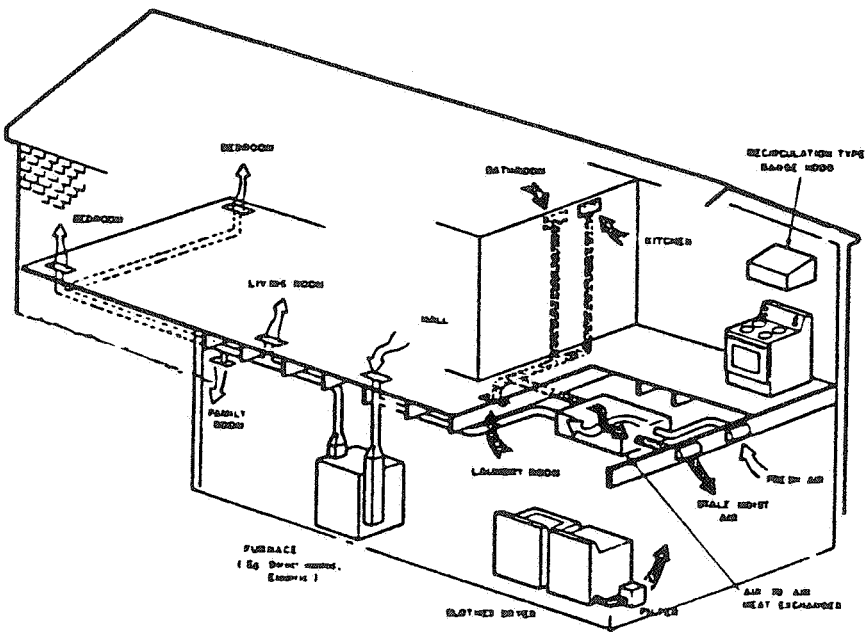


TABLE 1: GENERAL HOUSE CHARACTERISTICS

	R-2000 HOMES		CONTROL HOMES	
	Mean	St. Dev.	Mean	St. Dev.
HOUSE VOLUME (M3):	525	137	462	162
HOUSE TYPE AND SIZE	No.	Percent.	No.	Percent.
Slab on Grade Homes	15	0.5	3	0.05
Crawlspace Homes	6	0.1	6	0.1
All Homes: <500 M3	144	49.6	48	82.8
All Homes: >500 M3	146	51.4	10	17.2
Total: All Homes	290		58	
SPACE HEATING SYSTEMS	No.	Percent.	No.	Percent.
Radiant: Electric	108	37.6	26	34.2
Fuel-Fired	4	1.4	7	9.2
Forced Air: Electric	63	22.0	7	9.2
Fuel-Fired	112	39.0	36	47.4
FIREPLACES/WOODSTOVES	93	32.0	21	27.6
VENTILATION AIR DISCHARGE	No.	Percent.		
Basement	86	31.5	na	na
Main Living Area	106	38.8	na	na
Furnace Cold Air Return	28	10.3	na	na
Near Furnace Cold Air Return	53	19.4	na	na
THERMAL CHARACTERISTICS:	Mean	Range	Mean	Range
Ceiling (RSI)	8.2	4.9 - 11.9	6.1	3.5 - 7.0
Main Walls (RSI)	5.5	3.5 - 9.6	3.5	2.1 - 5.8
Basement Walls (RSI)	3.9	1.3 - 8.8	1.9	0.0 - 3.5
Basement Floors (RSI)	1.1	0.0 - 5.0	0.0	0.0 - 0.0
Windows (RSI)	0.44	0.21- 0.56	0.34	0.21- 0.49

	Cases	Mean	Range	Cases	Mean	Range
AIRTIGHTNESS (50 Pascals ACH)	259	0.84	0.03-1.49	4	4.58	2.0-7.1 (ACH)

TABLE 2: ASHRAE REQUIREMENTS AND MEASURED SYSTEM RESULTS-R-2000 HOMES

HOUSE CHARACTERISTICS	ASHRAE REQUIREMENTS (ACH)				MEASURED SYSTEM CAPACITY (ACH)			
HOUSE TYPE AND SIZE	Cases	Mean	St. Dev.	Median	Cases	Mean	St. Dev.	Median
Slab on Grade:	12	0.43	0.09	0.44	10	0.66	0.21	0.60
Crawlspace:	6	0.44	0.09	0.42	4	0.55	0.31	0.51
All Homes <500 M3:	132	0.38	0.07	0.37	124	0.61	0.23	0.58
All Homes >500 M3:	126	0.32	0.06	0.32	135	0.41	0.14	0.41
Total All R-2000 Homes:	258	0.35	0.07	0.34	259	0.50	0.21	0.47
SPACE HEATING FUEL TYPE:								
Electricity	155	0.35	0.07	0.35	159	0.52	0.20	0.50
Other	95	0.35	0.07	0.34	97	0.47	0.22	0.48
VENTILATION AIR DISCHARGE:								
Basement	74	0.34	0.06	0.34	78	0.48	0.16	0.46
Main Living Area	92	0.37	0.08	0.35	95	0.56	0.26	0.52
Furnace Cold Air Return	23	0.32	0.06	0.32	25	0.43	0.16	0.41
Near Furnace Cold Air Return	49	0.35	0.05	0.35	49	0.47	0.18	0.45

TABLE 3

HEAT RECOVERY VENTILATOR BALANCING CHARACTERISTICS

Heating Distribution	Airflow Imbalance	Low Speed Test		High Speed Test	
	Percent	No.	Percent (%)	No.	Percent (%)
Electric Baseboard:	0 -9%	11	10	16	15
	10-25%	12	11	40	37
	26-50%	17	16	28	26
	> 50%	4	4	7	7
	missing	63	59	16	15
Forced Air:	0 -9%	33	19	30	17
	10-25%	44	25	66	38
	26-50%	30	17	44	25
	> 50%	8	5	7	4
	missing	59	34	27	16
Total Average: R-2000	0 -9%	44	16	46	16
	10-25%	56	20	106	38
	26-50%	47	17	72	26
	> 50%	12	4	14	5
	missing	122	43	43	15

NOTE: The Airflow Imbalance percentages indicate the percent difference between supply and exhaust air as measured at the heat recovery ventilator. The No. value indicates the number of cases falling within the airflow imbalance range. The Percent value presents the number of cases within the range as a percentage of the total number of homes with measurements.

TABLE 4

CATS MEASURED AIR CHANGE RATES VS. SULPHUR HEXAFLUORIDE MEASURED AIR CHANGE RATES

HOUSE TYPE	SF6 RESULTS (ACH)				CATS RESULTS (ACH)		
	Cases	Mean	St. Dev.	Median	Mean	St. Dev.	Median
R-2000	6	0.37	0.13	0.23	0.33	0.20	0.43
Control	3	0.22	0.08	0.20	0.17	0.09	0.23
All Homes	9	0.32	0.13	0.23	0.29	0.18	0.23

NOTE: CATS Measured House Ventilation refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" method of determining average house ventilation rates over a specific time period[10].

TABLE 5: VENTILATION AND FORMALDEHYDE TEST RESULTS

HOUSE CHARACTERISTICS	MEASURED VENTILATION CAPACITY (ACH)				CATS MEASURED VENTILATION (ACH)				FORMALDEHYDE TESTING RESULTS (PPM) Bedroom Test Results			
HOUSE TYPE AND VOLUME RANGE	Cases	Mean	St. Dev.	Median	Cases	Mean	St. Dev.	Median	Cases	Mean	St. Dev.	Median
Slab on Grade:	10	0.66	0.21	0.60	5	0.40	0.38	0.29	12	0.044	0.018	0.038
Crawlspace:	4	0.55	0.31	0.51	5	0.47	0.33	0.27	5	0.041	0.009	0.040
All Homes: <500 M3	124	0.61	0.23	0.58	54	0.40	0.39	0.29	126	0.060	0.027	0.053
All Homes: >500 M3	135	0.41	0.14	0.41	69	0.34	0.29	0.27	122	0.060	0.031	0.055
Total All R-2000 Homes:	259	0.50	0.21	0.47	123	0.37	0.34	0.28	248	0.060	0.029	0.053
Total All Control Homes:	na	na	na	na	40	0.26	0.21	0.20	62	0.060	0.033	0.054
SPACE HEATING FUEL TYPE												
R-2000 HOMES:												
Electricity	159	0.52	0.20	0.50	71	0.38	0.49	0.27	153	0.063	0.030	0.057
Other	97	0.47	0.22	0.43	49	0.38	0.28	0.30	95	0.055	0.026	0.047
CONTROL HOMES:												
Electricity	na	na	na	na	14	0.20	0.18	0.14	27	0.061	0.029	0.058
Other	na	na	na	na	23	0.31	0.23	0.27	34	0.060	0.036	0.045
SPACE HEATING DISTRIBUTION TYPE												
R-2000 HOMES:												
Electric Baseboard	94	0.56	0.21	0.54	40	0.32	0.24	0.27	95	0.065	0.032	0.059
Forced Air	156	0.46	0.16	0.45	76	0.39	0.46	0.28	148	0.057	0.027	0.058
CONTROL HOMES:												
Electric Baseboard	na	na	na	na	13	0.18	0.19	0.12	20	0.065	0.028	0.059
Forced Air	na	na	na	na	27	0.30	0.21	0.26	42	0.057	0.035	0.043
VENTILATION AIR DISCHARGE (R-2000)												
Basement	78	0.48	0.16	0.46	36	0.39	0.56	0.27	82	0.066	0.028	0.059
Main Living Area	95	0.56	0.26	0.52	47	0.45	0.44	0.29	86	0.058	0.033	0.047
Furnace Cold Air Return	25	0.43	0.16	0.41	12	0.36	0.22	0.35	26	0.053	0.022	0.049
Near Furnace Cold Air Return	49	0.47	0.18	0.45	19	0.30	0.21	0.26	44	0.055	0.026	0.048

NOTE: CATS refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" tracer gas (perfluorocarbon) method.

TABLE 6: CATS AIR CHANGE RATE RESULTS FOR FORMALDEHYDE TESTED HOMES

HOUSE CHARACTERISTICS	CATS MEASURED VENTILATION (ACH)				FORMALDEHYDE TESTING RESULTS (PPM) Bedroom Test Results			
HOUSE TYPE AND VOLUME RANGE	Cases	Mean	St. Dev.	Median	Cases	Mean	St. Dev.	Median
Slab on Grade:	5	0.40	0.38	0.29	5	0.045	0.023	0.034
Crawlspace:	4	0.33	0.16	0.32	4	0.041	0.011	0.040
All Homes: <500 M3	48	0.35	0.31	0.28	48	0.063	0.028	0.060
All Homes: >500 M3	61	0.35	0.30	0.28	61	0.062	0.037	0.049
Total All R-2000 Homes:	109	0.35	0.30	0.28	109	0.063	0.033	0.054
Total All Control Homes:	34	0.25	0.20	0.17	34	0.059	0.028	0.050
SPACE HEATING FUEL TYPE								
R-2000 HOMES:								
Electricity	65	0.39	0.50	0.27	65	0.066	0.035	0.058
Other	44	0.36	0.29	0.30	44	0.058	0.030	0.049
CONTROL HOMES:								
Electricity	14	0.20	0.18	0.14	14	0.066	0.019	0.059
Other	19	0.28	0.22	0.20	19	0.055	0.033	0.042
SPACE HEATING DISTRIBUTION TYPE								
R-2000 HOMES:								
Electric Baseboard	39	0.33	0.25	0.27	39	0.069	0.036	0.062
Forced Air	67	0.39	0.49	0.28	67	0.060	0.031	0.054
CONTROL HOMES:								
Electric Baseboard	13	0.18	0.19	0.12	13	0.063	0.015	0.058
Forced Air	20	0.28	0.21	0.26	20	0.057	0.034	0.042
VENTILATION AIR DISCHARGE (R-2000)								
Basement	32	0.30	0.17	0.26	32	0.069	0.033	0.068
Main Living Area	37	0.40	0.39	0.28	37	0.062	0.038	0.046
Furnace Cold Air Return	12	0.36	0.22	0.36	12	0.053	0.026	0.049
Near Furnace Cold Air Return	18	0.31	0.21	0.27	18	0.060	0.033	0.051

NOTE: CATS Measured House Ventilation refers to the Brookhaven National Laboratory "Capillary Adsorption Tube Sampler" tracer gas (perfluorocarbon)method of determining average air change

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 17

INDOOR FORMALDEHYDE LEVELS IN HOUSES WITH DIFFERENT VENTILATION STRATEGIES

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1. Synopsis

This paper discusses the indoor formaldehyde levels in two groups of houses. With the exception of the heating and ventilation systems, the house construction, formaldehyde sources and occupancy were similar for the two groups. One group (A) used electric baseboard convective heaters for space heating and semi-ducted heat recovery ventilators (HRV) for supplying outdoor air and exhausting indoor air. The second group (B) had electric forced-air furnaces with a ducted air supply to every room. Outdoor air was drawn in via a connection to the return air ductwork.

During the winter, 77% of the Group A houses had bedroom formaldehyde levels higher than the living room levels. In the Group B houses, only 20% had a bedroom level higher than the living room level. These data suggest that the semi-ducted HRV systems provide limited air circulation within the houses compared to the fully ducted forced-air furnaces.

The average winter HCOH levels were similar for both house groups; however, the Group A houses had ventilation rates twice as high as the Group B houses. Since the HCOH source strengths within the house groups should be equal, superior mixing efficiency in the Group B houses may be responsible.

The results also show that a continuous supply of ventilation air is necessary to prevent the build-up of indoor pollutants. Ventilation systems that are coupled to the air circulation/heating system (Group B) are not reliable during low/no heat periods. In energy-efficient houses with low auxiliary heating requirements, indoor air quality problems may develop.

2. Introduction

Concerns over the build-up of pollutant levels in new "low-energy" houses have arisen recently. Typically, low-energy houses have well sealed air-vapour barriers to minimize air leakage and use mechanical systems to supply ventilation air.

This study was initiated to provide field data on the indoor formaldehyde (HCOH) concentrations in a group of 33 relatively new (1-2 years old) "low-energy" houses located in Winnipeg and Pinawa, Manitoba. Using passive dosimeters, concentrations were measured in December 1983 (ventilation via infiltration and mechanical system only) and again in September 1984 (occupant-controlled window openings to supplement ventilation).

The December 1983 HCOH data for a sub-group of 16 houses have already been analyzed in detail[1] and the results indicated that for a given type of occupancy, indoor HCOH levels could be related to the ventilation rate by the simple expression (Fig. 1):

$$C_i = C_o + \frac{\hat{N}A_f}{K\hat{V}} \qquad (1)$$

where C_i = indoor HCOH concentration ($\mu g/m^3$)
C_o = outdoor HCOH concentration ($\mu g/m^3$)
$\hat{N}$ = net apparent HCOH source strength ($\mu g/s \cdot m^2$)
$\hat{V}$ = net ventilation rate (m^3/s)
K = mixing factor (K = 1 perfect mixing)
A_f = main floor area (m^2).

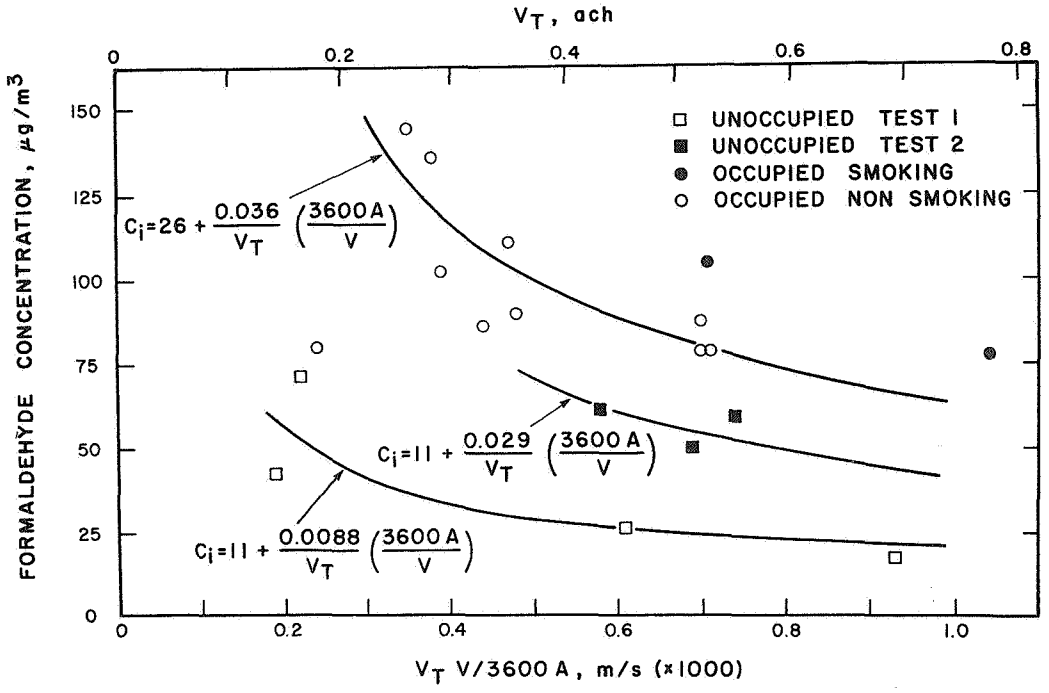


Fig. 1. Indoor formaldehyde concentration vs air flow rate for four test cases (Ref. 1)

Conversely, the study demonstrated that pollutant concentration measurements in the absence of ventilation rate data are difficult to analyze since variations in concentration levels could be caused by variations in pollutant source strengths and/or ventilation rates.

This paper is intended to outline the methodology of the indoor pollutant measurement program and discuss the implications of the data on the design of heating and ventilating systems for housing. This data base may also be of use to health professionals and policymakers who must assess the potential health risks of exposures to indoor pollutants.

For the purposes of the paper, ventilation air will refer to outdoor air introduced into the building via infiltration or mechanical means. Circulation air will refer to air moving within the building enclosure due to the action of a central forced-air distribution system.

3. Description of the Houses

All of the houses examined in this study were new, wood-frame single-family residences containing glass fibre insulation. The cast-in-place concrete basements were insulated on the interior using wood studs and glass fibre batts.

The houses in Group A were located in Pinawa, Manitoba and Winnipeg, Manitoba and were built by one contractor using similar construction materials and techniques. The above-grade walls were constructed using the double-stud technique.[2] Heat recovery ventilators (HRV) were used to supply outside air and circulate air within the houses. The units had interlocked supply and exhaust fans with the ON/OFF operation controlled by a humidistat. The exhaust air was removed (via ductwork) from the kitchen and bathroom. The outside air was supplied into the centre of the basement and allowed to migrate through the house. Floor registers were cut through the main floor to facilitate air movement between the main floor and basement. Electric baseboard heaters (convective) were used for space heating.

The houses in Group B were located in Pinawa, Manitoba but were built by a different contractor than those in Group A. The above-grade walls were conventional single-stud. All other construction materials and techniques were similar to those used in the Group A houses. Group B had electric forced-air heating systems (20-kW input) with ducted supply air into every room and two centralized main floor return air grilles. Outdoor air was supplied via a 125-mm diameter duct connected to the return air plenum. The single-speed furnace fan (≈400 L/s) operation was controlled by heating demand.

Details on the houses are given in Table 1.

4. Experimental Procedure

Airtightness measurements[3] were taken for all of the house envelopes. This involved depressurizing the house using an exhaust fan and measuring the air flow, Q(L/s), and corresponding values of the differential pressure across the building envelope, ΔP(Pa). Values for the flow coefficient, $C(L/s \cdot m^2(Pa)^n)$, and flow exponent, n (dimensionless), can then be calculated using the expression:

$$Q = CA\ (\Delta P)^n \qquad (2)$$

where A = area of the building envelope (m^2).

The Group A houses were extremely airtight, having a group average induced air leakage of 0.25 air change per hour (ach) @50 Pa with

Table 1. Basic House Data

	House Code	Year of Construction	Construction Style	Volume (m^3)	Total Floor Area Excluding Basement (m^2)	Pressure Test Result Q/V(ach @ 50 Pa)	Age of Furniture
Group A	2	82	Bungalow	465	91.7	0.18	none
	3	82	Bungalow	465	91.7	0.14	none
	4	82	Bungalow	465	91.7	0.26	none
	5	82	Bungalow	465	91.7	0.16	2-5 yr
	6	N/A	Bungalow	465	91.7	0.17	none
	7	82	Bungalow	465	91.7	0.15	N/A
	8	82	Bungalow	465	91.7	0.19	none
	17	81	1½ Storey	513	92.6	0.25	new
	18	81	Bungalow	465	91.7	0.22	3 yr
	19	82	Bungalow	455	91.0	0.67	2 yr
	20	83	Split Level	374	76.9	N/A	2-5 yr
	21	81	Bungalow	465	91.7	0.20	3 yr
	22	82	Split Level	373	75.1	0.19	2 yr
	23	82	Bungalow	465	91.7	0.21	2 yr
	24	81	1½ Storey	513	92.6	0.27	3 yr
	25	N/A	Bungalow	465	91.7	0.25	2 yr
	26	82	Bungalow	465	91.7	0.32	2-5 yr
	27	83	Split Level	304	59.3	0.39	new
	28	N/A	Bungalow	465	91.7	0.23	2-5 yr
	29	81	Bungalow	465	91.7	0.15	new
	30	81	Bungalow	465	91.7	0.35	2 yr
	31	N/A	Bungalow	465	91.7	0.27	N/A
	32	N/A	Bungalow	465	91.7	0.28	2 yr
	33	N/A	Bungalow	465	91.7	0.24	N/A
	34	81	1½ Storey	513	92.7	0.49	3 yr
	35	81	Bungalow	465	91.7	0.16	new
Group B	9	82	Bungalow	477	95.6	N/A	N/A
	10	82	1½ Storey	452	102.8	1.61	N/A
	11	N/A	Bungalow	507	102.1	1.23	N/A
	2	82	Bungalow	545	110.2	1.54	N/A
	13	82	Bungalow	477	95.6	1.54	2 yr
	14	82	Bungalow	545	110.2	1.95	N/A
	15	82	1½ Storey	452	102.8	2.12	none

a standard deviation of 0.12. For Group B, the average air leakage test value was 1.67 ach @50 Pa with a standard deviation of 0.32. Data for the individual houses are given in Table 1. The tests were conducted with all intentional envelope openings (doors, windows, air intake and exhaust ducts) blocked.

Two separate sets of HCOH and ventilation measurements were taken. One set (Test 1) was taken in December 1983 and the second (Test 2) in September 1984. The data for Test 1 and 2 are presented in Tables 2 and 3, respectively.

Formaldehyde levels were measured in the living room and master bedroom using Dupont C-60 dosimeters exposed for approximately seven days. During Test 2, outdoor HCOH levels were measured at five representative locations.

Elapsed time meters were installed to monitor the ON time of the interlocked HRV fans. The HRV air flow rates (supply and exhaust) and the outside air flows to the electric furnaces were measured using a heated probe anemometer traverse. At the beginning and end of the HCOH testing, the indoor air temperature and relative humidity were estimated using an aspirating psychrometer. Interviews were conducted with the household occupants to determine occupancy, smoking habits and non-building-related pollutant sources.

Outdoor air temperature and wind speed data were taken from Environment Canada[4] summaries.

5. Analysis of Data

The total ventilation rate (V_T) for the Group A houses was calculated as:

$$V_T = V_M + V_I \quad (3)$$

where V_M = time-averaged mechanical ventilation flow rate (ach)
V_I = infiltration flow rate (ach).

For the Group A houses, V_M was calculated by dividing the total volumetric air flow rate through the HRV during the test (total running time X average duct air velocity) by the total test time. In most cases, the supply and exhaust air flows through the HRV were not balanced, so the larger of the two values was used. This would normally result in a mechanically induced pressure difference which would upset the infiltration. However, since the initial calculated values of V_I were relatively small, no attempt was made to correct them. The value of V_M for the Group B houses was calculated by multiplying the furnace ON time by the outdoor air flow rate with the furnace fan ON (35 L/s) and dividing by the total test time. The furnace ON time was approximated as the total measured furnace electrical energy consumption (kWh) divided by the rated heat output (20 kW).

Shaw's[5] method was used to calculate the infiltration rate (V_I) using the value from the fan depressurization test.

The winter values were calculated for Type 1 infiltration (temperature-driven) data using the expression:

$$V_I = 0.32CA\ (\Delta T^n)/V \quad (4)$$

where V = house volume (m^3)
ΔT = average indoor/outdoor temperature difference (°C).

The summer values assume Type 2 infiltration (wind-driven) and were calculated as:

$$V_I = \frac{0.76\ CA\ v^n}{V} \quad (5)$$

where v = wind speed (m/s).

The values for V_T are given in Tables 2 and 3. The summer values of V_T will not represent the total ventilation rate since windows were frequently opened.

The average of the living room and bedroom indoor air HCOH levels for the Group A houses are shown in Figs. 2a and 2c. Figs. 2b and 2d show the distribution of the average indoor HCOH concentration for the Group B houses.

Table 2. Test 1 (Winter) Data

	HOUSE CODE	TEMP (°C)	RH (%)	V_T (ach)	LR HCOH (ppm)	BR HCOH (ppm)	AV HCOH (ppm)	(BR-LR)/LR (% diff.)	OCCUPANCY (Adults/ Children)	RADON (pCi/L)
Group A	2	22	29	0.51	0.035	0.046	0.041	31.4	0	6.71
	3	14	57	0.16	0.057	0.058	0.058	1.8	0	22.74
	4	20	34	0.55	0.039	0.058	0.049	48.7	0	7.20
	5	20	34	0.18	0.061	0.066	0.064	8.2	2/0	6.66
	6	21	31	0.42	0.051	0.049	0.051	-3.9	0	6.92
	7	17	55	0.77	0.056	0.067	0.062	19.6	0	5.58
	8	19	49	0.01	0.109	0.131	0.120	20.2	0	25.02
	17	21	48	0.29	0.074	0.089	0.082	20.3	3/1	2.83
	18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2/2	3.53
	19	23	38	N/A	0.093	0.078	0.086	-16.1	2/0	2.20
	20	20	32	0.40	0.042	0.044	0.043	4.8	2/4	1.71
	21	21	33	0.35	0.063	0.115	0.089	82.5	2/3	8.75
	22	23	46	0.33	0.069	0.069	0.069	0	2/0	2.61
	23	19	45	0.28	0.103	0.114	0.109	10.7	2/0	3.67
	24	N/A	N/A	0.20	N/A	N/A	N/A	N/A	2/0	3.33
	25	N/A	N/A	0.26	N/A	N/A	N/A	N/A	2/2	3.04
	26	22	48	0.61	0.123	0.124	0.124	0.8	2/0	1.69
	27	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1/0	2.63
	28	20	46	0.53	0.089	0.079	0.084	-11.2	2/2	3.37
	29	23	42	0.52	0.066	0.074	0.070	12.1	2/1	0.91
	30	22	41	0.52	0.054	0.071	0.063	31.5	2/1	6.91
	31	20	52	0.36	0.067	0.076	0.072	13.4	2/2	2.73
	32	21	46	0.53	0.051	0.075	0.063	47.1	2/1	4.15
	33	22	38	N/A	0.060	0.074	0.067	23.3	2/2	3.14
	34	22	48	0.26	0.112	0.119	0.116	6.3	4/0	0.95
	35	19	48	0.01	0.048	0.039	0.044	-18.8	2/0	2.17
Group B	9	21	55	N/A	0.061	0.065	0.063	6.6	2/0	3.31
	10	18	52	0.16	0.079	0.077	0.078	-2.5	4/1	3.59
	11	N/A	N/A	0.14	N/A	N/A	N/A	N/A	2/1	6.22
	12	21	50	0.17	0.111	0.084	0.098	-24.3	2/2	6.22
	13	20	63	0.17	0.069	0.059	0.064	-14.5	2/3	4.24
	14	23	40	0.20	0.059	0.057	0.058	-3.4	2/2	2.77
	15	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	4.37

Table 3. Test 2 (Summer) Data

	HOUSE CODE	TEMP (°C)	RH (%)	V_T (ach)	LR HCOH (ppm)	BR HCOH (ppm)	AV HCOH (ppm)	(BR-LR)/LR (% diff.)	OCCUPANCY (Adults/ Children)	RADON (pCi/L)
Group A	2	20.6	47	0.52	0.041	0.056	0.049	36.6	0	3.08
	3	21.1	50	0.52	0.055	0.076	0.066	38.2	0	6.27
	4	20.0	52	0.26	0.034	0.032	0.033	-5.9	2/1	6.94
	5	19.7	48	0.37	0.029	0.047	0.038	62.1	2/1	3.16
	6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0	N/A
	7	18.9	52	0.77	0.033	0.028	0.031	-15.2	2/1	1.91
	8	18.9	48	0.01	0.047	0.051	0.049	8.5	2/2	5.93
	17	20.6	51	0.39	0.048	0.067	0.058	39.6	4/0	2.02
	18	22.2	56	0.12	0.068	0.057	0.063	-16.2	2/2	2.97
	19	22.8	53	N/A	0.101	0.100	0.101	-1.0	2/0	1.07
	20	20.6	52	0.33	N/A	0.030	0.030	N/A	2/4	2.43
	21	21.1	52	0.36	0.039	0.046	0.043	17.9	2/3	4.19
	22	22.8	69	0.38	0.132	0.087	0.110	-34.1	2/0	8.57
	23	18.9	61	0.29	0.082	0.079	0.081	-3.7	2/0	2.30
	24	21.7	60	0.07	0.101	0.090	0.096	-10.9	2/0	N/A
	25	22.8	49	0.01	0.049	0.043	0.046	-12.2	2/2	6.27
	26	22.2	48	0.64	0.055	0.069	0.062	25.5	2/0	2.20
	27	19.4	38	0.33	0.045	0.068	0.057	51.1	1/0	N/A
	28	20.0	54	0.54	0.058	0.054	0.056	-6.9	2/2	4.75
	29	21.1	51	0.22	0.048	0.046	0.047	-4.2	2/1	1.42
	30	21.1	44	0.53	0.029	0.037	0.033	27.6	2/2	5.05
	31	22.2	45	0.06	0.059	0.037	0.048	-37.3	2/2	1.34
	32	22.2	42	0.01	0.038	0.047	0.043	23.7	2/1	1.27
	33	22.2	64	0.33	0.088	0.100	0.094	13.6	2/2	1.11
	34	22.2	56	0.31	0.097	0.072	0.085	-25.8	4/0	2.10
	35	20.0	60	0.01	0.066	0.062	0.064	-6.1	2/0	2.10
Group B	9	16.1	77	N/A	0.178	0.182	0.180	2.2	0	N/A
	10	19.4	53	0.08	0.054	0.048	0.051	-11.1	4/0	5.60
	11	20.0	71	0.05	0.106	0.093	0.100	-12.3	2/1	6.27
	12	19.4	53	0.06	0.115	0.038	0.077	-67.0	2/1	7.95
	13	19.4	57	0.06	0.037	0.036	0.037	1.4	2/2	2.41
	14	20.0	50	0.10	0.086	0.130	0.108	51.2	2/1	2.07
	15	18.6	59	0.10	0.185	0.235	0.210	27.0	0	9.96

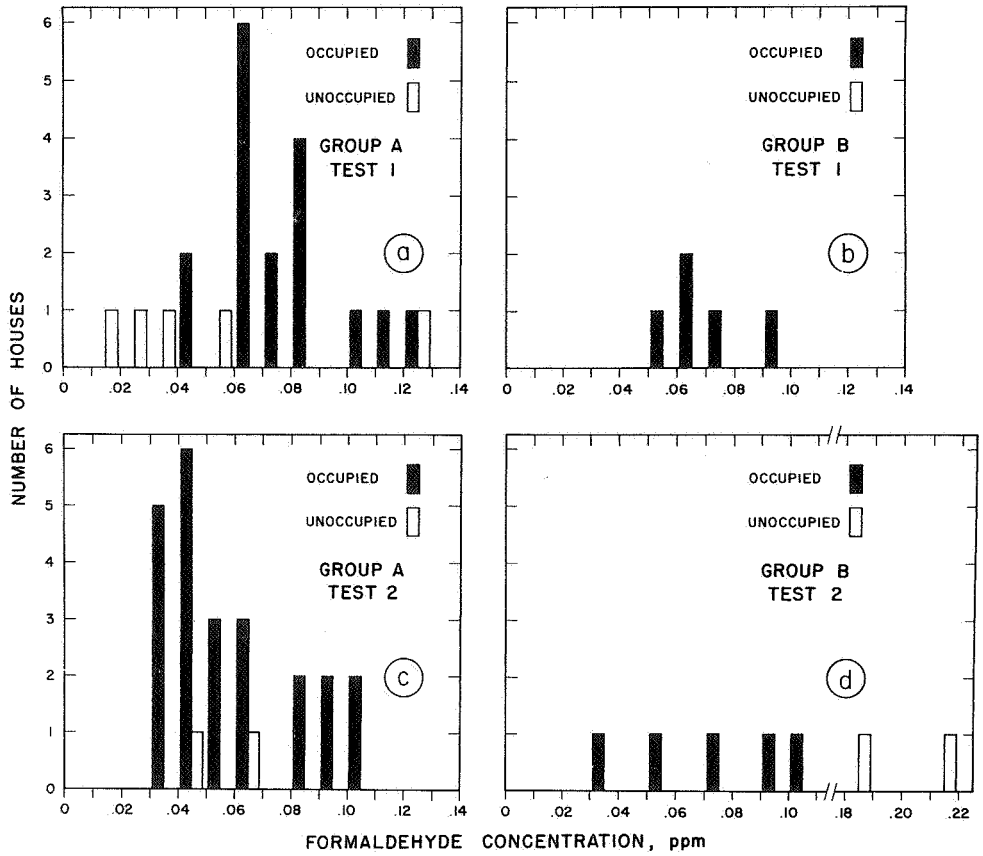


Fig. 2. Distribution of the average indoor formaldehyde levels

The distribution of pollutant levels in the houses was also examined by comparing the percentage difference between the bedroom and living room HCOH concentrations. The results are shown in Figs. 3a (Group A) and 3b (Group B) for Test 1, and Figs. 3c and 3d respectively for Test 2.

6. Discussion

To date, Canada does not have an accepted standard that defines the maximum allowable HCOH concentration in residences. For the purposes of this discussion, 0.1 ppm[6] will be used as an arbitrary standard.

The HCOH sources in the houses can be divided into two major areas: building sources and occupant sources. The major building sources are assumed to be urea formaldehyde resin bonded particle board construction materials including:

1) 9.5-mm subfloor
2) formica-covered counter tops
3) kitchen cupboards and vanities
4) closet shelving.

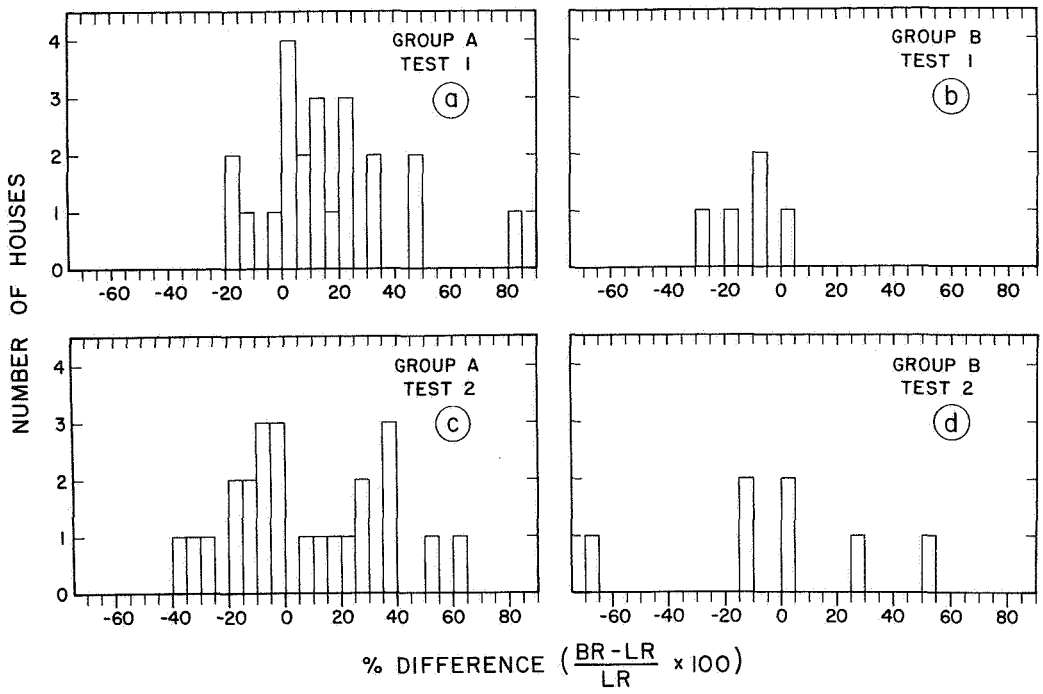


Fig. 3. Distribution of the percentage difference of formaldehyde levels between bedrooms and living rooms

All of the houses used similar quantities of these materials. The occupant-related sources included:

1) furnishings constructed with particle board
2) smoking
3) miscellaneous materials such as paper, textiles and cleaning products.

To establish a relationship between the HCOH level and the ventilation rate for a single house, a series of measurements of the HCOH concentration and ventilation rate would be required. An alternate analysis of these winter data[1] (Fig. 1) showed that the single individual house measurements could be grouped as having been taken from one "average house". The high correlations (correlation coefficient ≥ 0.8) obtained when an equation of the form of Equation 1 was fitted to the data suggested that (for a given occupancy load) the net apparent HCOH source strengths within the houses were similar. The major HCOH sources were the building materials ($\hat{N} = 0.029$ $\mu g/s \cdot m^2$). The study showed that normal occupancy (non-smokers) increased the net apparent HCOH source strength by approximately 20% to $\hat{N} = 0.036$ $\mu g/s \cdot m^2$. Hence, for this pollutant, developing ventilation criteria based on predicted source strengths seems to be a valid approach.

The average ventilation rates and HCOH levels for each of the groups (occupied and unoccupied) are given in Table 4.

Table 4. Average Ventilation Rates and Indoor HCOH Levels For Tests 1 and 2

	Winter (Test 1)		Summer (Test 2)	
House Group	V_T	HCOH (ppm)	V_T	HCOH (ppm)
A (unoccupied)	0.40	0.064	0.48	0.058
A (occupied)	0.35	0.078	0.29	0.060
B (unoccupied)	N/A	N/A	0.10	0.210
B (occupied)	0.18	0.075	0.07	0.075

The distribution of the average HCOH concentration in the Group A houses for December 1983 (Fig. 2a) shows that only three occupied and one unoccupied house exceeded the 0.1-ppm level. The 17 occupied houses had an average ventilation rate of 0.4 ach and a mean indoor HCOH level ($\bar{x}$) of 0.078 ppm. For two of the three occupied houses with HCOH levels above 0.1 ppm (houses 23 and 34), increased operation of the HRV fans (see Fig. 1) could reduce the levels to below 0.1 ppm. Both houses had average HCOH levels only slightly greater than 0.1 ppm with V_T values below 0.3 ach. The other occupied house (house 26) had a level of 0.12 ppm with the HRV operating continuously at maximum flow (0.6 ach). For this house, the mechanical ventilation system was inadequate to control the indoor level below 0.1 ppm. In the case of the unoccupied house (house 8), the HRV fans were shut off.

The Group B houses (Fig. 2b) maintained relatively low HCOH levels during the December 1983 test period ($\bar{x}$ = 0.075 ppm). All of the houses were occupied and none of the indoor levels exceeded 0.1 ppm.

For the winter test, the average HCOH concentration in the occupied Group B houses was comparable with that of the occupied Group A houses. However, the calculated ventilation rate was less than one-half. Since the net HCOH source strength should be similar for both groups, the initial comparison would indicate an inconsistency with Equation 1. The most likely explanation lies with the value of the mixing factor K. The forced circulation Group B houses would have a larger mixing factor than the Group A houses.

The summer (September 1984) values for the occupied, Group A houses showed a general reduction in the indoor levels ($\bar{x}$ = 0.060 ppm) when compared to the previous December 1983 data. The average mechanical ventilation rate was also lower, suggesting that additional ventilation must have been supplied via undocumented window and door openings. In this group, two occupied houses had average indoor HCOH levels marginally above 0.1 ppm, although increased operation of the HRV could have reduced the levels. The relationship between the indoor HCOH level and the ventilation rate did not change for the unoccupied Group A houses (this assumes no occupants, hence no window or door

openings), indicating that the net apparent source strength of the building had not changed appreciably.

In contrast, the September 1984 test showed acceptable levels in the occupied houses ($\bar{x}$ = 0.075 ppm) but high levels (average HCOH = 0.18 and 0.21 ppm) in the two unoccupied houses where windows were not opened. These data are consistent with the intuitive observation that during the cold weather monitoring period the furnace was running frequently and drawing in fresh air. In the summer, the furnace fans would not be operating; hence the primary source of ventilation would be window openings. In addition, the stack effect is reduced in the summer.

These data suggest that while both systems (passive or mechanical) can provide adequate ventilation for the control of indoor HCOH levels, properly maintained mechanical systems do not require deliberate occupant input and may, therefore, be more reliable. In cases where occupants of houses without mechanical ventilation systems do not use window openings to introduce passive ventilation (such as air-conditioned houses), indoor HCOH levels could become excessive.

During the winter (Test 1) the Group A houses had air circulation rates controlled by the air flow of the HRV. When ON, typical HRV flow rates were ≈0.7 ach; however, ON/OFF control reduced the time-averaged rates (see Tables 2 and 3). The absence of a supply air ductwork system further reduced the complete circulation of the available ventilation air. The furnace fans in the Group B houses had circulation capacities of between 2.6 and 3.0 ach when ON.

In the Group A houses (Test 1), 17 out of 22 had bedroom levels higher than living room levels (Fig. 3a). In contrast, only one of the five Group B houses (Fig. 3b) had a bedroom level higher than the living room level.

During the summer (Test 2) when window openings were extensively used by all of the house groups, the Group A houses had 11 out of 24 cases where the bedroom level was higher than that of the living room (Fig. 3c). Similarly, four out of seven of the Group 2 houses had elevated bedroom levels (Fig. 3d).

Although the pollutant level in a space is a function of the source strength and the air exchange rate, similarities in construction materials and occupancy loadings suggest that during the winter, poor air circulation in the Group A houses may be responsible for the elevated bedroom levels. During the summer, window openings increased the distribution of the ventilation in the Group A houses and the winter pattern of consistently high levels in the bedrooms was eliminated.

It is obvious from these data that difficulties in analysis arise when a one-compartment model is used for ventilation and a two-compartment model is used for measurements. In general, however, uniform pollutant levels throughout a house would be expected if the air circulation rate were relatively high, as in

the case of window openings or furnace fan operation. Conversely, in areas with uneven ventilation rates, stratified levels of pollutants should exist.

7. Conclusions

Although firm conclusions cannot be drawn from this small data set, a number of observations can be made:

- the only average HCOH levels substantially above 0.1 ppm were observed in unoccupied passively ventilated houses (Group B). This suggests that the mechanical ventilation systems used in the Group A houses were providing reliable indoor HCOH control. Further, since natural infiltration forces are minimal in summer, deliberate window openings are required to provide adequate ventilation in passively ventilated houses.

- houses with low air circulation rates can have significant interior variations in pollutant concentrations. For the group A houses, 77% of the houses had bedroom HCOH levels higher than those in the living room.

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PAPER 18

DEVELOPMENT OF A SIMPLIFIED MULTIZONE INFILTRATION MODEL

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Abstract

Several infiltration models treat the complexity of air flows in multizone buildings, but most of them are written as research tools and are not generally available or user-friendly. Professional engineers and architects are in need of a simplified multizone infiltration model. This paper describes the first step in Lawrence Berkeley Laboratory's development of a multizone infiltration model for calculating the air-flow distribution of a building without using any iteration procedure. To simplify the calculation procedure, buildings are classified into different categories, based on their ratios of permeabilities. These lumped parameters describing the air permeability distribution of a building are used to calculate its overall infiltration/exfiltration rate. The simplified multizone model described is illustrated by a sample calculation.

Keywords: Multizone Infiltration, Air-Flow Modeling, Lumped Parameters.

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1. Table of Symbols

c_k	pressure coefficient for surface element k [-]
$\overline{c}_{lee}$	average pressure coefficient on the leeward side [-]
$\overline{c}_{luv}$	average pressure coefficient on the windward side [-]
g	acceleration of gravity $[m/s^2]$
j	number of considered story [-]
k	number of stories [-]
m	air mass flow [kg/h]
n	exponent of the pressure difference [-]
p_0	atmospheric pressure [Pa]
p_{dyn}	dynamic pressure in the undisturbed flow [Pa]
p_i	inside pressure [Pa]
p_k	pressure at surface element k [Pa]
p_o	outside pressure [Pa]
Δp_{stack}	pressure difference due to stack [Pa]
Δp_{tot}	pressure difference due to stack and wind action [Pa]
Δp_{wind}	pressure difference due to wind [Pa]
v	wind velocity [m/s]
x, y, z	coordinates [m]
z_0	reference height for wind velocity measurements [m],
D	air permeability of the building component $[m^3/h\ Pa^n]$
$D_{lee,envelope}$	air permeability of the leeward side of the building envelope $[m^3/h\ Pa^n]$
D_r	resultant permeability at reference conditions $[m^3/h\ Pa^n]$
D_{res}	resultant permeability $[m^3/h\ Pa^n]$
D_{shaft}	air permeability from the story to the shaft $[m^3/h\ Pa^n]$
$D_{total,envelope}$	air permeability of the total building envelope $[m^3/h\ Pa^n]$
H	height of the building [m]
NPL	neutral pressure level [m]
Q	air flow through a building component $[m^3/h]$
Q_r	air flow at reference conditions $[m^3/h]$
Q_{tot}	superposition of flows $[m^3/h]$
Q_{wind}	air flow due to wind $[m^3/h]$
Q_{stack}	air flow due to temperature differences $[m^3/h]$
α	exponent [-]; value depends on terrain roughness[3,4]
ϕ	wind direction [°], usually 10 m above ground
ρ_o	density of the outside air $[kg/m^3]$
ρ_i	density of the inside air $[kg/m^3]$

2. Introduction

Numerous computer programs have been developed to calculate infiltration-related energy loss in buildings. To treat the true complexity of air flows in a multizone building requires extensive information about flow characteristics and pressure distribution; accordingly, simplified models have been developed. Most of these models, including the one developed at Lawrence Berkeley Laboratory (LBL), simulate infiltration associated with single-cell structures. A high percentage of existing buildings, however, have floor plans that characterize them more accurately as multizone structures, which cannot be treated by single-cell models. Although multizone models exist, most are either not generally available or are written as research tools[1]. Professional engineers and architects are in need of a simplified multizone infiltration model capable of providing the same accuracy as the existing single-zone models. In this paper the first steps in developing a simplified infiltration model for multizone buildings are explained and preliminary results are shown.

3. Modeling Infiltration in Multizone Buildings

3.1 Outline

Air flow through the building envelope is a combination of viscous and turbulent flow. Two different mechanisms are responsible for natural air flow in buildings -- wind pressure and thermal buoyancy forces. The distribution of openings in the building shell and the inner flow-paths influence the patterns of air flow.

In terms of air flow, a building can be regarded as a complicated, interlaced grid system of flow paths[2]. In this grid system the joints are the rooms of the buildings and the connections between the joints simulate the flow paths, which include flow resistances caused by open or closed doors and windows and/or air leakage through the walls. The grid points outside the building represent the boundary conditions for the pressure. Differences in air density, caused by differences between outside and inside air temperatures, result in additional pressures in the vertical direction, again influencing the building's air flow.

In buildings with mechanical ventilation systems, the duct system can be treated as another interior flow path and the fan as another source of pressure differences; i.e., the fan lifts the pressure level between two joints according to the characteristic curve of the fan. The HVAC components, such as heating and cooling coils, constitute additional sources of pressure loss.

Because of the nonlinear dependency of the volume flow on the pressure difference, the pressure distribution has usually been calculated by using a method of iterations. To describe buildings with complicated floor plans and to solve the set of nonlinear equations requires large computer storage capacity.

3.2 Physical Fundamentals of the Pressure Distribution

Wind flows produce a velocity and pressure field around the building. Compared to the static pressure associated with an undisturbed wind-velocity pattern, the pressure field around a building is generally characterized by regions of overpressure on the windward side and underpressure on the facades parallel to the air stream and on the leeward side of the building. The pressure distribution is usually described by dimensionless pressure coefficients; that is, the ratio of the surface pressure and the dynamic pressure in the undisturbed flow pattern:

$$c_k(x, y, z, \phi) = \frac{p_k(x, y, z) - p_0(z)}{p_{dyn}(z)} \tag{1}$$

with

$$p_{dyn}(z) = 0.5\ \rho_o\ v^2(z) \tag{2}$$

The vertical profile for the wind speed in the atmospheric boundary layer depends primarily on the roughness of the surface surrounding the building. The wind speed increases with increasing height above ground. The wind velocity profile can be calculated either by a logarithmic equation or by a power law expression[3,4]. The latter is usually used by engineers and building scientists.

$$\frac{v(z)}{v(z_0)} = \left\{ \frac{z}{z_0} \right\}^{\alpha} \tag{3}$$

Both mentioned equations describing the wind velocity profile assume that the wind flow is isothermal and horizontal. Furthermore, it is assumed that the wind flow will not change its direction as a result of differences in the terrain surface.

As noted, temperature differences between the outside and inside air create air density differences that cause pressure gradients. The stack-effect pressure gradient depends only on temperature differences and the vertical dimension of the structure [5,6,7]. The theoretical value of the pressure difference is dependent on the gradient and the distance of the neutral pressure level (NPL), which is defined as the height on the building facade where, under calm conditions, no pressure difference exists between inside and outside. The permeability distribution of the envelope determines the location of the NPL. The stack effect (or thermal buoyancy) can be calculated by the equation

$$\frac{d(p_i - p_o)}{dz} = g\ (\rho_o - \rho_i) \tag{4}$$

and, after integration,

$$(p_i - p_o)_{stack} = g\ (\rho_o - \rho_i)\,(z - NPL) \tag{5}$$

3.3 Building Classification

For purposes of modeling infiltration, buildings are classified as one of the following:

(a) row house (terrace house)
(b) detached house
(c) story-type house
(d) shaft-type house

These four basic categories (see Fig. 1) reflect different permeability distributions of the building's envelope (influence of the wind effect) and different vertical flow resistances inside the building (influence of the stack effect)[8,9].

The distinction between the four categories can be expressed by two permeability ratios. Krischer and Beck[8] used the following parameter to describe the envelope permeability ratio (*epr*) of the whole building for a given house type in categories a or b:

$$epr = \frac{D_{lee,envelope}}{D_{total,envelope}} \tag{6}$$

Based on Krischer and Beck's investigation, the *epr* of row houses can be described by the average permeability ratio of the leeward side to the overall permeability of the building envelope of $epr = 0.5$, whereas the corresponding value for a detached house rises to $epr = 0.75$.

In the latest issue of the German standard, DIN 4701[10], another parameter, internal vertical permeability, was introduced to further differentiate construction types in categories c and d. For further considerations, it is useful to also introduce the ratio of the permeabilities from one floor to another and the overall permeability of the building envelope. Eq. 7 describes the building vertical permeability ratio (*vpr*) for a given construction type for the whole building.

$$vpr = \frac{D_{shaft}}{D_{total,envelope} + D_{shaft}} \tag{7}$$

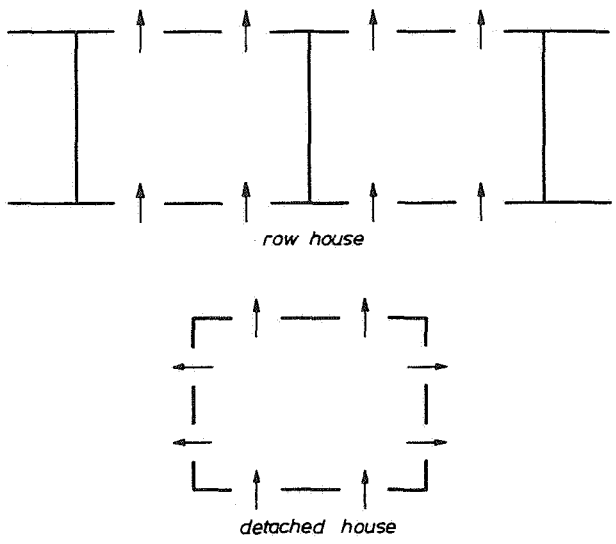


Fig. 1a: Subdivision on the Building Type according to the Permeability Ratio of the Building Envelope.

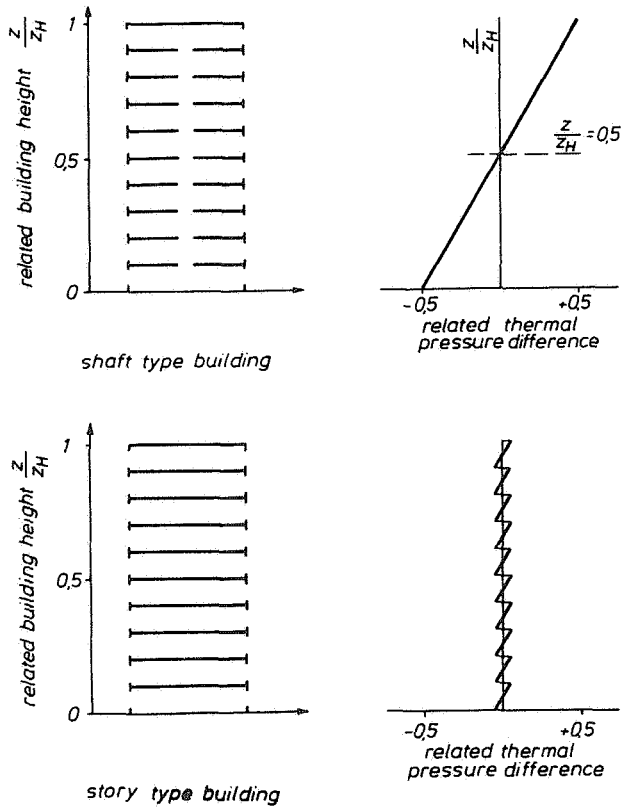


Fig. 1b: Thermal Pressure Difference as a Function of the Type of Construction and $t_i > t_o$

With regard to the thermal pressure distribution, two extremes exist: story-type buildings with no permeability between floors (vpr =0) and shaft-type buildings with no air-flow resistance between the different stories (vpr =1).

Parameters similar to those explained above were used in DIN 4701 to calculate the *maximum* air flow for the whole building so that the *maximum* possible heat loss due to infiltration could be calculated for each zone of a building at the design condition for the heating system.

To describe the air-flow distribution for the different zones at the story level, we defined two more lumped parameters[11,12]: the outside permeability ratio (opr) of the zone (which describes the influence on cross ventilation of the zone, cross ventilation being the portion of the air flow that exfiltrates out of the same zone where it infiltrates -- see Eq. 8), and the inside permeability ratio (ipr) of the zone (which describes the stack influence of the zone -- see Eq. 9).

$$opr = \frac{D_{zone,lee,outside\ envelope}}{D_{zone,outside\ envelope}} \tag{8}$$

$$ipr = \frac{D_{zone,shaft}}{D_{zone,outside\ envelope} + D_{zone,shaft}} \tag{9}$$

In a previous study, the use of a detailed multizone infiltration model showed a strong relationship between the two latter ratios and the flow distribution in buildings[11]. With increasing values for opr and decreasing values for ipr, the zones become more wind-dominated. Consequently, increasing ipr 's in combination with decreasing opr 's show the opposite effect.

Based on simulations using a detailed model [2,9,11], the ratios described in Eq. 6 - 9 can be used as parameters in a simplified model. In other words, the infiltration can be calculated as:

$$Q_{wind} = f\,(D_{lee}, D_{shaft}, epr, vpr, opr, ipr, v(z_0), \alpha, n, z, \phi, H) \tag{10}$$

and

$$Q_{stack} = f\,(D_{lee}, D_{shaft}, epr, vpr, opr, ipr, t_i, t_o, n, z, H, NPL) \tag{11}$$

3.4 Infiltration and Exfiltration

3.4.1 General Considerations

The following illustrations of the physical fundamentals of air-flow distribution in buildings are based on four assumptions:

1) The building has a simplified floor plan; all infiltrated air of a story passes a reference point;
2) The wind flows perpendicular to the windward facade of the building;
3) The vertical wind velocity profile can be expressed by a power-law expression;
4) No changes in the direction of wind flow occur as a result of other structures in the neighborhood of the building.

The only way of eliminating assumptions 2 to 4 is to use surface pressure measurements either on full-scale buildings or on models in the wind tunnel.

3.4.2 Physical Fundamentals

3.4.2.1 Air Flow through Openings

The permeability of a building's envelope is mainly determined by the number of cracks, windows, doors, and gaps between building components. Besides these observable visual leaks, there is background leakage caused by the porosity of building material, and cracks in these materials. Leakage measurements of building components and wall sections were reported as early as the second and third decade of this century (e.g. reviewed by Brinkmann[13]), and more recent articles, dealing with air flows through cracks were published by Kronvall[14] and McGrath[15]. The pressure drop along the crack length is expressed in terms of friction and resistance whereas the air flow through building components is usually described by the empirical power-law equation:

$$Q = D\ (p_1 - p_2)^n \tag{12}$$

The value of the air permeability and the exponent can be measured by the fan pressurization technique (DC)[16] or the AC pressurization technique[17]. The value of the exponent n can be expected to be between its physical limits of $n = 1.0$ for fully developed laminar flow and $n = 0.5$ for fully developed turbulent flow. Because of the intake and outlet losses, which are proportional to the square of the mean flow velocity, the exponent cannot become 1.0. On the other hand, for short flow length the friction becomes negligible compared to the intake and outlet losses. In that case the flow resistance can be treated like a local loss coefficient similar to the ones used to calculate duct losses ($n = 0.5$). A comparison of air leakage in 196 houses, by measure of the blower door technique (DC), showed, for the whole house, a mean value 0.66 for the exponent[18], which is in good agreement with the measured flow characteristic, n, of building components[19,20]

Usually the effective air permeability for a building is a combination of air permeabilities arranged in series, or parallel, or both. Parallel permeabilities can be easily added, but for a series arrangement permeability can be calculated as follows:

$$Q = D_{res} \left\{ (p_1 - p_2) + (p_2 - p_3) + \cdots + (p_{k-1} - p_k) \right\}^n \tag{13}$$

$$Q = D_1 (p_1 - p_2)^n = D_2 (p_2 - p_3)^n = D_{k-1} (p_{k-1} - p_k)^n \tag{14}$$

$$D_{res} = \left\{ D_1^{-1/n} + D_2^{-1/n} + \cdots + D_{k-1}^{-1/n} \right\}^{-n} \tag{15}$$

The use of these equations assumes that all permeabilities have the same flow characteristics, which means having the same exponent, n. Fig. 2 shows the resultant air permeability for two resistances in a series arrangement with an exponenent n = 2/3.

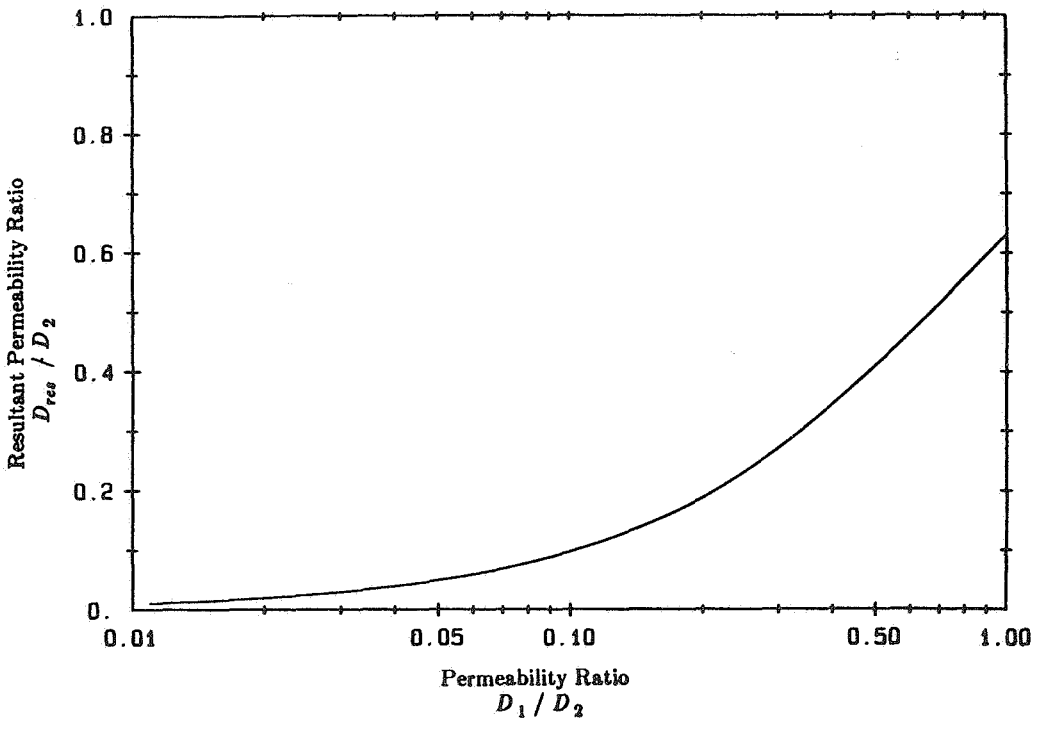


Fig. 2: Resultant Air Permeability for Series Arrangement

3.4.2.2 Superposition of Flows

Air-flows caused by the separate mechanisms of wind and thermal buoyancy are not additive because the flow rates are not linearly proportional to the pressure differences. Therefore, to superpose the flows, the pressures have to be added. The superposed volume rate can generally be calculated by:

$$Q_{tot} = D\ (\Delta p_{tot})^n \tag{16}$$

$$Q_{tot} \approx D\ (\Delta p_{wind} + \Delta p_{stack})^n \tag{17}$$

$$Q_{tot} \approx (Q_{wind}{}^{1/n} + Q_{stack}{}^{1/n})^n \tag{18}$$

Because each mechanism might force the air to flow in a different direction, the superposition of the flows for each facade and each story is given as:

$$Q_{tot} = sign\ |(sign\ |\ Q_{wind}\ |^{1/n} + sign\ |\ Q_{stack}\ |^{1/n})|^n \tag{19}$$

According to Eq. 19 both driving forces for natural ventilation can be calculated separately and superposed to obtain the total natural ventilation.

3.4.2.3 Air Flow due to Stack

The difference in thermal pressure for a given temperature difference under calm conditions is a linear function of the distance of the height above ground from the neutral pressure level (NPL -- see. Eq. 5). Therefore, the volume rate driven by thermal buoyancy only is:

$$Q_{stack}(z) = D_{res}(z)\ (p_i - p_o)^n_{stack} \tag{20}$$

$D_{res}(z)$ is the resultant permeability calculated for the arrangement of permeabilities in series or parallel between the place where the stack pressure occurs (elevator shaft, stair well, etc.) and the outside. For an apartment building, these permeabilities might be the elevator door, doors to individual apartments, doors inside the apartments, and the openings of the facades. In addition to the pressure gradient in shafts and vertical ducts there is the same bouyancy effect at each individual story of the building. Because of the limited height of the story and the relatively small distances of the different openings from the local NPL of the story, these pressure differences are negligible compared to those forced by wind and by the chimney effect of internal shafts.

3.4.2.4 Air Flow due to Wind

To calculate the pressure differences caused by wind, one has to know the outside pressure field as well as the internal pressure at a reference point. The reference point has to be located at a place where all infiltrated air flow from a given story passes. The internal pressure is a function of the permeability distribution of the building's envelope and of the internal flow resistances. From the continuity equation one can derive the air flow for each story:

$$D_{luv}(z)\left\{[p_{dyn}(z)\,\overline{c}_{luv}(z,\phi)]-p_i(z)+p_0(z)\right\}^n = D_{shaft}(z)\left\{p_i(z)-p_{shaft}\right\}^n + D_{lee}(z)\left\{p_i(z)-p_0(z)-[p_{dyn}(z)\,\overline{c}_{lee}(z,\phi)]\right\}^n \quad (21)$$

For story-type buildings this set of equations can be solved independently for each story using Eq. 22:

$$p_i(z,epr,vpr=0)-p_0(z) = \frac{D_{luv}(z)^{1/n}\;p_{dyn}(z)\,\overline{c}_{luv}(z,\phi)}{D_{luv}(z)^{1/n}+D_{lee}(z)^{1/n}} + \frac{D_{lee}(z)^{1/n}\;p_{dyn}(z)\,\overline{c}_{lee}(z,\phi)}{D_{luv}(z)^{1/n}+D_{lee}(z)^{1/n}} \quad (22)$$

For all other building types ($vpr \neq 0.0$) this set of equations (Eq. 21) has to be solved by using a method of iterations.

To simplify the infiltration model, a method for determining the internal pressure of a building has to be developed. The inside pressure distribution due to wind will become uniform with an increasing permeability from the stories to the shaft. The pressure difference responsible for the wind-driven air flow can be calculated by:

$$\Delta p_{wind}(z,\phi,T,epr,vpr) = 0.5\,\rho_o\left\{v(z_0)\left[\frac{z}{z_0}\right]^{\alpha}\right\}^2\overline{c}(z,\phi)-\left\{p_i(z,epr,vpr)-p_0(z)\right\} \quad (23)$$

This pressure difference is mainly a function of the building's height above ground and the building type. The volume rate driven by wind action only can be calculated by:

$$Q_{wind}(z,\phi,epr,vpr) = D_{luv}(z)\left\{p_{dyn}(z)\,\overline{c}_{luv}(z,\phi) - [p_i(z,epr,vpr) - p_0(z)]\right\}^n \quad (24)$$

3.4.3 Simplifications of Air Flow Calculations

3.4.3.1 Thermal Buoyancy

The calculation of air flow caused by the stack effect, as shown in Eq. 20, is very simple. For those who use pocket calculators, the algorithm can be simplified even further. In the following three equations we define a dimensionless volume ratio $q(z)$ that describes the air-flow caused by stack effect for a given temperature difference at a given distance from NPL divided by the air-flow at reference conditions:

$$q(z) = \frac{Q(z)}{Q_r} \quad (25)$$

$$q(z) = \frac{D(z)\,(p_i - p_o)^n}{D_r\,(p_i - p_o)_r^n} \quad (26)$$

If the permeability is evenly distributed over the building height and the temperature difference is equal to the one used to calculate the air-flow at the reference point, the volume ratio can be expressed as

$$q(z) = \frac{(z - NPL)^n}{(z_r - NPL)^n} \quad (27)$$

which is plotted in Fig. 3 for n = 2/3. Therefore, after calculating Q_r, the whole calculation of stack-related infiltration could be done using Fig. 3.

3.4.3.2 Wind Action

Besides the determination of the permeability distribution and the pressure field around the building, the most difficult aspect of calculating wind-driven infiltration is the determination of the inside pressure of the house. Because the air-flow through the shaft due to wind action and thermal buoyancy causes no significant friction losses in the shaft, it can be assumed to have no pressure gradient inside the shaft itself. Furthermore, a uniform distribution of the shaft leakage over the height of the shaft could be expected. This, in conjunction with Eq. 28, can be used to calculate the pressure of the shaft as a first approximation, which is shown in Eq. 29:

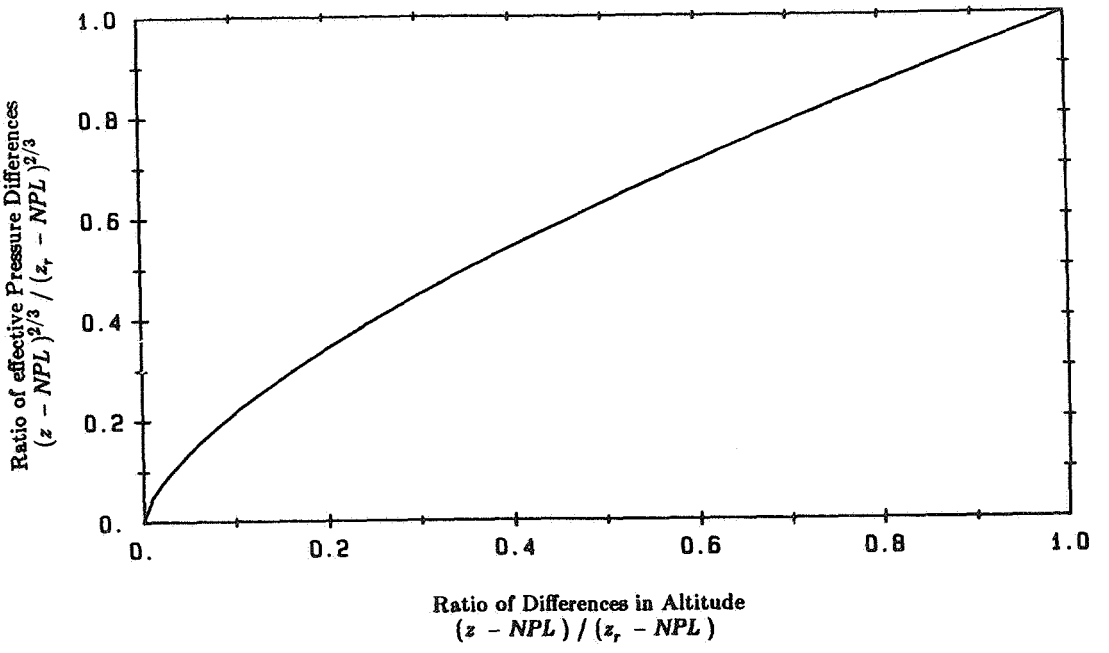


Fig. 3: **Ratio of effective Pressure Difference vs. Ratio of Differences in Altitude from NPL**

$$0 = \sum_{j=1}^{k} \left\{ p_i(j) - p_{shaft} \right\}^n \approx \sum_{j=1}^{k} \left\{ p_i(j) - p_{shaft} \right\} \tag{28}$$

$$p_{shaft} = \frac{1}{k} \sum_{j=1}^{k} p_i(j) \tag{29}$$

For this calculation the inside pressures of story-type buildings might be used. A further simplification for calculating the pressure of the shaft would be to use the average of the inside pressures for the top and bottom story.

$$p_{shaft} = 1/2 \left\{ p_i(j=1, epr, vpr=0) + p_i(j=k, epr, vpr=0) \right\} \tag{30}$$

This calculation gives slightly different values for the shaft pressure than does the calculation presented in Eq. 29. It uses the inside pressure from Eq. 22 for buildings with the envelope permeability ratio *epr* for detached houses or row houses as input. For that calculation story-type buildings with a central corridor and a

symmetrical floor plan, certain surface pressure coefficients of c_{luv} = 1.0 for the windward side and c_{lee} = -0.3 for the leeward side and perpendicular air flow[8] are assumed.

Using Eq. 21 the inside pressure for a story-type building can be calculated as:

$$p_i(z, epr, vpr=0) - p_0(z) = X(epr, vpr=0)\, p_{dyn}(z) \tag{31}$$

with

$$X(epr=0.75, vpr=0) = -0.09$$
$$X(epr=0.50, vpr=0) = 0.35$$

A comparison of different infiltration models[2] revealed the importance of the air flow through the shaft, even when no stack effect is present. The high pressures at the top of the building cause a downstream of infiltrated air in the shaft. This air is released into the lower levels of the building. This is an extremely significant effect for the flow distribution in houses having small *epr* -values. The following empirical equation gives the approximate value for the inside pressures as a function of the building's height above ground and the building type.

$$p_i(z, epr, 0<vpr<1) = p_{shaft}$$
$$+ \frac{\left\{ p_i(z=H, epr, vpr=0) - p_{shaft} \right\}}{H/2} (1 - vpr^n)(z - H/2) \tag{32}$$

With these assumptions the necessary data for the inside pressure distribution for the calculation of wind driven air-flow using Eq. 24 are determined.

3.5 Example of Application of Simplified Model

3.5.1 General

The use and accuracy of this simplified model for calculating overall infiltration and exfiltration in a multi-story building having a simple floor plan, (see Fig. 4) is shown in this section. Results will be compared for accuracy with data from a detailed multizone model[2], that uses the same kind of input for the permeabilities and weather conditions. These results are plotted in Fig. 5 and Fig. 6.

3.5.2 Boundary Conditions

The boundary conditions for both, the simplified and detailed mathematical models are given in Table 1.

Table 1: Input data for multizone model	
outdoor temperature	0 °C
inside temperature	20 °C
height of stories	3 m
number of stories	18
wind speed at reference height	4 m/s
reference height for wind speed measurement	10 m
exponent for vertical wind profile	1/3
exponent for pressure differences	2/3
surface pressure coefficients at windward side	1.
surface pressure coefficient at leeward side	-0.3
air permeability of building components (per Fig. 4)	$m^3/h\ Pa^n$

3.5.3 Results and Discussion

Comparison shows that the air mass flows due to natural ventilation are reasonably identical whether calculated with the detailed model or the simplified equations given in 3.4.3. The differences in results obtained with both models on the air flows on the windward side are very small at the bottom of the building and increase with the height above ground. The error of the overall infiltration rate for the whole windward side of the building is less than 5%, the difference between both models reaches almost 20% on the top floor.

Because of the smaller pressure difference between the envelope surface at the leeward side and the reference point inside the building, the simple algorithm used to calculate the inside pressure distribution produces significant differences between the exfiltration air flows, particularly in cases where the separate flows caused by wind action and thermal buoyancy are converse in their direction. The greatest relative differences (400%) are seen in the area of the NPL of the leeward side. The overall exfiltration is still in the range of $\pm$ 20% of the reference value given by the detailed program.

Nevertheless, this example shows that the simplified equations presented here can be used to calculate infiltration rates even for high-rise buildings. The advantage of this algorithm is that it does not require iteration procedures.

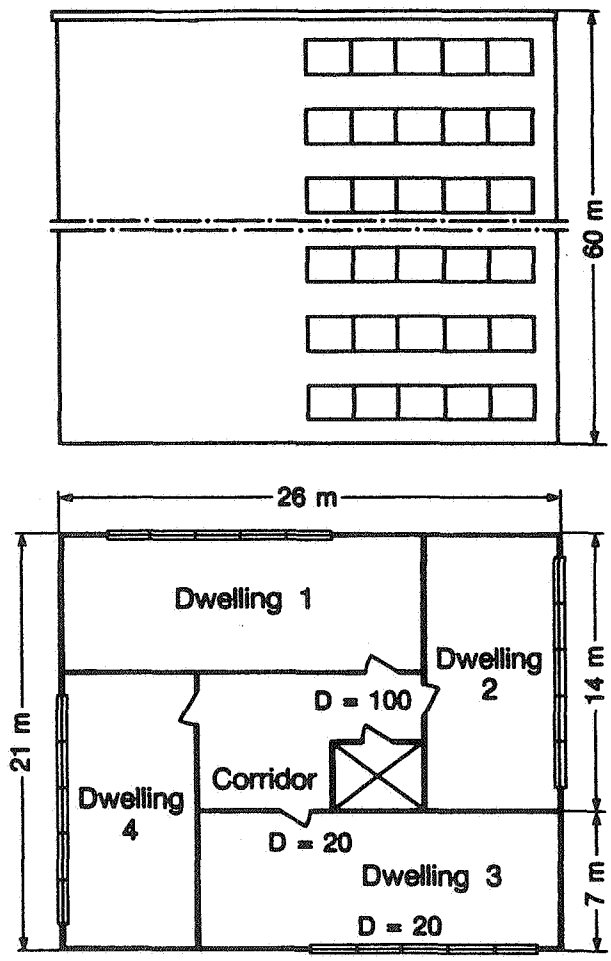


Fig. 4: Simplified Floor Plan and Elevation

3.5.4 Conclusions

In most infiltration models two important parameters --the pressure field around the building and the permeability distribution of the external and internal building components--are usually estimated only roughly. For evaluation and application of models both these parameters must be determined. With the growing proliferation of wind tunnel studies, one might soon be able to predict the pressure field around a building: but the need remains for a multizone pressurization method capable of yielding necessary information about a building's air permeability distribution. Until both of these input parameters can be determined, all multizone infiltration models will be handicapped.

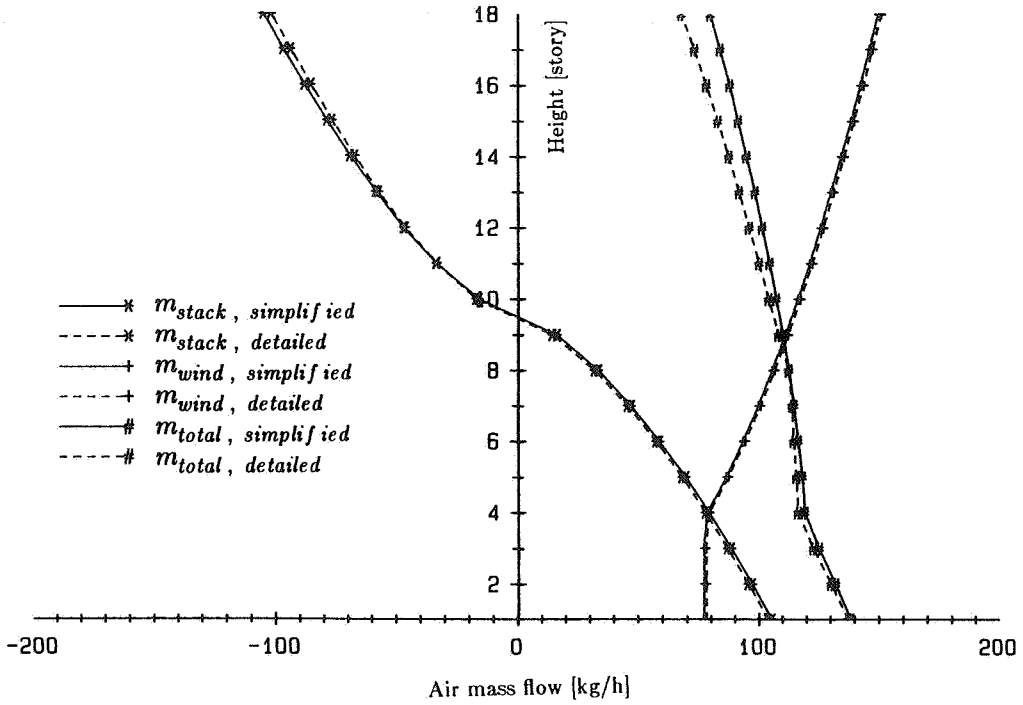


Fig. 5: Air Mass Flow for the Windward Side

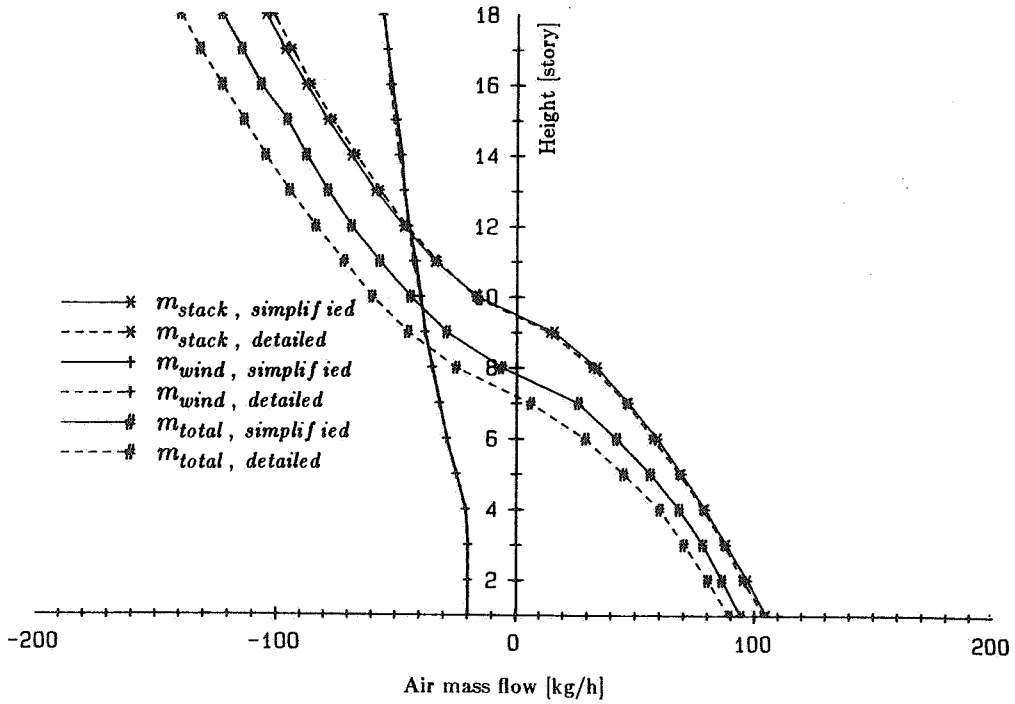


Fig. 6: Air Mass Flow for the Leeward Side

(for each of the three zones)

This research is critical to solving the problems of infiltration simulation for multizone buildings, and should receive international attention.

We at LBL intend to focus our studies on the air flow distribution between different zones using *opr* and *ipr* as guiding principles. One goal is to be able to calculate the air flow even when the wind direction is not perpendicular to the windward side of the building.

4. Summary

In describing the simplified multizone infiltration model developed at LBL, the physical fundamentals involved in the pressure distribution caused by wind action and the stack effect as well as air flow through a building's openings are discussed. Buildings are classified into different categories based on their air permeability distribution, an important step in reducing the input data and limiting the different cases that might occur. When extreme cases for vertical permeability distribution are used as a base, extremes of air-flow distribution can be studied. All other structures are in between these extremes.

The example shows the importance of the compensatory air flow between stories when only wind action is present (compare Q_{wind} in Fig. 5 and Fig. 6). Models that restrict the air flow due to wind action to the story under consideration only, miss an important part of the air-flow distribution in a building.

It has been shown that, by adding the pressures, the air flow due to wind action and the air flow due to stack effect can be calculated separately and superposed later. This calculation allows the air infiltration and exfiltration for buildings with simple floor plans to be calculated without using an iteration method.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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PAPER 19

MULTIZONE MODELING AND AIR LEAKAGE ANALYSIS

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Abstract

Research on ventilation and infiltration has proliferated steadily over the last several years. *Air leakage analysis* and *multicell modeling techniques* have emerged as two of the most interesting topics in current infiltration-related basic research. At the annual meeting of the *American Society of Heating, Refrigeration, and Air-conditioning Engineers* (ASHRAE) held in Honolulu, Hawaii in June of 1985, over two dozen papers related to infiltration and ventilation research were presented, the largest single group of which dealt with infiltration studies in multi-cellular structures. In this report we review twelve significant papers concerned with multizone infiltration and air leakage presented at the ASHRAE conference. Other infiltration-related papers are mentioned, and abstracts for the twelve symposium papers plus seven technical papers are presented.

Keywords. Modeling Air Leakage, Multicell Infiltration, Ventilation, Multizone Air-flow, Review

INTRODUCTION

Throughout the last ten years, research on infiltration in buildings has become quite intense.[1-3] In 1985 the American Society for Testing and Materials (ASTM) developed a standard test procedure for measuring infiltration by tracer dilution.[4] Since 1980 the *Air Infiltration Centre* (AIC) has held five conferences and published their proceedings.[5-9] This research effort has advanced understanding of the physical processes that drive infiltration and, in the process, raised many more research topics.

Of the numerous symposia and technical papers presented by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) on the topic of infiltration, it is the three symposia devoted to the topic at its annual meeting that will be discussed here: *Air Leakage Analysis Techniques* (HI-85-3);[10-13] *Multicell Infiltration Studies — Part 1* (HI-85-35);[14-17] *Multicell Infiltration Studies — Part 2* (HI-85-40).[18-21] (The full papers will be printed in the archival publication of ASHRAE, ASHRAE *Transactions*, Vol. 91 (II), 1985.)

MULTICELL INFILTRATION STUDIES

A whole range of computer programs has been developed for calculating a buildings energy consumption due to infiltration. Those that treat the true complexity of air-flows caused by internal flow resistances require extensive information about flow characteristics and pressure distributions. For this reason, simplified models have been developed to simulate infiltration of single-cell structures such as single-family houses. A high percentage of existing buildings, however, have floor plans that characterize them more accurately as multicellular structures, which cannot be treated by single-cell models.

The highlights of eight papers dealing with multicell infiltration studies presented at the 1985 annual ASHRAE meeting are summarized below. (The full abstract for each paper is reproduced in the appendix.)

"Modeling Parameters for Boundary Layer Wind-Tunnel Studies of Natural Ventilation" presented by **Richard Aynsley of Papua New Guinea University of Technology:** The primary purpose of this paper was to describe the modeling parameters for *Boundary-Layer Wind-Tunnel* (BLWT) modeling to ensure reliable data from tests. The author identifies four main purposes for BLWTs: 1) to gather data on local mean hourly wind speeds and directions at a site relative to long-term wind data from a nearby meteorological recording site; 2) to determine the influence of nearby obstructions, topographic features, or vegetation on local wind speeds; 3) to determine the influence of architectural features such as extended eaves, sun-screen devices, etc. on the surface pressure distribution around a building; and 4) to determine the influence of the size and location of a building's openings on its indoor air-flow pattern and pressure distribution. The author reports that there are three BLWT-specific modeling parameters: 1) the vertical profile of mean longitudinal velocity; 2) the vertical profile of turbulence intensity; and 3)

the power spectral density of the air-flow. He also determines and describes the six most important modeling considerations for using BLWTs in conjunction with buildings: 1) wind-tunnel blockage; 2) length scale; 3) ability to reproduce small architectural details; 4) modeling surrounding environment; 5) influences of Reynold's number influences; and 6) measurement time scale. The author notes that direct modeling of infiltration in a BLWT is not practical because of Reynold's number considerations, but the pressure coefficients measured in the BLWT can be used in various models to estimate it. The author admonishes the reader not to overlook these effects — especially the more subtle ones — when making a BLWT study.

"Estimating Comfort Cooling from Natural Wind inside Buildings Using Boundary Layer Wind Tunnels" presented by **Richard Aynsley:** In this paper, Aynsley describes two methods for using *Boundary-Layer Wind-Tunnel* (BLWT) data to estimate air-flow through buildings and use it to determine thermal comfort conditions for occupants. Two distinct methods are presented: the pressure difference/discharge coefficient method and the wind speed coefficient method. The former method relates the flow through an orifice to the dynamic pressure across it; since the method is only defined at the orifice, it must be combined if there are orifices in series. The latter method is more direct because it has the potential for defining the entire velocity field within the structure; but, because of wind speed coefficients require more detailed data collection, pressure coefficients are more widely compiled and published. The author believes that the primary advantage of the discharge equation approach is that estimates of air-flow can be calculated in design buildings without recourse to specific BLWT tests; the disadvantage is that local mean velocities can be estimated only near openings. Aynsley concludes that the use of mean wind speed coefficients is a potentially superior option, but that they will not be generally used until a larger database of measurements is created.

"Multizone Infiltration Measurements Using a Passive Perfluorocarbon Tracer Method" presented by **Russell Dietz of Brookhaven National Laboratory, USA:** This paper purports to be a validation of the *Brookhaven National Laboratory* (BNL) *Perfluorocarbon Tracer* (PFT) technique. In this technique one or more PFTs are continuously released from a passive emitter and the PFT contained in the room air is passively adsorbed using a diffusion tube sampler. Ignoring start-up effects, the result of this technique is to give a measurement of the *average inverse infiltration** over the sampling period. Although there is no validation *per se* in the paper, several datasets are generated using the PFT system in multizone buildings. The author describes the PFT methodology, applies it to several multizone buildings, and discusses some modeling concepts for larger buildings. The advantages of the technique appear to be its low cost and ease of installation; the disadvantages appear to be the limited number of tracers, the length of time required to obtain a measurement, and the lack of service centers to do the chemical analysis. The last half of the paper contains field data from a variety of applications where the BNL/PFT system was employed. The data is worthy of a closer look for those considering using a PFT-type system.

* Average inverse infiltration is the quantity of interest for indoor air quality; average infiltration is the quantity of interest for energy considerations. The two quantities can be simply related if the (geometric) standard deviation of either distribution is known.

"Errors Resulting from the Use of Single-Zone Ventilation Models for Multizone Buildings: Implications for Energy Conservation and Indoor Air Quality Studies" presented by **Russell Dietz:** The reason for the recent interest in multizone models is that the assumptions made by the simpler single-zone models are, in many situations, violated. Dietz looks at these assumptions and illustrates the errors that can result when single-zone methods are used but its assumptions are violated. A typical ranch-style house serves as an example of the errors so induced in tracer-decay measurements. The overall single-zone results evidently were better when the volume of the basement (i.e. the second zone) was included; however, in general, all single-zone models reportedly over-predicted the infiltration rate by at least 10%. When the authors calculated the amount of energy required to heat the infiltrating air, they found that if the entire structure was treated as a single zone the errors were less than 15% over a range of outdoor temperatures, but that if the basement volume was excluded the errors were over 35%. The authors concluded that an accurate measurement of air-exchange rate, combined with a single-zone model and (inappropriately) applied to a multizone dwelling, can give only a reasonable first approximation for energy conservation and indoor air quality calculations.

"MOVECOMP: A Static Multicell-Airflow Model" presented by **Magnus Herrlin of the Royal Institute of Technology, Stockholm, Sweden:** MOVECOMP is a multizone air-flow model developed for the Swedish Council for Building Research to study the following: 1) air movements in a building caused by wind, stack, and HVAC effects; 2) air movement effects on energy and power demands in different parts of the building; and 3) the distribution of pollutants within the building. Recognizing that there already exist many computer models capable of accomplishing these needs, after completing a survey of the open literature the author concludes that none of them are public domain programs and the ones available are still in development. MOVECOMP is constructed along the classic lines of such programs — a network of interconnected pressure/flow nodes solved iteratively from mass-balance considerations. The bulk of the paper is devoted to subtleties of the program and will be of interest to experts in such modeling techniques. A companion program, FLOWCOMP, used for designing mechanical ventilation systems, is also mentioned.

"An Automatic Multitracer Gas Method for Following Interzonal Air Movement" presented by **Josephine Prior of the Polytechnic of Central London, United Kingdom:** The paper presents a new technique for measuring multizone air movement using multiple tracer gas. The *Perfluorocarbon Tracer* (PFT) technique is similar in most ways to to the Brookhaven (BNL) technique described above with the notable exception of BNL's patented emission system. The paper is structured into three parts: the general description of the apparatus and method; an illustration of the development of a discrete time matrix analysis of both single-zone and multizone data; and a report of multizone experiments which have already been carried out by the authors. Because the injection system is automated, the approach has the advantage of versatility, but at a higher cost than the BNL technique. A sophisticated eigenvalue technique for reduction of the decay data is presented and demonstrated on measured data. It would have been interesting to see a comparison of the errors associated with the reduction of multizone tracer-decay data and those associated with the reduction of analogous continuous injection data (e.g. the BNL method).

"Documenting Air Movements and Infiltration in Multicell Buildings using Various Tracer Gas Techniques" presented by **David Harrje of Princeton University, Princeton, USA:** This paper summarizes the tracer gas techniques currently in use for determining infiltration in multizone buildings. The techniques are grouped into three categories: tracer gas dilution (i.e. decay techniques); constant injection of tracer gas; and constant concentration of tracer gas. One or more tracer gas can be used with any of these methods. The authors describe each technique and, in some detail, its own single-gas, multizone, constant-concentration technique including the control and analysis segments. Also discussed is the calibration of tracer-gas and related equipment, including the relationship of the measurement technique to the calibration requirements. The authors conclude that multiple gas are not always required in multizone measurement system provided that a) a constant concentration technique is used and b) information about interzone flows is not needed. The technique is intended for determining the outside infiltration rates from as many as ten building zones. The authors recommend that the constant injection technique be used for multiple tracer-gas applications, but state that the tracer-decay technique *can* be used for two-zone applications.

"Evaluation of a Simple Technique for Measuring Infiltration Rates in Large and Multicelled Buildings Using a Single Tracer Gas" presented by **Richard Walker of the Building Research Establishment, Garston, Watford, United Kingdom:** The purpose of the paper is to describe a simple, single-gas tracer technique for characterizing large or multicelled buildings. Determining the ventilation rates in such buildings involves such problems as local variations in infiltration, imperfect internal mixing, and difficulties associated with injection and distribution. According to the authors, these problems could be eliminated if an acceptable single-gas technique could be found. The report is based on the fact that if a building is seeded with a tracer and allowed to come to steady state, the concentration of gas in each zone in the building may be quite different but all will decay at the same rate. The authors claim that it is this global decay rate that characterizes the infiltration performance of the building. They then proceed to derive a matrix decay/eigenvalue method of analyzing the tracer data. They tested their technique on two buildings: a mechanically-ventilated, multicelled office building and a large, naturally-ventilated, single-zone building. Their most interesting conclusion is that the dominant decay rate can be measured by partially seeding the building with tracer gas (i.e. seeding any sub-section of the building), thus allowing measurements to be made on a large building with very modest equipment (e.g. bag sampling technology). Although the applicability of the dominant decay rate concept is debatable, the authors have presented an efficient and simple method of measuring it.

Discussion

This double symposium, presenting results from researchers all over the world, supplied a significant amount of information for potential multicellular users. The most common thread among the papers in the sessions was the discussion of tracer gas methods. Several different types of tracer techniques were discussed, including single-zone and multizone, active and passive, as well as decay and constant concentration. In addition to *true* multicell techniques, some of the papers discussed *limited* techniques that

could have advantages in specific circumstances; included in this category are two-zone decay techniques, single-gas techniques, and local seeding techniques. Several of the papers alluded to the advantages (necessities) and disadvantages (limitations) of the various techniques, but valid conclusions await more field data and comparative trials.

Two issues that have become topical of late were discussed by Richard Aynsley: the use of boundary-layer wind tunnels in infiltration modeling and the estimation of natural ventilation-induced cooling for summer comfort. The two associated papers were instructive in the art of wind-tunnel modeling and its relationship to ventilation.

Many of the papers discussed, presented, or referred to multizone analysis models that are currently under evaluation or testing. Notable for its public availability was the MOVECOMP program developed in Sweden.

These two sessions clearly indicate the international flavor of the research effort in multicell infiltration; eight papers from four countries were presented. Each research group had slightly different priorities (e.g. simplified testing procedures, error analysis methods, modeling capability, etc.), which led to differing research agenda. When viewed as a whole, these diverse efforts span most of the research topic. There is, however, still a lack of information exchange in the field; research groups are at times repeating experiments because the results of other's efforts (e.g. multicell model development) are not distributed sufficiently.

AIR LEAKAGE ANALYSIS TECHNIQUES

As the heat-load and indoor air quality aspects of infiltration become of increasing concern, the need to measure the air tightness of residential buildings becomes increasingly important. Various techniques are used to measure air tightness; most of them involve calculating of an effective leakage area, which can be used as a quantitative measure of air tightness. The most common technique for measuring a building's air tightness involves fan pressurization, but few practitioners understand the issues related to calibration accuracy and analysis techniques. This symposium contained four papers addressing some of the accuracy issues of conventional fan systems and introduced some less conventional techniques for analyzing air leakage in buildings. The paragraphs below summarize the highlights of these papers. (The full abstract for each one can be found in the appendix.)

"Fan Pressurization of Buildings: Standards, Calibration and Field Experience" presented by **Ken Gadsby of Princeton University, Princeton, USA:** This paper is a good review of current practices for measuring air leakage. It discusses the fan pressurization test method, ASTM Standard E779, as well as currently available pressurization equipment. It emphasizes the importance of appropriate calibration procedures and it presents field experiences that point out both the potential applications and the cautions necessary when using fan pressurization. Although current practice is limited to single-family detached structures, recently emphasis has been put on the problems associated with attached dwellings as, for example, in military housing. Multiple zones are currently being pressurized using multiple pressurization devices. The authors compare various techniques in use for calibrating pressurization devices and give special emphasis to low-

flow situations. The paper concludes with applications of pressurization results and a discussion of consensus standards in progress.

"Accuracy in Pressurization Data Analysis" presented by **Richard Grot of the National Bureau of Standards:** This paper zeros in on the issue of the accuracy and precision of pressurization results using current equipment. The authors point out the importance of measurement accuracy in the formulation of air-tightness standards. There are two types of internal errors: air-flow rate errors and differential pressure errors. Additionally, there are errors caused by external conditions at the time of the test, such as the building's configuration or the weather, wind being noted as the most significant. The authors have found that magnetic linkage gauges are often significantly out of adjustment and require frequent, individual calibration. Although some studies of *RPM*-type equipment have demonstrated an accuracy of 4%, the authors defer general statements about accuracy to the ASTM task group (E6.41.05) investigating this issue. The authors also discuss the statistical methods used to analyze pressurization data, and they compare the most widely used methods. The paper closes with some specific examples of errors in real data and offers specific recommendations for reducing them. The trade-off between accuracy and precision when extrapolating data is also discussed.

"AC Pressurization: A Technique for Measuring Leakage Area in Residential Buildings" presented by **Mark Modera of Lawrence Berkeley Laboratory, Berkeley, USA:** The previous two papers discuss the conventional air leakage measurement technique using fan pressurization. This paper presents a qualitatively different measurement technique, AC pressurization. In this system, air is alternately pulled in and pushed out of the building envelope by a sinusoidally driven piston mounted in the fabric of the building. This volume drive and the attendant oscillating pressure are detected synchronously and used to calculate the effective leakage area in real time. The device has only been used only by the research group that invented[↓] it, but there appear to be many advantages to the device: because it operates at low pressures, the issue of extrapolation discussed in earlier papers is not significant; because it operates at low flow rates, the problem of high air exchange in inclement weather is not relevant; because it operates in real time, the user receives immediate feedback as to the amount of air leakage and the amount of change in air leakage caused by on-site retrofits; and because it uses synchronous detection to exclude all but a small range of frequencies, most sources of random error are rejected. The paper contains both laboratory and field results using this device. Preliminary results indicate that AC pressurization can be used as a delicate probe of the physics of leakage. One limitation reported is that the device is "blind" to very large leaks, such as those associated with flues or undampered fireplaces. The authors conclude by indicating research areas they intend to pursue to further test their new technique.

"Determination of the Effective Leakage Areas of Houses by Multilinear Regression Analysis of the Energy Consumption Data" presented by **Gren Yuill of Yuill and Associates, Winnipeg, Manitoba, Canada:** The concept behind this paper is that for certain applications (e.g. the administration of energy audit programs) it may be desirable to have a cheap, but less precise method of estimating effective leakage area — a method

↓ Patent Pending

that would not require the use of instrumentation but, instead, would rely on utility-bill information. Utilities would then be able to determine prime candidates for envelope-sealing type measures without an on-site inspection. The regression model presented uses weather data and consumption data to fit a steady-state model to the energy consumed. The regression constants produced are interpreted as the conductances, the interior and solar gain utilization factors, and the effective leakage area. The approach was used on two (relatively tight) houses built since 1977, both of which were oil-fired, two-story buildings without basements. Although the method holds promise, the results of this albeit limited study are disappointing. The estimated leakage areas do not agree with the results obtained with fan pressurization. The author sees three possible interpretations: 1) that regression cannot be used to determine leakage area; 2) that the current regression model technique is insufficiently robust; and 3) that the data was contaminated. (The data was not collected by the author.) The author ends by suggesting that a larger, better controlled study be instigated to determine whether the approach is practical.

Discussion

The four papers of this symposium represent an excellent cross-section of ongoing studies of air-leakage detection. The paper by Harrje et al. is a snapshot of experiences of *blower door* users and serves as a good introduction to the topic. Persily and Grot, on the other hand, have already begun to explore the limitations on both accuracy and precision of standard fan pressurization techniques.

As a technology matures, such fine tuning is critical. The last two papers present novel methods--each quite different--that represent the leading edge of research in the field — but are quite different. Modera describes a *high-tech* method for real-time determination of leakage area, a method that could solve some of the well-known limitations of blower-door technology but at the cost of increased complexity. Yuill on the other hand attempts to use utility-bill information to *back out* leakage information without the need for on-site measurements. If these techniques prove viable, they could become important components of future energy conservation technology.

OTHER PAPERS

In addition to the symposia discussed above were other papers (not reviewed by the author) that may be of interest to the reader. Two technical sessions (seventh and eighth) contained seven papers relevant to measuring air leakage: #2922,[22] *Ventilation Measurements in Large Office Buildings;* #2923,[23] *Air Exchange Rate Measurements of the National Archives Building;* #2924,,[24] *A Correlation for Estimating Wind Ventilation;* #2925,[25] *Interrelations Among Different Ventilation Parameters and Indoor Pollutants;* #2926,[26] *Thermal Effect on Pressure Distribution in High-Rise Buildings: Experiment and Analysis;* #2927,[27] *Effect of an Exterior Air Infiltration Barrier on Moisture Condensation and Accumulation withing Insulated Frame Wall Cavities;* #2928,[28] *Air Leakage Flow Correlations for Varying House Construction.* The appendix contains the abstracts of these technical papers as well as the papers from the aforementioned symposia.

Several other symposia dealt with topics related to infiltration and ventilation: HI-85-20, *Design of Ventilation Systems for Hazardous Gas Processes;* HI-85-22, *Instrumentation and Measurement Methods for Performance Evaluation of Buildings;* HI-85-34, *Air Flow around Buildings and Exhaust Re-entry Problems;* and HI-85-39, *Measurement and Control of Radon and its Daughter Products.* Additionally, the reader is encouraged to investigate Vol. 91 (II), 1985, of *ASHRAE Trans.* for several isolated technical papers of some interest.

CONCLUSIONS

The 1985 annual meeting of the American Society of Heating Refrigeration and Air-conditioning Engineers presented an extraordinary amount of archival literature dealing with the topic of infiltration and ventilation. Although the symposia concentrated on the areas of multizone modeling and air leakage analysis techniques, spread throughout the proceedings were high quality research papers. Anyone interested in keeping up with research in this field should consult the ASHRAE's *Transactions* for the texts of the various papers.

ACKNOWLEDGEMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy Research and Development, Building Systems Division, of the U.S. Department of Energy Under Contract No. DE-AC03-76SF00098.

APPENDIX: *SELECTED ABSTRACTS*

This appendix contains author-prepared abstracts of selected papers referred to in the body of this report. All papers are to be published in *ASHRAE Trans.*, Vol. 91 (II), 1985.

HI-85-3, *Air Leakage Analysis Techniques*

1) **Fan Pressurization of Buildings: Standards, Calibration and Field Experience**

by David Harrje and Ken Gadsby

The fan pressurization method has been widely used by groups working with building retrofits and with new construction to evaluate the air tightness of building envelopes. To ensure uniformity in the testing method ASTM Standard E779-81 was developed. This standard is reviewed with commentary on practical aspects of its application. Calibration of these fan systems, often referred to as blower doors, will also be discussed, pointing out where calibration difficulties have arisen and the implications on field inspections. Use of fan pressurization together with infrared scanning is one of the best methods to pin-point air leakage sites in building envelopes. The application of such methods in a variety of buildings will be discussed in order to demonstrate the utility of the methods in the evaluation of building tightness, including seasonal variations; effectiveness of envelope sealing; and the location of problem areas in the building envelope.

2) **Accuracy in Pressurization Data Analysis**

by Andrew Persily and Richard Grot

There are several different ratings of building airtightness used to report the results of fan pressurization tests. These are generally based on air-flow rates at specific reference pressures predicted by curve fits to the test data. The statistical analysis of the data used to obtain these curves allows estimates of the predictive errors associated with these calculated airtightness ratings. The accuracy of the various ratings of building airtightness are important issues in airtightness standards enforcement and the evaluation of retrofit effectiveness. In this paper we discuss the uncertainties associated with pressurization test results due to measurement errors, fan calibration, and test conditions, but concentrate primarily on the errors in the airtightness ratings calculated using standard statistical techniques. Using data from many pressurization tests, we calculate several common airtightness ratings and determine the predictive errors associated with each. This discussion is based on a dataset of pressurization test results in about seventy houses of different sizes, construction and airtightness, along with detailed measurements made on a single house. The implications of the results are discussed in relation to the reporting of pressurization test results, their use in models to predict natural infiltration rates and airtightness standards.

3) **AC Pressurization: A technique for Measuring Leakage Area in Residential Buildings**

by Mark Modera and Max Sherman

Currently, fan pressurization (often performed using a "Blower Door") is the predominant technique for measuring the airtightness of residential buildings. This technique has several known deficiencies from both a theoretical and practical perspective: 1) it exerts pressures on the envelope which are significantly higher than those experienced under natural conditions; 2) it requires extrapolation outside of the measurement range in order to calculate the effective leakage area; 3) because pressurization or depressurization require separate tests, and extrapolation must be performed for both sets of results, it cannot give real- time results; 4) the physical process of installing a blower door is cumbersome and time consuming; 5) the large volumes of air displaced by the fan may cause inconveniences such as fireplace ashes on the floor, indoor temperature changes, etc; and 6) the accuracy of the test can be severely degraded by wind effects. In this report we present a new air-leakage measurement technique called AC Pressurization. This technique is designed to overcome most of the short-comings of fan pressurization (sometimes known as DC pressurization) and to quantify air tightness more accurately and conveniently. The physical apparatus and analysis technique, as well as the laboratory measurements which led to the specifications of the final field device are described. Finally, field measurements of leakage area using AC pressurization are compared with fan pressurization measurements.

4) **Determination of the Effective Leakage Areas of Houses by Multilinear Regression Analysis of the Energy Consumption Data**

by Gren Yuill

The steady state heat loss of a house can be expressed as the sum of the above grade conduction loss, the below grade conduction loss, and the infiltration loss, minus the solar gain. Each of these terms is the product of a weather related variable and a coefficient which describes a physical characteristic of the house.

If the infiltration driving force is properly defined, the infiltration coefficient is the equivalent leakage area. Thus a multilinear regression analysis of the total energy consumption of the house (including internal gains) against the four weather parameters will yield values of the four coefficients, including the equivalent leakage area.

This technique has been applied to two houses. The equivalent leakage areas determined correlate well enough with those measured by a blower door, to indicate that the method has promise.

1) **Modeling Parameters for Boundary Layer Wind-Tunnel Studies of Natural Ventilation**

by Richard Aynsley

Reliable surface pressure and indoor wind speed data from model buildings in boundary layer wind tunnels can only be expected if appropriate modeling parameters are carefully considered. Modeling parameters to consider when planning boundary layer wind tunnel studies of indoor air-flow and external surface pressures due to wind are identified and criteria for assessment are suggested.

2) **Estimating Comfort Cooling from Natural Wind Inside Buildings Using Boundary Layer Wind Tunnels**

by Richard Aynsley

Two techniques for estimating natural wind air-flow through buildings for comfort cooling utilizing data derived from boundary layer wind studies are presented. The modeling parameters necessary for reliable data from the boundary layer wind tunnel studies of indoor air-flow are identified.

3) **Multizone Infiltration Measurements Using A Passive Perfluorocarbon Tracer Method**

by Russell Dietz, Robert Goodrich, and Ted D'Ottavio

A miniature passive perfluorocarbon tracer system was successfully applied to the determination of air infiltration and exfiltration rates from each zone of a multizoned structure as well as the air exchange rates between zones in homes, multiple unit condominiums, naturally ventilated apartment buildings, and large commercial buildings with multiple air handling systems. Use of the multizone technique in indoor air quality assessments and air handling system stratification studies appears to be quite feasible with the availability of this measurement system.

4) **Errors Resulting from the Use of Single-Zone Ventilation Models on Multizone Buildings: Implications for Energy Conservation and Indoor Air Quality Studies**

by Ted D'Ottavio and Russell Dietz

Errors resulting from treating a house as an enclosure surrounding a single, well-mixed volume of air are explored in detail for a ranch house with a basement. A fairly typical ventilation pattern is assumed and three quantities, the air exchange rate, the indoor pollutant concentration from a given emission, and the energy required to heat infiltrating air, are calculated and compared using both the one and two zone models for this house. In general, the errors were around 10-20% if the basement was included in the one zone models and 30-40% if the basement was neglected. Other factors that affect the magnitude of these errors include the length

of a pollutant release, the outdoor temperature and the air exchange rate measurement protocol as well as the particular ventilation characteristics of the house.

HI-85-40, *Multicell Infiltration Studies — Part 2.*

1) **MOVECOMP: A Static Multicell-Airflow Model**

by Magnus Herrlin

This paper deals with a new computer program, MOVECOMP, which calculates the in- and exfiltration and the air-flows between the rooms of a multicell building. The calculations are made due to wind- and thermal forces and the characteristics of the leakage openings.

MOVECOMP is intended to be incorporated in a more complex model, AIRCOMP. This latter model will be used also to calculate the air-flows in a ventilation system.

MOVECOMP was developed to be "user friendly"; input data are limited and output data are very flexible. The user chooses which output he wants from a menu. The building is described with a system of pressure nodes, connected to each other through flow - pressure difference functions. A modified Newton-Raphson method was chosen to solve the nonlinear system of equations. AIRCOMP was started to be developed because no complex model was found to be available.

2) **An Automatic Multitracer Gas Method for Following Interzonal Air Movement**

by Josephine Prior, John Littler, and Christopher Martin

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

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

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

3) **Documenting Air Movements and Infiltration in Multicell Buildings using Various Tracer Gas Techniques**

by David Harrje, Gautum Dutt, D.L. Bohac, and Ken Gadsby.

Tracer gas techniques for measuring air-flows in buildings fall into three categories -- dilution, constant injection, and constant concentration. Dilution of a single tracer works well in buildings with a single zone and also in some two zone buildings. Multiple tracer gas measurements, necessary to characterize flows among more zones, are best conducted using the constant injection approach. The constant concentration method uses single tracer gas to determine the air-flow rates from the outside into each of as many as ten building zones.

The paper outlines the different tracer techniques for making air flow measurements in multi-cell buildings and describes the operation of a constant concentration system. This system measures tracer gas concentration in different zones and injects accordingly to maintain a constant concentration in each zone. The system was tested in a single zone structure and successfully applied to a small three-zone house. Sensitivity analyses and calibration procedures described in this paper define the capabilities and limitations of this technique. Although this method does not fully characterize all inter-zone air-flows in the building it can be useful in analyzing the energy balance of multi-zone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.

4) **Evaluation of a Simple Technique for Measuring Infiltration Rates in Large and Multicelled Buildings using a Single Tracer Gas**

by Richard Walker, M.D.A.E.S. Perera, O.D. Oglesby and M.B. Hathaway.

Large, multicelled and naturally ventilated buildings pose many inherent problems for the measurement of overall infiltration rates using tracer gases. Considering a single tracer gas decay technique, the most obvious problems are:

1. local variations in infiltration,
2. imperfect internal mixing of the air, and
3. practical difficulties in distributing (i.e. seeding) the tracer gas and subsequently obtaining air samples.

A previous paper proposed a relatively simple technique which avoids these problems. By considering a multicell model, it showed that it was sufficient to seed part of a building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.

#2922 **Ventilation Measurements in Large Office Buildings**

by Andrew Persily and Richard Grot

Ventilation rates were measured in nine office buildings using an automated tracer gas measurement system. The buildings range in size from a two-story federal building with a floor area of about 2000 m^2 to a 26-story office building with a floor area of 64,000 m^2. The ventilation rates were measured for about one hundred hours in each building over a range of weather conditions. The measured ventilation rates are discussed in relation to the outside air intake strategy in each building. The ventilation rates are also compared to design rates in the buildings and ventilation rates in ASHRAE standard 62-81. Some of the buildings are at times operated at lower ventilation rates than recommended in Standard 62-81.

#2923 **Air Exchange Rate Measurements of the National Archives Building**

by Samuel Silberstein and Richard Grot

To aid in improving the performance of the heating, ventilating, and air-conditioning system of the National Archives Building so that it can better protect paper-based records of the United States, the National Bureau of Standards (NBS) measured air exchange rates under various combinations of temperature and wind speed. The average air exchange rate under normal operation of the HVAC system was 0.9 h^{-1} for an average temperature difference of 11.3°C and an average wind speed of 2.7 m/s. This rate is approximately twice those for new General Services Administration (GSA) office buildings. No clear dependence of air exchange rate on temperature differences up to 17°C or wind speeds up to 5 m/s was found.

#2924 **A Correlation for Estimating Wind Ventilation**

by C.K. Krishnakumar, Stephen Fields, Robert Henninger Clyde Schafer, Donald A. Bettge

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used in these tests. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas and the velocity of the approach wind. Results were compared with those projected from available correlations for general type buildings.

#2925 **Interrelations Among Different Ventilation Parameters and Indoor Pollutants**

by Elia Sterling and Theodore Sterling

Measures of a number of ventilation parameters and of a number of pollutants from 21 locations furnished data for evaluating interrelations among commonly used descriptors of ventilation as well as their relation to frequently measured indoor gaseous and particulate pollutants (including carbon dioxide, carbon monoxide, particulates, and hydrocarbons). The analysis of the data is presented in three sections: (1) The intercomparison between different ventilation measures, (2) The relationship between ventilation and pollutant concentrations across buildings, (3) The relation of pollutants to ventilation measures in specific buildings.

#2926 **Thermal Effect on Pressure Distribution in High-Rise Buildings: Experiment and Analysis**

by Yung Lee and Kyu Lee

A study has been made, both experimentally and analytically, on the characteristics of thermal performance of high-rise buildings using an idealized model building with a number of openings at various locations and temperature distributions. The building was assumed to have no internal partitions. The effect of the factors affecting on the location of the neutral pressure level (NPL) was of particular interest of the present study.

#2927 **Effect of an Exterior Air Infiltration Barrier on Moisture Condensation and Accumulation within Insulated Frame Wall Cavities**

by Heinz Treschel and J. Robert Ebbets

Increased air tightness of buildings has been promoted for energy savings. One method for achieving greater air tightness is the installation of an air infiltration barrier on the exterior of building sheathing. Although most barrier materials promoted for this application have a high water vapor permeance, it has been a concern that such installations could lead to moisture problems. To evaluate the potential for such problems, a series of laboratory tests were conducted. The results indicate that the air infiltration barrier installed between the sheathing and the siding causes a more even moisture distribution by decreasing the accumulation of condensation in building materials in areas of high moisture content and by increasing it in areas of low moisture content. It was also observed that the highest moisture content in the sheathing occurred under moderately cold conditions, while the highest moisture accumulation in the fiberglass occurred under more severely cold conditions.

#2928 **Air Leakage Flow Correlations for Varying House Construction**

by David Wilson, Darwin Kiel, and Max Sherman

Fan pressurization techniques are being employed by an increasingly large number of contractors and auditors to determine the leakage characteristics of structures. In this study, a large data base of flow exponents and flow coefficients are compiled to determine the degree of correlation that exists between flow parameters. The resulting empirical relationships are then used to determine the feasibility of predicting these flow parameters directly from a single pressure difference test.

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 20

INHABITANTS' BEHAVIOUR WITH REGARD TO VENTILATION; THE USE OF WINDOWS. FIRST HEATING SEASON.

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SYNOPSIS

A research is being carried out concernin g the use of windows and doors in an appartment building in Schiedam in the Netherlands.
The investigations consist of an inquiry and of continous measurements for a period of about two years on 1280 windows and doors of 80 dwellings.
During the measurements there is only a distinction between the closed and not-closed positions of windows and outside doors, because simple switches are used.

The following conclusions can be drawn:

- the measurement technique is reliable even if the visibility is bad.
- there is a linnear relation between the weekly mean of the number of open windows and outside doors and the mean outside temperature.
- there is a characteristic day-night pattern for the use of doors, pivoting windows and flap windows for the living room, the bedrooms, the kitchen, galery side and balcony side.
- the most important motive for ventilation is the discharge of polluted indoor air.
- 25% of the windows that are open are set ajar, 75% are opened more wide.
- there is a good correspondence of the results of the inquiry and those of the measurements
- the windows and doors that are open during too many hours a day result in a mean estimated heatingloss of 4.5 GJ per heating season per dwelling.

1. INTRODUCTION

1.1 General

An investigation is being carried out By the TNO Division of Technology for Society concerning the use of windows and doors in an appartment building in Schiedam. Schiedam is situated at the west side of Rotterdam in the Netherlands.
The project that has been initiated by Switzerland within the frame of the International Energy Agency (IEA) program with the title :
"Inhabitants Behaviour with Regard to Ventilation" (Annex VIII)

The situation on this moment is that Belgium, The Netherlands, Germany,Switzerland, and England participate in this research project. Belgium is the "Operating Agent".
Our measurements started on 26 November 1984 and will continue till the end of the heating season of 1985/1986.

1.2 Purpose

The purpose of the project is:

1. Determination of the inhabitants behaviour with respect to ventilation and its relations to the inner and outer climate conditions.
2. The estimation of the energy loss due to this behaviour.
3. The study of the motives of the behaviour.
4. The study of changes in the behaviour due to information and instruction to the inhabitants.

1.3 The building

In the middle of the building is a staicase and elevators. There are 14 dwellings per floor and 10 floors.
From the total of 140 dwellings 80 are taken on basis of willingness of the inhabitants, looking at the front facade 44 at the right of the staircase and 36 at the left (Figures 1 to 7).
Above every pivot window is a ventlight or flap window.

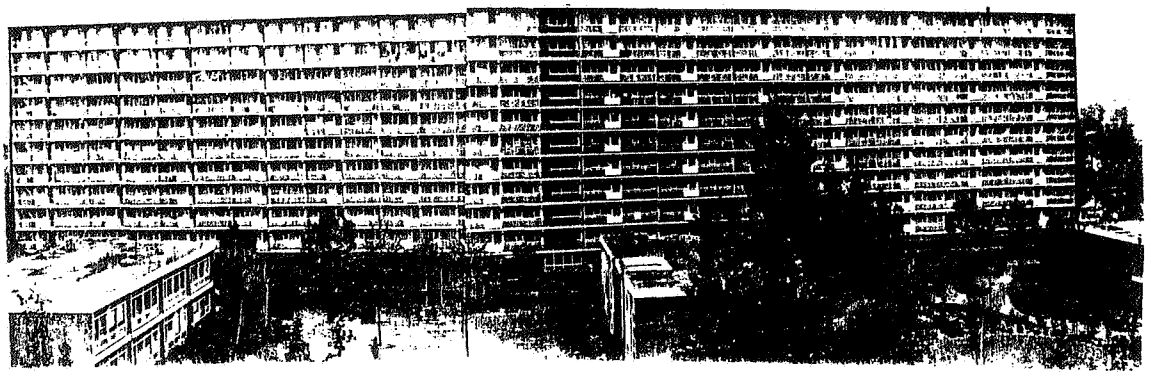


Figure 1 .Front facade as seen from the West.

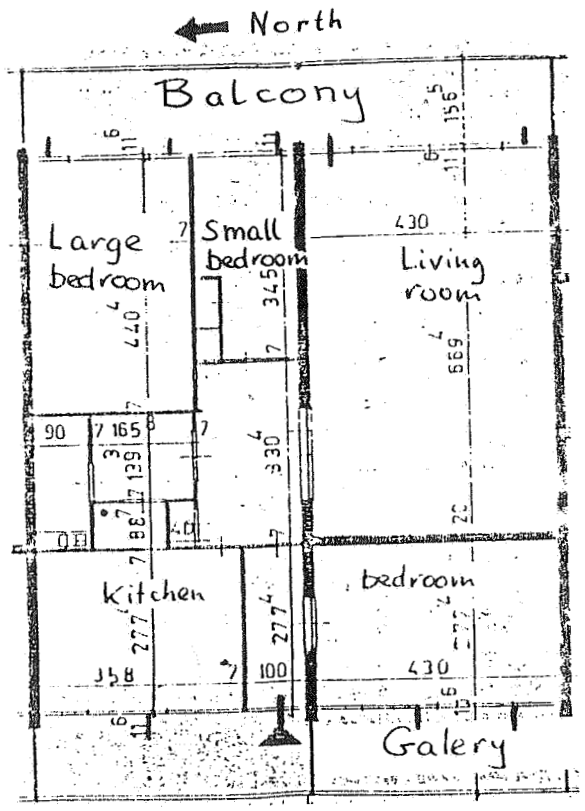


Figure 2 . Floorplan of one dwelling.



Figure 6 . The building as it can be viewed from the North-East.

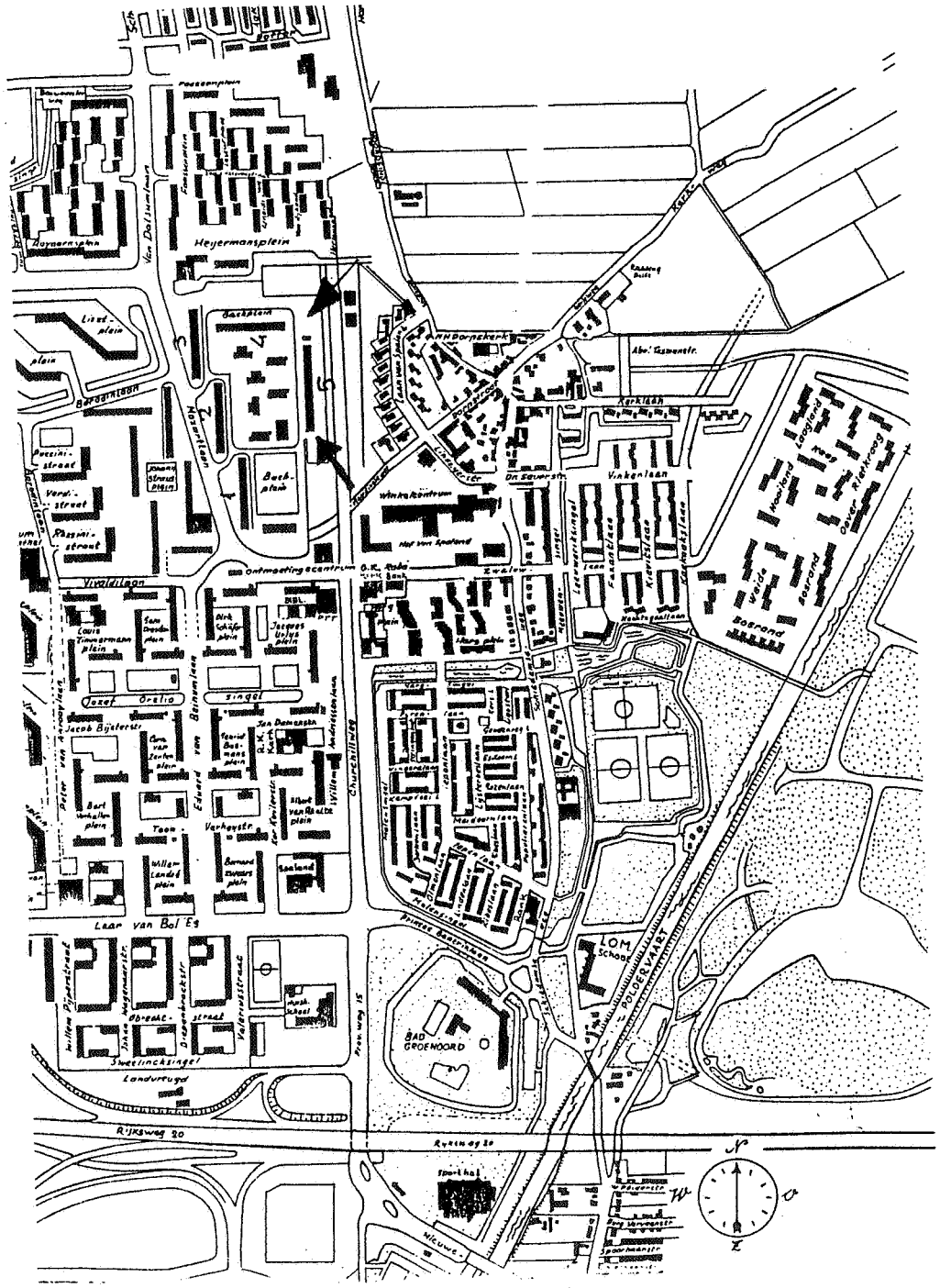


Figure 3 . Surroundings of the building.

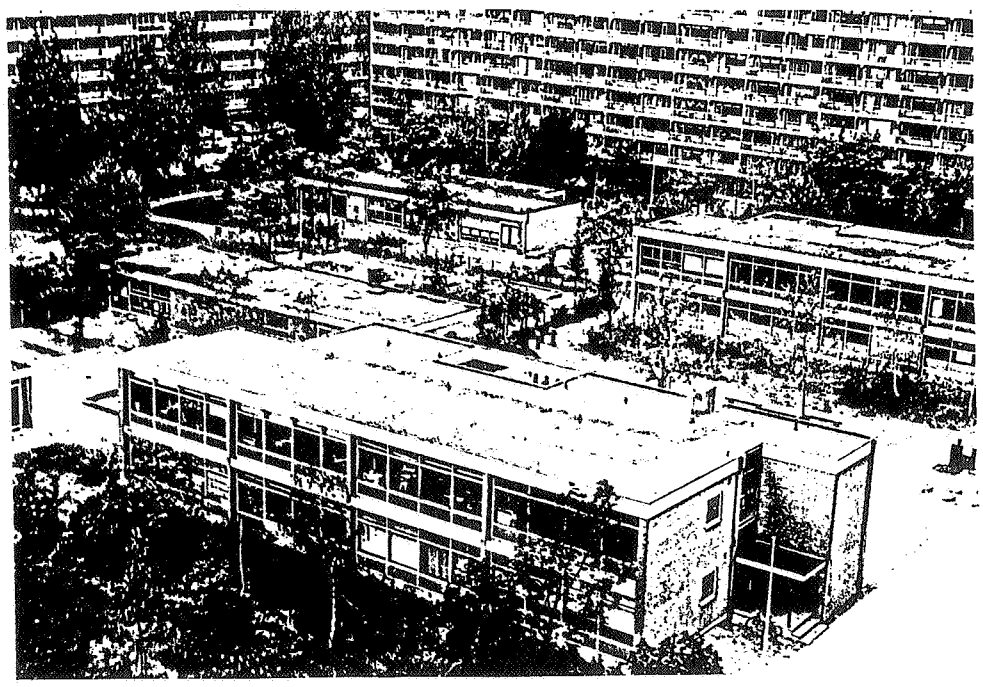


Figure 4 . Looking to the North-West from the building.



Figure 5 . Balcony facade of one appartment as seen from the East.

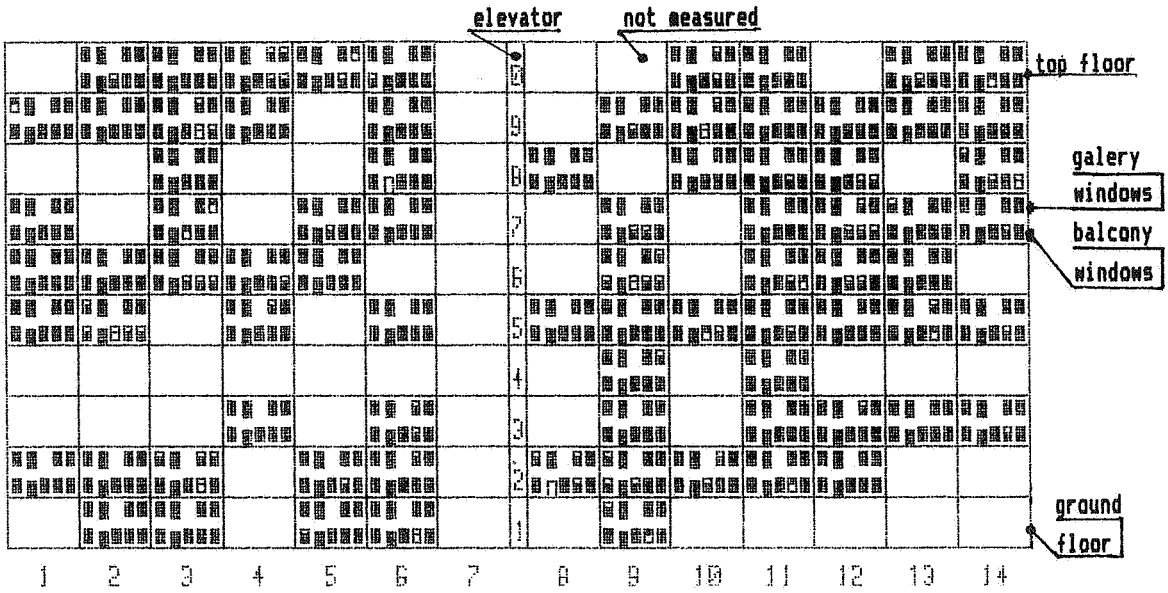


Figure 7 . Schematic view of the front facade as it appears on de CRT of the measuring computer in the building. The black rectangles represent the windows and doors. Filled black means closed.

In Figure 7 a printer dump is shown from de CRT of the measuring computer. It shows a schematic front view of the building in which the floors are numbered from 1 to 9 and 0 on the position of the elevator and the apartments from left to the right 1 to 14. The large blank rectangles are the apartments that are not included in the measurements. The others show on the top side small rectangles being the windows and the door on the galery side (front facade) and on the bottom the windows on the balcony side. In this way every window in the measurements is represented as a small rectangle that is filled when the window is closed (apearing black on the printer dump) and open or not filled when the window is open. This screen layout was very effective during the initial check on the functioning of all windows.

2. The Inquiry

On January 16 and 17, 1985, verbal inquiries have been set up in 70 of the 80 dwellings.
Most of the results are expressed in percentages of the total 70 dwellings.
Some results are:

Table 1 . The number of persons per dwelling.

	number of dwellings	
	%	n
1 person	9	6
2 persons	47	33
3 persons	26	18
4 persons	17	12
5 persons	1	1

total= 246 persons in 70 dwellings
n is the absolute number , 100 % = 70

Only in 6 dwellings are children under the age of 10. In 46% of the dwellings (32) one or more persons were older than 50.
In 71% of the dwellings one is home most of the time.
In 11% of the dwellings nobody is home for more than 5 hours a day.
In 4% of the dwellings this is the case during the weekends.
At night there is only one dwelling in which one is frequently absent.

The large bedroom on the balcony side is used in 95% of the dwellings.
In Table 2 is indicated which problems occur most frequently.

Table 2. Problems in the dwellings

objective, aspect	% dwellings with problems
the heating of rooms on the top floor	89 (of 9 dwellings)
odour from neighbours	70
condensation on windows	51
draught	50
noise from neighbours	39
discharge of cooking odours	36
stench from outside	36
cold temperature radiance	34
discharge of water vapour	24
discharge of sigarette smoke where one smokes	24
oudours from the own dwelling	17
heating of rooms (without the top floor)	16
cooling of rooms	14
noise from outside	14
noise from the own dwelling	13
moisture on walls	9
mould growth	7

Problems with the discharge of polluted indoor air and with the heating on the top floor here occur most frequently.

Table 3. The amount in which one is satisfied with the indoor climate

	%
very much satisfied	20
satisfied	59
not satisfied	6
just not satisfied	7
dissatisfied	6
very much dissatisfied	3

Table 4. The use of windows and the balcony door in the livingroom

	vent light				pivot window				balcony door			
hours open	cold		less cold		cold		less cold		cold		less cold	
per day	%	n	%	n	%	n	%	n	%	n	%	n
0-0.5	7	5	9	6	3	2	4	3	24	17	19	13
0.5-1					-		4	3	20	14	20	14
1 - 2	3	2	4	3	1	1	-		6	4	6	4
2 - 4					1	1	1	1	1	1	11	8
4 - 8	-		1	1	-		-		1	1	9	6
> 8	4	3	8	5	-		-		1	1	7	5
24	4	3	9	6	-		-		-		-	
total	19	13	30	21	6	4	10	7	54	38	71	50

cold = below 0 degree Celsius
less cold= above 0 degree Celsius
n is the absolute number , 100 % = 70

There has also been asked how wide windows are opened. For all windows and the balcony door it is valid that 25% of the windows that are open are opened about 20 mm and 75% was opened more wide.

In Table 5 the use of the windows in the large bedroom on the balcony side is indicated.

Table 5. The use of windows in the bedroom.

	ventlight				ventlight				pivot window				pivot window			
	left				right				left				right			
hours open	cold		less cold		cold		less cold		cold		less cold		cold		less cold	
per day	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n
< 0.5	8	5	5	3	6	4	2	1	8	5	3	2	9	6	5	3
0.5-1									5	3	12	8	17	11	17	11
1 - 2	2	1	2	1	8	5	3	2	9	6	6	4	9	6	6	4
2 - 4									3	2	2	1	5	3	11	7
4 - 8	-		-		-		3	2	3	2	3	2	6	4	8	5
> 8	-		3	2	3	2	11	7	5	3	12	8	15	10	32	21
24	8	5	14	9	38	25	55	36	-		-		-		-	
total	17	11	23	15	55	36	74	48	32	21	38	25	62	40	78	51

Left and right of the windows has been defined as seen from inside.

3. MEASUREMENTS OF WINDOW AND OUTSIDE DOOR POSITIONS

3.1. Method and setup for the measurements

For the being open or closed of the 1280 windows and outside doors reed relais and magnets are used. Per dwelling there are 7 openable windows and doors on the galery side and 9 on the balcony side.
A total of 16 per dwelling. On every window or outside door a magnet has been attached. The reeds are mounted on the window frame and every reed has parallel to its contacts a binary coded resistance. This means that the resistance values increase with a factor two.
The reedrelais are connected in series per facade of one dwelling.
From every facade of a dwelling a twin cable is connected to the data accquisition system placed in a room on the basement floor.
With the total series resistance for one facade it can be decoded which individual windows are open. An open window corresponds with an open reed so the parallel resistor is measured. A closed window means a closed contact and the resistor is short circuited. The hysteresis from open to close and vice versa amounts aproximately 15 mm on the window opposite the pivots.

The lowest resistance is 100 Ohm. The largest resistance on the galery side is 6400 Ohm and 25600 Ohm on the balcony side, the total series resistance on one facade is 25k5 and 51k1 Ohm.
The maximal tolerance in the series resistance is half the value of the smallest resistance i.e. 50 Ohm. This means that the inaccuracy of the largest resistances has to be less than 0.39 % on the galery side and 0.097% on the balcony side.
The resistances are selected and trimmed with a combination of fixed metal film resistors with the aid of the same multimeter that is used in the measurements controlled by a program which tells which resistor has to be added to trim. The maximum deviation is 11 Ohm on the galery and 19 and for some loops 25 Ohm on the balcony side (max 0,04%).

High demands are made on the quality of the multimeter for the (more than) 9 bit on site measurements. The total wire length is 25 km, all connected to the single ended scanner!
Adjustments are made for the temperature coefficient of the metalfilm and the resistance of the copper leads of the twin cable which is 16 to 30 Ohm.

The computer program that controls the measurements stores all window positions as 1280 bits at the start of each hour. During the hour only the changes within one dwelling are stored with the house number and the elapsed time since the beginning of the hour.
Every window will be measured every 15 to 20 seconds (rougly 240 times an hour).
Every 10 minutes 12 other channels are scanned. They include:
outside temperature, rainfall, sun shine, windvelocity near the facades, pressure difference over the building, the temperature of the central heating system supply, retour and the temperature in a ventilation shaft.
Every three hours the data is recorded on the disc, which can contain up to 15 days of measurements (=260 kbytes).

All measured resistances are compared with their last values on the same facade and dwelling. This is necessary when a window switches during the measurement time of the multimeter. This chance is small but it would result in a meaningless decimal resistance somewhere inbetween the range of the transient. Therefore when a change occurs the measurements loop a limited number of times until two sequential readings give the same window positions.

3.2. Results of the measurements

The positions of all 1280 windows and doors has been measured from week 48 in 1984 to week 19 in 1985. Some relatively small interruptions occurred caused by a disturbance in the main electrical supply, a disc failure and probably a scanner failure. The data that has been lost by this is not so important.
The available measurements represent the heating season quite well. Measurements have been made at cold and very cold (-15 degree Celsius) weather and also weather changes to relatively warmer periods are included.

3.2.1. A typical 24 hour pattern

In Figure 8 a typical pattern of the use of all 1280 windows and outside doors is represented. On the 10th of December 1984 the outside temperature has been 8 to 9 degrees (day and night) with a windspeed of 7 to 8 m/s from the South-West and West. During the day there was some sunshine given in in percentage of the longest possible time of sunshine on that day.

At night the number of open windows is very constant. Then there are 154 windows and doors open (12%). In the morning from 7:00 to 9:00 a morningpeak with 218 windows and doors (17%). During the morning a smooth decrease to the practically constant afternoon level (15% = 192 windows and doors). Then from 17:00 in the beginning a sharp decrease and further on gradual to the night level.
The number of windows and doors that switches shows the following things:
At night very little switchings. From 7:00 an increase of the number of windows that are closed and the number of windows that are opened. Moost of these changes are however door switchings, of which the greater part is always one opening followed by a closing.
On 12:00 a relative low number of changes. On 17:00 an increased level, probably caused by persons coming home. And after that a steady decrease with a minimum on the time of the 20:00 news on the television .
This is followed by some more switchings before going to sleep.

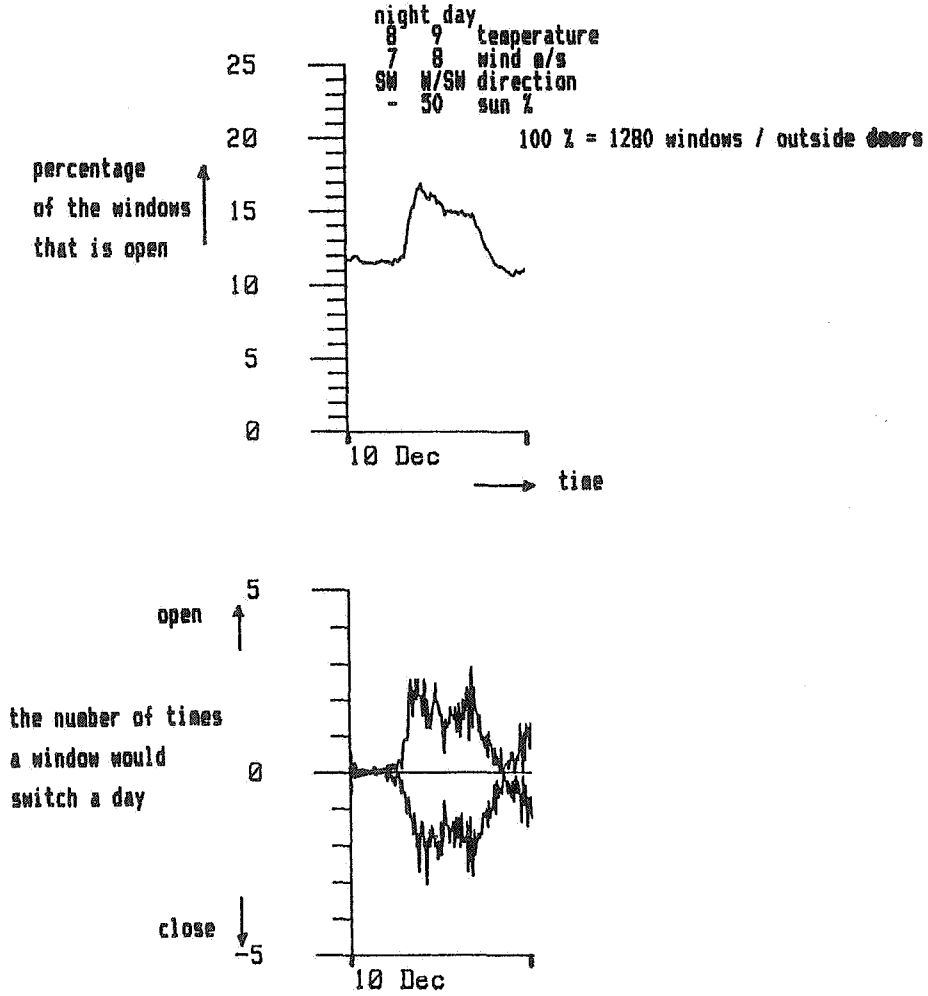


Figure 8 . A typical 24 hour pattern

The graphs of opening and closing windows seem to bee very symetrically. This is caused bij the relatively large number of door passages which they include.

Per day there is a mean of 35 switches per dwelling. It has to be noted that not all door passages can be detected when they occur in less than 15 to 20 seconds, as that is the time of one scan trough all 1280 windows. A door passage which takes 5 seconds has a 25% chance of being detected. And if it is detected it will seem from the recordings that it was open for 15 to 20 seconds, which is the time resolution in this setup.

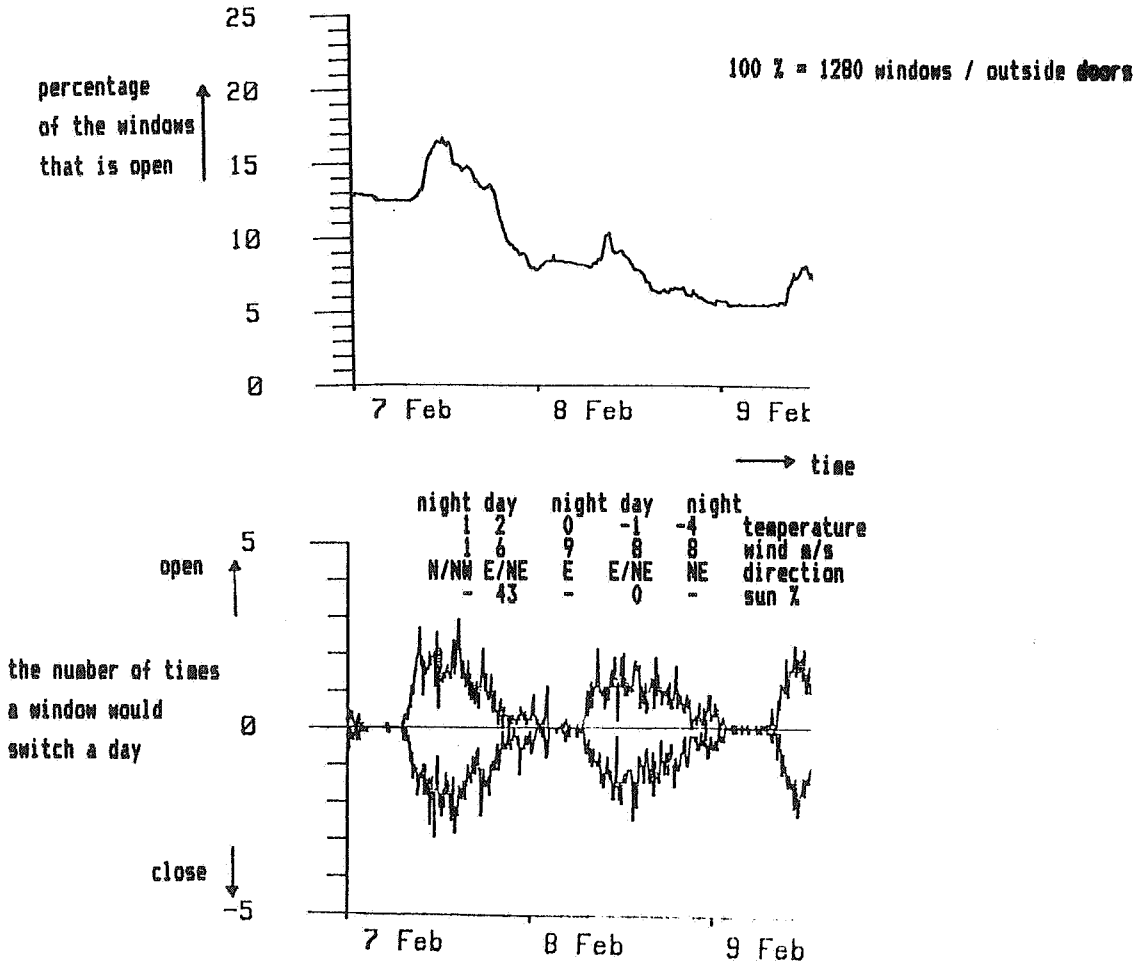


Figure 9 . A wheather change and the use of windows and doors.

3.2.2. A weather change

In Figure 9 the use of windows and doors is represented for the days 7,8 and 9 February 1985. This is a part of week 6. During these days there was a sudden weather change. The night levels are decreasing from 13 % to 8% and 6%, while the outside temperature is decreasing a little from 1 degree to 0 and -4 degrees. More important, however, is the change

in windspeed and direction from 1 m/s to 9 m/s on the night of February 8, while the wind direction changed from North-West to East. This means that the wind blows to the balcony facades where most of te used windows are situated.
The decreasing use of the windows is probably caused by the stronger wind which blows on the windows and not by the lowering of the temperature. This weather change is the most pronounced one in the present measuring period.

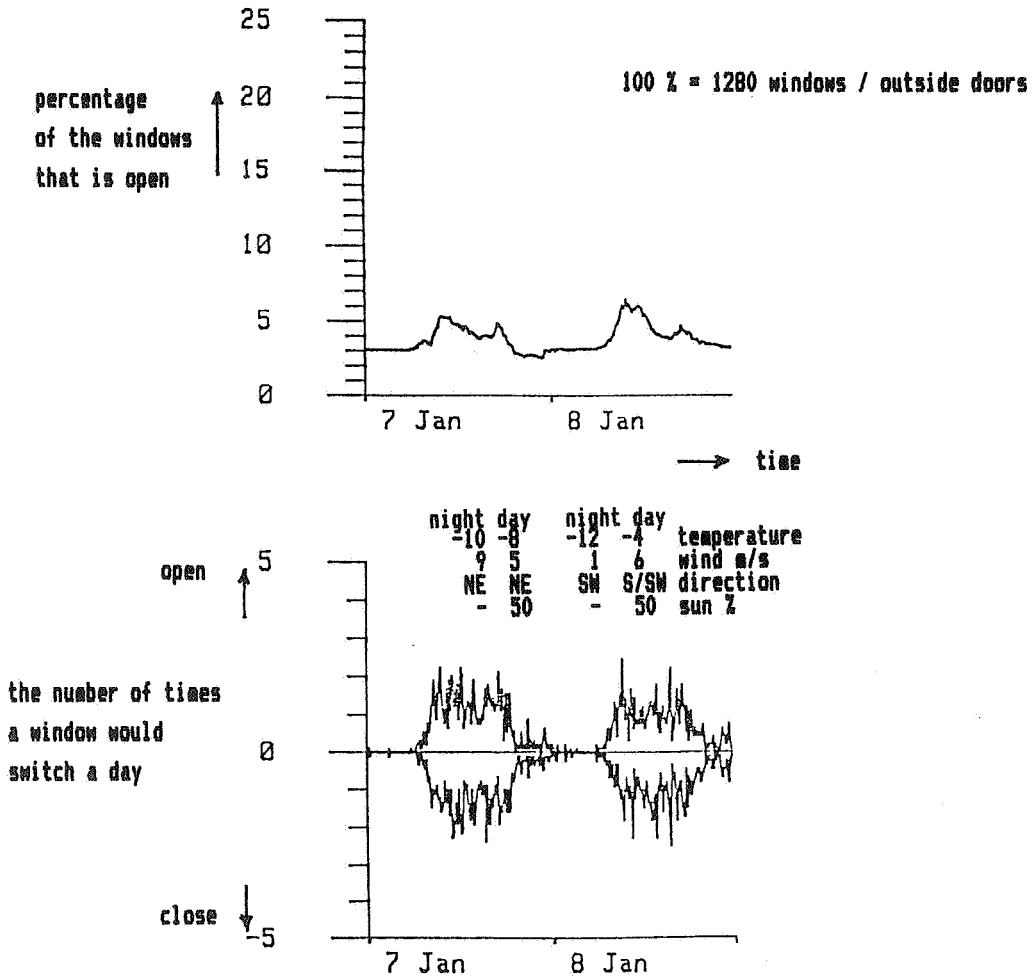


Figure 10. Cold winter days

3.2.3. Cold winter days

Even on these cold days (see Figure 10) with rather much wind from the North_East there are still 38 of the windows open (3%).
The day_night amplitude is obviously smaller then for instance on December 10 ,1984, (5 to 6% peak-peak). Here approximately 2% peak-peak.
Compared to December 10, 1984, there the number of of open windows is 3 to 4 times smaller.

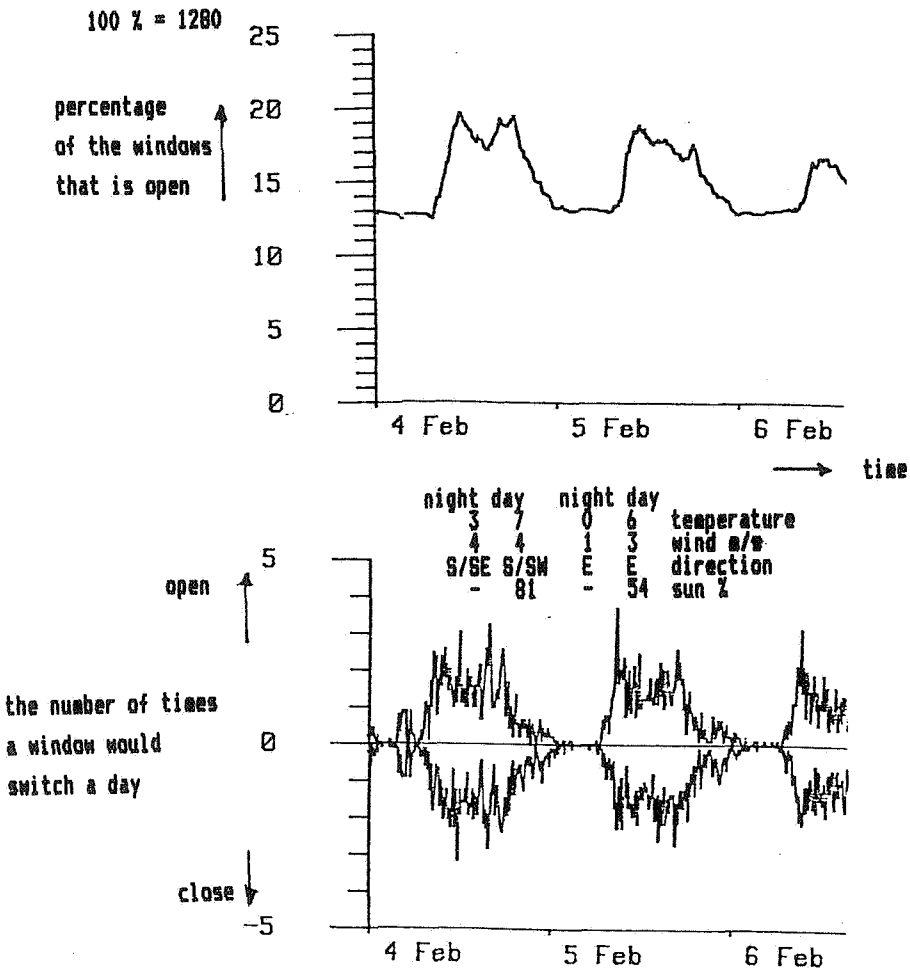


Figure 11. Mean winter days

3.2.4. Mean winter days

In Figure 11 the use of windows on Februari 4 and 5, 1985, is represented.
There is a fair amount of sunshine on these days.
The night level 13% (= 166) is practically the same as on December 10, 1984.
The day-night amplitude (peak-peak) is about 7% , with which the day level reaches 19 to 20 % (= 243 to 276 windows and outside doors open).
In the afternoon the balcony side is the leeward side and we believe that this results in a second peak of the number of open windows in the afternoon.

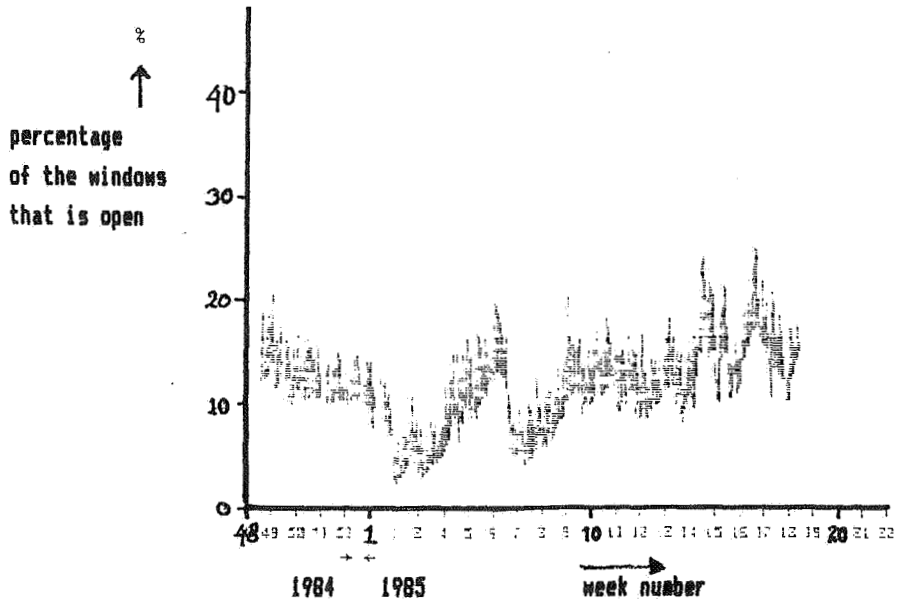


Figure 12. The precentage of open windows during the whole measuring time till week 19, 1985. (100%=1280 windows/outside doors)

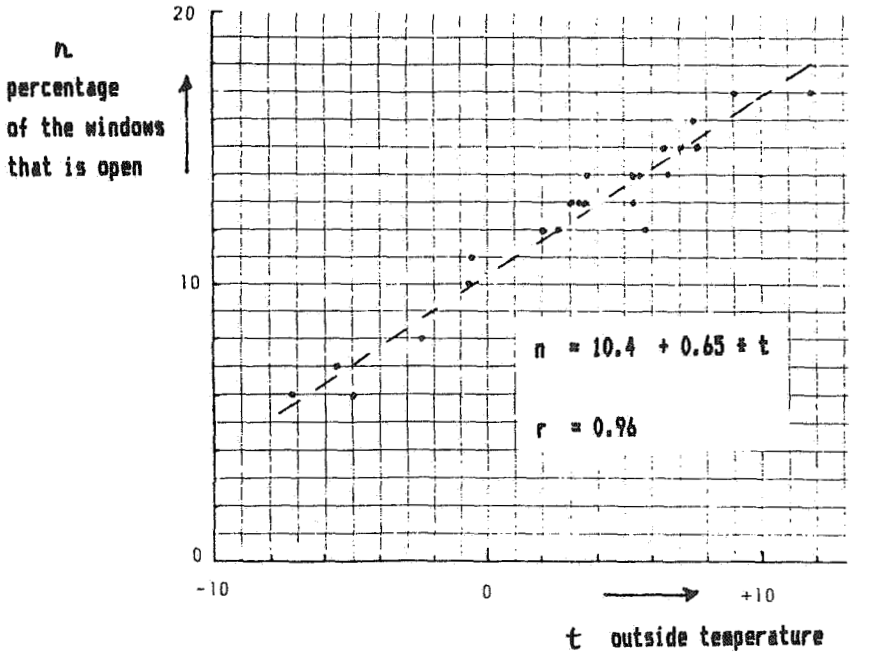


Figure 13. The relation between the weekly mean outside temperature and the weekly mean use of windows and outside doors. (100%=1280 windows/outside doors)

3.2.5 The course of the use of windows and doors during the heating season

In Figure 12 the course of the use of windows and outside doors is plotted against the week numbers. The very cold periods in the weeks 2, 3 and 6 and 7.
are obvious. The most striking weather change happens in week 6 .
In Figure 13 the relation between the outside temperature and the use of windows and outside doors are represented, both based on weekly mean values.
The following results can be noticed:

- there is a linear relation between the weekly mean number of windows that are open and the outside temperature.
- the correlation is very high for human behaviour (r=0.96).
- the deviations are caused by other weather and time influences.

It must be said that most wind influences are smoothed in the weekly means.
This is probably the main reason for the high correlation of 0.96 .
Lyberg has summarised 8 reseachs on the use of windows and found that:

$$n * Dt = \text{constant}$$

in which n = the percentage of open windows
Dt= the temperature difference between inside and outside
the value of the constant is 1.8 to 2.6 .

When we take some point of the measurements form Figure 13, say 0 degrees and 10 %, it yields a constant of 2 with an inside temperature of 20 degrees C.
This value is fairly within the range 1.8 to 2.6 of Lyberg.
However the formula of Lyberg would result in a hyperbolic function in Figure 13.

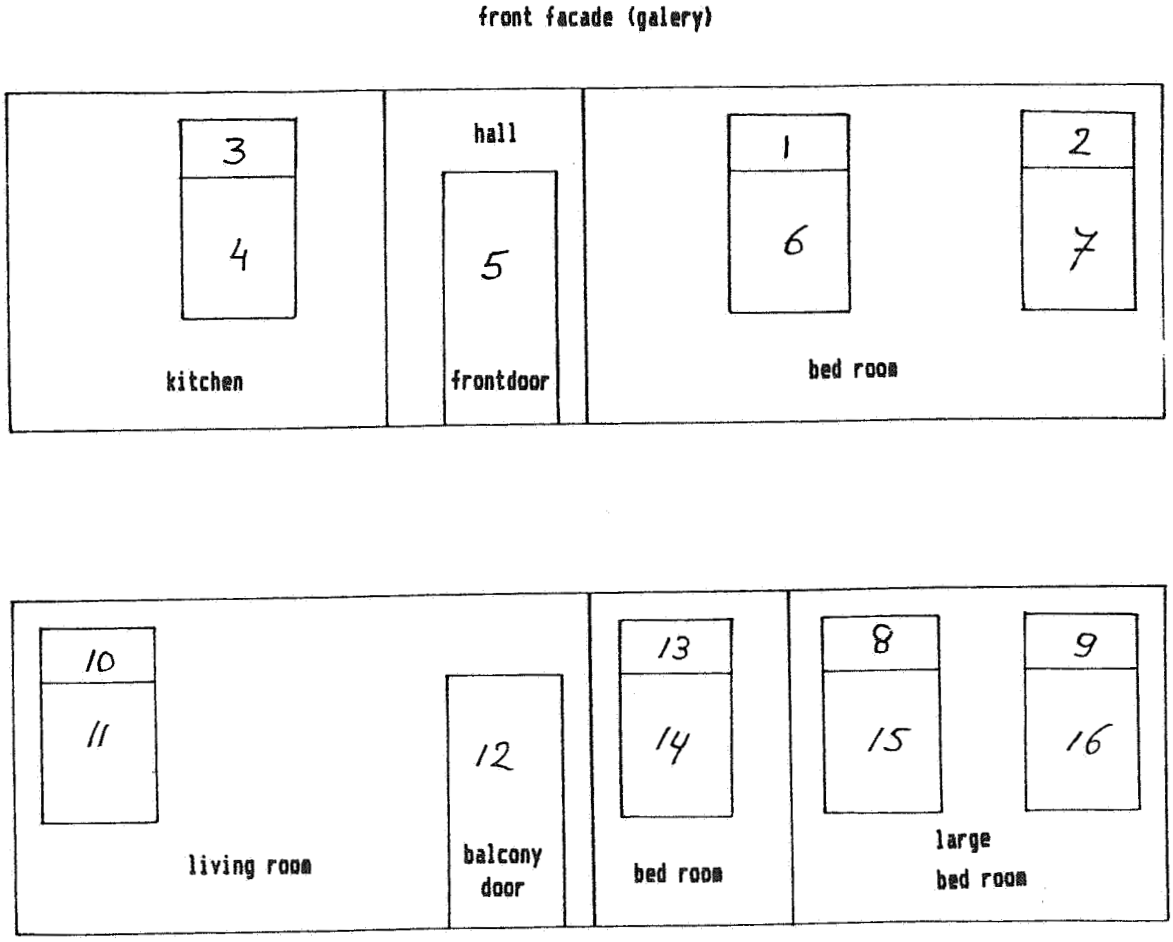


Figure 14. View on the facades. The numbers in the windows are the bit numbers in the computer and they are used in the following Figures and text.

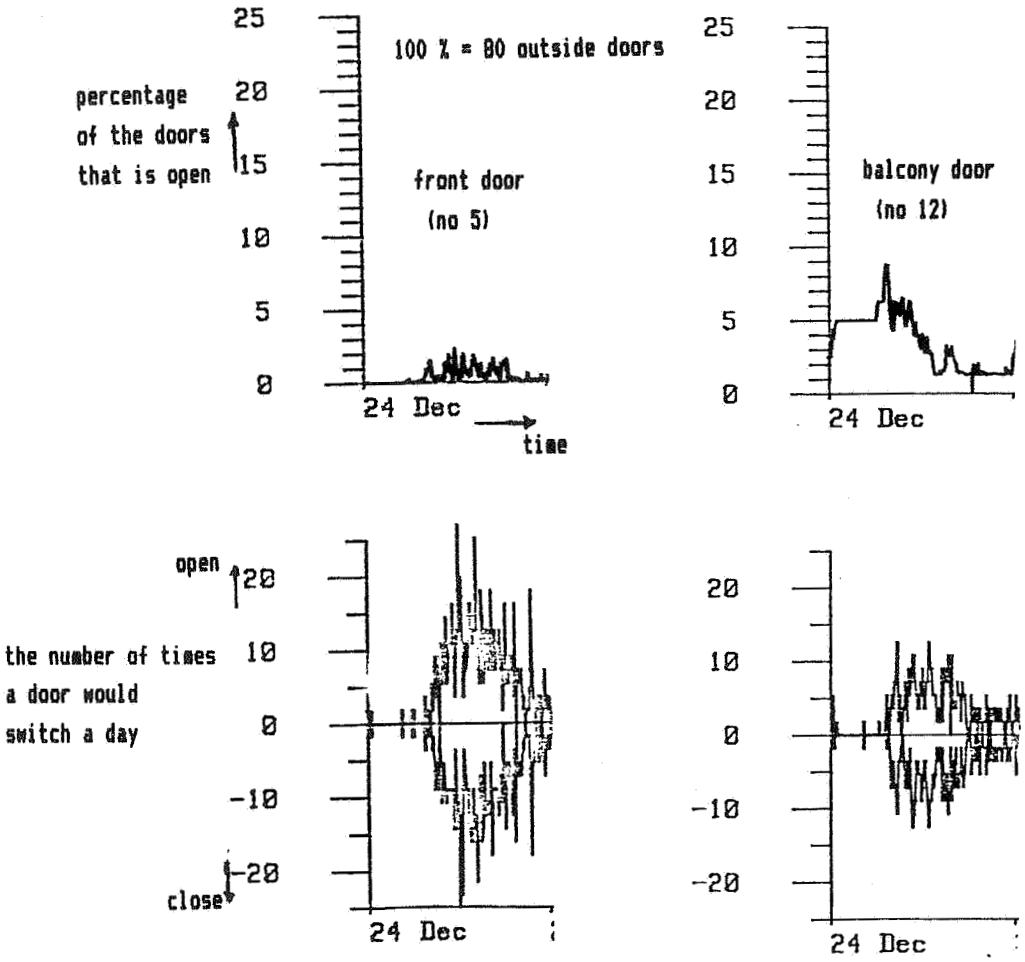


Figure 15. The use of outside doors. (100% = 80 doors)

3.2.6 The use of the outside doors

The being open and the number of switches for the front door and the balcony door differ a lot. The mean percentage of open is for the front door aprox 0.5 % . But we have to take in account that not all door passages can be detected because the whole scan along the 1280 windows is too slow (15 to 20 seconds) to catch them all. From the measurements it is 0.5 % open which means every front door is open for 7 minutes per day, but this will be more in reality. The balcony door is open about 3 % of the time. During this winter time there are 5% of the balcony doors open at night, surely set ajar. It appears that this door in the living room is used similar to the use of windows in the bedrooms. Before leaving the room windows are opened to air. When one is in the room less windows are open. But we have to admit that it is a small group that has this behaviour. The number of door passages of the front door is higer than that of the balcony door.

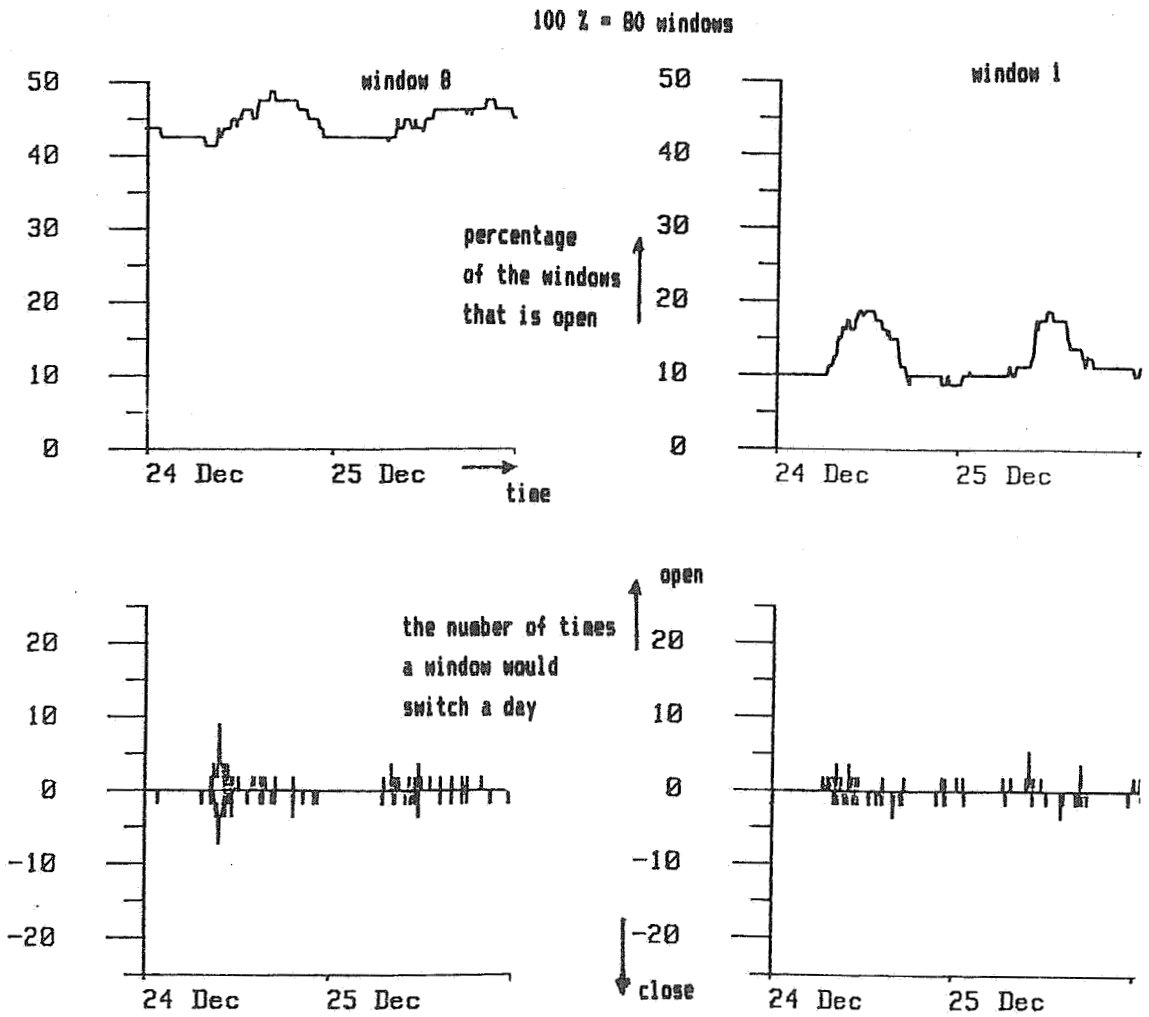


Figure 16. Ventlights on the balcony side and the galery side.

3.2.7. Ventlights on the balcony side and the galery side

A comparison of the use of the ventlights on the balcony side (no 8) and on the galery side (no 1) can be made from Figure 16.
Several aspects are causing this difference. Some of them are:

- rooms on the balcony side are more frequently used
- burgulary effect on the galery side
- the galery side is often the windward side

In Figure 20 it can be seen that in the bedrooms 2.5 times more ventlights are open on the balcony side than on the galery side.

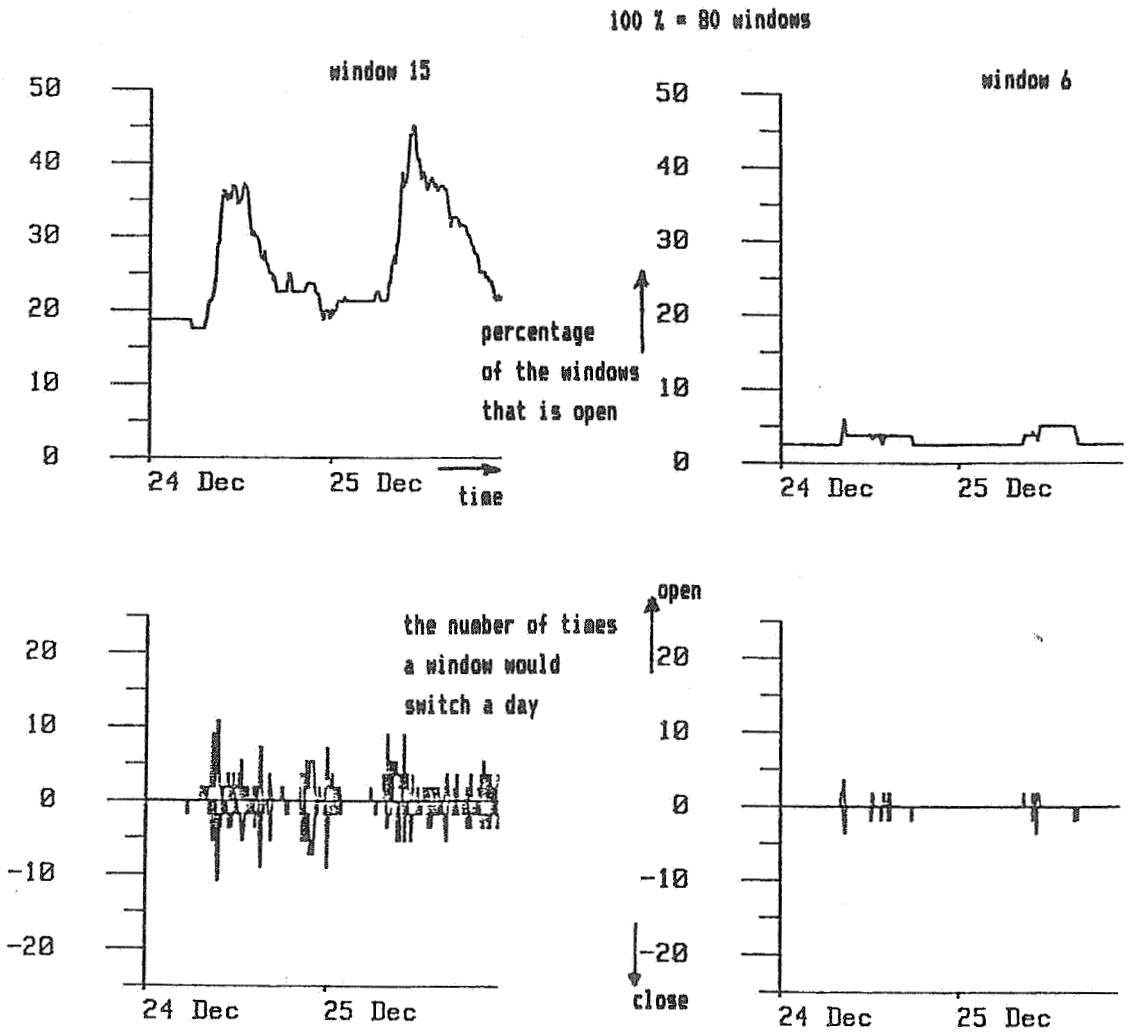


Figure 17. Pivot windows on the balcony side and the galery side.

3.2.8. Pivot windows on the balcony side and on the galery side

In Figure 17 the use of the pivot window on the balcony side (no 15) and one on the galery side (no 6) are represented for the same bedrooms as in the previous paragraph 3.2.7. .
The difference is large in the percentage open as well as in the number of switchings a day. Two windows on the galery side are continuously left open. They have fly grid in front.
On the balcony side the number of open pivot windows is more than 4 times greater than on the galery side (see Figure 20).

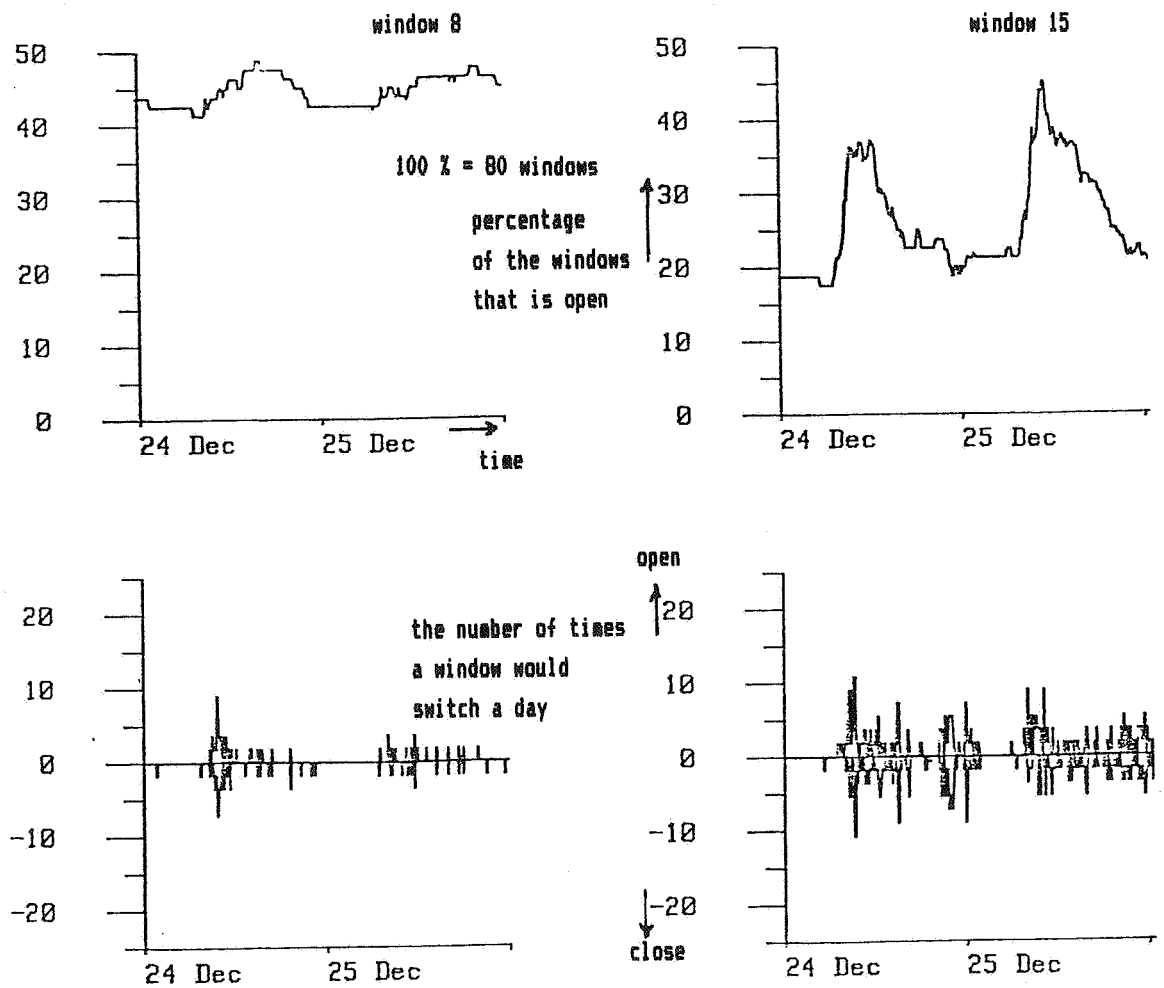


Figure 18 . The most widely used ventlight and the pivot window.

3.2.9 The most frequently used ventlight and pivot window.

In Figure 18 it can be seen that the day-night changes for the ventlight are smaller than those for the pivot window. Pivot windows show more switchings too. The ventlight has a larger percentage open (about 45 %) than the pivot window (20 % to about 40 %).

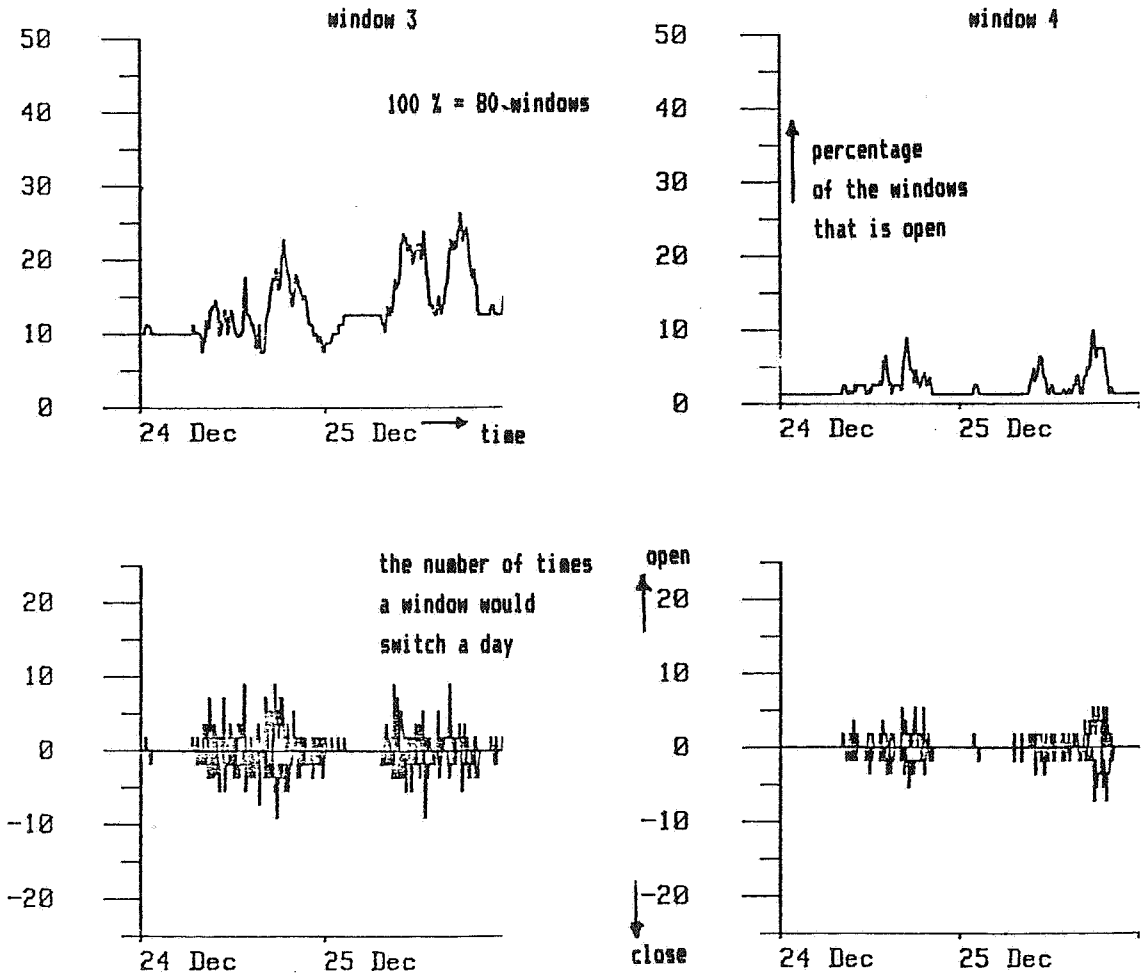


Figure 19 . The ventlight and the pivot window in the kitchen.

The kitchen is at the galery side. The peaks in the use of the windows coincide with the moments of preparing meals. One large window (no 4) is left open also at night, here again the one with a fly grid in front. The ventlight (no 3) is far more frequently used. The fact that December 24 is a special day for kitchen use does not show up in the use of the windows as we have seen in further analysis.

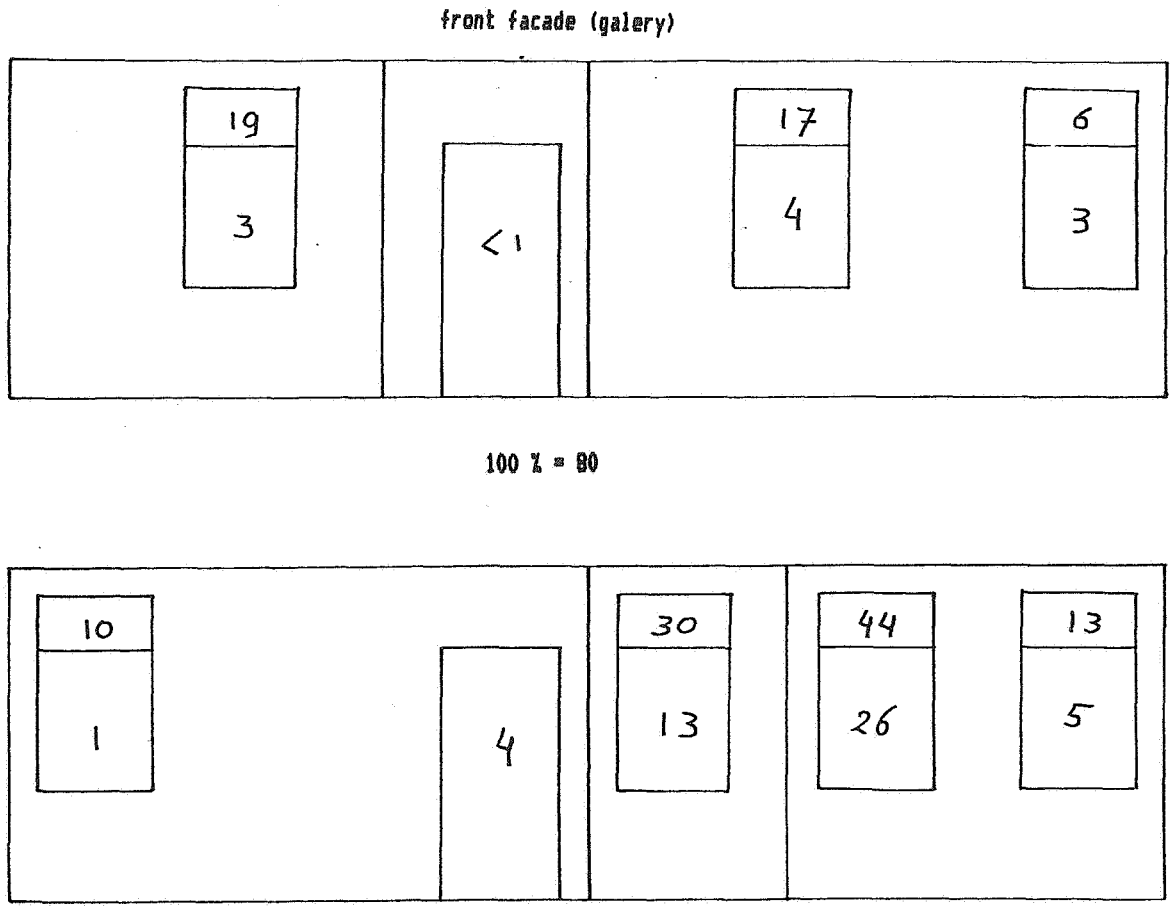


Figure 20. Overview of the mean use of windows in week 52 in % of the number of each specific window (= 80).

3.2.11. Overview of the use of windows and doors in week 52.

Figure 20 shows the mean percentage of open windows and doors in week 52. The livingroom for instance shows a 10% (=8 windows) use of the ventlight. This also means that for energy considerations every ventlight is open for 2.4 hours a day.

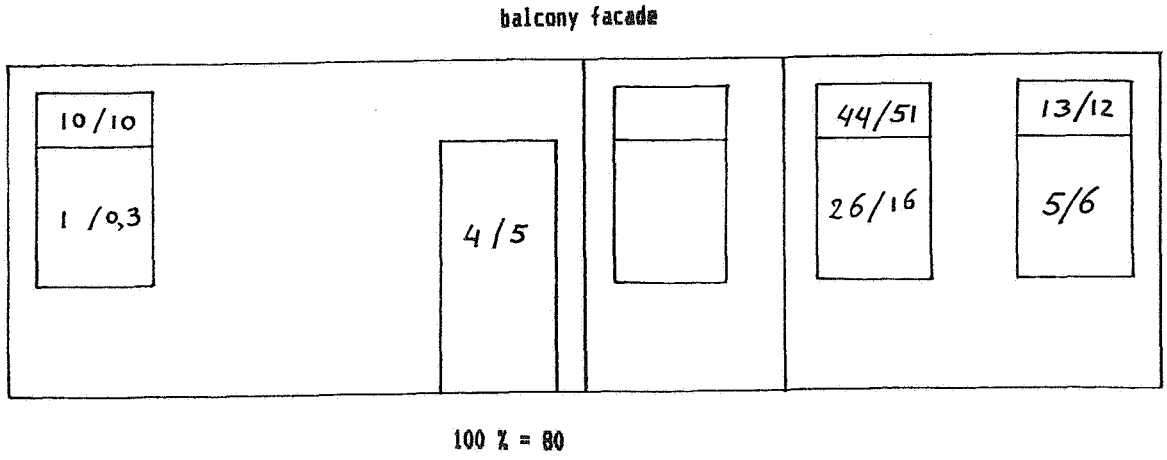


Figure 21. Comparison of the results from the inquiry and from the measurements. The percentage of open windows is indicated. First the measurements/second the inquiry result.

4. Comparison of the results of the measurements and the inquiry

In a first superficial consideration we looked at what people say they do and what they do in reality. This is done by taking the mean of the results of the inquiry for cold and less cold weather, and the results of the measurements for week 52. This has been done for the large bedroom and the living room.

5. Preliminary energy consideration

From the inquiry it has been seen that 25 % of the windows and doors that are open are set ajar and the remaining 75 % is open more wide. Based on previous investigations [4] the contribution of all windows can be estimated. A shortcoming of this preliminary estimation is the neglection of the flow through the cracks of the windows when they are closed or the increase of the flow when they are opened on opposite facades. Here we take only the flow throuhg single windows and thus make a too low estimate.

The flow through the specific windows is calculated at a windspeed of 5 m/s and a temperature difference of 15 degrees and then multiplied by the percentage of open windows.

open ventlights	15	dm3/s
open pivot windows	27	dm3/s
open balcony doors	2	dm3/s
total	44	dm3/s

When we assume a reasonable ventilation at about 25 dm3/s (say 100 m3 per hour) then the mean overshoot amounts at least 19 dm3/s.
This means an unnecessary energy loss of about 5000 MJ (200 m3 dutch natural gas or about 200 litres of oil) per heating season.
For those that make an excessive use of the windows these figures will be a factor 3 higher.
It has to be noticed that, although not frequently mentioned in the inquiry, over heating of the rooms due to the one-pipe heating system and the large building mass will become a problem for some occupants when they will make less use of the windows.
Isolation of the heating pipes will solve the problem but since the heat from the pipes is not detected by the heat-cost-counters it can partly be considered as charge free heating, and it has to be doubted if occupants can be instructed to act more fundamental and thereby save energy for their fellow building occupants.

6. CONCLUSIONS

- The chosen measurement technique with reed relays, magnets and coded resistances operates even at low temperatures .
- The chosen measurement technique has the advantage of also measuring at night and bad visibility.
- There is a strong linear relation between the percentage open windows and the outside temperature when both are the weekly means.
- Weather changes can be seen distinctly in the recordings (figure 9).
- There is a clear difference in the use of windows on the balcony and the galery side.

- In week 52 in December 1984 can be seen (figure 20) :
  Ventlights are 14% open on the galery and 24 % on the balcony side
  Pivot windows are 3% open on the galery and 11% on the balcony side
  The front door is open 0.5% (with some tolerance) and the balcony door 4% .
  There is a characteristic pattern for the use of windows and doors. This pattern is different for example for the living room, bedroom and kitchen.
- Ventlights are opened or closed (changed) less frequently than large pivot windows.

- Pivot windows show a large morning peak to air the rooms. This takes 10 hours on the average for the windows that are opened.
- In a number of dwellings the balcony door is used to air the living room at night.
- From the inquiry the most important contribution is how far windows are opened, besides the motives for ventilation.
  25% of the open windows are set ajar, 75% is opened more wide.
- the most important motive for the use of windows is discharge of polluted indoor air.
- The agreement between the inquiry and the measurements for the percentage of open windows is good.
- an estimation for the unnecessary heat loss due to leaving windows too long open is 5000 MJ per dwelling per heating season (this is about 200 m3 dutch natural gas or 200 litres of oil, 1400 kWh)
  For the group that makes excessive use of the windows these figures can be up to 15000 MJ per dwelling per heatingseason (600 m3 gas , 600 litres oil or 4000 kWh).

Notice: These conclusions are determined for an appartment building and they will probably not be valid for other buildings or other locations.

7. LITERATURE

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 21

BASIC MATERIAL FOR THE INSTRUCTION OF OCCUPANTS OF HOMES. HOW, WHEN AND WHERE TO USE YOUR WINDOWS.

W.F. de Gids

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Department of Indoor Environment
PO 214
Delft
Netherlands

1. INTRODUCTION

Because from energy considerations houses must be built better air tight and problems of air pollution in homes occur more and more it is desirable to examine how occupants must be advised about the use of ventilating provisions. Building more air tight means namely that more than before opening of ventilating windows or gratings consciously will be necessary for supplementing the background ventilation through the cracks and chinks to a certain desired level.
This publication must be seen as a first endeavour to come from the existing situation of the use of windows and the occupants' ideas to the desired situation weighing on the one hand the energy aspect and on the other hand a right indoor environment.

2. PROCEDURE

On the basis of literature data [1], [2] on the behaviour of occupants relating to the use of ventilating provisions establishing how and why occupants ventilate it can be examined whether this is necessary or desirable.
Therefore, for this investigation, air tightness measurements have been carried out in ten typically Dutch dwelling complexes [3]. In each complex four homes were measured.
With the aid of the IMG calculation model for ventilation a calculation study has been carried out into the ventilation to be expected of these dwelling [4].
From these data basic material has been developed which can be used by public relation officers for special information of the group aimed at (e.g. occupants, housing association).

3. THE USE OF THE VENTILATING PROVISIONS

Table 1 summarizes the results of an inquiry among 1500 occupants of homes [1].
Table 1: Use of ventilating provisions

1500 homes Source: NWR Netherlands Housing Council

%

		Flap windows or ventilating slide in living room always	sometimes	never
Pivoting windows in the home	some hours per day	17	11	13
	1 hour a day and/or some hours per week	12	12	12
	sometimes a week one hour	7	7	9

This table shows the use of the ventilating provisions, namely the windows, in 1500 homes. The data were obtained through an inquiry.
The use of flap windows or a ventilating slide (above) and pivoting windows (left) is given. The flap windows can be opened always, somethimes or never, the pivoting windows some hours a day, one hour a day and/or some hours a week or some times a week one hour.
Three groups can be discerned.
Above to the left there are about 40% of the people ventilating rather much; in the middle there is a group of people ventilating to an average, about 30%; they will never use a flap window and sometimes a ventilating slide, but they will use the windows several times a week.
Below to the right are the people, also about 30%, who ventilate only (very) little. If these people live in air tight homes the problems are obvious.

A study which is directed more at the specific use of ventilating provisions in 610 homes [2] gives results over the question which window how long will be used and why.

Table 2 summarizes the use of the flap windows (vent lights).
Table 2 Use of ventilating provisions in 610 homes
Source Netherlands housing council

	Flap window	24 h	12 h	<12 h	one hour	shorter	not
530	living room	3	5	8	31	17	36
473	kitchen	12	20	13	30	13	12
455	bedroom	29	30	8	15	8	10
287	bathroom	24	24	9	24	9	11

In the living room the flap windows are used little: 36% do not use them at all, 31% use them an hour and 17% use them a shorter time. 8% use them shorter than 12 hours and 8% longer. The kitchen gives a dispersed picture.
The conclusion is that the flap windows are used rather frequently, though it is unknown wheter this is always at the right moments.
The bedroom flap windows are generally open for a long time and in some cases they are open for some hours. The same applies to the bathroom. So the flap windows are used rather much.

The use of the ventilating slides is summarized in Table 3.

Table 3: Use of ventilating slides in 610 homes

Ventilating slide	24 h	12 h	<12 h	one hour	shorter	not
114 living room	26	5	4	9	5	50
120 kitchen	62	8	2	9	2	17
79 bedroom	59	8	-	3	-	30
110 bathroom	73	3	1	6	2	15

The ventilating slide is found in about 100 homes in the living room. In 50% of the cases it is not used in view of possible complaints about draught, but yet in 26% it is open 24 hours a day. This may be related to the situation on the seaside in respect of the most frequent wind direction, so that complaints about draught will not occur so soon as a result of entering air. In many cases the slide in the kitchen is always open. This applies also to the bedroom and the bathroom.

Table 4: The use of pivoting windows

Pivoting window ajar	24 h	12 h	<12 h	one hour	shorter	not
528 living room	-	-	2	12	21	65
580 bedroom	12	19	16	25	12	16

In the living room nobody uses these windows very long. A reasonable percentage 'airs' one hour and 65% does not use a pivoting window at all. In the bedroom all kinds of use occur.
The right users are found here among people who use the window one hour or shorter.

Table 5: The use of mechanical ventilating provisions

Mechanical ventilation 210 kitchen	24 h	12 h	<12 h	one hour	shorter	not
	-	1	8	64	23	4

In 210 homes of the 610 there was such a provision, but it was not clear wheter this was a mechanical system (a central provision) or an exhaust hood (a decentralized provision).
64% of the people uses it one hour, 23% still shorter. It must be observed that, if it concern specifically the kitchen ventilation with a device, it does not seem so unreasonable. Turning on the ventilation for twelve hours seems a little long.

4. WHY ARE VENTILATING PROVISIONS USED

Table 6: Why do people ventilate?

Considerations	% thinking of it		
	strongly	a little	total
Energy	52	25	= 77
Health	52	25	= 77
Fresh air	70	21	= 91
No draught	71	19	= 90

The reasons energy and health have the same score, 52% thinks of it strongly and 25% a little. The others do not think of it or do not answer.
Fresh air and avoiding draught score higher. Obviously people have the idea that they must ventilate to keep the home fresh.

5. RESULTS OF THE AIR TIGHTNESS MEASUREMENTS AND CALCULATION STUDY

The results of the air tightness measurements are divided into one-family homes and flat dwelling as follows.

5.1 One-family houses

Number of homes examined: 19, divided over 5 locations.
Air passage measured:
C_{av} = 122 dm^3/s at 1 Pa; A_{net} = 915 cm^2; n_{av} = 67
Dispersion:
lowest value C_{min} = 74 dm^3/s at 1 Pa
highest value C_{max} = 194 dm^3/s at 1 Pa
standard devation σ_{n-1} = 36 dm^3/s at 1 Pa
standard deviation in $n\sigma$ = 0,16
Distribution over the skin of the home:
- fronts 3-20%; ducts 20-35%; other (roof, floor etc.) 25-70%.

5.2 Flat dwellings

Number of homes examined: 20, divided over 5 locations.
Air passage measured:
C_{av} = 23 dm^3/s at 1 Pa; A_{net} = 169 cm^2; n_{av} = 1.58
Dispersion:
lowest value C_{min} = 3 dm^3/s at 1 Pa; highest value C_{max} = 50 dm^3/s at 1 Pa;
standard deviation σ_{n-1} = 11.5 dm^3 at 1 Pa; standard deviation in $n\sigma$ = 0.17
It should be observed that the minimum value was measured in a flat with mechanical ventilation, with the mechanical ventilation sealed. So the air leakage measured is the front + possible rest, such as in flats mainly the meter box.
Distribution:
- fronts 13-60%; ducts 30-70%; other <7%.

5.3 Results of the calculation study

Table 7 summarizes the results of the calculation study [4].

Table 7: Review of the total ventilation (calculated) at an outdoor temperature of 5°C and an average shelter, indoor temperature 18°C, volume flow in dm^3/s (q_v); all windows and doors closed.

home	wind velocity m/s	air tight q_v dm^3/s	normal q_v dm^3/s
one family home	2	16-34	55-78
	5	30-42	80-100
	10	55-70	120-162
flat dwelling	2	5-12	20-33
	5	9-16	28-40
	10	20-26	49-70

The dispersion per column is caused by:
- ventilating system - natural
  - mechanical exhaust
- characteristics of the home (architectural)
- effect of wind directions, e.g. wind on fore front or back front
- temperature influences.

6. WHAT VENTILATION LEVELS ARE DESIRED

What would people desire for ventilation dependent on use and occupation of the home?

Figure 1: What is desired for a family of four persons? living room; bedroom (2 persons); time; dm^3/s.

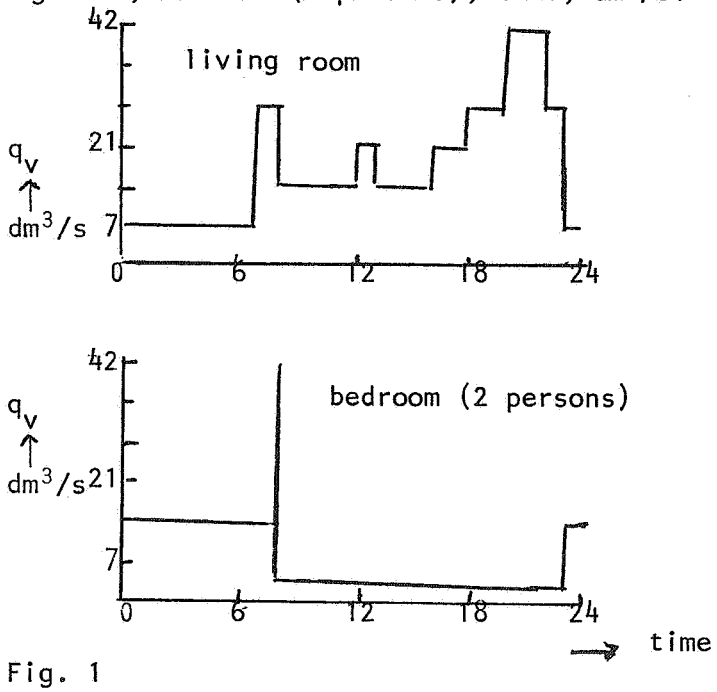


Fig. 1

The time is plotted horizontally, the volume flow vertically. For a family of four persons, with all people in one room, the amount which must be ventilated is 4 x 7 = 28 dm^3/s. In the morning the family has breakfast in the living room and then this amount is needed. It is not necessary to go lower than 7, because in the living room there will be always someone present. During the day with one child at home a level of 14 is necessary. If there is still another child at home from school 21 dm^3/s, and at the end of the workday if there are four persons 28 dm^3/s is desired and in the evening with two visitors 6 x 7 = 42 dm^3/s. At night 7 suffices. This pattern can be considered desired optimum pattern. The occupant should reckon with this, though a difficulty is added to it as will be obvious in a moment. Take a look at the volume flow and the time during the day of one bedroom for two persons (lower figure), this must be vented by 14 dm^3/s or 50 m^3/h. In the morning the wife makes the beds and wishes that the dust raised dilures and disappears with air. So, she open a pivoting window for a very short time, 20 minutes is quite sufficient, and causes then a high peak of 42 dm^3/s, or higher.
After that, if there are no persons left, the level may be low, but a minimum level is desired.

Consider a similar approach for the kitchen and the bathroom, the most important two wet rooms, then we see for the kitchen the following picture (figure 2).
Figure 2: Kitchen. Bathroom. time.

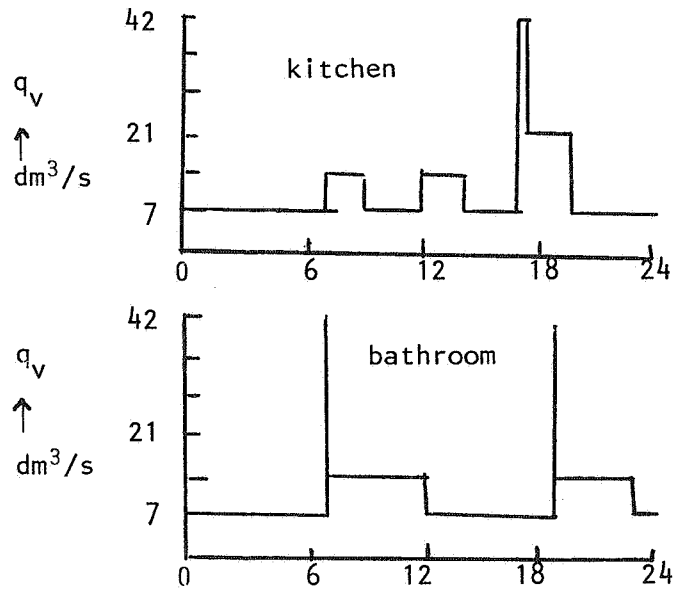


Fig. 2

It is assumed that there is always one person present. The requirement for the kitchen is that is must be possible to attain 21 dm^3/s or 75 m^3/h. Normally this is necessary for cooking, so in the evening for 1 or 2 hours and further over the part which produces humidity. In the morning when preparing breakfast and in the afternoon when preparing dinner a little more is needed than during the rest of the day. Really, during cooking, one would like to have a high peak to ventilate vapour and cooking smells. For this the temporarily higher value is needed. Using a high reading on an exhaust hood without an engine is a reasonable possibility to put a peak on it.
For a good use of windows and other ventilating provisions, dependent on the type of home, the degree of shelter and the wind velocity one can use the data from Table 8.

Table 8: Basic ventilation for three persons.
Which type of windows open? How far?
What chinks sealed?

Type of home	Situation	Age	Air tightness	Calm/quiet 2 m/s	Normal 5 m/s	Strong wind/Storm 10 m/s
One-family home	normal	older than 1950	leaky	no windows open, chinks of front/roof floor to be sealed from energy considerations		
	shelter	1950 1975/1980	normal	no windows open, chinks of roof/floor to be sealed from energy consideratio		
		from 1975/1980	tight	1 flap window open or 3 ajar	nothing open	nothing open
	very tight shelter	older than '50	leaky	see normal shelter		
		1950-1975/80	normal		see normal shelter	
		from 1975/80	tight	1 flap window open or 3 ajar		nothing op
Flat dwelling	normal shelter	older than '50	leaky		nothing open	
		1950-1975/80	normal	1 flap window ajar	nothing open	
		from 1975/80	tight	1 flap window open or 3ajar		1flap wind ajar
	very tight shelter	older than '50	leaky	1 flap window ajar	nothing open	
		1950-1975/80	normal	1 flap window ajar	1 flap window ajar nothing open	
		from 1975/80	tight		see normal shelter	

Let us now consider the bathroom: the requirement for a bath room in the Dutch Standard NEN 1087 is 14 dm^3/s. There are moments when one should like to exceed this level, e.g. if the bathroom is entirely filled with vapour. Generally, a minimum level is required, surely for evaporating humidity from the building construction, over a longer time. In general one should not go below 7 dm^3/s. Perhaps the 14 dm^3/s line should be continued with a few temporary peaks. It is essential that the occupants are not instructed to use the ventilating provisions of the bathroom only during bathing or washing, but especially a long time afterwards.
Some hours after the use of the bathroom switch the ventilating provisions at a high reading and afterwards at a low reading, but do not swithch them off, that is absolutely necessary for wet rooms.

7. WHAT IS NECESSARY TO ATTAINS THE FOREGOING?

At any case two matters are necessary: good provisions and a good use of these provisions. Mostly there is something wrong with both. The requirements for good provisions in the Netherlands can be improved and in the revision of NEN 1087 we shall strive for improvement of the controllability and the adjustability.
In the first place a good design and a good dimensioning are important.
The window must be large enough; the ventilating installation must be well-designed/dimensioned, such that the flow is sufficiently strong. Exhaust at a rate of 100 m^3/h for a home the toilet of which is ventilated naturally, is below the standard, actually.
Firstly, the toilet may not be ventilated only naturally, but the total air flow, the nominal flow of the ventilator of 100 m^3/h, is also too low. Therefore, a good design and dimensioning are important, in the first place.

Often, there is a lack of good forms of controlability. The standard is very simple, perhaps too simple: the volume flows must be adjustable.
The controlablility can be improved to a great extent in the ventilating industry in general. Also good adjustability is necessary, for the ventilating installation can be grovided with a good control device, but if this is disturbed by a minor cause, e.g. the wind presure, it is of no use.

The ventilating provisions must be well within reach. Often one knows how to open flap windows, but does not know how to close them, for then they are out of reach.

They must be easy to handle, not complicated. If the window must be handled by pulling a cord one must know then if the window is open or closed.

They may cause no inconvenience by draught and no noise annoyance. As concerns this last item the mechanical installations often are designed wrong.

8. CONCLUSION

The right use of ventilating provisions at any rate requires good instructions, better than has been the case till now, that will be clear. The instruction must take account of the building type of the home, one-family house or flat. Also other things such as open staircase and open kitchen will affect the ventilation.
Further the degree of air tightness, the weather conditions, the occupation and the activities. They must form the centre in the instruction and it can be imagined that if such a whimsical pattern is added it is no easy task for the instruction. But I think it a challenge which surely can lead to reasonable results, if there is sufficient knowledge of all these matters. How do people ventilate at the moment, why do they close or open windows and at what moments in a given type of building and air tightness? Where must people open windows then under what weather conditions? And they must be urged that it very much depends on the occupation and the activities. Systems which independent of the occupation and activity are always on the nominal power are not at all ideal. They are not well controllable namely and perhaps do not meet one starting point of the Dutch standard.
Finally, a good attitude of the occupants is required. If this lacks it is impossible to attain a good operation with this kind of systems, wheter they are mechanical or natural.

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[3] Gids, W.F. de
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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 22

MONITORING OF VENTILATION AND HUMIDITY IN CRAWL SPACES OF DWELLINGS

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Synopsis

This paper presents some experimental results from field studies on physical phenomena in crawl spaces of dwellings. Particular attention is paid to air transport phenomena that may lead to moisture problems in the living spaces.

1. Introduction

In the Netherlands an increasing attention is paid to moisture and mould problems in dwellings.
It is believed that many of these problems are caused by moisture migration from the crawl space.
Several physical phenomena may attribute to this moisture transport. In this paper we will review briefly the possible moisture transport processes and discuss how these phenomena can be assessed experimentally. Some experimental results will be presented from some field studies.

2. The crawl space

In the Netherlands the majority of the single family houses have a crawl space. A typical construction is shown in figure 1. From practical experience we know that the relative air humidity in crawl spaces is very high in general. A RH of 95% is quite normal. The reason is that in large parts of the Netherlands the ground water level is only a few centimeters below the crawl space bottom surface, while in many cases open water is even present during a large period of the year. Although these facts were known for many years it is just recent that one recognized the crawl space as a potential source for many moisture and mould problems in dwellings. For this reason more effort has been undertaken to collect more practical data, in particular with respect to infiltration of air from crawl spaces to the living spaces.

3. Moisture transport

The following physical phenomena may play a role in moisture migration from the crawl space to the living spaces (see figure 1).:

- Moisture transport by infiltration of crawl space air through air leakages in the ground floor construction.
- Moisture transport by infiltration of crawl space air through air leakages between the crawl space and the air cavity of the facade construction.
- Moisture transport from the crawl space by vapour diffusion or capillary transport through the ground floor construction.
  An increased moisture transport may occur at cold surface areas where condensation takes place.
- Moisture transport from the ground water by capillary transport through the foundation and floor connnections.

Factors that influence these moisture transport phenomena are the outdoor and indoor climate parameters (temperature, air humidity, wind pressure, etc.) and the physical properties of the building

materials and the building constructions used.

4. Experimental techniques

Several experimental techniques are available to assess the relative importance of the different physical phenomena in practical situations. For the continuous measurement of moisture content of air in different spaces we have developed a specific measuring system as shown schematically in figure 2. The basic elements in this system are an electronic dew point sensor and an air channel selector consisting of remotely controlled valves. A personal computer is used to control the air sampling and to collect and process the measured data.
Another experimental technique is the pressurization test, as shown in figure 3, for the assessment of the air tightness of the crawl space.

5. Results from some experimental field studies

5.1 The Delft project

In this project the crawl space of a terraced house has been monitored during one heating season. One of the striking phenomena observed was the stratified nature of the crawl space air. Figure 4 shows the air flow pattern that has been observed. The ventilating air flow consists of layer of relatively cold air moving along the ground surface of the crawl space. As a result of this the vertical temperature profile takes a form as shown in figure 5. Because of this stratification one should aspect a low convective heat transfer from the lower floor surface to the crawl space air. This has been confirmed by heat flow measurements as illustrated in figure 6.
To study the ventilation of the crawl space simultaneous measurements have been made of wind speed and pressure differences across the ventilation channels located in the facade. The wind speed was measured at about 1 m above the roof level of the house. The wind pressure coefficient has been determined as follows. First the measured wind speed is decomposed into two components as shown in figure 7.
Then a regression analyis can be made for ΔP and V_L as shown in figure 8.
Next a regression is made between the measured wind speed and the meteorological wind speed at a neighbouring weather station (see figure 9) in order to find the wind pressure coefficient which is related to the meteorological wind speed.
Finally, we are able to calculate the air change rate of the crawl space as a function of the meteorological wind speed. The result is shown in figure 10.
More details of the Delft crawl space monitoring project are found in [1].

5.2 The Katwijk project

In this project the crawl spaces of two houses have been monitored during several weeks.
The purpose of this project was to investigate the effect of a new

product that claims to be a solution for moisture problems caused by high humidity levels in crawl spaces.
The product consists of polyethylene bags filled with polystyrene pellets and hence forms a combination of insulation and a vapour barrier. Some experimental data collected in this project are shown in figure 11, 12 and 13.
Figure 11 shows the results of pressurization tests at the crawl space. The results indicate that the crawl space is not as air tight as expected. Further inspections revealed the presence of cracks between the ground floor construction and the cavity space of the facade wall. Consequently, air transport is possible between the crawl space and the wall cavity.
Figure 12 shows some measurement results of pressure differences. An important conclusion is that the living space always shows an underpressure of a few Pascals with respect to the crawl space.
Finally, figure 13 shows the daily avarages for the moisture content of air in different spaces as measured by the system shown in figure 2.
More detailed results will become available in the near future.

6. Concluding remarks

In the Netherlands there is a growing interest in the building physics of crawl spaces, because they are believed to be the cause for many moisture problems in dwellings.
The results of field studies presented in this paper are the first steps for a better understanding of crawl space physics and its influence on the indoor climate of dwellings.
More field work is needed, in particular with respect to remedial treatments, that may help to solve moisture problems.

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[1] "Een kruipruimte thermisch aangemeten" (in Dutch).
Published by Stichting Bouwresearch, P.O. Box 20750, 3001 JA Rotterdam, The Netherlands.

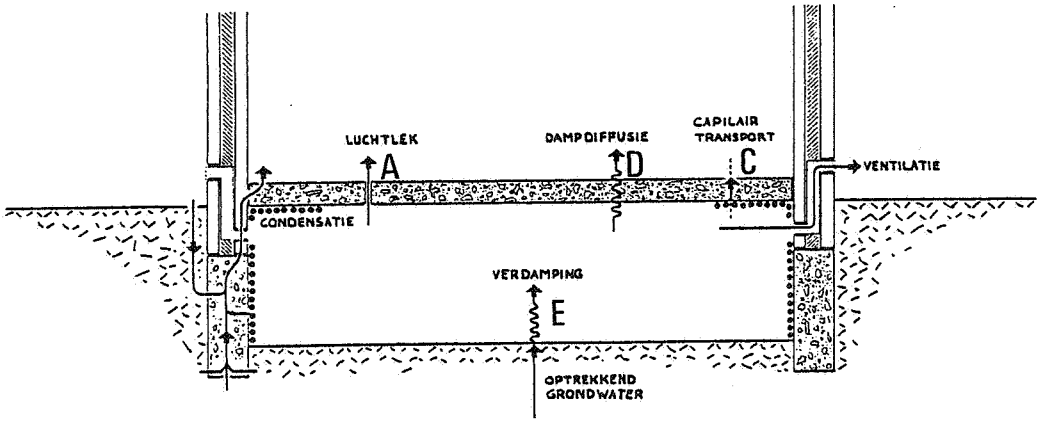


Figure 1: Moisture transport mechanisms.
A = air transport; D = water vapour diffusion;
C = capillary transport; E = evaporation of water.

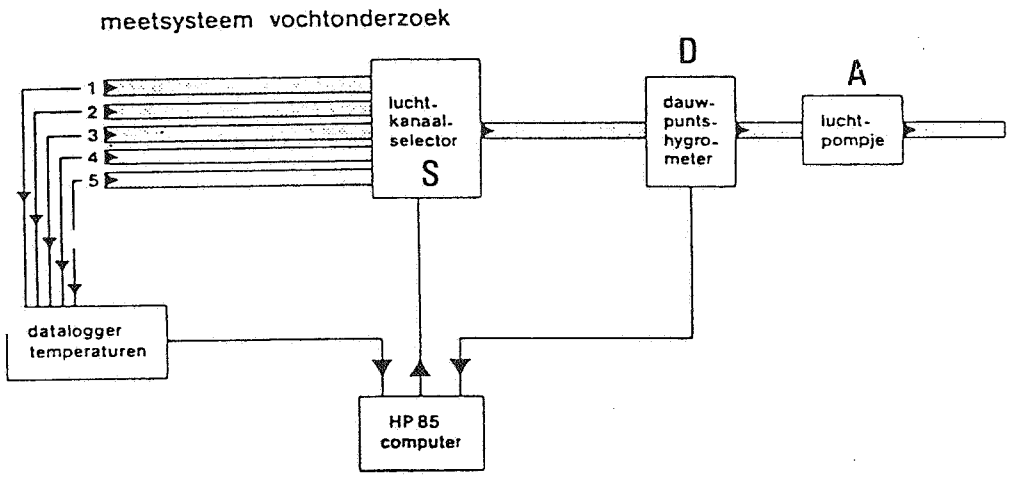


Figure 2: Multi-channel automated measurement system used for moisture analysis in field studies.
A = air pump; D = dew point hygrometer; S = air sample selector.

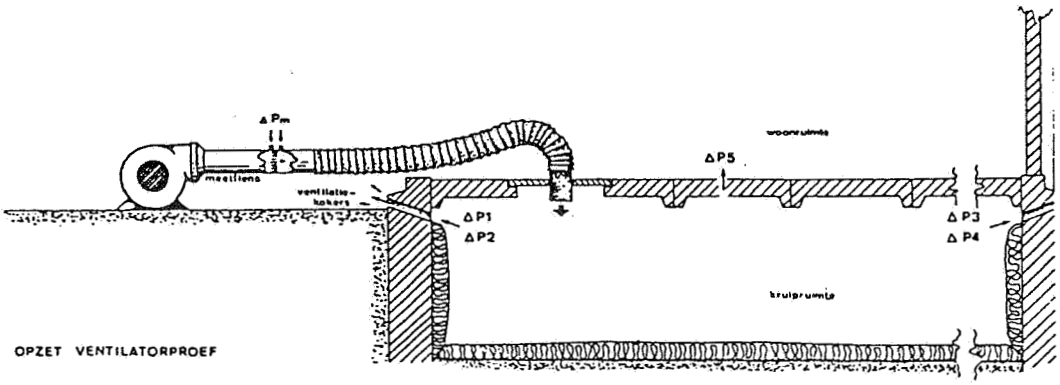


Figure 3: Pressurization test of the crawl space.

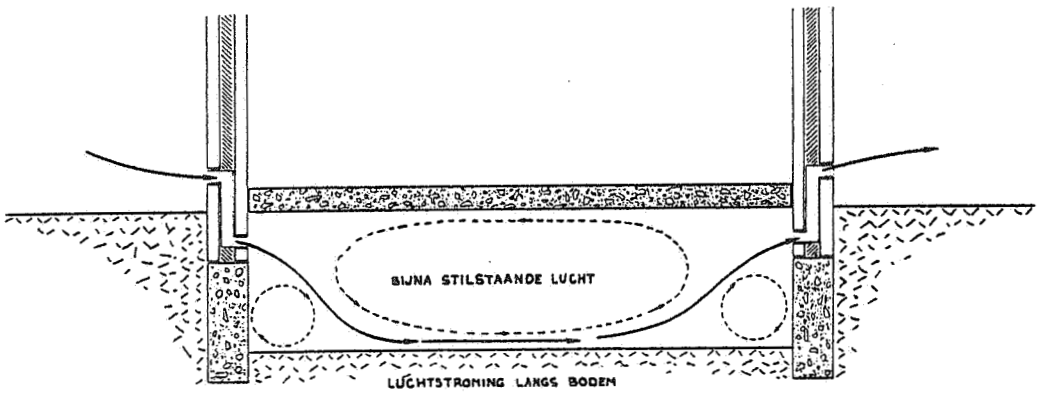


Figure 4: Observed air flow pattern in winter conditions.

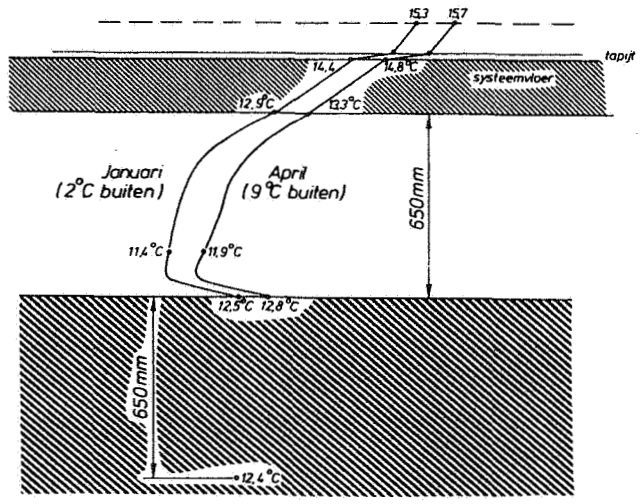


Figure 5: Measured temperatures of the crawl and the ground floor construction. The values shown are monthly averaged temperatures for January and April.

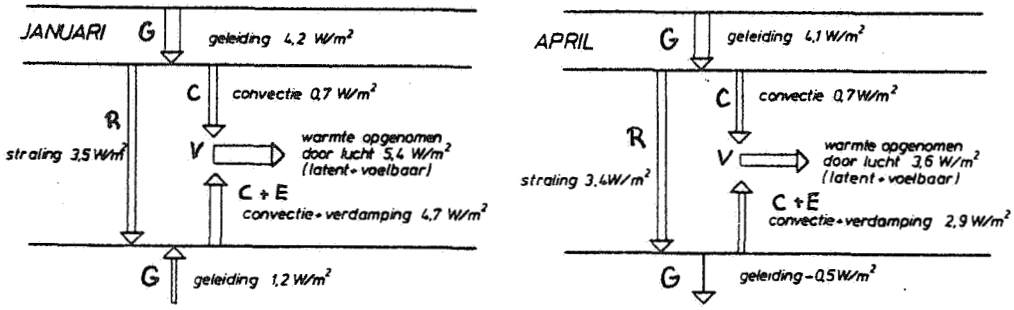


Figure 6: Heat flows in the crawl space.
G = conduction; C = convection; R = radiation; E = evaporation; V = ventilation.
Monthly averaged values are shown.

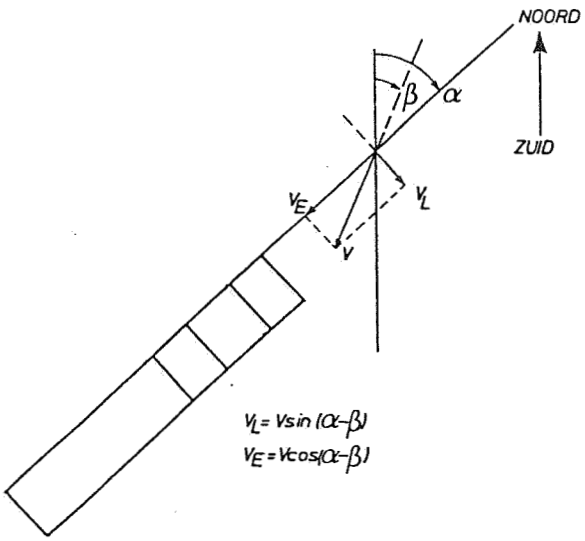


Figure 7: Decomposition of the wind velocity vector. α = orientation angle of the facade with respect to the north; β = wind direction angle; V_E = wind velocity component along the facade; V_L = wind velocity component across the facade; V = wind speed.

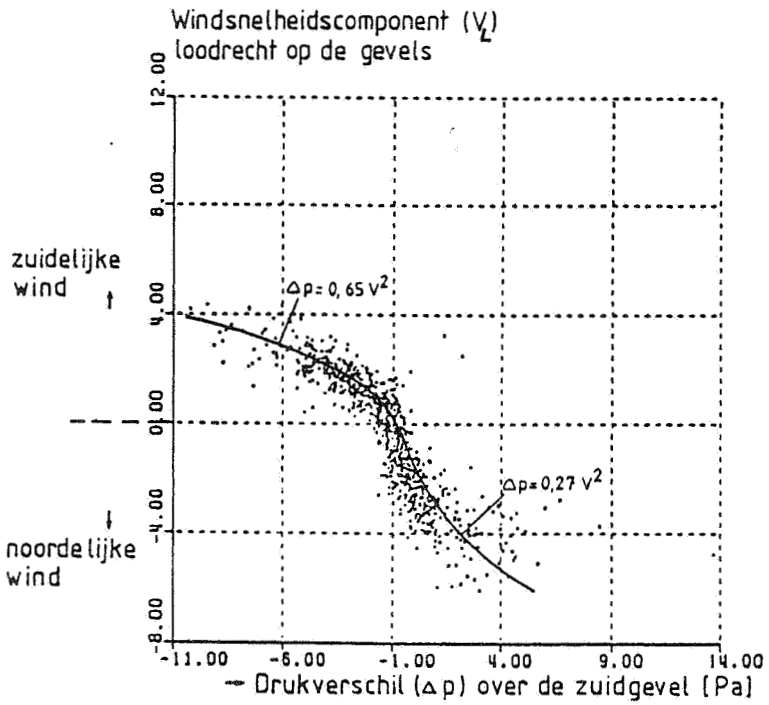


Figure 8: Correlation of pressure difference on south facade (ΔP) against the wind velocity component (V_L).

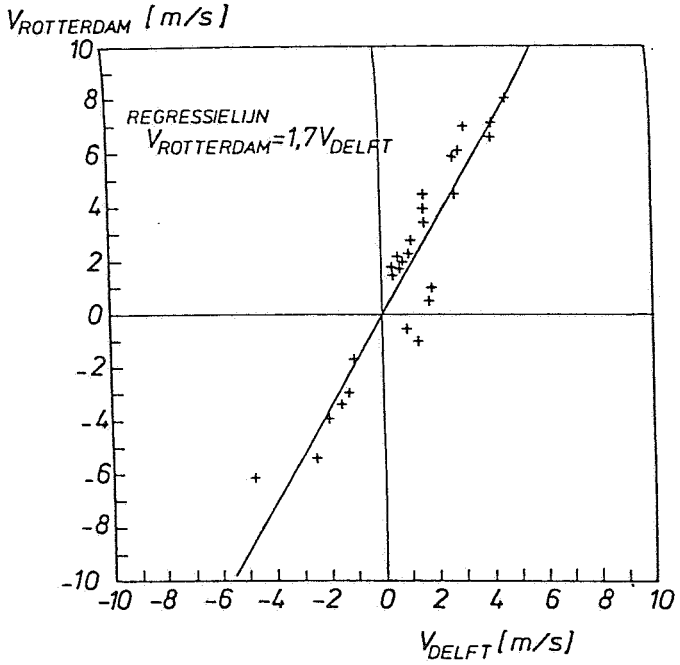


Figure 9: Regression of wind speed measured at roof level (V_{delft}) and the meteorological wind speed data from a neighbouring weather station ($V_{rotterdam}$).

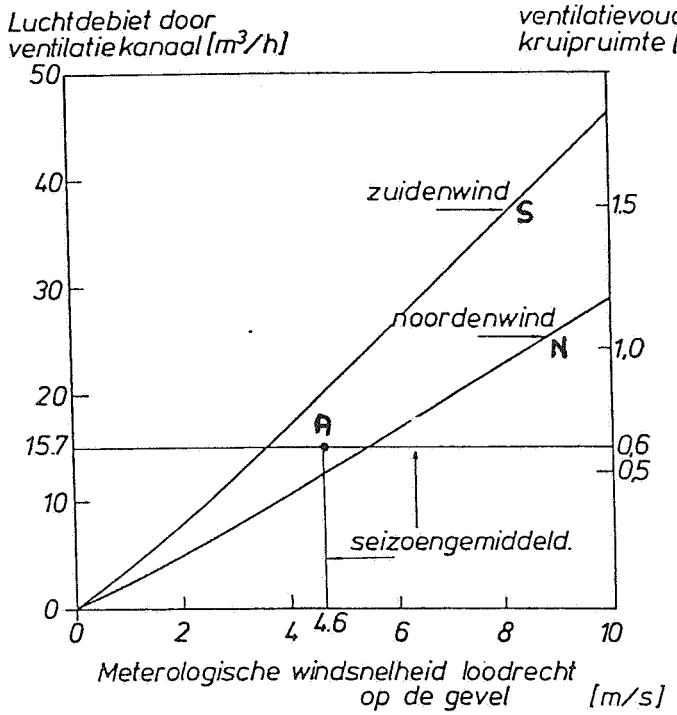


Figure 10: Calculated air change rate of the crawl space expressed in $[m^3/h]$ (left scale) and in ach $[h^{-1}]$ (right scale) as a function of the meteorological wind speed.
S = south wind; N = north wind; A = averaged value for the heating season.

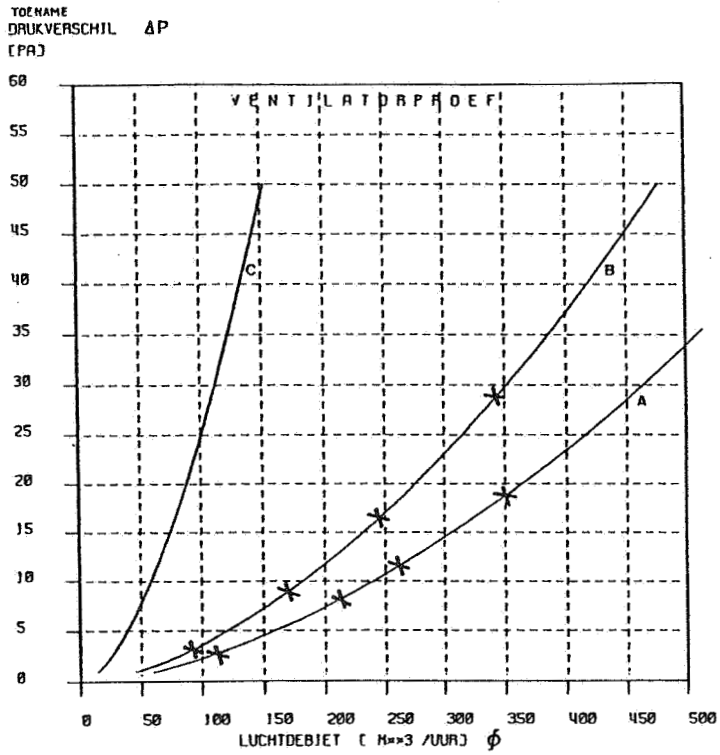


Figure 11: Results of a depressurization test of a crawl space. A = ventilation channels open; B = sealed ventilation channels; C = A-B = ΔP-ϕ curve for the ventilation channels; ϕ = air flow rate.

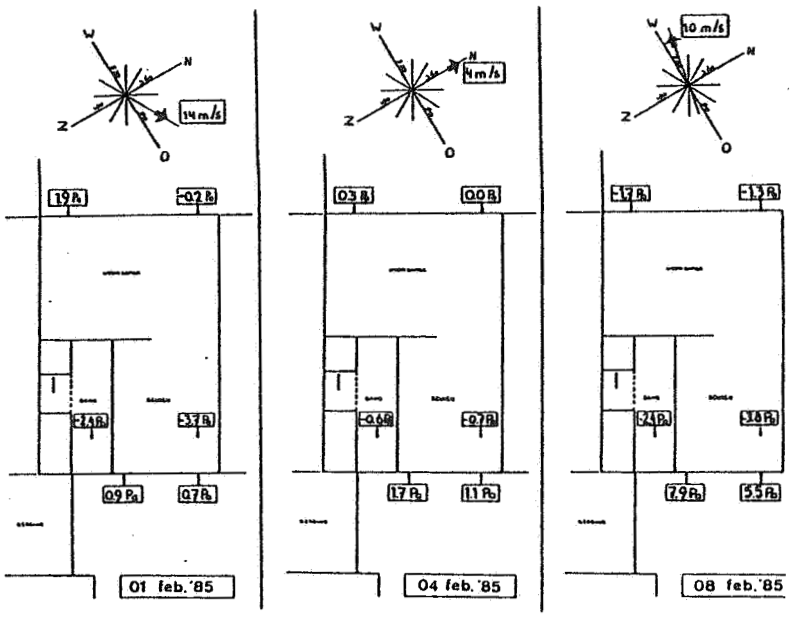


Figure 12: Observed pressure differences (with the crawl space as reference) at different locations for different wind speed situations.

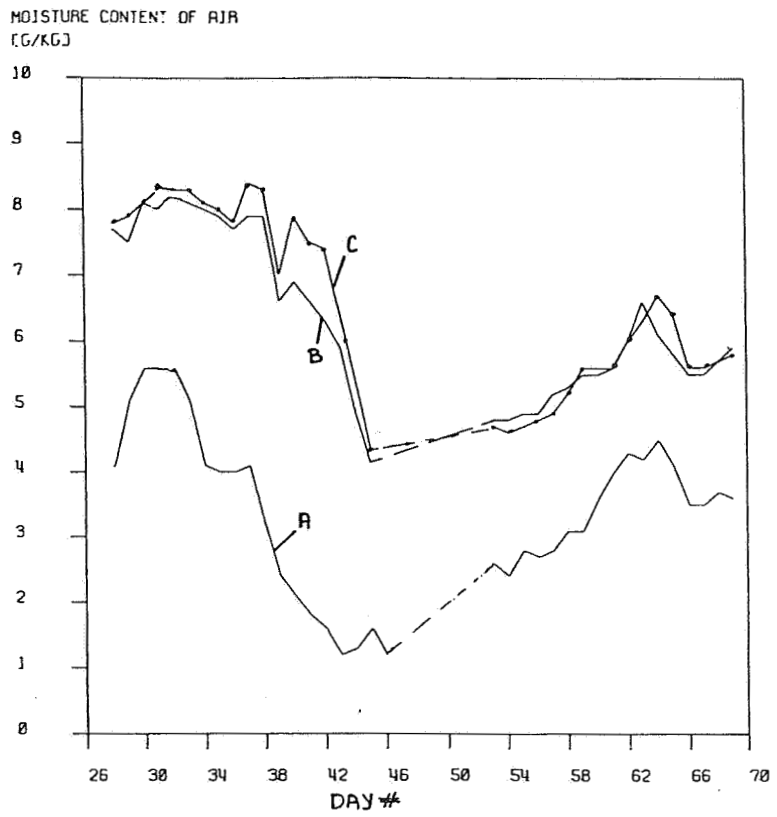


Figure 13: Moisture content of air in [g/kg] for:
A = outdoor air; B = living space; C = crawl space.
Daily averaged values are shown.

VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 23

VENTILATION STRATEGIES FOR CRAWL-SPACES, ATTICS ETC.

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1. SYNOPSIS

In this paper ventilation of attics and crawl-spaces is investigated theoretically. Ventilation rates and temperatures of the spaces are calculated by means of flow balance procedures. Flow characteristics of ventilators and openings for attics and crawl-spaces are far from well known, so a laboratory investigation on pressure drops across such devices was undertaken and reported in the paper. As convective flows from the heated part of a house into a colder, ventilated space can create moisture problems this situation has been investigated extensively.

2. INTRODUCTION

Spaces connected to heated parts of a building, such as crawl-spaces, attics etc, are normally ventilated. The need for ventilation is mainly based on ambitions of moisture control. An adequate ventilation of these spaces prevents moisture problems and damages. The ventilation need for this purpose depends on many factors such as outer climate, heat insulation degree, moisture sources within the space itself, for example evaporation from the ground in a crawl-space, or built- in moisture in the building material, degree of moisture convection from the heated part of the buildning into the space. The ultimate ventilation need is settled by the critical level of moisture load for buildning materials within the ventilated space. This critical level is normally formulated in terms of maximum allowable relative humidity (RH) for different materials. For wood and wood-based materials this level is often claimed to be around 75% for avoiding mould growth on wood and around 80% for avoiding rot in wood. (NEVANDER & ELMARSSON, 1981). For chip-boards moisture-related movements may cause trouble for example om attic floors prepared for making dwelling room on later on. For steel and other metals, risk for corrosion may create certain critical moisture levels.

Considerations as these mentioned above lead to settlement of a minimum ventilation degree.

On the other hand, excessive ventilation of such spaces creates unnecessarily high energy losses due to transmission between the heated part of the building and the ventilated space. For example, the design philosophy of crawl-space foundation implies a certain insulation gain due to the presense of the crawl-space. This implies a maximum ventilation degree.
The desired ventilation intensity can be achieved by means of natural forces such as wind and/or temperature differences or by mechanical ventilation devices. The degree of wind-driven ventilation of these spaces is depending on several factors:

- local wind velocity
- shape of the surrounding of the building
- geometrical proportions of the building
- dimensions and design of air inlet/outlet openings and ventilators
- location of these openings and ventilators
- etc.

Estimating climate in ventilated non heated spaces belongs to the more severe problems in building physics. For a complete analysis of the problems a lot of factors have to be taken into account:

- The ventilation degree (see above)
- The air tightness behaviour of the buildning component between the space and the heated part of the buildning
- The heat exchange within the space involving transmission, convection and radiation
- Moisture sources, moisture flow and moisture capacity

The analysis is strongly simplified if average conditions are sufficient for the considerations. As a first step such an analysis may be enough as far as durability risks are concerned. The radiative part of the heat exchange is also a difficult step in a complete heat exchange analysis. However, for modern well-insulated constructions between heated and ventilated spaces the

influence of heat radiation may be small. The long wave radiation though can cause considerable surface temperature phenomena especially on the outside of roofs on clear nights.
In this paper a method for calculating ventilation intensities in attics and crawl-spaces is presented. Furthermore an average based analysis of the climate in the spaces is carried out.

3. REFERENCE HOUSE

The calculations presented further on in the paper are all performed for a house outlined in figure 3.1.

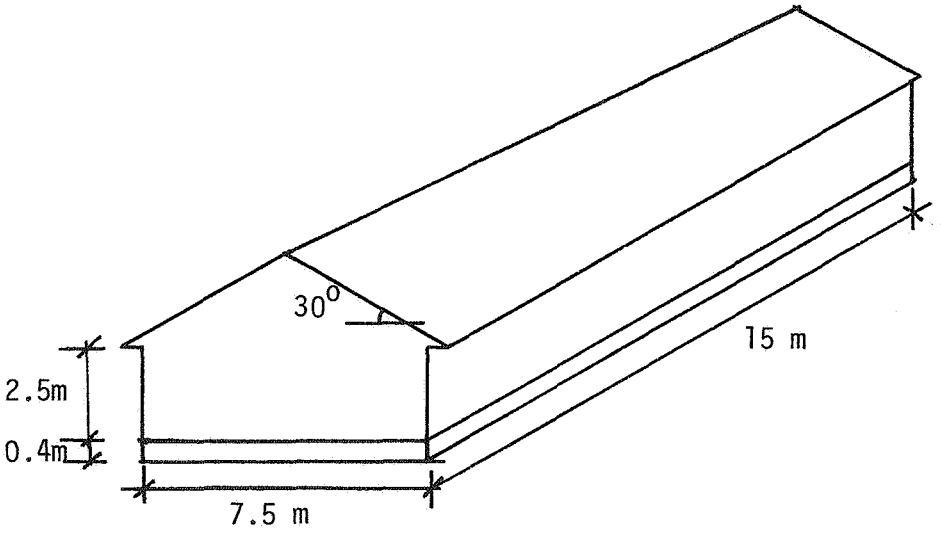


FIG. 3.1 Reference house.

For wind load considerations the house is intended to be located in a built up area. The shape factors used for the calculations figure 3.2-3.4 are mainly based on comparisons and analyses of results reported by JENSEN & FRANK, 1965; GANDEMER, 1978; LEUTHENSSER, 1970; NEWBERRY & EATON, 1974; THURESSON, 1977; GUSTEN, 1984; AIC, 1984 & SOLIMAN, 1973.

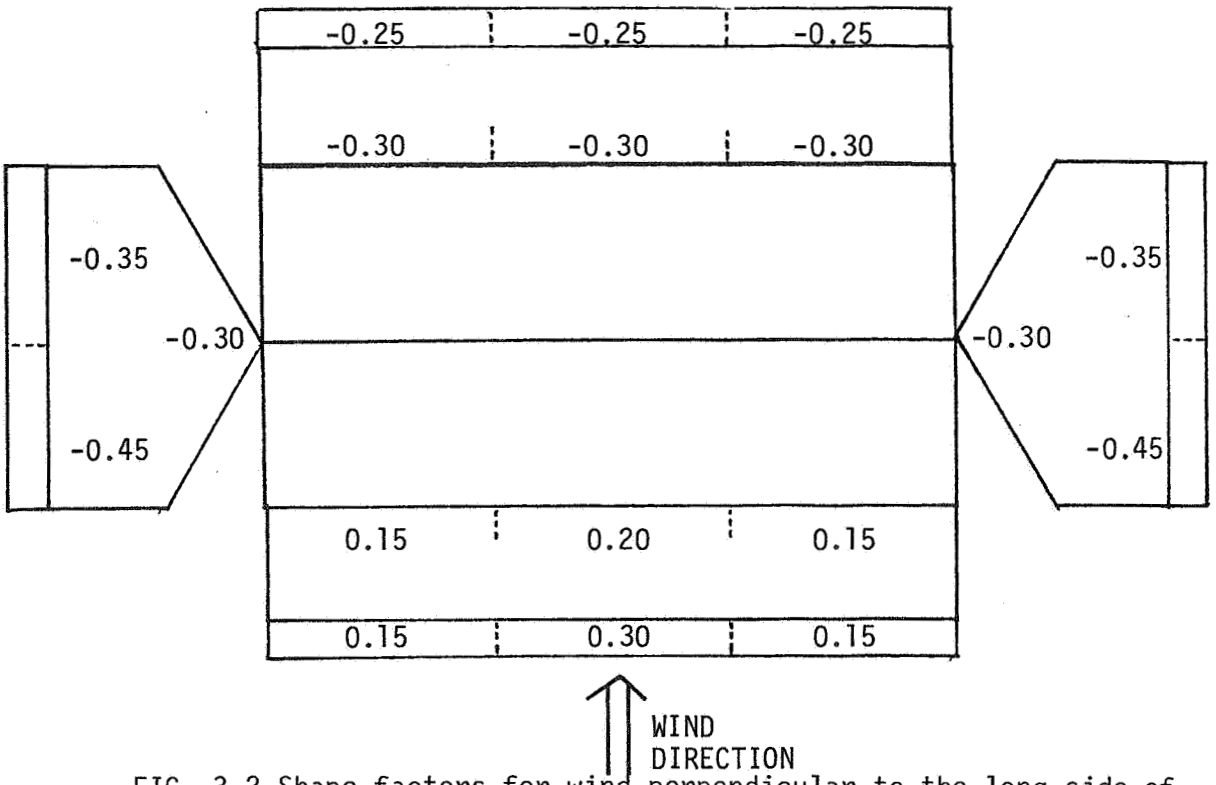


FIG. 3.2 Shape factors for wind perpendicular to the long side of the reference house.

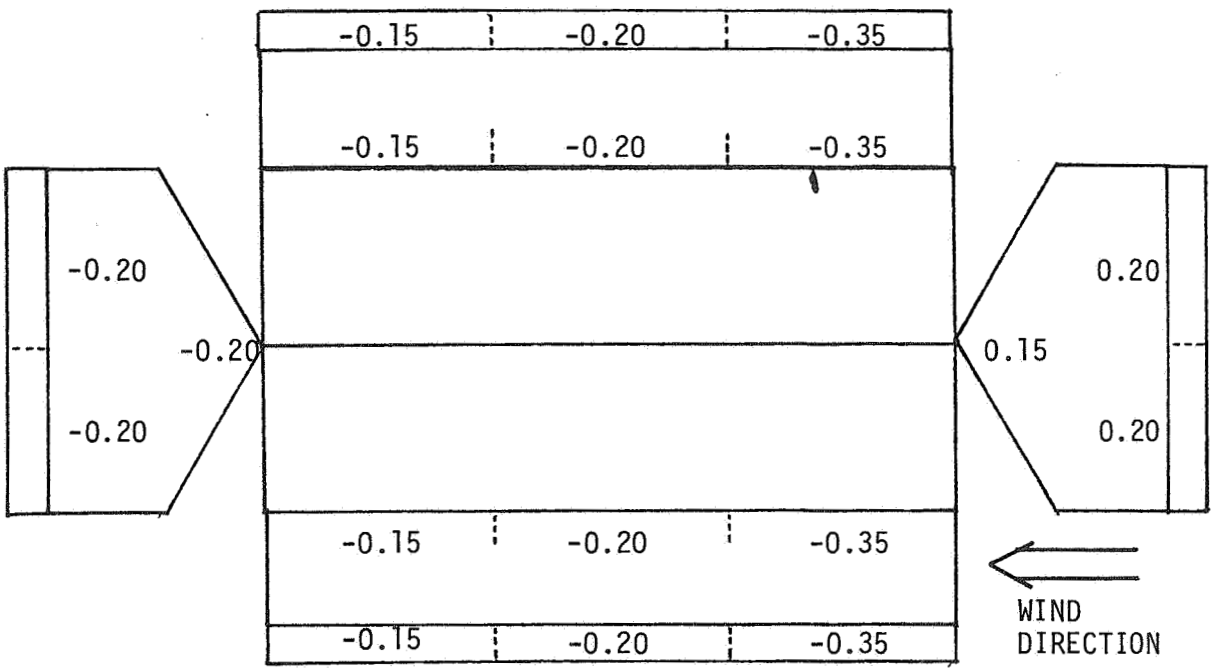


FIG. 3.3 Shape factors for wind perpendicular to gable part of the reference house.

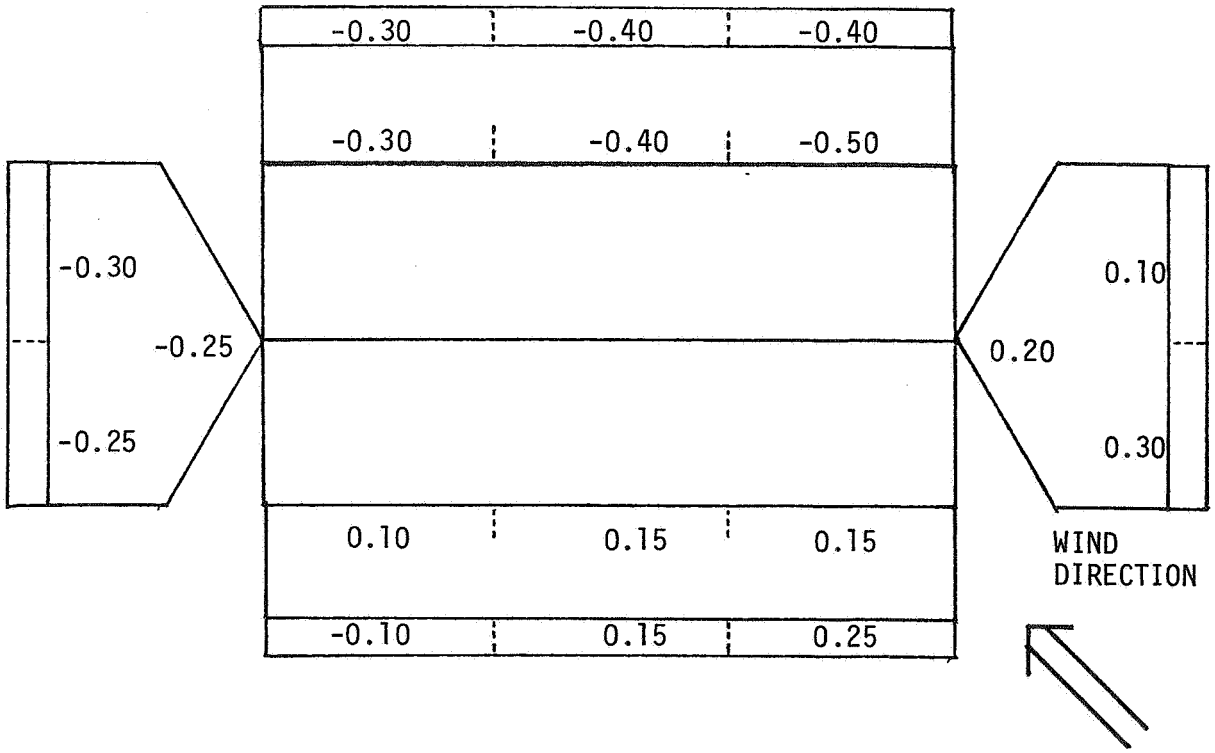


FIG. 3.4 Shape factors for wind 45° to longside and gable part of the reference house.

4. AIR FLOW CHARACTERISTICS OF VENTILATION OPENINGS AND VENTILATORS

In the laboratory the air flow behaviours of different ventilation openings and commercially offered ventilators were investigated. The openings and ventilators were connected to a pressurized box, airtight except for the investigated specimen. The pressure difference between the two sides of the specimen was monitored by means of an electrical micro-manometer. The air flow rate supplied to the box was monitored by means of an orifice plate and a micro-manometer. The pressure regime investigated was 0-100 Pa. The results are given in table 4.1 as pressure loss factors, ξ , originating from the well-known expression

$$\Delta p = \xi \frac{\rho \cdot u_m^2}{2}$$

where

Δp = pressure difference, Pa

ξ = pressure loss factor, -

ρ = density, kg/m^3

U_m = mean velocity i.e. q_v/A
where q_v = volume flow rate, m^3/s and A = nominal frontal area, m^2

Ventilator/opening, type	Area mm^2	Pressure loss factor, ζ
Pressed steel	125 x 125	48
"-	150 x 150	47
"-	200 x 200	45
"-	250 x 250	32
"-	65 x 250	26
Light metal	125 x 125	7,7
"-	150 x 150	6,9
"-	200 x 200	6,8
"-	250 x 250	7,1
Open hole	71 x 71	2,1
"-	150 x 150	2,3
Hole with plastic net	71 x 71	2,3
Hole with brass net	71 x 71	2,4
Hole with plastic net	150 x 150	2,9
Hole with brass net	150 x 150	2,6

TABLE 4.1 Pressure loss factors for different ventilators and openings.

5. VENTILATION RATE CALCULATION PROCEDURE

The rates of air flow into and out from the ventilated space for different flow types were calculated using the following expressions. (see for example KRONVALL, 1980):

Single resistance flow

$$|q_v| = \sqrt{\frac{|(\mu \cdot \rho \cdot u_0^2/2 - p)| \cdot \hat{2}}{\xi \cdot \rho}} \cdot A \qquad \ldots 5a$$

where

q_v = volume flow rate, m^3/s

μ = shape factor, -

u_0 = reference wind velocity, m/s

ρ = density, kg/m^3

p = pressure in the ventilated space, Pa

ξ = pressure loss factor, -

A = flow (frontal) area, m^2

Flow through building components etc.

Laminar flow:

$$q_v = (\mu \cdot \rho \cdot u_0^2/2 - p) \cdot L \cdot A \qquad \ldots 5b$$

where

L = flow coefficient, $m^3/(m^2 \cdot s \cdot Pa)$

Exponent flow:

$$|q_v| = \alpha \, |(\mu \cdot \rho \cdot u_0^2/2 - p|^{\beta} \cdot A \qquad \ldots 5c$$

where

α = flow coefficient, $m^3/(m^2 \cdot s \cdot Pa^{\beta})$

β = flow exponent, - , $0{,}5 \leq \beta \leq 1.0$

The flow expressions are written as flows into the ventilated spaces. For the flow balance calculation of the pressure differences 5 a and 5 c are given positive or negative values depending on the sign of the pressure expressions.
Summing up all the different flows into the space and putting the

sum equal to 0 i.e. :

$$\Sigma q_v = 0 \qquad \ldots 5d$$

makes it possible to determine the unknown variabel p (pressure inside the space). If different flow types are involved the implicite function must be treated iteratively. The calculations were performed by using the Newton-Raphson procedure and executed on a Hewlett-Packard HP 85 computer. The computer program is listed in appendix 1.

6. CALCULATION RESULTS

Some of the results of executed calculations are given in diagraph form in
figure 6.1-6.6.

6.1 ATTICS

Two main alternatives for ventilating the attic were investigated:

- slot at roof bottom of the long sides of the house, width 20, 10 and 2 mm (the last case representing non volontarily made slots).
- ventilators in the gable tops, pressed steel and light metal, dimensions 150 x 150 mm and 250 x 250 mm.

The calculations were performed for different wind directions.

Results:
A 45^{o} angle between wind direction and the long side of building seems to produce higher ventilation rates than that of wind perpendicular to the long sides of the house. The least effective ventilation seems to be obtained when the wind is parallel to the long sides of the house. In the case of ventilation openings in the gable tops however the situation is the opposite.
There are linear relationships between

- wind velocity and ventilation rate
- ventilation opening area and ventilation rate

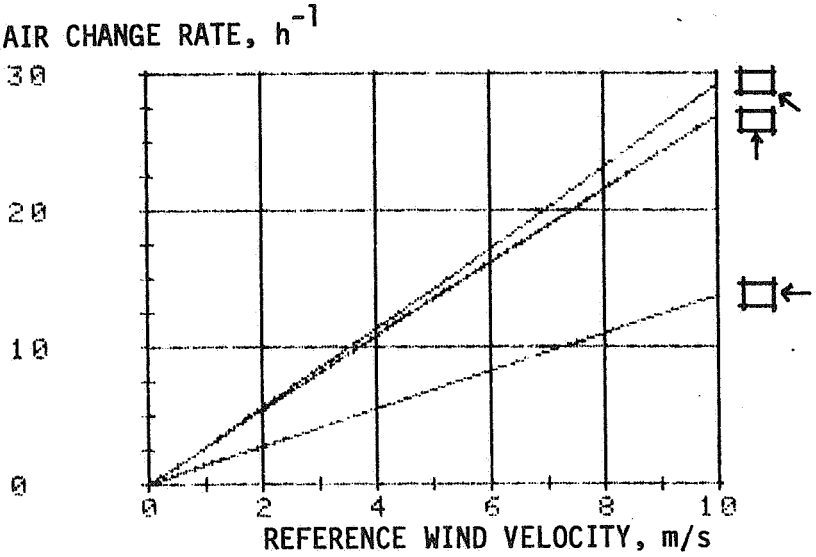


FIG. 6.1 Slot at roof bottom, width 20 mm, permeable gable tops $0.14 \cdot 10^{-3}$ $m^3/(m^2 \cdot s \cdot Pa)$

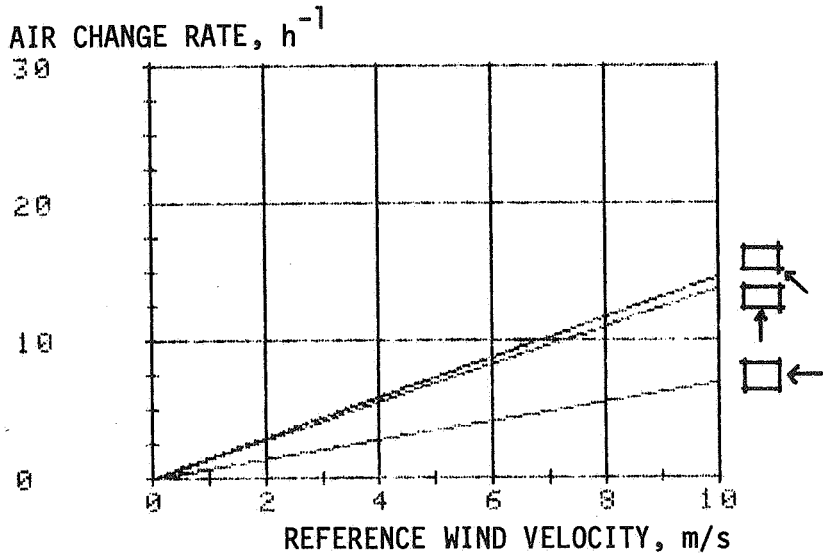


FIG. 6.2 Slot at roof bottom, width 10 mm, permeable gable tops $0.14 \cdot 10^{-3}$ $m^3/(m^2 \cdot s \cdot Pa)$

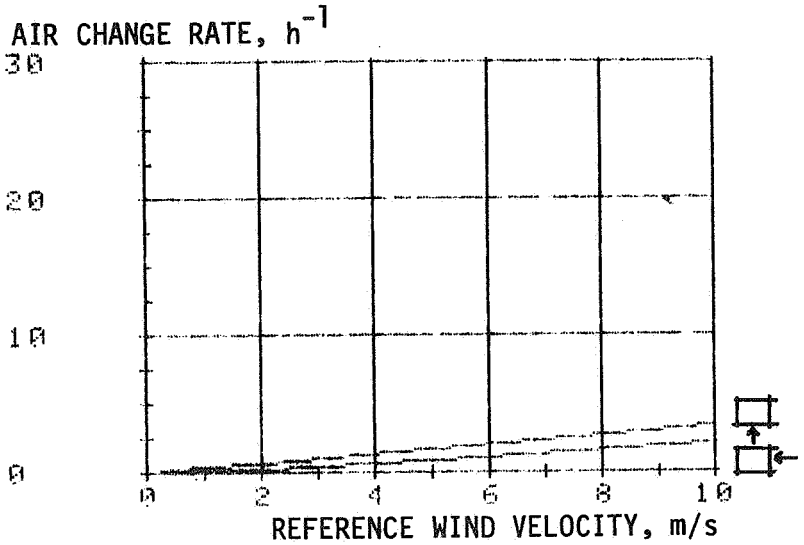


FIG. 6.3 Slot at roof bottom, width 2 mm, permeable gable tops 0.14 · 10^{-3} $m^3/(m^2 \cdot s \cdot Pa)$
1 ventilator 150 x 150 mm, pressed steel, in each gable top

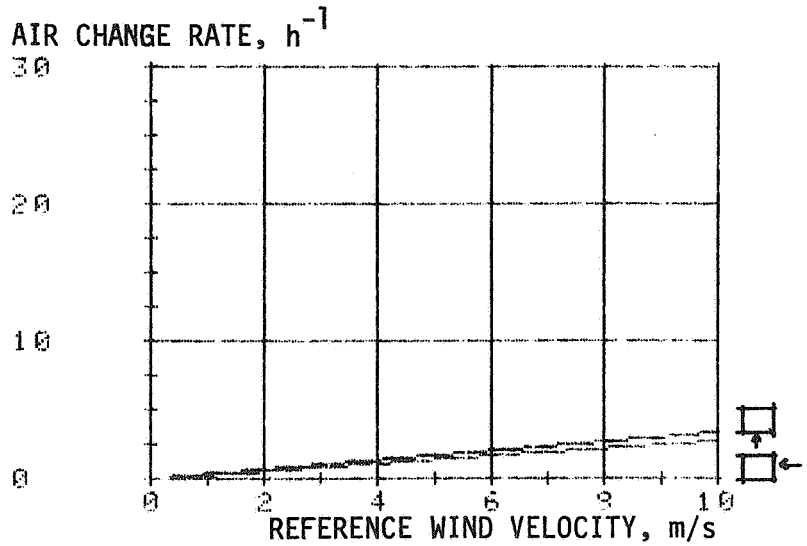


FIG. 6.4 Slot at roof bottom, width 2 mm, permeable gable tops 0.14 · 10^{-3} $m^3/(m^2 \cdot s \cdot Pa)$
1 ventilator 150 x 150 mm2, light metal, in each gable top

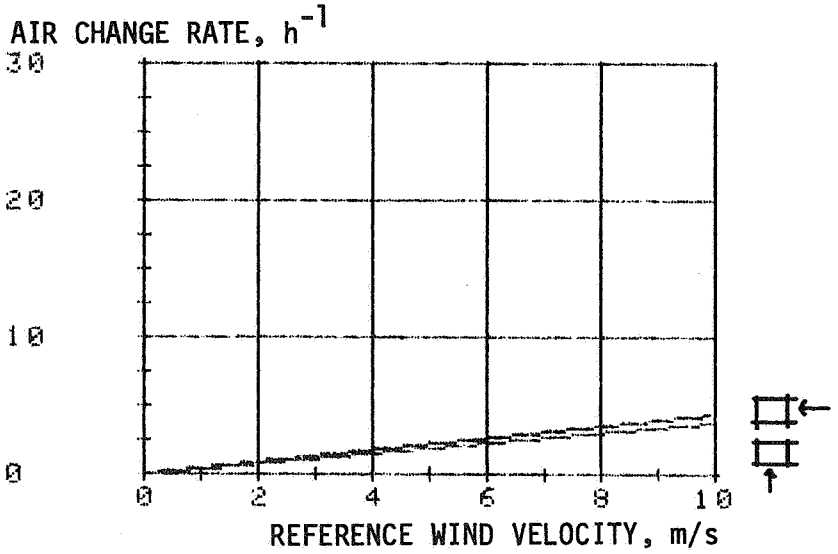


FIG. 6.5 Slot at roof bottom, width 2 mm, permeable gable tops $0.14 \cdot 10^{-3}$ $m^3/(m^2 \cdot s \cdot Pa)$
1 ventilator 250 x 250 mm2, light metal, in each gable top

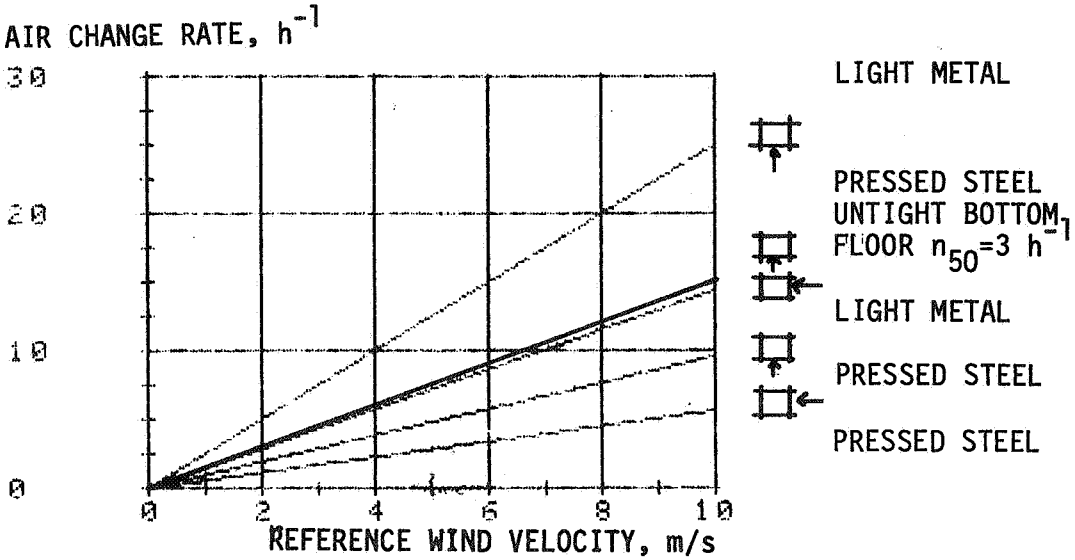


FIG. 6.6 24 ventilators 150 x 150 mm2, 9 on each long side, 3 on each gable side, pressed steel and light metal, average height of crawl-space 0,60 m

These facts are of course due to the small influence of the presumed laminar flow through the gable tops.
($L = 0{,}14 \cdot 10^{-3}$ $m^3/(m^2 \cdot s \cdot Pa)$; value for wood panel according to BANKVALL, 1981.)
The most effective ventilation of the attic space seems to be obtained by means of ventilation slots at the roof bottoms of the long sides of the house.

6.2 CRAWL-SPACES

The ventilation devices chosen for the crawl-space are ventilators 150 x 150 mm, pressed steel and light metal. The number of ventilators was chosen according to recommendations in the Swedish Building Code. (0,10 m^2 open area/100 m^2 floor area, which is a recommendation for houses in tight built up areas when using wood bottom floor. For pressed steel ventilators an area reduction is prescribed, namely 22% of ventilator frontal area.)
In order to study the consequences of a leaky bottom floor, one calculation was made for a bottom floor having an air leakage of a value corresponding to 3,0 h^{-1} at 50 Pa pressure difference, evenly distributed over the house envelope area.

Results:
Apart from the linear relationship between wind velocity and ventilation rate mentioned above, the ventilation rate is strongly depending on type of ventilator used. This is of course due to the large differences between pressure loss factors for pressed steel and light metal ventilators, cf. table 4.1. When using light metal ventilators instead of pressed steel ones, both being of the same size, the ventilation rate is raised by a factor of appr. 2.5.
($= \xi_{\text{pressed steel}} / \xi_{\text{light metal}}$).
When the untight bottom floor is added to the calculation the ventilation rate increases and the air flow through the bottom floor, directed from the crawl-space to the heated part of the house is of considerable magnitude, appr. 75% of the total ventilation flow rate !

7. HEAT BALANCE CALCULATIONS

Heat balance calculations have been conducted for a winter case with the temperature of outside air equals $\pm$ 0 ^{o} C. Conductive and convective parts of the heat exchange have been taken into account. For the roofing a heat transmission coefficient of 1,5 W/(m^2 · K) was chosen.

7.1 ATTICS

Figure 7.1-7.4 illustrate the resulting air temperature in the attic space under influence of different ventilation rates (fresh air), heattransmission coeffients of the attic floor and convection flows from the heated part of the house into the attic.

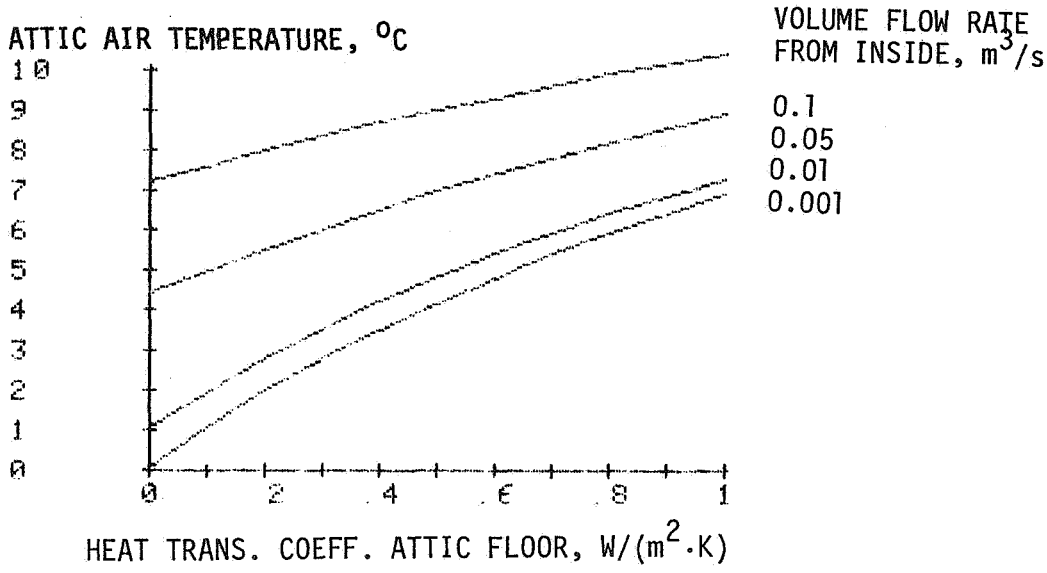


FIG. 7.1 Heat balance calculation
n_{attic} = 0,5 h^{-1}

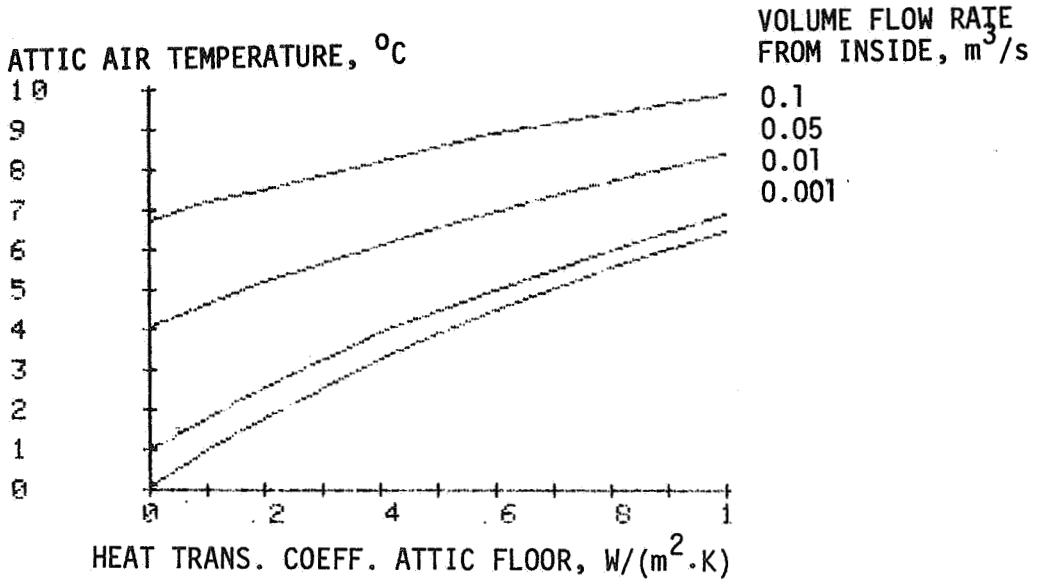


FIG. 7.2 Heat balance calculation
$n_{attic} = 1.0\ h^{-1}$

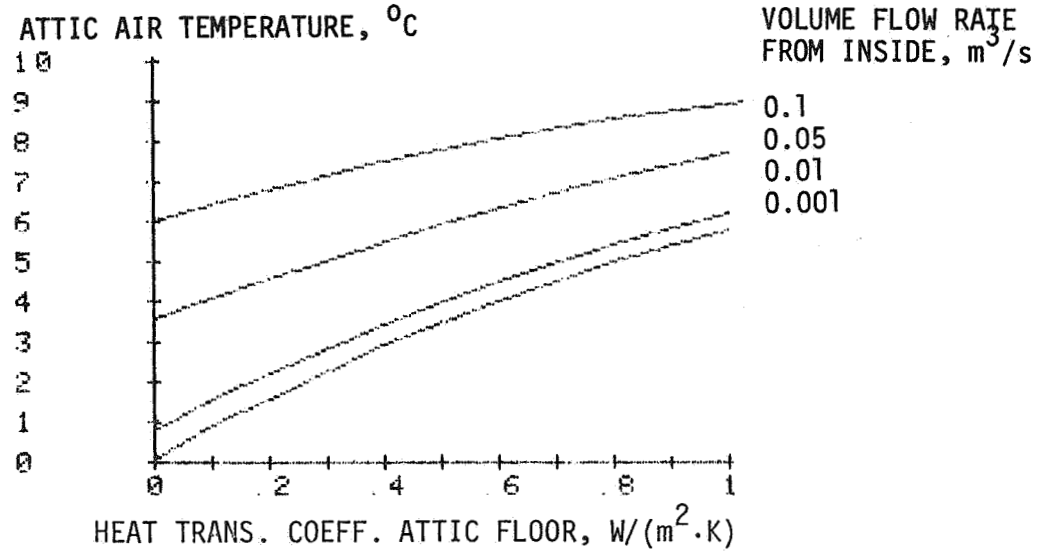


FIG. 7.3 Heat balance calculation
$n = 2.0\ h^{-1}$

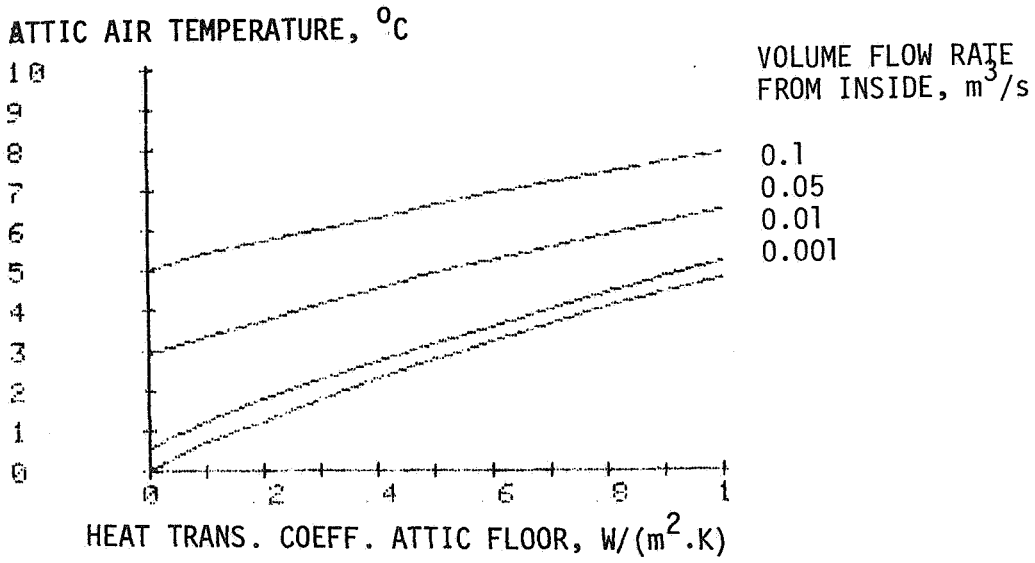


FIG. 7.4 Heat balance calculation
$n = 4{,}0\ h^{-1}$

In order to make it possible to perform proper considerations on the magnitude of the convective flow into the attic, figure 7.5 can serve as a basis. Even distribution of leaks all over the house envelope is assumed, why n_{50} describes the air tightness of the attic floor. For different pressure differences the resulting air flow into the attic can be seen. The air tightness behaviour of the attic floor can also be included in the air flow balance calculation revued in ch. 5. However, as stack effect inside the house must be considered at winter conditions the "normally" used inner shape factor, μ_i of a magnitude - 0,3, see for example NEWBERRY & EATON, 1974, must be modified for stack effect. This was made for a "typical" winter condition assuming that the pressure difference caused by stack effect inside the house was appr. + 2 Pa at ceiling height.

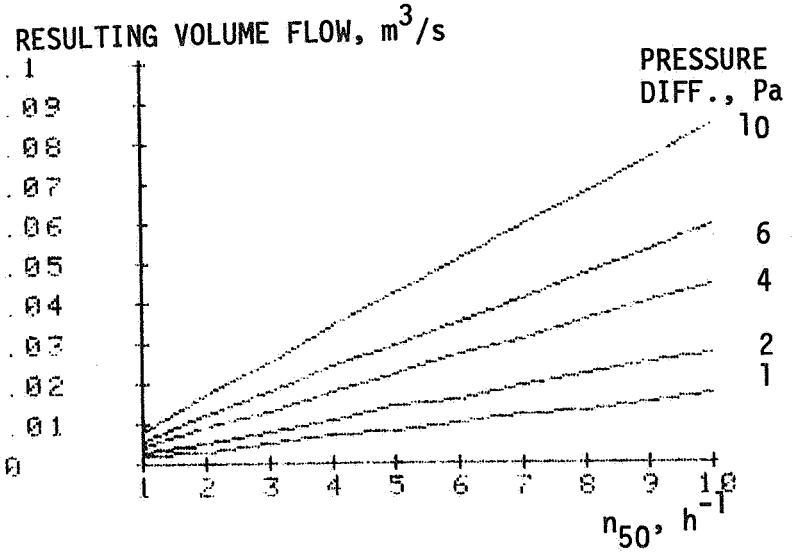


FIG. 7.5 Resulting air flow through the top floor for different n_{50} -values and pressure differences.

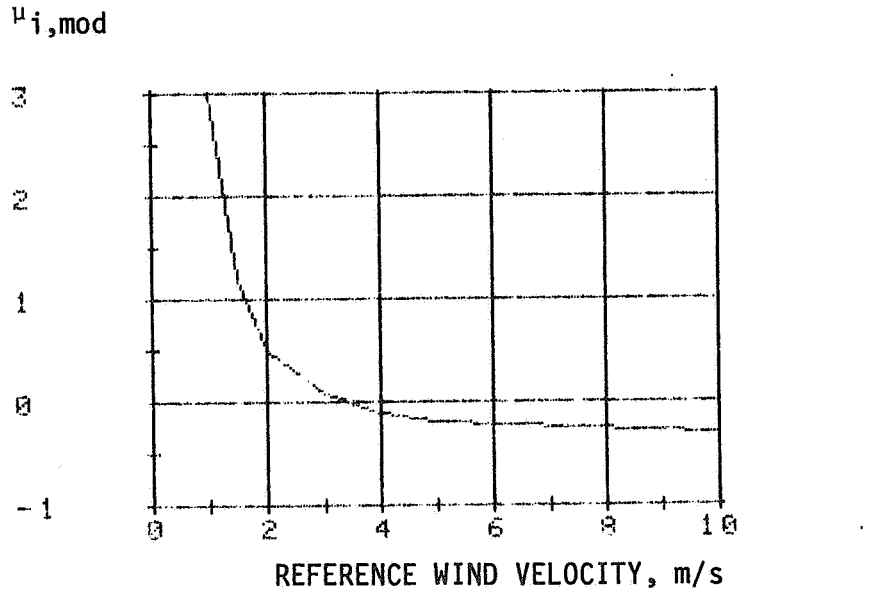


FIG. 7.6 Modified inner shape factor $\mu_{i,mod}$ for different wind velocities.

This modified shape factor, $\mu_{i,mod}$, of course different for different wind velocities, is plotted in figure 7.6. Using $\mu_{i,mod}$ in a calculation with conditions presented in figure 6.1 (wind along the long sides of the house), the contribution to the total ventilation flow from leaking indoor air can be studied for different n_{50} - values. Figure 7.7.
The calculation was run for one wind velocity only; 2 m/s.

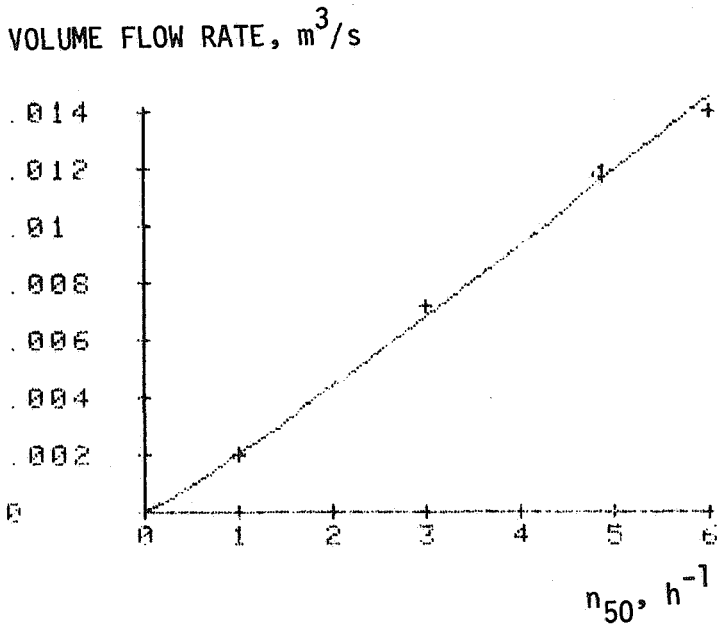


FIG. 7.7. Incoming heated air into the attic. Wind velocity 2 m/s.

In table 7.1 the resulting ventilation flows of fresh and heated air can be studied for different tightnessdegrees of the attic floor.

n_{50}	fresh air		heated air from the house	
h^{-1}	m^3/s	h^{-1}	m^3/s	h^{-1}
0	0.092	2.72	0	0
1	0.090	2.66	0.002	0.06
3	0.085	2.51	0.007	0.21
6	0.078	2.31	0.014	0.41

TABLE 7.1

7.2 CRAWL-SPACES

Meaningful heat balance calculations must be based on non-steady state calculations, mainly due to the considerable heat capacity of the ground under the crawl-space. Such calculations are not presented in this paper.

8. MOISTURE CONSIDERATIONS. ATTICS

Calculations on heat and air flow balances may serve as a basis for moisture considerations. A simple moisture damage criterion could be:

$$(RH)_{\text{attic air}} \leq (RH)_{\text{critical}} \qquad \ldots 8\ a$$

The moisture content in air within a ventilated space, in this case the attic, can (under steady state conditions) be written

$$v_a = v_o + \frac{G}{nV} \qquad \ldots 8\ b$$

where

v_a = moisture content in attic air, g/m^3

v_o = "- "- in outdoor air, g/m^3

G = moisture supply in or into the attic, g/h

n = ventilation rate (fresh air), h^{-1}

V = attic inner volume, m^3

Furthermore:

$$(RH)_a = \frac{v_a}{(v_s)_{\theta_a}} = \frac{v_o + \frac{G}{nV}}{(v_s)_{\theta_a}} \qquad \ldots 8c$$

where

RH = relative humidity, -

$(v_s)_{\theta_a}$ = moisture saturation value at $\theta = \theta_a$, g/m^3

The same outer condition of air temperature as for the heat balance calculations is chosen i.e. $\theta_o = \pm 0^oC$. Outdoor relative humidity is chosen to 80%. Since the saturation value for $\pm 0^oC$ = 4,84 g/m^3, $v_o = 0{,}8 \cdot 4{,}84 = 3{,}87\ g/m^3$.

Indoor conditions are $\pm 20^oC$, RH = 45%, so the moisture content of indoor air is $0{,}45 \cdot 17{,}28 = 7{,}78\ g/m^3$.

Using attic temperatures calculated by means of the heat balance procedure it is possible to calculate maximum moisture supply, G, under different conditions.

$$G_{max} = \{ (RH)_{critical} \cdot (v_s)_{\theta_a} - v_o \} \cdot nV \qquad ...8d$$

Such calculations were made for different air tightness degrees of the attic floor (i.e. the whole house tightness, even tightness distribution prescribed). Two heat transmission coefficients were chosen, 0,2 W/m^2K (modern, highly insulated construction) and 1,0 W/m^2K (older, badly insulated construction). Furthermore two levels of $(RH)_{critical}$ were chosen; 70% and 80%.

The calculation results can be studied in figure 8.1.

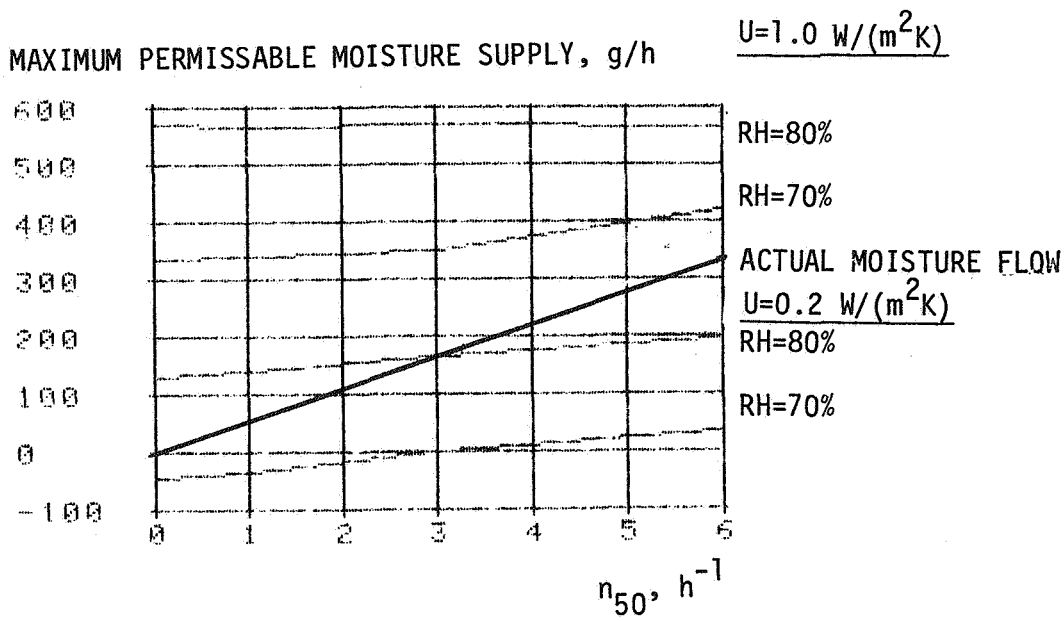


FIG. 8.1 Maximum pernissable moisture supply (g/h) to the attic for different $(RH)_{critical}$, U-value and airtightness levels for the attic floor. The line "actual moisture flow" refers to calculated moisture flow. (See below.)

The result should be compared to actual levels of moisture supply (see table 7.1 or figure 7.7). The relation between $_{50}$ and moisture supply is almost linear. The conection between air flow and moisture flow is

$$q_{moisture}\ (g/h) = q_v\ (m^3/s) \cdot 3600\ (s/h) \cdot v_{in}\ (g/m^3) \quad ...8e$$

Since $q_v = 0.002 \cdot n_{50}\ (m^3/s)$ (Fig. 7.7)

and $v_{in} = 7.78\ g/m^3$ (see above)

$$q_{moisture} = 0.002 \cdot n_{50} \cdot 3600 \cdot 7.78\ g/h = 56.0 \cdot n_{50}\ g/h \quad ...8f$$

This line i also included in figure 8.1.

If RH = 80% is chosen as a critical level, it could be seen that for n_{50} - values less than 3.0 h^{-1}, the actual moisture flow rate is below the highest permissable moisture supply rate. If the air tightness is less than so ($n_{50} \geq 3{,}0\ h^{-1}$) the critical RH-level (80%) will be exceeded. RH = 70% will not be possible to attain.

For the badly insulated attic floor case, actual moisture supply flow rate is always lower than critical flow rates.

Thus, moisture problems can be expected if a house with bad air tightness in the attic floor will be additionally insulated without any attempts made to tighten up the attic floor in connection with the additional insulation procedure.

Bad conditions can also arise if, in a new, highly insulated house, large air leaks are left in the attic floor. Such leaks may occur for example around pipes penetrating the floor if no special care is undertaken to tighten up around the pipe. Large leaks are also frequent in the connection between the attic floor and the gable wall, especially in 1½ story buildings.

8.1 CONCLUDING REMARKS

It would be strongly desirable to execute calculations similar to the presented ones for other outside climates than this single

investigated one ($\pm$ 0°C, RH = 80%.) Experience shows for example that severe moisture conditions in attic spaces are frequent at spring and autumn conditions.

In a coming research project under my direction at the Lund Institute of Technology such calculations will be performed. Also the influence of non stationary conditions and moisture capacity effects will be investigated both theoretically and in field measurements.

APPENDIX 1.

Computer program "AIRBAL" written in HP-BASIC for HP-85 for calculation of ventilation rate of ventilated spaces such as attics, crawl-spaces etc.

```
100 REM PROGRAM "AIRBAL" FOR
120 REM CALCULATING VENTILATION
140 REM INTENSITY OF CRAWL SPACE
    S
160 REM ATTICS ETC.
180 REM CREATED BY JOHNNY KRONVA
    LL
200 REM NATIONAL SWEDISH TESTING
     INSTITUTE
220 ASSIGN# 1 TO "TEST1"
240 PRINT "DENSITY OF AIR"
260 READ# 1 ; R1@ PRINT R1;"kg/m
    3"
280 PRINT "DYNAMIC VISCOSITY OF
    AIR"
300 READ# 1 ; V1@ PRINT V1;"Ns/m
    2"
320 PRINT "NUMBER OF SINGLE RESI
    STANCES"
340 READ# 1 ; N1@ PRINT N1
360 PRINT "NUMBER OF EXPONENT FL
    OWS"
380 READ# 1 ; N2@ PRINT N2
400 PRINT "NUMBER OF LAMINAR FLO
    WS"
420 READ# 1 ; N3@ PRINT N3
440 PRINT "NUMBER OF MECHANICAL
    VENTILATION DEVICES"
460 READ# 1 ; N4@ PRINT N4
480 REM
500 REM
520 PRINT "SINGLE RESISTANCE CHA
    RACTERISTICS"
540 FOR I1=1 TO N1
560 READ# 1 ; A1(I1)@ PRINT "ARE
    A";A1(I1);"m2"
580 READ# 1 ; K1(I1)@ PRINT "LOS
    S FACTOR";K1(I1)
600 READ# 1 ; M1(I1)@ PRINT "SHA
    PE FACTOR";M1(I1)
620 NEXT I1
640 PRINT "EXPONENT FLOW CHARACT
    ERISTICS"
660 FOR I2=1 TO N2
680 READ# 1 ; A2(I2)@ PRINT "ARE
    A";A2(I2);"m2"
700 READ# 1 ; W2(I2)@ PRINT "FLO
    W COEFFICIENT";W2(I2);"m3/(s
    *m2*Pa^B)"
720 READ# 1 ; B2(I2)@ PRINT "FLO
    W EXPONENT, BETA";B2(I2)
740 READ# 1 ; M2(I2)@ PRINT "SHA
    PE FACTOR";M2(I2)
760 NEXT I2
780 PRINT "LAMINAR FLOW CHARACTE
    RISTICS"
800 FOR I3=1 TO N3
820 READ# 1 ; A3(I3)@ PRINT "ARE
    A";A3(I3);"m2"
840 READ# 1 ; L3(I3)@ PRINT "FLO
    W COEFFICIENT";L3(I3);"m3/(m
    2*s*Pa)"
820 READ# 1 ; A3(I3)@ PRINT "ARE
    A";A3(I3);"m2"
840 READ# 1 ; L3(I3)@ PRINT "FLO
    W COEFFICIENT";L3(I3);"m3/(m
    2*s*Pa)"
860 READ# 1 ; M3(I3)@ PRINT "SHA
    PE FACTOR";M3(I3)
880 NEXT I3
900 PRINT "MECHANICAL VENTILATIO
    N DEVICES"
920 FOR I4=1 TO N4
940 READ# 1 ; Q4(I4)@ PRINT "AIR
     FLOW RATE";Q4(I4);"m3/s"
960 NEXT I4
980 PRINT "REFERENCE WIND VELOCI
    TY"
1000 INPUT U@ PRINT U;"m/s"
1020 PRINT "INTERNAL START PRESS
    URE"
1040 INPUT P0@ PRINT P0;"Pa"
1060 PRINT "TOLERANCE VALUE"
1080 DISP "NORMALLY 1.E-6"
1100 INPUT E@ PRINT E
1120 PRINT "MAX NUMBER OF LOOPS"
1140 INPUT N9@ PRINT N9
1160 PRINT "LIMIT DELTA P"
1180 DISP "NORMALLY .001 Pa"
1200 INPUT P9@ PRINT P9
1220 D=.00001*P0 @ P1=P0 @ N=0
1240 GOTO 1320
1260 REM
1280 N=0
1300 D=P1-P0
1320 P=P1
1340 GOSUB 1780
1360 Q6=Q
1380 IF ABS(Q6)<=E THEN 1600
1400 P=P1+D
1420 GOSUB 1780
1440 Q7=Q
1460 P2=P1-D*Q6/(Q7-Q6)
1480 IF ABS(P2-P1)<=P9 THEN 1640
1500 P0=P1
1520 P1=P2
1540 N=N+1 @ PRINT N;
1560 IF N>=N9 THEN 1680
1580 GOTO 1300
1600 PRINT "CALCULATION TERMINAT
    ED DUE TO FLOW CRITERION"
1620 GOTO 1700
1640 PRINT "CALCULATION TERMINAT
    ED DUE TO PRESSURE CRITERIO
    N"
1660 GOTO 1700
1680 PRINT "CALCULATION TERMINAT
    ED DUE TO MAX LOOP CRITERIO
    N"
1700 REM
1720 GOTO 2440
1740 REM
```

```
1760 REM
1780 REM SUBROUTINE FLOW RATE
1800 REM FLOW THROUGH SINGLE RES
     ISTANCES
1820 Q1=0
1840 FOR I1=1 TO N1
1860 Q1(I1)=SGR(ABS(M1(I1)*U^2*R
     1^2-P)*2*A1(I1)^2/K1(I1)^R1
     )
1880 IF SGN(M1(I1)*U^2*R1^2-P)>=
     0 THEN 1920
1900 Q1(I1)=-Q1(I1)
1920 Q1=Q1+Q1(I1)
1940 NEXT I1
1960 REM FLOW THROUGH EXPONENT
1980 REM FLOW COMPONENTS
2000 Q2=0
2020 FOR I2=1 TO N2
2040 Q2(I2)=W2(I2)*ABS(M2(I2)*U^
     2*R1^2-P)^B2(I2)*A2(I2)
2060 IF SGN(M2(I2)*U^2*R1^2-P)>=
     0 THEN 2100
2080 Q2(I2)=-Q2(I2)
2100 Q2=Q2+Q2(I2)
2120 NEXT I2
2140 REM FLOW THROUGH LAMINAR
2160 REM FLOW COMPONENTS
2180 Q3=0
2200 FOR I3=1 TO N3
2220 Q3(I3)=(M3(I3)*U^2*R1^2-P)*
     L1^I3)*A3(I3)
2240 Q3=Q3+Q3(I3)
2260 NEXT I3
2280 REM FLOW THROUGH MECHANICAL
      1201REM VENTILATION DEVICE
     S
2300 Q4=0
2320 FOR I4=1 TO N4
2340 Q4=Q4+Q4(I4)
2360 NEXT I4
2380 REM TOTAL AIR FLOW
2400 Q=Q1+Q2+Q3+Q4
2420 RETURN
2440 PRINT @ PRINT @ PRINT
2460 PRINT "RESULT:"
2480 PRINT "INTERNAL PRESSURE (P
     a)";
2500 PRINT P2
2520 PRINT
2540 FOR J=1 TO N1
2560 PRINT "Q1(J)=";Q1(J),"m3/s"
2580 NEXT J
2600 J=0
2620 PRINT "Q1=";Q1;"m3/s"
2640 FOR J=1 TO N2
2660 PRINT "Q2(J)=";Q2(J),"m3/s"
2680 NEXT J
2700 PRINT "Q2=";Q2;"m3/s"
2720 J=0
2740 FOR J=1 TO N3
2760 PRINT "Q3(J)=";Q2(J);"m3/s"
2780 NEXT J
2800 PRINT "Q3=";Q3;"m3/s"
2820 J=0
2840 FOR J=1 TO N4
2860 PRINT "Q4(J)=";Q4(J);"m3/s"
2880 NEXT J
2900 PRINT "Q4=";Q4;"m3/s"
2920 PRINT "Q tot=";Q;"m3/s"
2940 DISP "NEW WIND VELOCITY YES
     /NO"
2960 INPUT H$
2980 IF H$="YES" THEN 580
3000 PRINT "CALCULATION FINISHED
     "
3020 END
```

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 24

Use of a single tracer gas for measurement of ventilation rates in a large enclosure

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SYNOPSIS

This paper describes a preliminary investigation of the validity of a means of calculating the ventilation rate of a large enclosure from experimental data.

It was assumed that the air in the enclosure is not perfectly mixed. The measurement method selected was tracer gas concentration decay. The calculation of ventilation rate was performed by "least squares" fitting of a model to the observed tracer gas concentrations.

Simulations of tracer gas concentration decay measurements were performed with varying initial distribution of tracer gas. The ventilation rate was then calculated from the simulated concentration data.

Conclusions are drawn concerning the accuracy of such calculations and general strategy for meauring ventilation rates using tracer gases.

LIST OF SYMBOLS

C_n	Tracer gas concentration in zone n (zone 0 = outside air)
N	Total number of zones
Q_{mn}	Air flow rate from zone m to zone n
Q^1_{mn}	Air flow rate from zone m to zone n calculated from tracer gas concentration data
t	Time
V_n	Volume of zone n

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1 INTRODUCTION

The measurement of ventilation rates in small enclosures using tracer gas is a well understood and proven technique of ventilation research. The use of tracer gases for measurement of ventilation rates and air movements in large enclosures and multi-cell buildings, typical of factories and office buildings, is not yet at the same stage of development.

A paper presented by the present author at the 4th Air Infiltration Centre Conference[1] described work aimed at measuring ventilation rates in large enclosures for the purpose of estimating ventilation energy loss. The work was not intended to study internal air movements or their implications for air quality.

An instrument system was described which consisted of infra-red gas analysers for the measurement of nitrous oxide concentrations, sampling valves and automatic control and data recording equipment. The fundamentals of a method for calculating ventilation rates from measured data were described and a programme for validation of the measurement and analysis methods proposed.

This paper reports the results of calculating ventilation rates from simulated tracer gas concentration histories and compares the calculated ventilation rates with those assumed for the simulation.

2 SIMULATION AND VENTILATION RATE CALCULATION METHODS

2.1 Simulation Model

The model used for the generation of simulated tracer gas concentration data is shown in figure 1. The model consists of nine zones, which may represent parts of a large enclosure or cells of a multi-cell building. It is assumed that each zone is well mixed. The volumes of the zones and the air flow rates between them are shown in figure 1. These zone volumes and air flow rates were selected so as to give a pattern of tracer gas concentration decay similar to patterns which have been found in practice[4].

The simulation of the tracer gas concentration histories was performed by calculating, for each zone in turn, the net gain or loss of tracer gas over a short period of time assuming that the concentrations in all zones are constant. The new concentrations in the various zones were then calculated from the adjusted quantities of tracer gas.

The initial tracer gas concentrations assumed are given in table 1. The concentration in the outside air is taken to be zero at all times.

The results of the simulations are shown in figures 2, 3 and 4.

2.2 Ventilation Rate Calculation Method

This method is adapted from that described by Penman and Rashid [2].

The general equation governing the tracer gas concentrations within the space is:

Rate of supply of gas - Rate of removal of gas
= Rate of change of quantity of gas in the space

The easiest ventilation rate measurement method to use is the concentration decay method, in which:

Rate of supply of gas = 0

The rate of removal of gas from the space is simply the sum of the air flow rates from each zone to the outside, each multiplied by its appropriate tracer gas concentration:

$$Q_{10}\ C_1 + Q_{20}\ C_2 + \cdots\cdots + Q_{NO}\ C_N$$

$$= \sum_{n=1}^{N} Q_{no}\ C_n$$

The rate of change of the quantity of tracer gas in the space is the sum of the volumes of the zones each multiplied by the appropriate rate of change of tracer gas concentration:

$$V_1 \frac{dC_1}{dt} + V_2 \frac{dC_2}{dt} + \cdots\cdots + V_N \frac{dC_N}{dt}$$

$$= \sum_{n=1}^{N} V_n \frac{dC_n}{dt}$$

Thus

$$0 - \sum_{n=1}^{N} Q_{no}\ C_n = \sum_{n=1}^{N} V_n \frac{dC_n}{dt}$$

If this equation is integrated the effect of random fluctuations in C_n will be reduced without the need for fitting curves to the data. Integrating from time t_o to t_1 the following is obtained:

$$-\sum_{n=1}^{N} Q_{no} \int_{t_o}^{t_1} C_n\, dt = \sum_{n=1}^{N} (V_n\ (C_n, t_1 - C_n, t_o)) \qquad (1)$$

In this equation Q_{no} are unknown (assumed constant), C_n are measured and V_n are estimated.

In order to form N different equations which can be solved to find the N unknowns Q_1, Q_2 ..... Q_N, equation (1) can be integrated over N time intervals. If the time intervals are selected to be successive, then in the later stages of a concentration decay measurement independent equations will not be obtained, the (x + 1)th equation being simply a multiple of the xth. This is because the concentration decay in any zone tends to the form

$$C_n = A_n e^{(-B_n t)}$$

where A_n and B_n are constants for zone n. The N equations were therefore formed by integrating equation (1) from the beginning of the experiment to N different values of time.

The N equations can be represented in matrix form as:

$$-[C]\,[q] = [b]$$

where:

$$C_{m,n} = \int_{t=o}^{t_m} C_n \, dt$$

$$q_m = Q_{no}$$

and $$b_m = \sum_{n=1}^{N} (V_n \ (C_{n,t_m} - C_{n,o}))$$

Experimental errors will mean that an exact solution of these equations is not possible. The equations can be solved in a least squares sense by minimising the length of the residual vector r, where:

$$[r] = [b] + [C]\,[q]$$

Routines are available in the NAG computer program library to perform this operation without the constraint derived from physical considerations that:

$$Q_{no} \geqslant 0$$

for all n. NAG library routines were used for the calculations for the sake of convenience and in order to see how frequently negative values of Q_{no} were generated. In a practical case the presence of large negative values of Q_{no} might suggest poor accuracy.

3 RESULTS OF CALCULATIONS

Table 1 gives the initial tracer gas concentrations assumed for the calculations. Tables 2, 3 and 4 give the calculated exfiltration rates from each zone compared with the exfiltration rates used in the simulation for experiments 1, 2 and 3 respectively. For each experiment the exfiltration rates were calculated four times, using data from 9, 4.5, 1.8 and 0.9 hours of the experiment respectively. These times should be compared with the reciprocal of the model's ventilation rate i.e. 1.25 hours.

Three errors have been calculated. The percentage error in each zone exfiltration rate was calculated as:

$$\frac{100\ (Q^1_{no} - Q_{no})}{\Sigma Q_{no}}$$

The percentage error in the total exfiltration rate was calculated as:

$$\frac{100\ (\Sigma Q^1_{no} - \Sigma Q_{no})}{\Sigma Q_{no}}$$

The percentage total squared error was calcuated as:

$$\frac{100\ (\Sigma (Q^1_{no} - Q_{no})^2)}{\Sigma (Q_{no})^2}$$

Examination of the tables suggests a number of conclusions.

Firstly, the total exfiltration rate was generally calculated with an accuracy sufficient for practical purposes, only 2 cases out of 12 being worse than $\pm$ 25%. As it is the total exfiltration (ventilation) rate which is mainly of interest for energy conservation purposes these results can be regarded as encouraging. It may be thought that these errors are rather large considering that the calculations were performed using simulated data, but it must be remembered that the equations used by the calculations were not fully independent. The two cases of unsatisfactory accuracy occured in the 9-hour calculation in Experiment 1 and the 0.9 hour calculation in Experiment 2. In the former case the loss of accuracy could be expected to result from the combination of uniform initial tracer distrubution and long calculation period leading to the exponential concentration decays mentioned in section 2.2 The latter result is surprising considering the similarity of the plotted tracer concentrations for experiments 2 and 3.

Secondly, the presence of negative calculated flow rates did not indicate poor accuracy either of the total ventilation rate or of the individual flow rates, as quantified by the error terms at the

bottom of the tables. There seems therefore to be no advantage in using an unrestrained solution, whereas it has the disadvantage that negative flow rates have no physical meaning.

Thirdly, the individual zone exfiltration rates were generally predicted with rather poor accuracy.

Fourthly, provided unreasonably short measurement periods were avoided (0.9 hour calculation of Experiment 2), uniform initial distribution of the tracer gas did not improve the accuracy of the calculations. This means that in a space where poor mixing exists naturally, the tracer gas can be released at a known site or sites and provided that these partake in the general air circulation in the space then useful experimental data should be obtained. Artificial mixing will not be required.

4 DISCUSSION AND CONCLUSIONS

It is not difficult to produce good mixing in practice in small rooms by the use of oscillating fans, indeed good mixing often occurs naturally. Thus the representation in the model presented here of each zone as well mixed can accord well with reality when the zones represent the rooms of a multi-cell building. In a large enclosure, however, good mixing does not always occur[1,3,4,5]. The division of a large enclosure into a number of well-mixed zones constitutes an approximation to the real situation of a continuously varying concentration field. If a larger number of zones is used in the model better approximation to reality is attained, but the complexity of the analysis increases and the number of measurement points required in an actual experiment also increases if the concentrations in all zones are to be measured. It is this latter, practical, constraint which is the most severe.

If the initial distribution of tracer gas is not uniform then the tracer gas concentrations at the various sampling points vary rapidly both in time and space during the early part of a measurement[1]. The assumption of well-mixed zones may thus introduce considerable inaccuracy into the measurement of the quantity of tracer gas in the space, this being the key variable in the subsequent analysis.

In measuring ventilation rates using tracer gas we can therefore identify two situations. In the first situation, good mixing through the whole building or good mixing of every zone in the building occurs naturally or can be arranged by the investigator. In this case tracer gas experimental techniqes and single or multi-zone calculation methods can be applied with confidence. In the second situation, good mixing does not occur and can not be arranged. It is intended that a future paper will deal with the approximate representation of a continuous tracer gas concentration field.

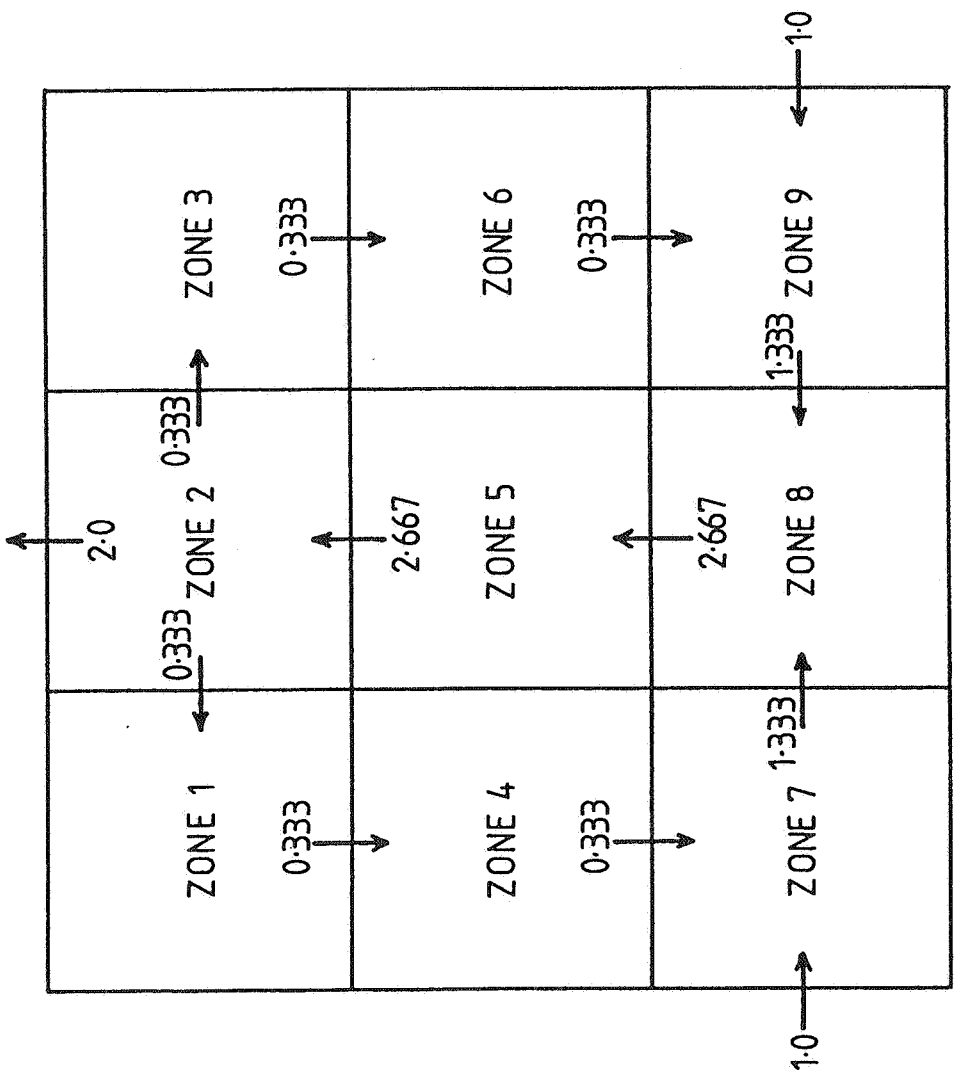

All zones 1000 m³
Air flows in m³/s.
ZONE 1
ZONE 2
ZONE 3
ZONE 4
ZONE 5
ZONE 6
ZONE 7
ZONE 8
ZONE 9
2·0
0·333
0·333
0·333
0·333
2·667
2·667
1·333
1·333
1·0
1·0

Figure 1

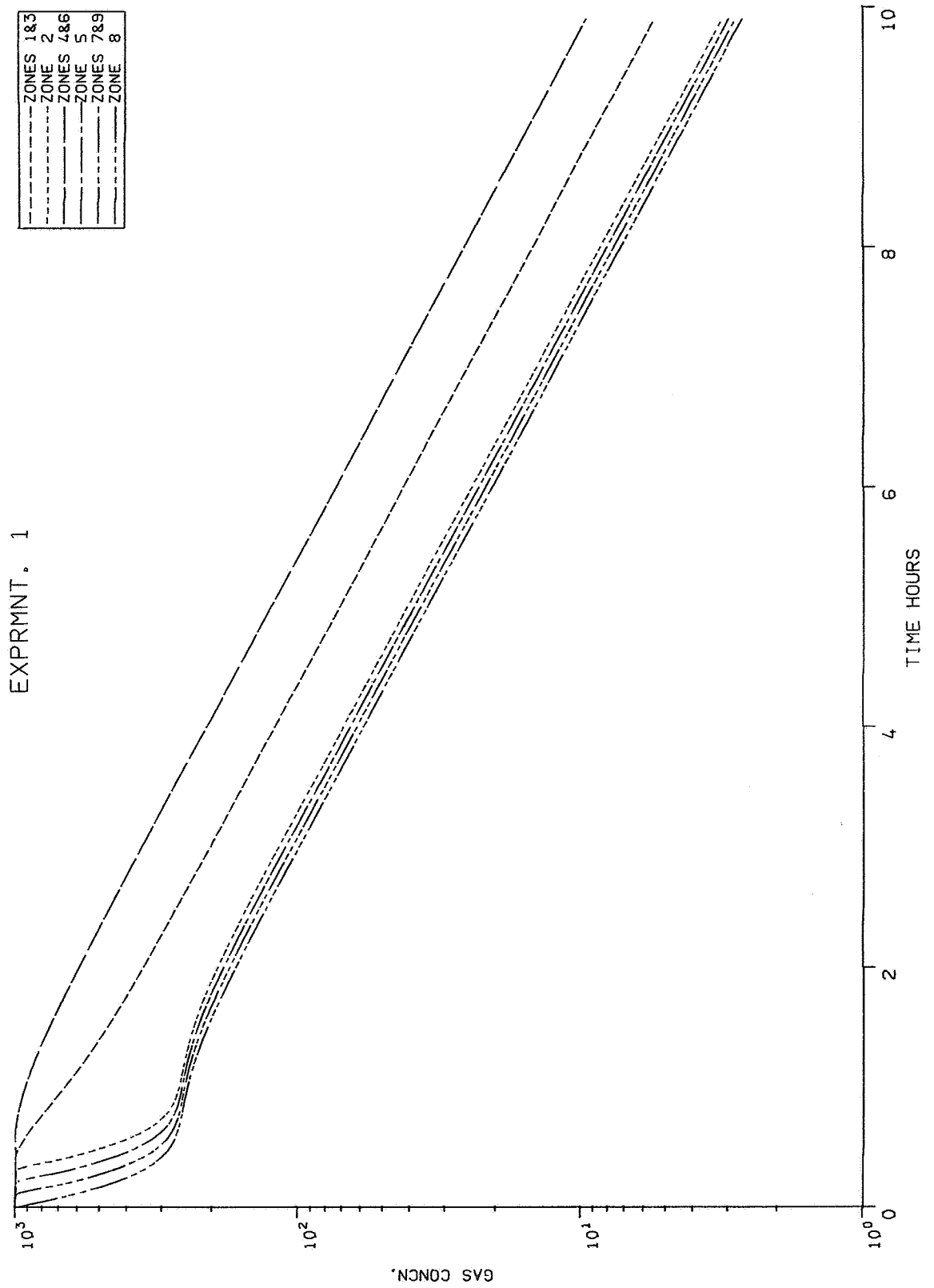

ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONES 7&9
ZONE 8
EXPRMNT. 1
GAS CONCN.
10^3
10^2
10^1
10^0
0
2
4
6
8
10
TIME HOURS

Figure 2

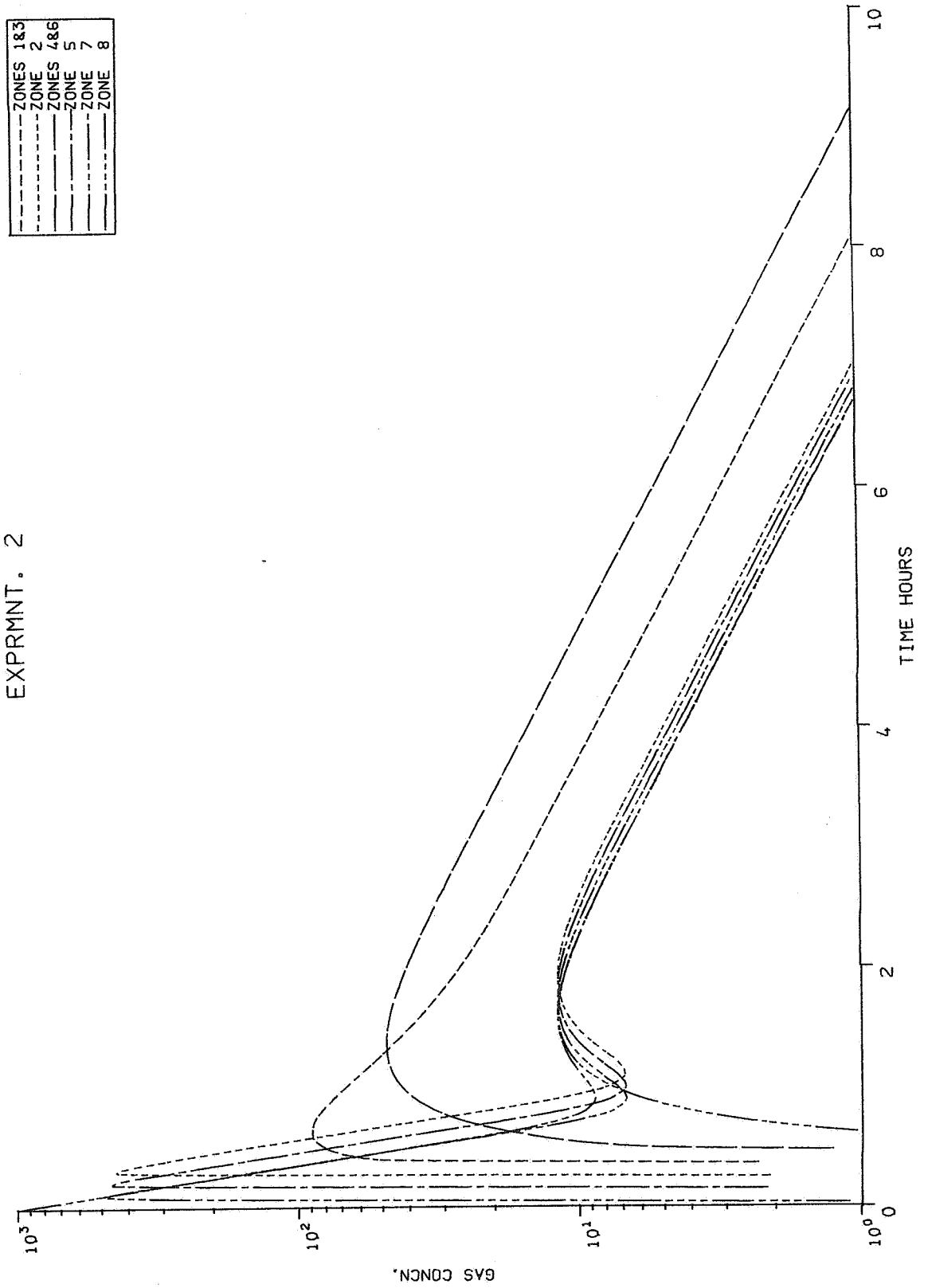

ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONE 7
ZONE 8
EXPRMNT. 2
GAS CONCN.
10^3
10^2
10^1
10^0
0
2
4
6
8
10
TIME HOURS

Figure 3


ZONES 1&3
ZONE 2
ZONES 4&6
ZONE 5
ZONES 7&9
ZONE 8
EXPRMNT. 3
GAS CONCN.
10^3
10^2
10^1
10^0
0
2
4
6
8
10
TIME HOURS

Figure 4

TABLE 1

Initial tracer gas distributions for simulations

Zone	Experiment[1]	Experiment[2]	Experiment[3]
1	1000	0	0
2	1000	0	0
3	1000	0	0
4	1000	0	0
5	1000	0	0
6	1000	0	0
7	1000	1000	0
8	1000	0	1000
9	1000	0	0

Units of concentration are arbitrary.

TABLE 2

Assumed and calculated exfiltration rates, Experiment 1

Zone	Actual m^3/h	9 hour calcn		4.5 hour calcn		1.8 hour calcn		0.9 hour calcn	
		Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %
1	0	-79	-1	573	+8	269	+4	1521	+21
2	7200	3889	-46	2551	-65	5222	-27	4334	-40
3	0	-79	-1	573	+8	269	+4	1521	+14
4	0	-471	-7	-515	-7	-55	-1	-1014	-14
5	0	2955	+41	2285	+32	2997	+42	2364	+33
6	0	-471	-7	-515	-7	-55	-1	-1014	-14
7	0	1175	+16	1140	+16	-1136	-16	-562	-8
8	0	2047	+28	1791	+25	342	+5	446	+6
9	0	1175	+16	1140	+16	-1136	-16	-562	-8
Totals	7200	10141	+41	9023	+25	6717	-7	7034	-2
% total squared errors			52		65		30		41

TABLE 3

Assumed and calculated exfiltration rates, Experiment 2

Zone	Actual m^3/h	9 hour calcn		4.5 hour calcn		1.8 hour calcn		0.9 hour calcn	
		Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %
1	0	-445	-6	174	+2	68	1	761	+11
2	7200	1525	-79	6313	-12	7194	0	6513	-10
3	0	-445	-6	174	+2	68	1	761	+11
4	0	468	+7	-282	-4	-40	-1	-1410	-20
5	0	1477	+21	2979	+41	1042	+14	882	+12
6	0	468	+7	-282	-4	-40	-1	-1410	-20
7	0	1926	+27	-1525	-21	369	+5	83	+1
8	0	1414	+20	486	+7	-1796	-25	-677	-9
9	0	236	+3	121	+2	160	+2	-334	-5
Totals	7200	6624	-8	8158	+13	7025	-2	5169	-28
% total squared errors			79		24		9		13

TABLE 4

Assumed and calculated exfiltration rates, Experiment 3

Zone	Actual m^3/h	9 hour calcn		4.5 hour calcn		1.8 hour calcn		0.9 hour calcn	
		Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %	Calc m^3/h	Error %
1	0	-401	-6	106	+1	38	+1	5	0
2	7200	3438	-52	8599	+19	7911	+10	7599	+5
3	0	-401	-6	106	+1	38	+1	5	0
4	0	73	+1	-257	-4	-137	-2	-20	0
5	0	3223	+45	-10	0	-774	11	-378	-5
6	0	73	+1	-257	-4	-137	-2	-20	0
7	0	171	+2	943	+13	430	+6	67	+1
8	0	1730	+24	-1901	-26	54	+1	18	0
9	0	171	+2	943	+13	430	+6	67	+1
Totals	7200	8077	+12	8272	+15	7853	+9	7303	+1
% total squared errors			54		14		3		1

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PAPER 25

IMPROVING THE ACCURACY OF A CONSTANT CONCENTRATION TRACER GAS SYSTEM

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SYNOPSIS

Air infiltration flows into different zones of a building can be measured with the constant concentration technique by injecting a metered amount of tracer gas to hold the concentration of the gas constant. The control and estimation algorithm used to calculate the injection rate is designed using classical transform and optimal estimation methods. The ability of the control algorithm to keep the concentration constant and to accurately measure time varying infiltration flows is demonstrated using digital computer simulations and laboratory experiments. Field demonstrations then complete the confirmation that all components of the total system are performing as designed, and that the desired accuracy targets have been achieved.

The details of how constant concentration system accuracy targets were attained in the Princeton constant concentration tracer gas measurement system are outlined in this paper. Before the total system accuracy goals could be achieved it was necessary to focus attention on the commercial SF_6 detection unit based upon the principles of gas chromatography and electron capture. Gas flow paths, sequencing and critical times in a given sample analysis all directly impinge on the total system function and ultimate accuracy. Some of the points discussed are: internal air leakage, valve switching, and calibration of various subsystems.

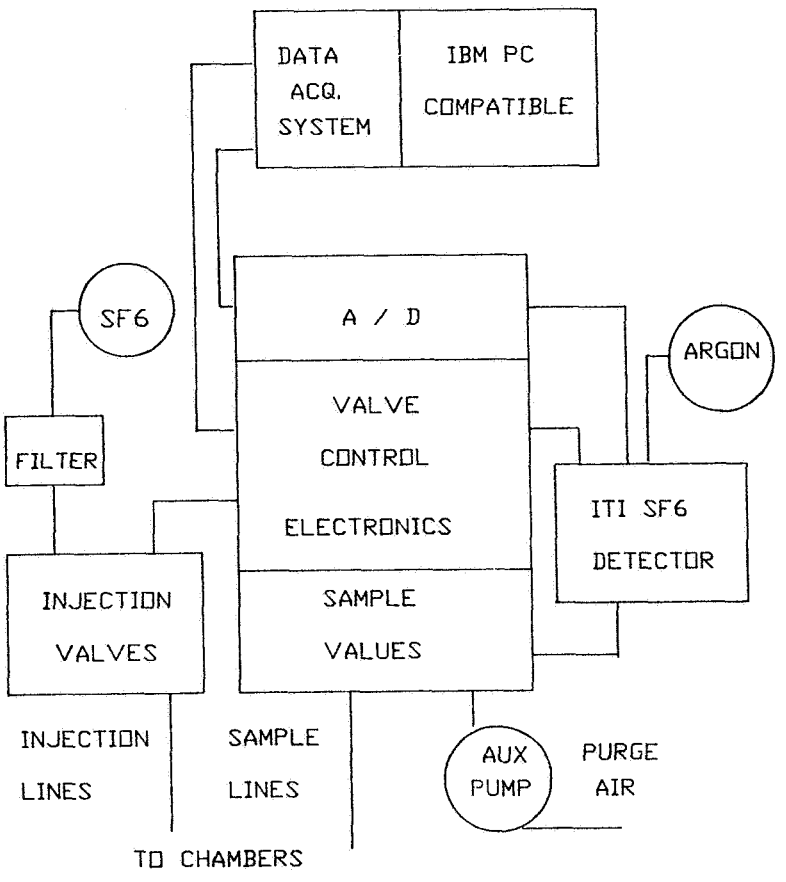
1.0 INTRODUCTION

The increased use of constant concentration tracer gas (CCTG) systems to provide the detailed measurements of air infiltration in multiple zones necessary to analyse building energy and indoor air quality performance is evident in AIC literature.[1-5] In addition numerous reports and conference proceedings point out that more than a decade of automated air infiltration system developments has taken place in the IEA countries[6-15] seeking improved air infiltration measurement approaches. This paper attempts to add to that literature related to CCTG systems in providing information on the use of control theory in the system design to aid in the achievement of the accuracy goals. The actual mechanical and electrical design considerations in the tracer gas detection system itself are also covered in some detail in order to document what has proven to be critical factors in the development of our CCTG system which is shown in the schematic of Figure 1.

In the June 1985 ASHRAE annual meeting, we attempted to place CCTG systems in prospective with other techniques for documenting air movements and infiltration in multi-cell buildings.[16] Further details on the control method used in the Princeton CCTG system, on accuracy evaluations using laboratory tests, field evaluations and computer simulations will be presented in December 1985, ASHRAE Florida conference. Detailed field studies of the Princeton CCTG system in a well-documented research house are presented as a companion paper in this conference.[17]

Figure 1

BLOCK DIAGRAM OF
CONSTANT CONCENTRATION SYSTEM



2.0 CONTROL AND ESTIMATION ALGORITHM FOR CCTG SYSTEM

The constant concentration technique measures the air infiltration flow into each zone of a building. To make this measurement a metered amount of tracer gas is injected into each zone so that the concentration of the tracer gas is kept at a target level in all the zones. If the tracer concentration in a zone is not near the target the measured air infiltration rate (AIR) in that zone is in error and the air flowing from the zone causes the measured AIRs in the adjoining zones to be in error. To compute the rate of tracer injection, the control and estimation algorithm may consider the present and past level of the measured concentrations, the past injection rates, and the estimated air flow. The following section presents a detailed analysis of how to best compute the injection rate and estimate the air infiltration flow from the measured concentrations and previous injection rates.

2.1 Simplified Air Flow Model

The first step in the analysis of a control system is to form a accurate model of the process being controlled. The coupled set of first order differential equations which govern the level of tracer gas in a multi-zone building is [18]:

$$V_j \frac{dc_j}{dt} = -c_j \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n} c_k \cdot F_{kj} + S_j \qquad (1)$$

where V_j = volume of zone j

F_{ji} = air flow from zone j to zone i

c_j = tracer gas concentration in zone j (state variable)

S_j = rate of tracer gas injection into zone j (control)

the n^{th} zone is the outside air

This model assumes that imperfect mixing in the zone does not introduce a time lag or delay in the system.

By keeping the concentration of the tracer gas at the concentration target (c_t) in all the zones, the tracer gas equations reduce to:

$$V_j \frac{dc_j}{dt} = c_t \left\{ - \sum_{i=1}^{n} F_{ji} + \sum_{k=1}^{n-1} F_{kj} \right\} + c_n \cdot F_{nj} + S_j \qquad (2)$$

For an appropriate choice of tracer gas, the outside concentration c_n is negligible compared to c_t. Assuming that the density of the gas in each zone is equal, the conservation of mass equation gives:

$$\sum_{i=1}^{n} F_{ij} = \sum_{i=1}^{n} F_{ji} \qquad (3)$$

Thus, in Equation (2) the sum of the flows leaving the zone can be replaced by the sum of the flows entering the zone. This reduces the flow terms in the brackets to F_{nj}, the air infiltration flow. By applying this simplification, assuming that dc_j/dt is negligible, and that $c_n << c_t$, the air infiltration flows are found to be:

$$F_{nj} = \frac{S_j}{c_t} \qquad (4)$$

Thus, by holding the concentration constant, the infiltration into a zone is simply the tracer injection rate into the zone divided by the steady concentration.

2.2 Discrete Model and Z-plane Analysis

The system of tracer gas concentrations and air flow rates is described in a continuous manner by the differential Equations (1). Although the goal of the system control is to keep the zone

concentration steady at the target level, the concentration does at times deviate from the target level. These deviations occur during system startup and when there are changes in AIR. During these times the differential term is not negligible and must be retained in order to properly model the movement of the concentration. The nature of the constant concentration instrumentation requires that the concentration sampling and calculation of the level of the injection rate to be discrete. Thus, the system is modeled with difference equations, and the analysis of the control is carried out using discrete analysis techniques, Z-transforms and pole placement in the Z-plane.

By applying the assumptions that the tracer concentrations in the zones are near the target and that $c_n << c_t$ the levels of tracer gas in the j building zones are approximated by:

$$V_j \frac{dcj}{dt} = -cj \cdot F_{nj} + S_j \qquad (5)$$

It is advantageous that the equations do not contain air flow rates between the building zones (interzone air flows) since the flow rates are not measurable by the system and are difficult to estimate. The remaining variables in the equations can either be estimated or are measured.

The differential Equations (5) are also separate. Thus, the modeling and analysis can be carried out on one zone and applied to the rest of the zones. Integrating the approximated differential equation over the sample period yields a difference equation for the tracer concentration:

$$c_{k+1} = a_k c_k + b_k u_k \qquad (6)$$

where c_{k+1} = concentration at time (k+1) Ts [1/1]

u_k = S_k/V (control variable-injection rate) [1/t]

AIR_k = F_{nk}/V (air infiltration rate) [1/t]

a_k = $\exp(-AIR_k \text{ Ts})$ [1/1]

b_k = $(1 - a_k)/AIR_k$ [t]

Ts = time between samples [t]

AIR_k is assumed to be constant over Ts

- dimension of variable is shown in brackets -

The analysis of the control algorithm can be carried out by two methods. One method is to transform the difference equation to state space using Z-transforms and find the control which will give the desired pole placement (i.e., desired response) in the Z-plane. This method is applicable to systems whose difference equation is easily transformed (i.e., linear difference equations with constant coefficients). Often the control which yields the desired response

can be found empirically. Another method is the simulation of the system response to each proposed control algorithm until the desired response is found. Without prior knowledge or intuition of which control is proper this can be a time consuming process. However, it may be necessary if the difference equation is not easily transformed. It also has the advantage of providing a qualitative view of the response. The analysis of the constant concentration system control utilizes both methods.

The constant concentration system operates in two modes: (1) the startup period and (2) continuous response to changes in air infiltration rate. The startup period is modeled as a step change in the desired concentration from 0 at the initial time to c_t at all following times. The control design during this period is a classic servodesign problem. The goal of the design is for the concentration to rapidly follow the change in the desired concentration with little or no overshoot. The response of the system to the step change in c_t is conveniently analyzed using pole placement (also called state-space method) in the Z-plane.

When there are changes in AIR the goal is to keep the concentration at the target level. This is a classic regulator problem The difference equation is not easily transformed into the Z-domain for the case of time varying values of a and b. However, the response of the system is similar for changes in c_t and AIR. Simulations confirm that the system response to a step change in c_t is similar in form to that of a step change in AIR. Thus, a state-space analysis of the startup period is used as an indicator of the form of the response of both the startup period and for changes in AIR. The simulations of changes in AIR are used to verify the state-space analysis and provide a qualitative analysis of the response.

2.3 Evaluation of the Control Algorithm

To accurately measure the air infiltration flows in a building the constant concentration measurement technique requires the level of tracer gas to remain near the target level in each zone while the air infiltration flow is changing. The criteria to meet this condition are:

1) fast response with little overshoot

2) low steady state error

3) low sensitivity to measurement errors

In the state-space analysis the first two criteria translate to having the transfer function poles located near the origin and the final value of c (found from the final value theorem) close to c_t. The sensitivity to measurement errors criterion is examined using monte carlo type simulations that include gaussian measurement errors.

The analysis has involved four proposed control methods - proportional (P), integral (I), proportional-integral (PI), and proportional-

integral-derivative (PID). The discussion will focus on proportional adaptive and proportional integral methods. The analysis is carried out in the following way:

1) the difference equation is transformed into the Z-domain to find the poles of the transfer function $H(z) = C(z)/C_t(z)$,

2) the root locus of the poles is displayed in the Z-plane,

3) given the Z-transform of the target concentration- $C_t(z) = c_t\ z/(z-1)$, the final value of the concentration is found from the final value theorem,

4) the response to a step change in AIR from 0.2 to 0.5 ACH for selected values of control gains and Ts= 4 minutes is simulated,

5) the response to a step change in AIR from 0.2 to 0.5 ACH and a gaussian measurement error of 1% is simulated for the best control parameters- the average standard deviation of the concentration and the average of the concentration over five, simulations is computed as a measure of the ability of the control to keep the concentration near the target when measurement errors are present,

6) the change in response is studied when the level of AIR is different from the level used to compute the control parameters, and

7) the relative advantages and disadvantages of the method are discussed.

2.3.1 A Proportional Control

Proportional control is the most simple feedback control. For a first order system P control provides a fast response with little or no overshoot. Its one drawback is that there is a steady state error when the control parameters (i.e., control gains and constants) are kept constant. When the control parameters are continuously updated the steady-state error is eliminated and the speed of response is slightly decreased.

The proportional control feeds back the present error signal (the difference of the present concentration from the target concentration (c_t)) multiplied by a gain K_p [1/t]. The expression for the control is:

$$u_k = K_p\ (c_t - c_k) \tag{7}$$

The difference equation for the tracer concentration is:

$$c_{k+1} = a_k \cdot c_k + b_k \cdot K_p\ (c_t - c_k) \tag{8}$$

The analysis of the startup period assumes that a_k and b_k are constant and the response of concentration to a change in c_t is studied. Thus, the transfer function of interest is $H(z) = C(z)/C_t(z)$. By taking the Z-transform of both sides of Eqn.(8)

this is found to be:

$$H(z) = \frac{bKp}{(z - (a - bKp))} \qquad (9)$$

This equation has one pole at (a - bKp), thus to place the pole at zero, Kp = a/b.

During the operation of the system the sample time does not vary. Thus, the transient response of the system will not significantly change for a constant value of K_p and changes in the levels of AIR from 0.1 to 2.0 ACH. However, the percent error of the final concentration reaches an unacceptable level for AIRs higher than 1.0 ACH. The error in c_f is caused by failing to reset the control level to the higher value required by higher AIRs. At higher AIR levels the system increases the proportional control term by settling at a level of concentration below the target.

The error in the final concentration does not have to be as large as the analysis indicates. The target concentration can be reached exactly by replacing the parameter c_t in the control Equation (7) with a larger value, e_o, dependent on the level of AIR and the sample time. This method, called adaptive control, responds properly when the measured AIR is not greatly different than the true AIR. For slowly changing AIRs the measured AIR is within 10% of the true AIR and the concentration error is less than 1%. The concentration error is not as small, however, for sudden changes in AIR. The method of estimating the AIR by dividing the injection rate summed over a period of time by the desired concentration does not respond quickly to sudden changes in AIR. For a step increase in the AIR the estimated value of AIR lags behind the true value; which causes a lag in the concentration reaching the target concentration.

Proportional control is a simple method that provides a quick response with no overshoot to changes in AIR. The one drawback to the method is the presence of steady state error. By replacing c_t with a value dependent on AIR the proportional adaptive method is slightly oscillatory.

2.3.2 Proportional-Integral Control

Proportional-Integral control is a combination of proportional and integral terms. The addition of the integral term to the proportional method eliminates the final concentration error of proportional control and the need for adaptive control. When broken into parts, the proportional term can be thought of as providing the amount of control needed to bring the concentration from the measured to the target level and the integral terms adds an amount needed to counteract the drop in concentration that would result from air infiltration. By properly choosing the control gains the system response to changes in AIRs is a one step delay with no overshoot. Thus, PI control satisfies the two response criteria of a fast response with no overshoot and no steady state error.

The PI method feeds back the error signal multiplied by K_p [1/t] added to the integral of the error signal multiplied by Ki [1/t^2]. As in the analysis of the integral method, the difference equation is found by working back from the Z-transform equivalent of the control method. The Z-transform of PI control method is the sum of the transforms of the proportional and integral terms. Multiplying the PI control method transform by the error signal transform yields the control transform:

$$U(z) = E(z)\,[Kp + Ki\ Ts\ z/(z - 1)] \qquad (10)$$

or $$z\,U(z) - U(z) = E(z)\,[\,Kp(z - 1) + Ki \cdot Ts \cdot z]$$

Which is transformed into the discrete time domain to yield:

$$u_{k+1} = u_k + (K_p + Ki \cdot Ts)(c_t - c_{k+1}) - K_p(c_t - c_k) \qquad (11)$$

or $$u_{k+1} = u_k + Ki \cdot Ts(c_t - c_{k+1}) + K_p(c_k - c_{k+1})$$

Then Eqn. (11) is inserted into Eqn. (6) with the z transform providing the required transfer function:

$$H(z) = \frac{bz(Kp + Ki \cdot Ts) - bKp}{(z - 1)(z - a) + bz(Kp + Ki \cdot Ts) - bKp} \qquad (12)$$

The Equations for the two poles are then:

$$p1,p2 = \frac{a + 1 - b(Kp + Ki \cdot Ts)}{2} \qquad (13)$$

$$+\!- \frac{[(a + 1 - b(Kp + Ki \cdot Ts))^2 - 4(a - bKp)]^{0.5}}{4}$$

By choosing Kp = a/b and Ki = 1/bTs, PI control satisfies the two response criteria of a fast response with little overshoot and no steady state error. The computation of the values of Kp and Ki to meet the two criteria is straightforward. The analysis has shown that the steady state error is zero for all values of Ts, Kp, and Ki and that using the values of Kp and Ki given by Kp = Ki•Ts = 1/Ts provides a fast response with little overshoot.

2.3.3 Comparison of the Control Methods

AP and PI control provide fast system response with little or no overshoot and no steady state error. The difference between the two controls is that the AIR feedback for AP is indirect while PI has direct feedback. AP control adjusts the level of control for varying AIRs by changing the magnitude of the control parameter c_o. The lag in the estimation of AIR introduces a time lag in the

system. This causes concentrations to be below the target for increasing AIRs and above the target for decreasing AIRs. For PI control the integral term directly compensates for the level of AIR. This method has the drawback of being sensitive to measurement errors. The sensitivity of the control and the restriction on negative injection rates cause concentrations to be above the target.

2.4. System Model for Estimation

In order to evaluate the response of the system to different control methods the derivation of the tracer concentration model included only the injection rate as an input to the system. A complete model of the system includes the effect of uncontrolled inputs - these inputs are called system disturbances. An example of a system disturbance is the flow of air from an adjoining zone that has a concentration different than the target. The equation which models the tracer concentration in the presence of disturbances is:

$$c_{k+1} = a_k c_k + b_k u_k + w_k \tag{14}$$

where w_k is the disturbance into the system

A final addition to the system model is the equation describing concentration measurement:

$$cm_{k+1} = c_{k+1} + n_{k+1} \tag{15}$$

where cm_{k+1} is the measured concentration

n_{k+1} is the measurement error.

As stated earlier, the measurement error is due to detector measurement errors and the nonuniformity of the concentration caused by imperfect mixing.

A Kalman filter is a method of estimating the concentration so that the variance in the estimated concentration (c) from the true concentration is minimized. This is accomplished by properly computing the estimation gain (Ke_k) used to combine the measured (c_m) and extrapolated (*) concentration to form an estimation of the true concentration:

$$c_{k+1} = c^*_{k+1} + Ke_{k+1} (c_{mk+1} - c^*_{k+1}) \tag{16}$$

Ke^k is computed by considering the covariance of the past estimate of the concentration (P^k), the covariance of the disturbance into the system (Q^k), and the covariance of the measurement error (R^k). The Kalman filter equations provide for a concentration extrapolation:

$$c^*_{k+1} = a'_k c_k + b'_k u_k \tag{17}$$

The calculation of the Kalman filter gain has assumed that the disturbance and measurement errors are known and/or measurable. Unfortunately, for most structures these values are difficult to obtain. Measurement errors depend on the error in the detector and the uniformity of the concentration in the zone. The precision of the detector can be quantified and is approximately less than or equal to 1% of the measured value for the system in use. However, the uniformity of the concentration in the zone will be dependent on the strength and direction of air flow in the zone (intra-zone flow) and the rate of infiltration flow (i.e., larger AIRs will cause greater dilution near the exterior envelope). Since the natural intra-zone flow can show large fluctuations and is usually too low to provide adequate mixing small fans are placed in the room to accelerate the diffusion of the injected tracer gas and increase mixing[2,4,5].

The second value required for the computation of Ke is the covariance of the disturbance. The disturbance input to a zone is a result of the flow of air from an adjoining zone that has a concentration different than the target. Since it is not possible to measure the flow rate and concentration of each air stream entering and leaving a zone, it is not possible to directly measure the covariance of the disturbance input.

2.5 Air Infiltration Rate Estimation

The estimated specific air infiltration rate is used for three purposes: 1) the reported value of the outdoor air flow rate into the zone is equal to the AIR multiplied by the zone volume, 2) the AIR is used in the process of estimating the concentration, and 3) the AIR is used by the proportional adapative control method to compute c_o. Thus, any error in the estimated AIR not only causes incorrect values of the reported infiltration flow rate but also affects the control of the system. Three methods of AIR estimation are discussed in this section. The averaging method computes an estimate of the average infiltration flow rate by dividing the tracer injection rate averaged over a period of time by the target concentration. The assumption is made in the derivation of the averaging method that this concentration is held constant at the target level. Although the averaging method provides a fairly accurate estimation of the AIR[19] in general, neglecting the information of the movement of the concentration decreases the accuracy of the AIR estimation. The two alternatives to the averaging method, modified averaging and weighted least squares (WLS), do not neglect the movement of the concentration. Modified averaging includes the change in the concentration from the beginning to the end of the averaging time and divides by the average concentration instead of the target concentration. The WLS method computes the AIR which best fits the time history data of the control and concentration values. In addition to incorporating the concentration data, the WLS technique weights the most recent data more heavily than past data. As a result, the WLS method provides an estimate of time varying AIRs that is more accurate than the AIR estimated by the averaging method. Figures 2 and 3 illustrate the ability of methods described to follow a step change in AIR.

Figure 2

Simulation of AIR Estimation

for Averaging and Modified Averaging

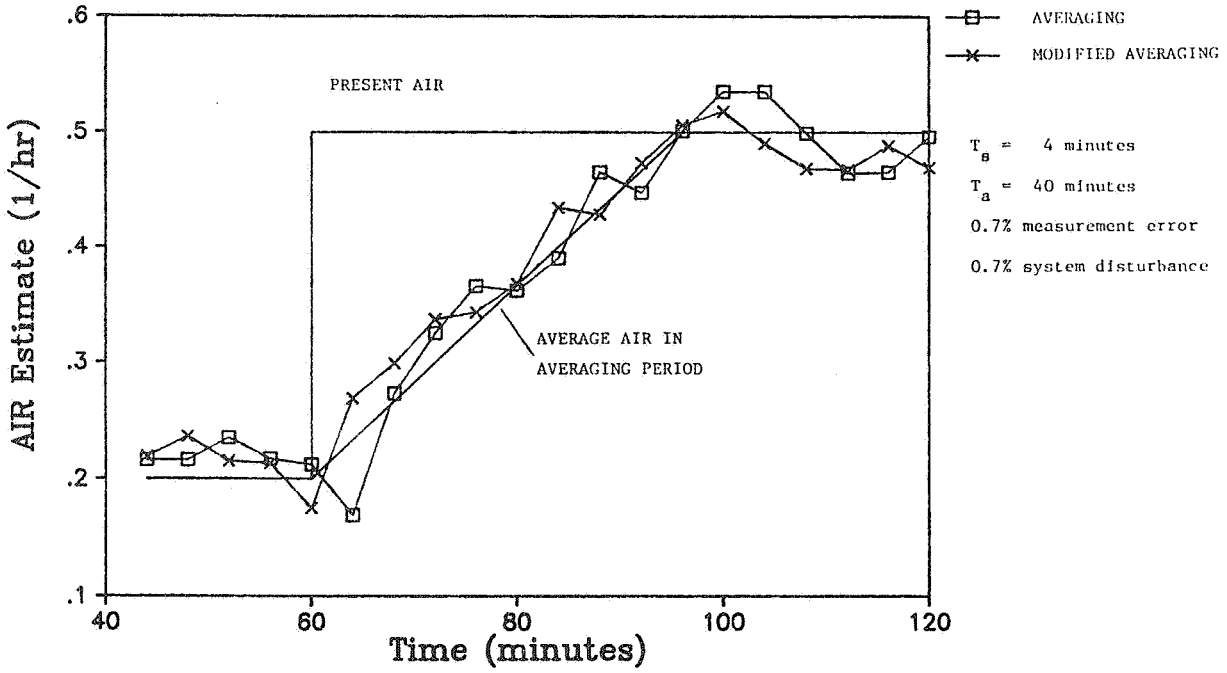
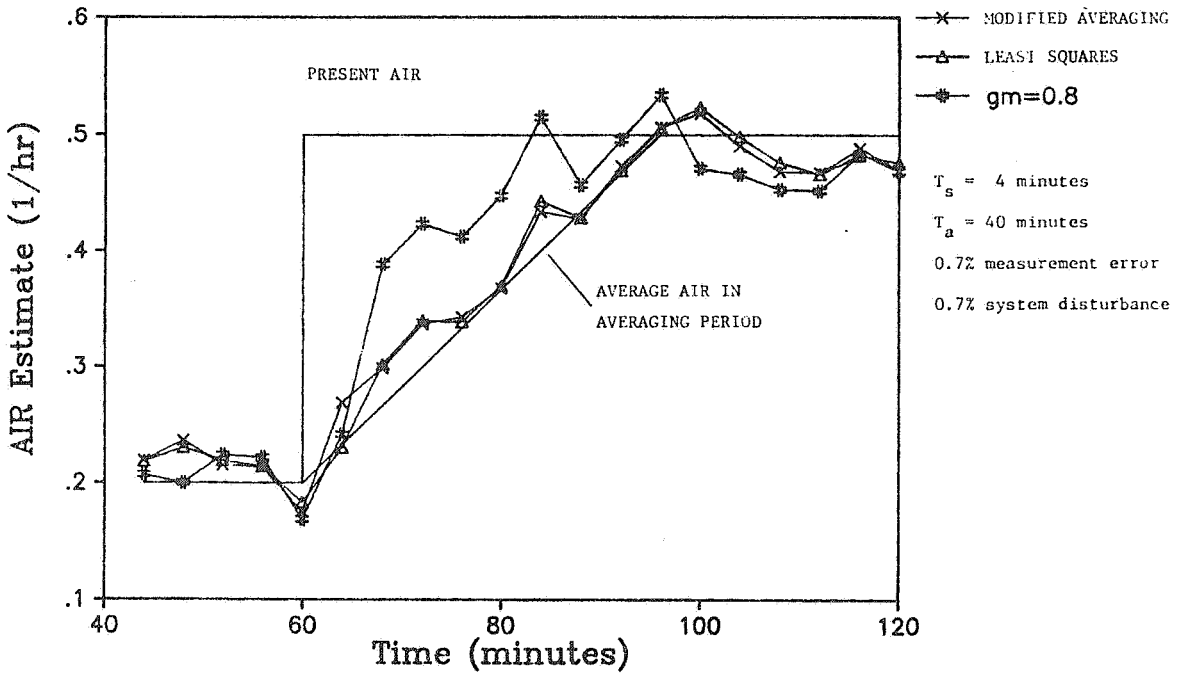


Figure 3

Simulation of AIR Estimation

for Averaging and Least Squares Methods



The analysis of the error of the estimated average AIR leads to the following general conclusions:

1) The modified averaging method is significantly more accurate than the averaging method.

2) Except at high levels of measurement error the accuracy of the modified averaging and least squares methods are nearly equivalent.

3) For disturbances less than 1.5% and measurement errors less than 3% the least squares and modified averaging methods estimate the average AIR within approximately 5% of the average AIR.

3.0 SF6 DETECTOR OPERATION AND MODIFICATIONS

3.1 Detector Operation

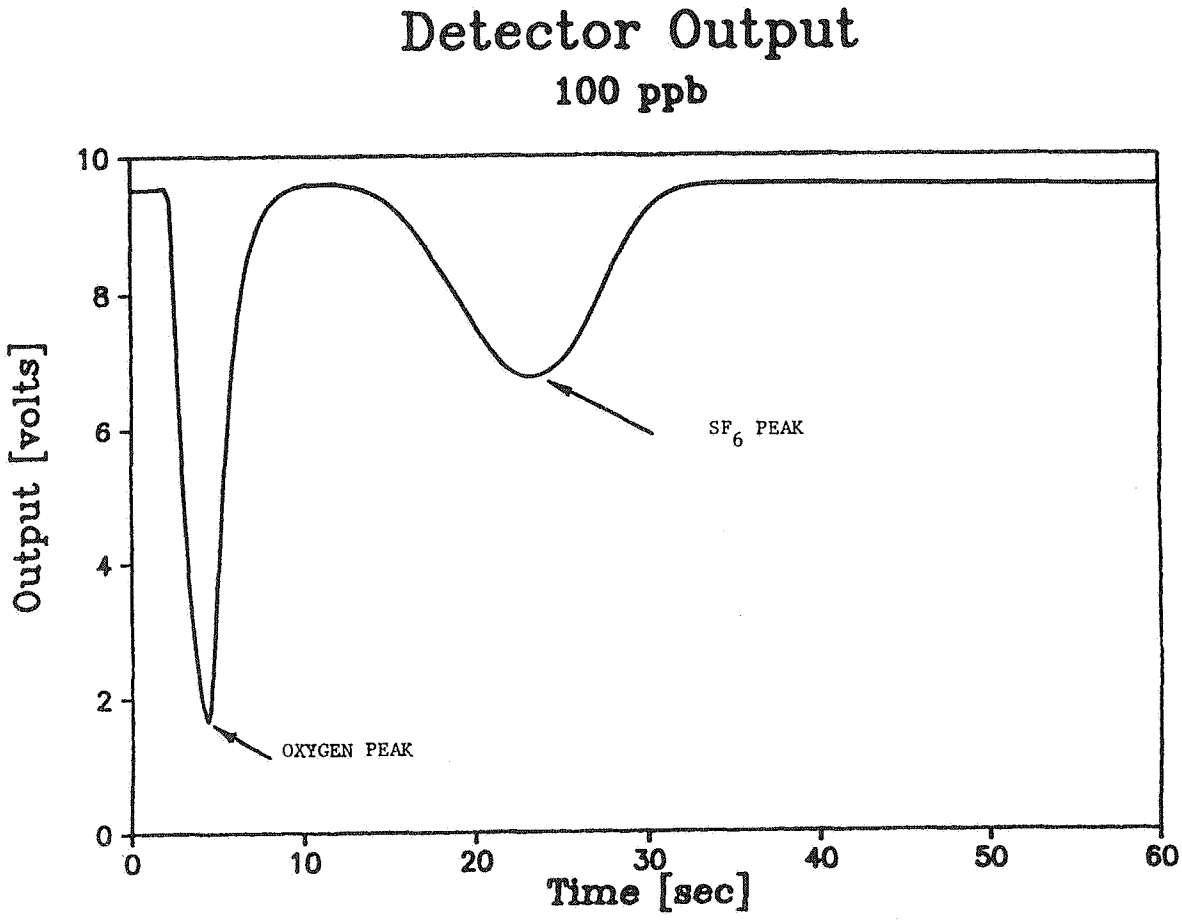
Before discussing the details of the improvements to the operation of a typical SF6 detector, we should review the existing equipment. Princeton's constant concentration system measures the SF6 concentration in the individual zones with an ITI model 505 SF6 electron capture gas chromatograph. The primary components in the chromatograph are an electron capture detector cell fitted with an Ni63 beta source, a 380mm long 100-120 mesh aluminum oxide packed column, three 3-way sample valves, and the electronic circuitry needed to convert the detector output into a voltage signal. The detector is able to precisely measure SF6 concentrations from 10 to 500 parts per billion with a 60 second cycle time between samples.

In the detector a source of electrons is provided by the stream of beta particles emitted from the Ni63. The strength of the electron flow is measured by the detector - this level is generally called the "standing current". As oxygen and SF6 flow through the detector they capture electrons in proportion to their concentration and decrease the output of the detector. Since these gases are separated in time by the packed column the magnitude of the decrease of the detector output can be measured for each gas. Figure 4 displays the typical conditioned output of the detector analyzing air with a concentration of 100 ppb SF6 that has been injected into the column. The oxygen peak occurs first at approximately five seconds and the SF6 peak occurs at about 23 seconds when argon pressures are maintained at three atmospheres. The concentration of SF6 is a function of the ratio of the standing current to the peak current.

The operation of the detector can be split into two phases: sample injection and sample detection. During the injection phase all 3-way sample valves are activated which causes the carrier gas to flow in the "ON" direction as shown in the flow diagram in Figure 5a. This allows the carrier gas to flush the sampled air in the sample loop into the column. After allowing two seconds for complete flushing, all the 3-way valves are deactivated and the detection phase begins. During this phase, air from the zone being sampled is pumped through the sample loop and out the exhaust port. The carrier gas (argon) now flows directly to the column where it continues to force the gas from the sample loop through the column.

The argon and sample gas then flow through the electron capture detector and are exhausted outside the detector enclosure.

Figure 4



3.2 Detector modifications

This commercial detector has been primarily designed for use in finding leaks in underground pipes. In this application the ease of use is emphasized rather than the accuracy of the instrument. Over the past year many modifications have been made to the plumbing and electrical system which limit the use of the detector to the sample mode but improve its reliability and accuracy.

Figures 5a, 6a, and 7a show the plumbing, wiring, and detector supply and amplifier diagrams of the original detector. Figures 5b, 6b, and 7b show the same diagrams for the modified detector. The following is a summary of the modifications and the reasons for the changes.

3.2.1 Plumbing System

Changes:

1) Eliminate by-pass valve, continuous/sample mode valve, and capillary restriction.

2) Bypass column and detector flushing outlets.

3) Replace rotary injection valve with three 3-way solenoid valves.
4) The detector output is exhausted directly to outside of the enclosure.

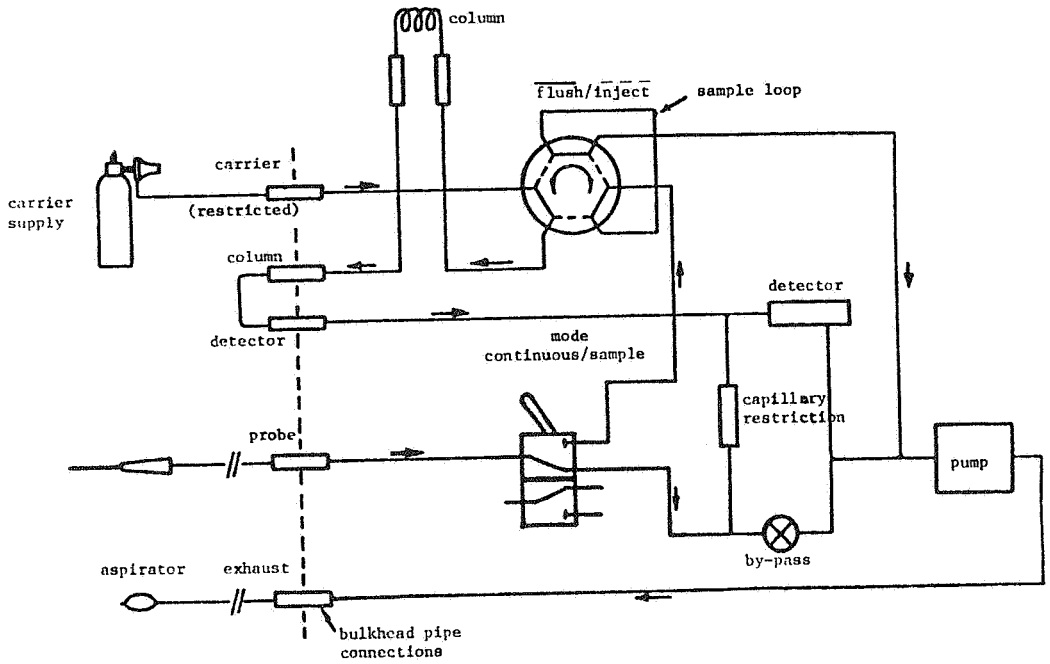


Figure 5a. Original pipework diagram.

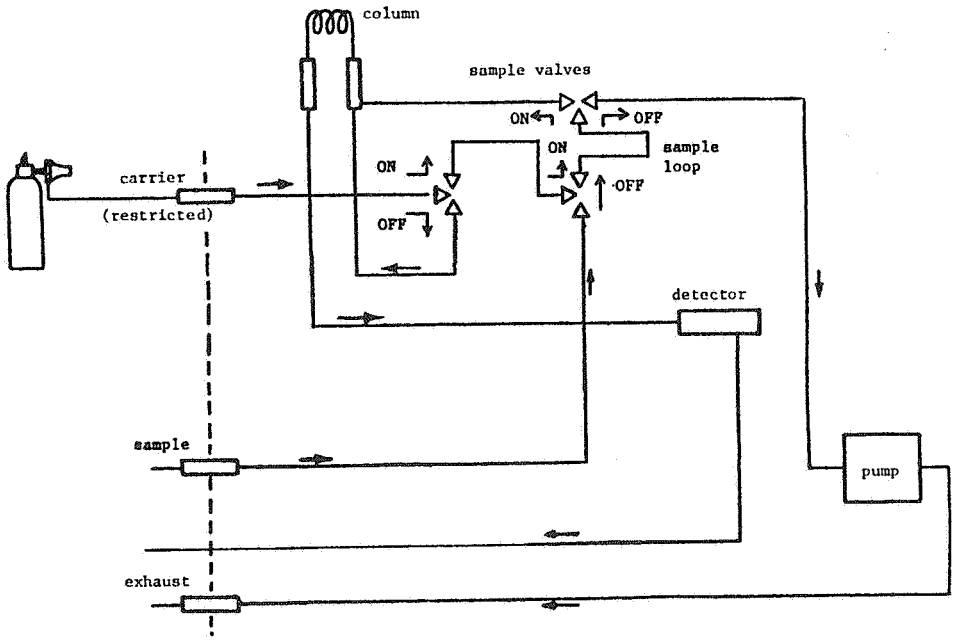


Figure 5b. Revised pipework diagram.

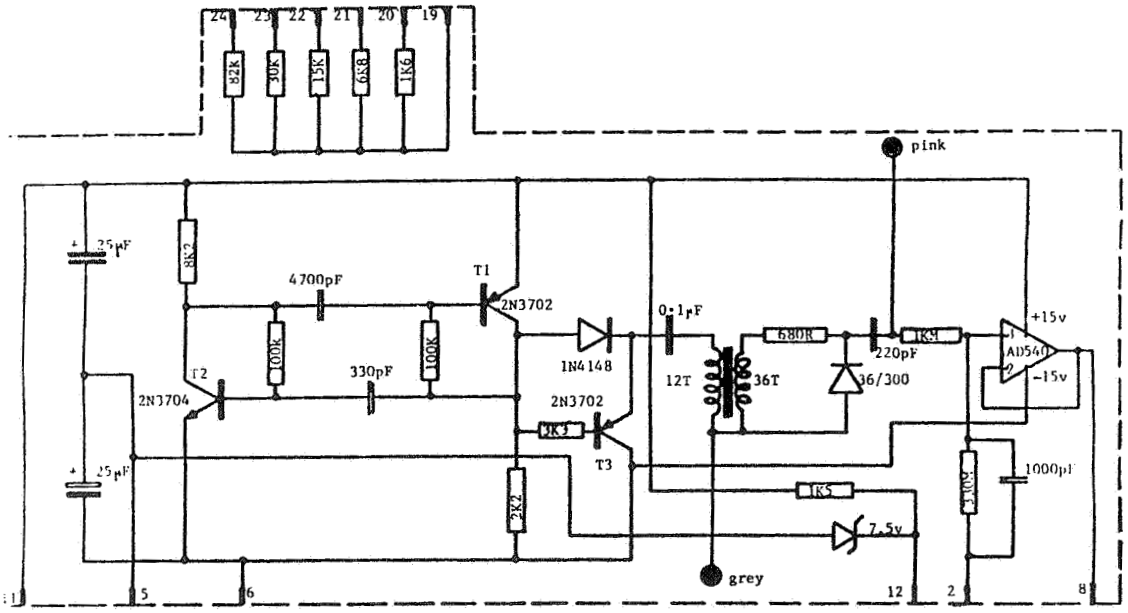


Figure 6a. Original detector supply and amplifier.

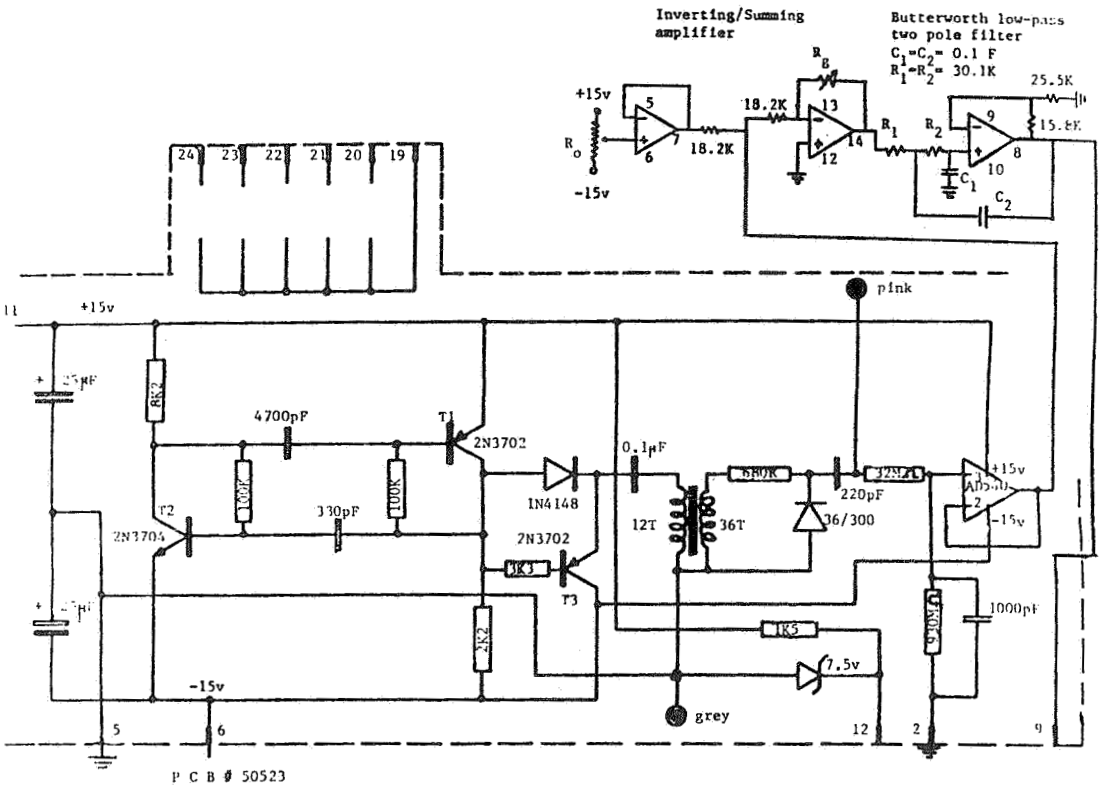


Figure 6b. Revised detector supply and amplifier.

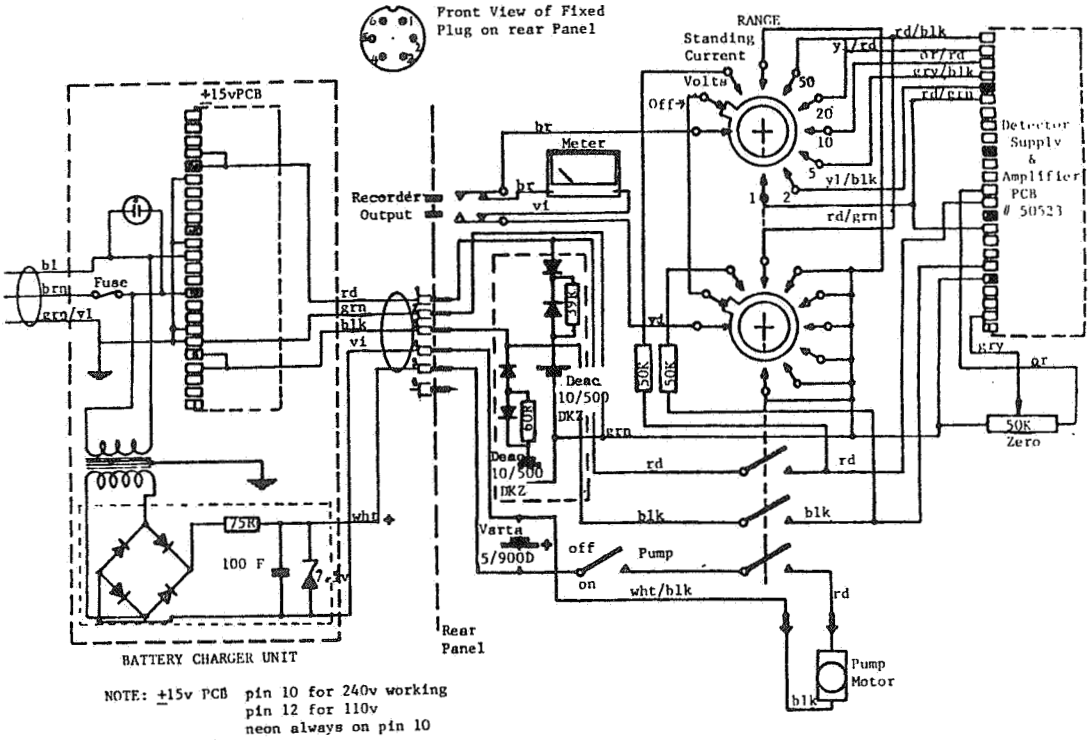


Figure 7a. Original wiring diagram.

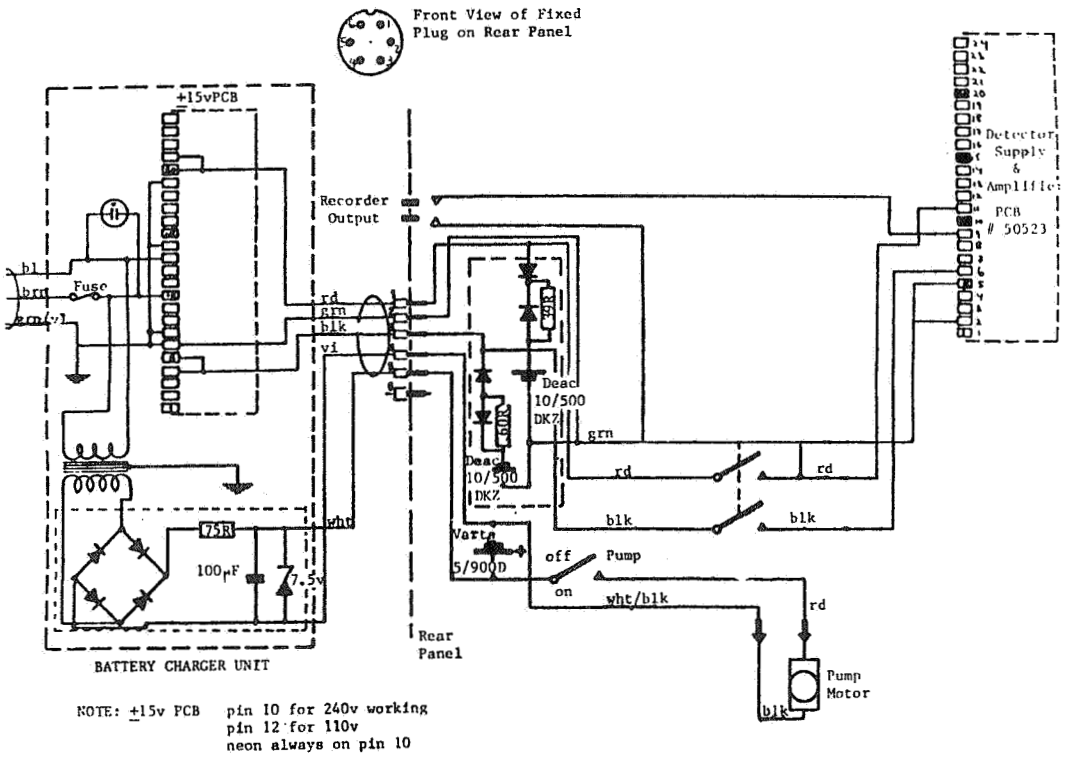


Figure 7b. Revised wiring diagram.

Reasons for changes:

1) The continuous/sample mode valve and by-pass valve are prone to leaks that are difficult to eliminate. Elimination of the capillary restriction reduces the level of the carrier gas flow needed to provide the proper standing current.

2) Bypassing the column and detector flushing outlets further eliminates connections that may be sources of leaks. It also leads to a more compact system.

3) The three 3-way solenoid valves are less prone to leaks than the rotary valve. The solenoid valves also eliminate the need for a high pressure gas source (usually) argon to actuate the rotary valve. This reduces the amount of argon used by the detector and allows the operator the option of using a lower argon pressure to the column.

4) The separation of the detector output from the pump input has two effects:

   a) The pressure in the lines through the column and detector are above instead of below atmospheric pressure. This eliminates the possibility of contamination of the sample by leaks through the plumbing.

   b) The pressure across the pump no longer affects the flow through the detector. Since the pump pressure will vary depending on the restriction in the sample line, the power provided to it, and the condition of the pump, the flow through the detector is more stable. This also allows the user to employ a variety of different flow rates through the sample loop without affecting the calibration of the detector. Thus, low flow rates can be used during calibration to decrease the amount of calibration gas, and high flow rates can be used during operation to decrease the transportation time from the zone to the detector.

3.2.2 Electrical System

Changes:

1) Voltage output signal

   a) Invert and provide adjustable offset and amplification of signal.

   b) Filter signal through a low-pass filter, frequency = 53Hz.

   c) Run signal from the detector supply and amplifier card to the output jack through a coaxial cable.

2) Replace rotary switch with a single pole double throw switch for the +15 and -15 volt lines.

3) Interrupt pump power with pump switch only.

4) Disconnect meter.

5) Disconnect "zero" potentiometer.

6) Remove wires and resistors for range output.

Reasons for Changes:

1) The output from the detector is a negative voltage with the standing voltage being from 1.5 to 3.2 volts. The voltage can be read as a positive voltage with the rotary switch in the standing current position. However, if the battery charger is connected and the device used to read the voltage is connected to the outlet ground the signal output is shorted out. Typically both these situations occur. In the particular example of the present system (a Techmar Lab Master system), the analog to digital converter is connected to ground and requires a 0 to +10 volt input. In order to achieve high resolution and convert the signal to a positive voltage, the signal from the detector supply and amplification card is passed through a op-amp inverting amplifier with offset.

2) Because of the changes in the plumbing system (conversion to dedicated sample mode system) it is no longer necessary to be able to adjust the level of the output voltage as needed in the continuous mode. Thus, the "zero" potentiometer, rotary switch, and range resistors have been eliminated. The output voltage is run directly from the card to the output jack and the voltage supplies are interrupted by a single throw switch. This has several advantages:

   a) Better noise protection through the coaxial cable.

   b) A very low output impedance (the original system had an impedance as high as 82K ohms).

   c) The level of the output voltage (which affects the detector's calibration) can not be accidentally changed by twisting the "zero" potentiometer. It can be adjusted internally to keep a high resolution of the SF6 peak.

   d) It provides easier switching, fewer connections, and less cluttered wiring.

3) The first half of the detector supply and amplifier circuit supplies a high voltage, high frequency (15 kHz) pulse to the detector. Although the pulses do not affect the detector's meter or a high inertia recorder, these pulses are passed through to the output signal (the input pulses and output signal are carried on the same line) and can be recorded by analog to digital converters. The addition of the op-amp filter with a cutoff frequency of 53 Hz. greatly reduces the magnitude of the pulses and does not distort the shape of the peaks.

4) The meter is not required for normal operation and the high output voltage could damage it.

5) The single pump power switch allows individual control of the pump.

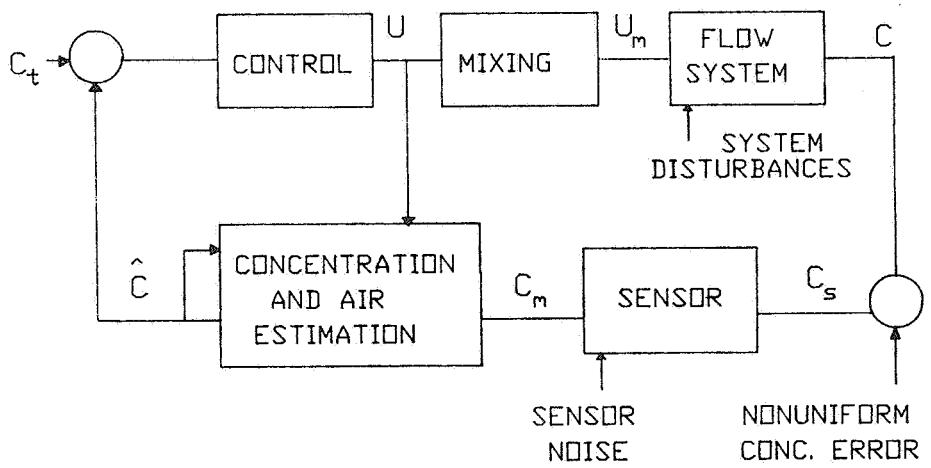
4.0 SYSTEM

The total system using the constant concentration principle was shown schematically in Figure 1. The block diagram indicates how the data acquistion system is integrated with the A/D, valve control electronics, injection system, sample system and SF6 detector. The tracer gas is actually SF6 diluted to a 0.1% concentration so that metering of the SF6 can be accurately performed. Flow rates through the injection lines to the individual zones are all carefully calibrated [16] to insure the valve open times can be related directly to the flow of SF6 to each zone.

Figure 8 is another block diagram, this time of the control and air infiltration rate estimation system. Seeking the target concentration c^t, the individual control system elements take care of system disturbances, sensor noise and nonuniform concentration errors.

Figure 8

BLOCK DIAGRAM OF SYSTEM CONTROL AND ESTIMATION



U - computed control value

U_m - control applied to system

C - average zone concentration

C_s - sampled concentration

C_m - measured concentration

$\hat{C}$ - estimated concentration

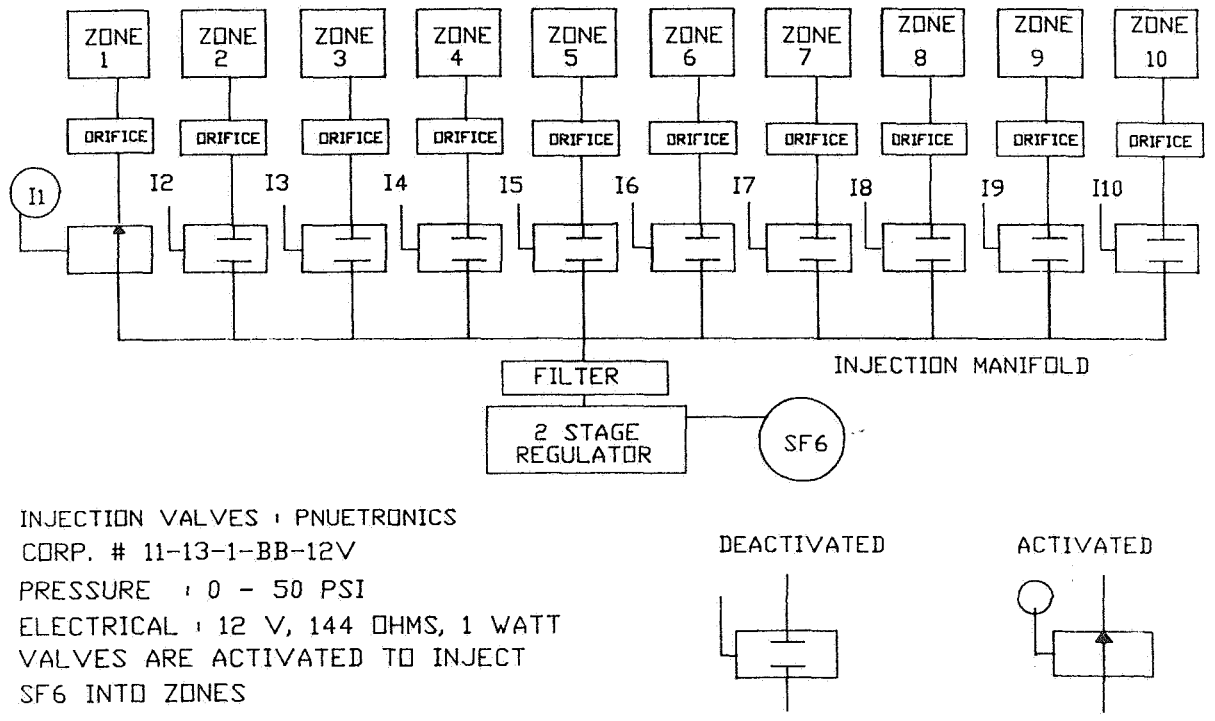
C_t - target concentration

AIR_e - estimated air

The sampling system pumping diagram and injection system diagrams have a number of similar characteristics. Valving is achieved with 10 subminiature DC valves (1 watt) protected by upstream filtering. In the injection system, Figure 9, flow rates are controlled with two stages of regulation on the dilute SF6. Each zone has a selected micro orifice to match zone volume tracer gas needs. The sampling schematic is shown in Figure 10 with details on the circuitry explained. When this system is deployed in larger zones sampling locations in the zone are multiplied by branching the sampling part to several locations[17].

Figure 9

INJECTION SYSTEM PLUMBING DIAGRAMS



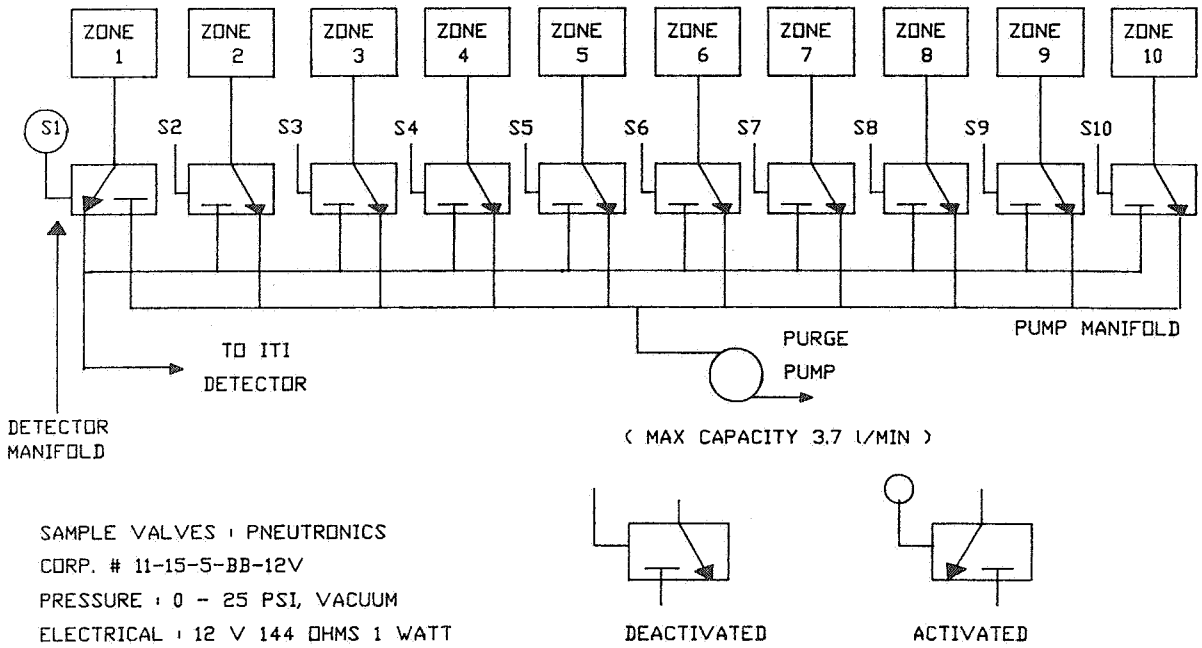
INJECTION VALVES : PNUETRONICS
CORP. # 11-13-1-BB-12V
PRESSURE : 0 - 50 PSI
ELECTRICAL : 12 V, 144 OHMS, 1 WATT
VALVES ARE ACTIVATED TO INJECT
SF6 INTO ZONES

5.0 CONCLUSIONS

The rationale for the design of the control system to achieve suitably rapid control response, while maintaining accurate values of the tracer gas concentration, in the constant concentration tracer gas measurement system was described. More than one choice of control and concentration averaging is acceptable and modified averaging or least squares methods can be used with the adaptive proportional and proportional integral control methods to achieve the system goals. The need is justified and the actions required for numerous modifications to the commerical SF6 detection system to raise the accuracy of SF6 concentration evaluation of the equipment. The total CCTG system incorporates a recommended control approach, the upgraded SF6 detection unit, individually calibrated micro orifices and subminiature DC valves to meter out the desired quantities of SF6. Finally, the sampling system, using similar valving arrangements, provides the individual zone samples

Figure 10

SAMPLE SYSTEM PUMPING DIAGRAM



to the SF6 detection system and associated data acquisition system operated by a microcomputer. The total system is operating very effectively in both field and laboratory tests, maintaining hourly SF6 concentrations at ± 0.6% with data scatter well within design limits.[17]

6.0 ACKNOWLEDGMENTS

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 26

VENTILATION SYSTEM PERFORMANCE EVALUATION USING TRACER GAS TECHNIQUES

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SYNOPSIS

Based on current concerns regarding indoor air quality and energy use, there is a need for in situ techniques for evaluating buildings' infiltration and ventilation characteristics. The U.S. National Bureau of Standards has developed and employed equipment and techniques for such evaluation. The measurement of whole building leakage and ventilation rates has been reported on previously.

Additional procedures are presented here for a more complete evaluation of the ventilation system operation and the distribution of air within the building. The measurements reveal both the amount of outside air infiltrating through the envelope and the amount of intentional intake through the air handlers. Tracer gas techniques to study the uniformity of air distribution throughout a building are also discussed.

These in situ evaluation techniques are described and results from their application are presented. The measurements reveal that, in some cases, a significant amount of a building's net ventilation rate is due to envelope leakage as opposed to intentional outside air intake through the air handling system. Also, air distribution inadequacies are often encountered in buildings, leading to effective ventilation rates of occupied zones which are less than intended or advised.

1. INTRODUCTION

The infiltration and ventilation characteristics of mechanically ventilated buildings are areas of increasing importance. The performance of the ventilation system and the air leakage characteristics of the building envelope impact upon energy use, thermal comfort, and indoor contaminant levels. The use of new ventilation system and envelope designs, and attempts to decrease energy use, have additional effects on ventilation. This situation leads to a need for in situ measurement techniques to evaluate the infiltration and ventilation performance of buildings. The factors which require evaluation include envelope airtightness, mechanical ventilation rates, and interior air distribution or ventilation effectiveness. Basically, one needs to evaluate the design and performance of the building envelope and mechanical ventilation system as they relate to the goals of providing a safe and comfortable environment for the building occupants without an excessive expenditure of energy.

A variety of tracer gas measurement techniques already exist to characterize building infiltration and ventilation, and new techniques are being developed.[1] Single tracer gas decay techniques have been developed and employed for determining whole building infiltration and ventilation rates, and these have been reported on previously.[2-4] These techniques are used to study the weather dependence of infiltration and ventilation rates, but do not distinguish between envelope leakage and intentional outside air intake. More recently, techniques have been developed to study the performance of ventilation systems including the

separation of envelope leakage rates from intentional outside air intake rates, and the determination of the rates of recirculation of return air and total airflow through the ventilation system. In addition, techniques to quantify interior air distribution performance or ventilation effectiveness are also being developed. This paper discusses these tracer gas techniques for the characterization of ventilation and infiltration in mechanically ventilated office buildings. Past work involving single tracer gas decay is briefly summarized. Single tracer measurement techniques, developed more recently, to determine ventilation system performance and ventilation effectiveness are also presented along with some preliminary results of their application. In general, the material in this paper concerns modern mechanically ventilated office buildings, but much of the discussion is relevant to other building types.

2. WHOLE BUILDING DECAY MEASUREMENTS

Various tracer gas decay techniques have been applied to mechanically ventilated office buildings to measure infiltration and ventilation rates. NBS has employed an automated system to collect a large amount of data in about one dozen office buildings.[2-5] The measurement technique and results have been reported on previously, and are described briefly below.

2.1 Measurement Technique

The measurement system employs the tracer gas decay technique, using sulfur hexafluoride (SF_6) as the tracer and measuring its concentration with an electron capture detector gas chromatograph. The system is completely automated with a microcomputer controlling tracer injection, air sampling, and concentration measurement, performing data analysis, and recording the infiltration rates and weather conditions. The system operates totally unattended for periods of several weeks and yields continuous measurements of hourly, average air exchange rates. It is typically deployed in a building for several weeks during each season of the year in order to obtain measurements under a wide range of weather conditions.

In the tracer gas decay method it is important to begin the concentration decay with a uniform tracer gas concentration throughout the building. This can be ensured by using injection strategies appropriate to the building and verified by sampling at several locations in the building. Most large buildings have several main air handlers which serve the bulk of the building, and the tracer must be injected into the supply duct of each one to get the tracer throughout most of the building volume. Buildings often also have smaller air handlers for spaces such as lobbies, and tracer must also be released into the supply ducts of these systems. Such a multi-point injection strategy distributes the tracer throughout the building. After the tracer gas injection, one must wait for the tracer to mix with the interior air until a uniform concentration is obtained. The operation of the air handlers assists in mixing the tracer, but it can still

take from twenty minutes to one hour to obtain a sufficiently uniform tracer gas concentration. It is necessary, however, to verify that the concentration is indeed uniform. This is done by sampling the tracer concentration at several locations within the building. In actual installations, these sampling locations have generally included return air shaft openings on each floor of the building, main return ducts of large air handlers, and return ducts of any smaller air handlers. The specific locations for tracer injection and air sampling depend on the building layout and air handling system design.

The past studies of office buildings have included measurements of both ventilation and infiltration. Ventilation rates refer to measurements made with the building HVAC system operating normally under occupied conditions. In this case the spill and intake dampers open and close as the control system dictates, in response to inside and outside temperature and humidity, and time of day. Infiltration refers to uncontrolled air leakage through the building envelope. These measurements are made with the spill and intake dampers closed (including minimum outside air dampers), all local exhausts off, and the air handlers running. These test results provide an indication of the airtightness of the building envelope. The operation of the fans during these measurements is necessary for mixing and may affect the test results through local pressurization and depressurization within the building, or through leakage across the intake and exhaust dampers. In several cases these dampers have been sealed with polyethylene, and the infiltration rates were no different than those measured without the dampers sealed.

2.2 Measurement Results

The results of the past measurements have provided a great deal of information with regard to infiltration and ventilation characteristics of office buildings. The infiltration measurements have shown a range in the air exchange rates of buildings, and varying degrees of weather dependence of the infiltration rates for the various buildings studied. In several recently constructed office buildings, the measured infiltration rates ranged from about 0.1 to 0.7 exchanges per hour, except under extremely windy conditions. These infiltration rates, which consume energy even when the building is unoccupied, account for 20 to 60% of the buildings' design heating load.[5] Some of the buildings' infiltration rates show significant dependence on inside-outside temperature difference and wind speed, while others were insensitive to weather conditions. No correlations between building characteristics, such as height, and the extent of weather dependence were observed.

The ventilation measurements have also revealed important findings. The measured ventilation rates were found to vary with weather conditions due primarily to the effect of the control systems and, to a lesser degree, due to uncontrolled infiltration. Typically the buildings have low ventilation rates under heating and cooling conditions when the control system brings in a minimum amount of outside air in order to control the space conditioning

load. These minimum rates range from about 0.2 to 0.6 exchanges per hour, except under extreme weather conditions. During mild weather, outside air is used to cool the buildings and large ventilation rates are induced. This pattern of low ventilation rates under heating and cooling conditions and higher rates during mild weather was exhibited in almost all of the buildings studied by NBS.[4]

The ability to determine actual building ventilation rates and compare them to design values and recommended outside air intake levels is an important feature of whole building ventilation measurements. If the measured ventilation rates are extremely low, the air quality within the building may be compromised, but if they are too high an excessive amount of energy will be used. The measured minimum ventilation rates in several office buildings were compared to the recommendations of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62-1981[6] for office spaces with smoking present. Roughly one-third of the buildings were found to be ventilated at rates significantly above the standard, one-third were close to the standard, and one-third were ventilated at rates lower than the standard recommends. In two of the buildings, the measured rates were less than 50% of the ASHRAE recommendations.[4] The existence of such low ventilation rates has important implications for building operation, and points out the value of and need for in situ measurement of ventilation rates.

The ventilation data also revealed the importance of uncontrolled air leakage through the building envelope as a component of the net ventilation rate. Under conditions of minimum intentional outside air intake, the measured net ventilation rate of several buildings was found to increase with temperature difference. This occurs because temperature dependent infiltration increases and becomes comparable in magnitude to the intentional ventilation rate. Also, high net ventilation rates due to the influence of wind-induced infiltration were also observed. Several buildings exhibited this property of weather induced infiltration being a significant, or even predominant, portion of the net ventilation rate. Thus, the measurements revealed that modern office building envelopes are not necessarily airtight, and under extreme weather conditions there is little control of the net ventilation rate. Such uncontrolled leakage occurs continuously, and can account for a significant waste of energy and adversely affect thermal comfort.

In the ventilation measurements discussed above, there were also indications of nonuniform air distribution within the buildings. One example in a 26-story office building in Newark, New Jersey has been described previously.[3] In this building the SF_6 concentration was sampled on several floors of the building, and the results were quite similar on all floors except for two. On these two floors the initial SF_6 concentration was significantly less than in the rest of the building, as was the decay rate. This indicates that the supply airflow rate for these floors was proportionally less than for the rest of the building, and therefore these floors have lower ventilation rates. Other

examples of such large scale variations in internal air distribution and local ventilation rates have been observed, and similar problems are suspected to exist within individual rooms. When specific areas suffer from poor air distribution, they may have indoor air quality problems even if the whole building or room is adequately ventilated. Tracer gas measurement techniques to quantify air distribution are discussed below.

3. VENTILATION EFFECTIVENESS

The NBS ventilation measurements, and other experience, has pointed out the potential for inadequate air distribution within mechanically ventilated buildings. In order to quantify building or room air distribution, the concept of ventilation effectiveness has been developed. Several definitions and associated measurement procedures exist and have been applied in experimental studies.[7-10] In this section existing definitions of ventilation effectiveness are discussed, along with practical considerations affecting their use in mechanically ventilated office buildings. A more detailed discussion of ventilation effectiveness definitions and their application to mechanically ventilated buildings is presented in reference 11.

3.1 Definitions of Ventilation Effectiveness

Several definitions and theoretical frameworks have been used to discuss ventilation effectiveness. One group of ventilation effectiveness definitions, referred to here as "concentration efficiencies," are based on relations between pollutant or tracer gas concentrations in the supply air, the exhaust air, and at locations within the ventilated space.[7-9] A steady-state concentration efficiency has been defined, which is measured with a tracer gas by injecting the gas at a constant, known rate into the zone being studied and waiting until the concentrations reach equilibrium. The injection strategy, including the location of the source and whether it is diffuse or a point, depends on the nature of the pollutant one wishes to simulate. There are also transient ventilation efficiencies, which are measured by starting with the tracer gas distributed within the space and no tracer gas sources. Various transient efficiencies are defined based on the ratio of the exhaust concentration to the concentration at some location within the occupied space. These definitions include the ratio of the instantaneous exhaust concentration to the instantaneous concentration in the space, and the ratio of the integrals of these concentrations over time.

Age distributions and residence times, concepts employed in chemical reactor engineering, have also been applied to the study of ventilation effectiveness.[8,10] Ventilation effectiveness definitions based on age distributions involve average ages of interior air and residence times of contaminants. To determine ventilation effectiveness, these ages are compared to their values under conditions of perfect mixing within the ventilated space or pure piston flow through the space. Various tracer gas measurement strategies are used to determine these age distribution efficiencies. These involve tracer gas injection at

a constant rate into the room or supply airstream, and pulses into these same locations. The time responses of the exhaust and/or room concentrations are then used to determine the age or residence time of interest.[8,10-11]

Both concentration and age distribution efficiencies have been applied in experimental work in laboratory test facilities.[7-9] These rooms have reconfigurable supply and exhaust opening positions, and controllable supply air temperature, ventilation rates, and internal thermal loads. The rooms are essentially airtight with airflow in and out of the space occuring only through the ventilation system. In these tests, various measures of ventilation effectiveness have been determined under a range of conditions. These experiments have been extremely useful in studying the occurrence of short-circuiting between the supply and return air vents, stratification of room air, and the performance of alternative ventilation strategies.

Ventilation Effectiveness Measurement in Buildings

While the experimental study of ventilation effectiveness in test rooms has been useful, it is also important to measure ventilation effectiveness in actual buildings. The application of the tracer gas measurement procedures discussed above is difficult in real buildings for various reasons discussed in this section. One problem is the difficulty in defining and measuring the exhaust concentration. Most modern office buildings, especially in the U.S., employ ceiling return plenums. The exhaust air vents are simply openings in the dropped ceiling through which room air flows into the plenum space, mixes with return air from other locations on the same floor, and flows to an opening in the return air shaft. There are generally only one or two return air shaft openings per floor, and therefore a well-defined exhaust concentration measurement point exists only for whole floors or large portions of floors. To measure the exhaust concentration for a smaller area, even a single room, one must sample the air at several return air openings into the ceiling plenum. This procedure can be impractical in many cases due to the large number of measurement points and limitations of the measuring equipment.

Depending on the particular measure of ventilation effectiveness being employed, and the size and arrangement of the space being studied, the required tracer gas injection may be difficult to achieve. The application of certain measures of ventilation effectiveness in a large area of a building requires a diffuse tracer gas injection in the lower, occupied zone of the ventilated space. The diffuse injection of tracer throughout a large area at a rate that is uniform in units of tracer gas flow rate per floor area may be difficult.

Another problem in measuring ventilation effectiveness in buildings is associated with the difference between an airtight test room and a ventilated space in an actual building. In the laboratory test facilties discussed above, air enters only through supply vents and leaves only through the exhausts, leading to well-defined supply and exhaust airstreams and concentrations. In

this situation all quantities of interest (airflow rates, mixing factors, residence times, and ventilation efficiencies) can be determined with a single tracer gas in a straightforward manner. In real buildings, the space under study is subject to additional airflows to and from adjacent interior spaces and in and out through exterior walls. The supply and exhaust concentrations are no longer well characterized, and the existence of the additional airflows greatly complicates the situation. Even if one determines a value of the ventilation effectiveness, the results are no longer related to the quantities of interest.

Finally, almost all procedures for measuring ventilation effectiveness assume there is no recirculation of the return air. However, ventilation systems operate with 100% outside air intake only during limited periods of time. To study the ventilation system performance of actual buildings under realistic operation, modifications to existing ventilation effectiveness measurement procedures must be made to deal with recirculation. In addition, to characterize the ventilation effectiveness for large zones within a building or for whole buildings, one must deal with the fact that these spaces are often served by more than one air handler. These air handlers may be moving different amounts of total air and outside air. All of the above factors make the measurement of ventilation effectiveness in actual buildings difficult, but in many cases procedures can be employed to evaluate the ventilation system performance.

4. VENTILATION SYSTEM CHARACTERIZATION PROCEDURES

In this section ventilation system performance evaluation procedures for use in real buildings are presented, along with some preliminary results from their application in a three-story office building. A technique for measuring system flows and envelope leakage simultaneously is described, followed by a discussion of procedures to measure ventilation effectiveness.

4.1 System Flow Measurement

The whole building ventilation measurement results discussed previously revealed the fact that uncontrolled air leakage could be an important part of a building's net ventilation rate. In order to simultaneously measure this air leakage rate and the rate of intentional outside air intake, one can employ a constant injection tracer gas technique. This procedure is illustrated in the schematic in figure 1. In this schematic Q_{OA} is the rate of intentional outside air intake, Q_{RC} is the recirculation airflow rate, and Q_{SU} is their sum, the supply airflow rate. Q_{IN} is the rate of uncontrolled air leakage in through the building shell, and Q_{EX} is the sum of the uncontrolled air leakage out through the building shell and the airflow out of intentional openings such as bathroom exhausts. Q_{RE} is the return airflow rate and Q_{SP} is the airflow rate through the spill dampers. Tracer gas decay tests determine the sum of Q_{OA} and Q_{IN}, but their individual values are important in evaluating the ventilation system operation and the airtightness of the building envelope.

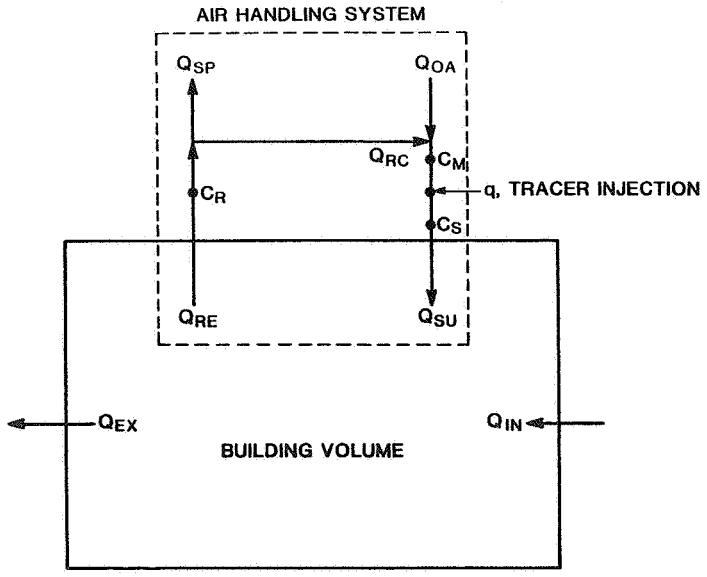


Figure 1 Schematic of Ventilation Evaluation Procedure

In this measurement procedure, one injects tracer at a constant rate into the supply airstream as indicated in figure 1. One then measures the return air concentration C_R, the supply air concentration C_S, and the mixed air concentration C_M. C_M must be measured some distance downstream of where the recirculation air meets the new outside air in order to provide the two airstreams an opportunity to mix. Similarly, C_S must be measured downstream of the tracer gas injection location after the tracer mixes with the supply airstream. The tracer gas mixing can be enhanced by releasing the tracer at several locations across a supply duct cross-section. Under conditions of good mixing, the value of Q_{SU} can be determined from the tracer gas injection rate q and the difference between C_S and C_M. To make this determination, one must wait for steady-state conditions, which can take several hours depending on the net ventilation rate and the extent of mixing within the building. From various mass balances of the airflows and tracer gas, one can determine the values of Q_{OA}, Q_{RC}, Q_{SU}, and Q_{IN} from the three concentrations and the tracer injection rate. In this analysis it is convenient to define two ratios,

$$R = C_M/C_R = Q_{RC}/Q_{SU} \tag{1}$$

and

$$L = C_R/C_S = Q_{SU}/(Q_{EX} + Q_{RE}) \tag{2}$$

R, the recirculation fraction, is the percentage of return air which is recirculated. L is called the leakage fraction.

In addition to the requirement of good mixing in measuring the values of C_M and C_S, there is another complication in the general case in which a building is served by more than one air handler. In this situation, it is desirable that the value of C_S be the same for all the air handlers. For a given tracer gas injection

rate, the value of C_S depends on R, L, and Q_{SU}, and these may certainly vary among the air handlers. Some guesswork is involved in determining the appropriate values of the tracer injection rate q for each air handler, and trial runs may be necessary to achieve satisfactory tracer injection rates.

4.2 Ventilation Effectiveness Measurement

Despite the difficulties involved with making ventilation effectiveness measurements in real buildings, there is a need to quantify air distribution characteristics. The procedure discussed in the last section to determine system flows can be extended to study ventilation effectiveness. This is done by analyzing the tracer gas concentrations as the system approaches equilibrium and, again, during the decay after the tracer gas injection is turned off.

There have been only a few cases of ventilation effectiveness measurement in real buildings.[10,12] The work in reference 10, done at the Norwegian Institute of Technology, involved the determination of residence times in a 400 m^2 room in a hotel in Trondheim, Norway. The room was considered to be isolated from the rest of the building in terms of airflow and was ventilated with no recirculation, avoiding some of the difficulties discussed earlier. A constant flow of tracer gas was introduced into the supply air and the tracer concentration was monitored in the supply, exhaust, and at a location within the room. During the build-up in tracer, the local mean age of the air at a specific point in the room τ_i and internal mean age for the entire space $\{\tau_i\}$ are given by

$$\tau_i = \int_0^\infty [1 - (C_i(t)/C_i(\infty)] \, dt \tag{3}$$

and

$$\{\tau_i\} = (1/\tau_n) \int_0^\infty [1 - (C_e(t)/C_e(\infty)]t \, dt \tag{4}$$

$C_i(t)$ is the tracer concentration at the point in question, and τ_n is the inverse of the air exchange rate of the space. τ_i can be conveniently determined by filling an air sample container at the location of interest from the time the injection starts until the concentration attains equilibrium. The determination of $\{\tau_i\}$ requires the continuous monitoring of $C_e(t)$. Both τ_i and $\{\tau_i\}$ can also be determined from the concentration decay after the injection is stopped with expressions similar to equations (3) and (4). Skaret and Mathisen point out that when there is envelope leakage the decay results are more reliable because during buildup all the incoming air cannot be labelled with the tracer gas.[10] Based on the ages in equations (3) and (4) one defines a mean air exchange efficiency as

$$\{\eta_a\} = \tau_n/2\{\tau_i\} \tag{5}$$

This efficiency attains a maximum value of 1.0 under conditions of pure piston flow through the space and equals 0.5 under perfect mixing. The existence of stagnant zones within the space yields a

value less than 0.5. Local conditions are characterized by the local air exchange efficiency

$$e_a = \{\tau_i\}/\tau_i \tag{6}$$

If the local interior air age is less than the room average age, a generally favorable situation at that location, then e_a has a value greater than one. These quantities were determined for the hotel space in Trondheim using this procedure on two different occassions. The values of $\{\eta_a\}$ were 0.59 and 0.58, and the local air exchange efficiencies were 0.87 and 1.24.[10] This room had a displacement type ventilation system, which is consistent with values of $\{\eta_a\}$ above 0.5.

The definitions in equations (3) and (4) are appropriate for the case of a building ventilated with 100% outside air, but we also require techniques when there is recirculation of return air. One option is to employ these definitions with no modifications, ignoring the fact that there is recirculation. The values of $\{\eta_a\}$ and e_a will then reflect more complete mixing than is actually occurring within the building. The values of these measures of ventilation effectiveness will be affected by the amount of recirculation occurring, regardless of the actual air distribution characteristics within the building. Alternatively, a measure of ventilation effectiveness that is not affected by the amount of recirculation is required. This analysis is more involved than for the case of 100% outside air intake and is not yet available.

While the analysis techniques to determine building average and local internal ages with nonzero recirculation have not been completed, some interesting relations have been developed. For example, the average age of the air leaving the building, i.e. the return air, can be determined when there is recirculation. In the case of 100% outside air intake, this average residence time τ_r is equal to τ_n regardless of the flow pattern within the building. When there is less than 100% outside air intake, one may still determine this average residence time. To do so, one considers the average time for the ventilation air to make a circuit of the building from the supply fan back to the return fan, τ_s. τ_s is equal to the building volume V divided by the supply airflow rate Q_{SU}. The average age of the return air is then given by

$$\begin{aligned}\tau_r &= (1-R)\tau_s + R(1-R)2\tau_s + \ldots + R^{n-1}(1-R)n\tau_s + \ldots \\ &= \tau_s/(1-R)\end{aligned} \tag{7}$$

As expected, when there is 100% recirculation (R=0), $\tau_r=\tau_s=\tau_n$. One can also determine τ_s by analyzing the values of C_R and C_M during the concentration buildup and decay. The values of C_S are not used because they rise quickly during buildup and typically exhibit more scatter than C_R and C_M, making their analysis difficult. Also, the values of C_M and C_S are identical during the decay. During the buildup the concentrations are given by

$$\begin{aligned}C_R(n\tau_s) &= (q/Q_{SU})\ [\ L + RL^2 + \ldots + R^{n-1}L^n\ ] \\ &= (q/Q_{SU})\ L\ [1-(RL)^n]/(1-RL)\end{aligned} \tag{8a}$$

$$C_M(n\tau_s) = (q/Q_{SU}) \left[RL + R^2L^2 + \ldots + R^nL^n \right]$$

$$= RC_R(n\tau_s) \qquad (8b)$$

During the decay, the concentrations are given by

$$C_R(t + \tau_s) = RL\ C_R(t) \qquad (9a)$$

$$C_M(t + \tau_s) = RL\ C_M(t) \qquad (9b)$$

Given the average age of the return air τ_r and the recirculation fraction R, the average age of the supply air is given by

$$\tau_{su} = R\tau_r = R\tau_s/(1-R) \qquad (10)$$

This equation, and equation (7), are only true after many system time constants τ_s have elapsed. Earlier in the fan operation schedule, one must account for the age of the building air when the fans are turned on. Depending on the values of R and τ_s, it may take several hours for the supply air are τ_{su} to approach the value given in equation (10). If T is the average age of the building air when the fans are turned on, then the supply air age after n time constants τ_s have elapsed is given by

$$\tau_{su}(n\tau_s) = TR^{n+1} + R\tau_s/(1-R) \qquad (11)$$

For example, consider the case in which the average building air age is 10 hours when the fans come on in the morning, R=0.75, and τ_s=0.5 hr. The equilibrium value of τ_{su} in equation (10) is 1.5 hr, but it takes 5 hours before the actual value of τ_{su} is less than 2 hours. Thus, the supply air age varies through the day and is strongly dependent on fan operation schedules. Note that all of the above discussion neglects the age of the air in the breathing zone of the occupants, which may be much older than the supply air for some interior airflow patterns.

4.3 Measurement Results

In order to investigate the applicability of the techniques discussed above, experiments were conducted in a three-story office building in Plainsboro, New Jersey. This privately owned building was completed in the fall of 1984, and an overhead view of its floor plan is shown in figure 2. The building dimensions are roughly 90 by 55 m, including an unconditioned atrium. The volume of the conditioned space is 46,000 m^3 and the floor area is 12,000 m^2. A skylighted corridor, extending all three stories, is isolated from the office space except for glass panels and doorways. There are two air handlers, serving the east and west sides of the building. Openings to each fan's return air shaft are shown in the figure, and these are the only connections between the entire floor's ceiling return plenum and the return fans. Note that the return air from office space near the bottom of the figure must go all the way around the skylighted corridor to reach the return shaft. The layout of this building suggests the potential for air distribution problems, making this building an interesting candidate for ventilation effectiveness tests.

In these tests, a known flow of tracer gas was injected into the main supply duct of each air handler and the concentrations C_M, C_S and C_R, as shown in figure 1, were monitored over time for each air handler. Once steady-state was achieved, the injection was stopped and the decay in the concentrations were monitored. During the buildup, and during the decay, air sample bags were filled at six locations on the first floor, as noted in figure 2. All six locations were at approximately desktop height. The tests were carried out on two consecutive days. The results of the steady-state evaluation of system flows are shown in table 1. This table lists the equilibrium values of the concentrations, the recirculation and leakage ratios (R and L), and the calculated values of Q_{SU}, Q_{OA} and Q_{IN}. Based on the differences between the east and west sides observed on 6/13, the tracer injection rates were adjusted on 6/14 and the equilibrium values of the concentrations on the two sides of the building were closer together. The values of R, L, and the airflow rates are quite similar for the two days. As noted in figure 1, Q_{OA} is the rate of intentional outside air intake through the air handlers and Q_{IN} is the rate of uncontrolled air leakage through the building shell. Table 1 shows that this uncontrolled leakage constitutes about two-thirds of the net outside air ventilation rate. This is not expected since the building is intended to be operated at a slight overpressure of the interior, which should cause Q_{IN} to equal zero.

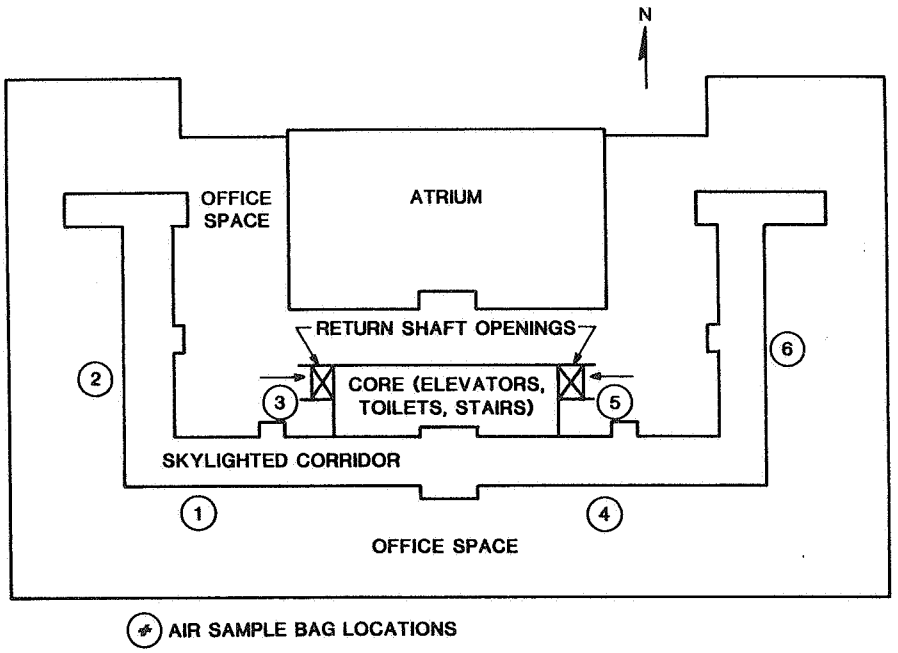


Figure 2 Schematic of Test Building

The values of τ_i and $\{\tau_i\}$ from equations (3) and (4) were determined for the two days of testing in this same building, and are given in table 2. The values of τ_n in this table (the inverse of the air exchange rate) is based on the net ventilation rate of the building, $Q_{IN}+Q_{OA}$. The fact that more outside air enters the building through the envelope than through the ventilation system

may make the analysis procedure inapplicable. It will at least make the decay results more accurate than the buildup results, as pointed out by Skaret and Mathisen.[10] The values of $\{\tau_i\}$ are calculated using equation (4) during the buildup and a variation of this equation during decay. While the values determined during the decay are almost twice those from the buildup period, the values are similar over the two tests. The values of $\{\eta_a\}$ are also given in the table. On both nights the west-buildup value of $\{\eta_a\}$ is greater than its theoretical maximum of 1.0, but the buildup values are expected to be less reliable. The averages of the east and west down values are 0.41 and 0.44 for the two tests, corresponding to less than perfect mixing. The fact that the down values on the west side are greater than 0.5, corresponding to displacement flow, may or may not be significant. It is doubtful that the west side of the building performs like a displacement system and the east side does not. Table 2 also presents values of τ_i (equation (3)) determined at the six locations in figure 2 using air sample bags. With only a few exceptions, the values at each location are somewhat similar over the two days and for both the up and down data. The value of e_a (equation (6)) based on these values of τ_i are also given and no consistent patterns are evident. The values of the average concentrations over buildup and decay, and the concentrations at the steady-state, at the six different locations were suprisingly similar. This implies relatively good mixing on the floor and no significant differences for locations 3 and 5, which are directly below the return shaft openings.

	C_S	C_R	C_M	R	L	Q_{SU}	Q_{OA}	Q_{IN}	$Q_{IN}/(Q_{OA}+Q_{IN})$
6/13/85									
EAST	82.5	60.1	45.2	.75	.73	10.7	2.7	4.0	60%
WEST	100.1	70.4	57.3	.81	.70	7.0	1.3	3.0	70%
6/14/85									
EAST	76.9	54.7	39.9	.73	.71	10.8	2.9	4.4	60%
WEST	86.8	61.2	48.5	.79	.71	6.6	1.4	2.7	66%

Concentrations in pbb, flows in m^3/s.

Table 1 Results of System Flow Measurements

The results of the residence time analysis are presented in table 3. As mentioned earlier, the average time for the ventilation air to make a circuit of the building τ_s can be determined in more than one ways. τ_s is equal to V/Q_{SU}, and this quantity is given in the table for the east and west side of the building and for the building as a whole. Alternatively, τ_s can be determined during the buildup from equation (8) and during the decay from equation (9). These values for the two sides of the building are also given in table 3. While the values of V/Q_{SU} for the east and west sides are quite different, the values of τ_s based on equations (8) and (9) are essentially the same for both sides of the building. This may be due to mixing between the two sides of

the building. Also, the values of τ_s based on the decay data are larger than those based on buildup. However, the average of the decay and buildup values are very close to the whole building values of V/Q_{SU}.

	6/13/85 East		6/13/85 West		6/14/85 East		6/14/85 West	
τ_n(minutes)	57		89		53		93	
	Up	Down	Up	Down	Up	Down	Up	Down
$\{\tau_i\}$(min)	55	113	37	79	43	116	29	73
$\{\eta_a\}$	.52	.25	1.2	.56	.62	.23	1.6	.64
τ_1(min)	55	--			50	109		
τ_2	93	105			76	80		
τ_3	65	99			27	--		
τ_4			39	--			40	75
τ_5			71	--			68	88
τ_6			60	--			61	77
e_{a1}	1.00	--			.86	1.06		
e_{a2}	.59	1.08			.57	1.45		
e_{a3}	.85	1.14			1.59	--		
e_{a4}			.95	--			.73	1.00
e_{a5}			.52	--			.43	.83
e_{a6}			.62	--			.48	.95

Table 2 Internal Air Age Results

	6/13/85 East	6/13/85 West	6/13/85 Whole Building	6/14/85 East	6/14/85 West	6/14/85 Whole Building
V/Q_{SU}	36	55	43	35	58	44
τ_s Buildup (eq (8))						
Return	39	37		38	40	
Mixed	43	39		42	40	
τ_s Decay (eq (9))						
Return	53	52		52	48	
Decay	50	48		49	46	

Table 3 Residence Time Results (minutes)

5. CONCLUSIONS

In this paper we have discussed existing and recently developed tracer gas techniques for the in situ evaluation of ventilation system performance. Past work on whole building infiltration and ventilation measurement was discussed and the major findings

reviewed. The use of tracer gas to measure ventilation effectiveness in mechanically ventilated buildings was also discussed. While techniques exist for such measurements under conditions of 100% outside air intake, the evaluation of systems operating with recirculation is more difficult. Techniques appropriate to this latter situation are not yet available, but some limited evaluation is possible. Measurement procedures are also described to separately measure the intentional outside air intake through the air handlers and the amount of uncontrolled air leakage through the building shell. The results of the application of these techniques in a three-story office building are presented and discussed.

6. ACKNOWLEDGEMENTS

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VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

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

PAPER 27

Ventilation efficiency measurements in occupied mechanically ventilated buildings

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SYNOPSIS

The various meanings of ventilation efficiency are briefly summarised. The residual life time of a released tracer gas is chosen as the most meaningful and convenient basis for local efficiency measurements in large, occupied, mechanically ventilated buildings. Measurements were carried out in ten public swimming pool halls. Sulphur hexafluoride tracer gas was released from a 20 ml syringe at various locations around the pool hall and the integrated concentration with respect to time was measured at the exhaust air duct. This was extrapolated to infinite time using the measured decay rate. Hence the median residence time of the tracer after release was found and compared with the corresponding value for uniform and complete mixing using the measured exponential decay rate. The ratio of these two times was taken as a measure of the ventilation efficiency.

None of the ventilation systems tested proved significantly more efficient than the others overall. Local variations were however detected at individual sites and the method shows promise for application in occupied buildings, where minimum intrusion is required.

Symbols

A	fresh air change rate
C	contaminant or tracer concentration
q	volume of tracer gas
Q	rate of supply of fresh air
r	rate of supply of tracer
t	time
T	transfer index
Σ	ventilation efficiency
τ	median residence time

1. Introduction

The general purpose of ventilation is to supply 'fresh air' and to remove unwanted or harmful constituents from the local environment. The contamination may be released steadily or in discrete short bursts; alternatively there may be an existing contaminant of unknown history. However, in all cases the objective is to achieve as rapidly as possible, and maintain, an acceptably low concentration of contaminant in the occupied parts of the space. This means that not only must the ventilating air be 'uncontaminated' but also it must be delivered in such a way that the contamination is removed 'efficiently' to where it can do no harm.

It is not usually feasible to drive out the contamination before an advancing front of clean air (so-called piston flow) because intermixing of the old and new air is inevitable. However, this situation would represent the best possible ventilation and is most nearly approached by a local exhaust facility, such as a hood, which removes most of the contaminant before it has time to mix with the room air. Most often contamination is removed by dilution; fresh air is supplied, and stale air therefore removed, at a rate Q sufficient to maintain the local contaminant concentration C_j at point j below a specified maximum permissible value C_{max}. If the contaminant concentration C is uniform throughout the space then it will be removed at rate CQ and if the rate of supply is q the requirement for acceptable conditions is:

$$Q \geqslant \frac{q}{C_{max}}$$

This process is in some sense obviously less 'efficient' than the former situation, and it will take longer for the contaminant to be removed.

2. Background

The above brief description of the ventilation process suggests two approaches for defining and measuring 'ventilation efficiency': either in terms of concentrations or residence times. The rate of decay of an existing contaminant, or the equilibrium concentration for a continuous release, are both frequently used to measure ventilation rates in spaces where the air is well mixed. The usefulness of the measurement of local decay rates has been questioned by Sandberg[1] who shows that decay rates at different locations in a space are time dependent and no unique local air change rate can be defined. He suggests that the use of residence times is more meaningful, i.e. the time taken for the contaminant to be removed from the space.

A similar approach was adopted earlier by Lidwell[2] who introduced the idea of measuring the 'transfer index' between two points, defined as 'the integrated concentration at one point following the liberation of unit quantity of tracer at the other'. Thus if a quantity q of tracer is released at point P and the concentration C(t) is measured at point Q then the transfer index

between P and Q is defined as

$$T = \frac{1}{q} \int_o^\infty C(t)\, dt.$$

T has the dimensions of time/volume and under complete mixing conditions T is the reciprocal of the air change rate as usually measured. Hence $\frac{1}{T}$ can be described as the 'equivalent ventilation'.

Sandberg[1] developed this idea further in terms of the 'age' of the air at a point, which is defined as the time that has elapsed since the air entered the room. This represents therefore the 'freshness' of the air at that point. Efficient ventilation at a chosen location is associated with a young age of the air there. Owing to the inevitable random fluctuations in air flow there will exist a distribution over time of ages which can be described by an average value at a point j given by

$$\frac{\int_o^\infty C_j\,(t)\; t\; dt}{\int_o^\infty C_j\,(t)\;\; dt} \qquad (1)$$

In the context of contaminant removal it is convenient to think of the fate of a contaminant or tracer released at the point of interest. The time taken for the contaminant to leave the space has been called the 'residual life time'[3]. The internal age distribution and the residual life time distribution have been shown by Sandberg to be identical.

3. Ventilation efficiency

In an occupied mechanically ventilated building it is convenient to release a tracer gas at a chosen location and measure the integrated concentration versus time at the exhaust terminal or duct. The ventilation efficiency at the place where the tracer was released can then be defined in terms of a measured mean residual life time.

Imagine tracer gas to be released as a short burst at the chosen location. If the ventilation is efficient then the tracer will be rapidly removed and will soon appear at the exhaust terminal. If on the other hand the local ventilation is poor, the tracer will linger around the location where it was released and will take a longer time to reach the exhaust terminal. Thus if the tracer concentration is recorded versus time at the exhaust terminal the results, for a pulse released at time zero, would be as indicated in Figure 1.

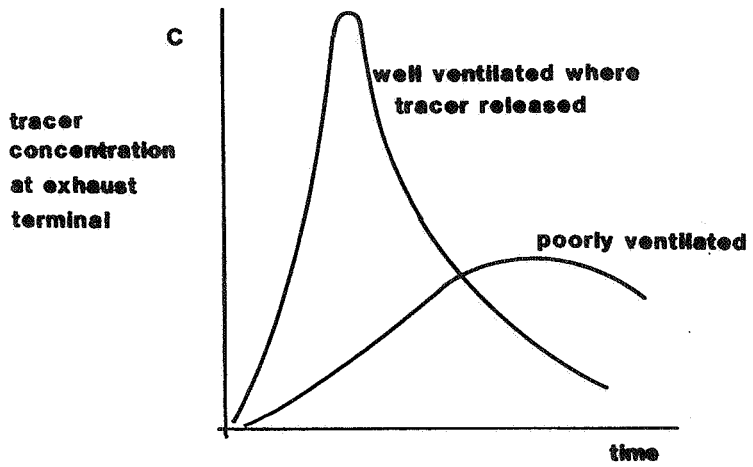


Figure 1 Tracer gas concentration at the exhaust terminal following release of a short burst of tracer at time = 0

The integrated area under the curves $\int_o^\infty$ Cdt will be the same in both cases since eventually all the tracer will pass the exhaust terminal, unless air leakage occurs other than through the ventilation system. If $\int_o^t$ Cdt is plotted against t then the result will be as shown in Figure 2 where in a well ventilated situation a rapid rise of $\int_o^t$ Cdt occurs soon reaching the maximum value equal to $\int_o^\infty$ Cdt.

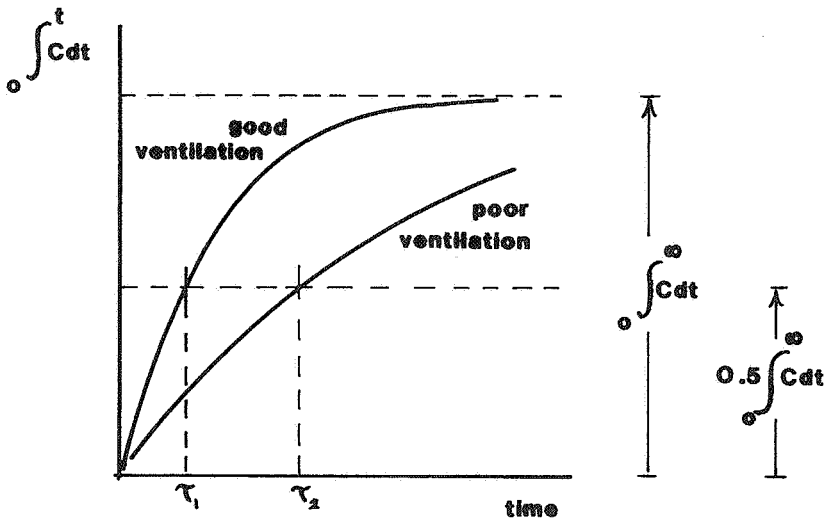


Figure 2 Integrated concentration versus time at the exhaust terminal following release of a short burst of tracer at a chosen location at time = 0

Rather than using expression (1) to find the average residence time of the tracer in the space it is more convenient, following Danckwerts[4], to use the median age τ which is the time taken for half the tracer to reach the exhaust terminal. τ is simply the value of t for which

$$\int_0^t C\,dt = \tfrac{1}{2} \int_0^\infty C\,dt$$

see Figure 2.

The ventilation efficiency can then be defined by comparing this measured median residence time τ_s with the residence time which would occur if the air in the space was completely and uniformly mixed τ_x. For uniform mixing the tracer concentration would decay exponentially according to

$$C_t = C_o e^{-At} \qquad (2)$$

where C_t = concentration of tracer at time t
C_o = concentration of tracer at time 0
A = air change rate per unit time

From equation (2)

$$\int_0^\infty C\,dt = \frac{C_o}{A}$$

where C_o is the initial tracer concentration which would exist if instantaneous complete mixing took place = (volume of tracer released/room volume). The value of t for $\int_0^t C\,dt = \tfrac{1}{2} C_o/A$ can be shown to be given by $e^{-At} = 0.5$. The median life time for a released contaminant under fully mixed conditions is therefore $\tau_x = 0.693/A$. If the measured median life time is τ_s then the ventilation efficiency, equivalent to Sandberg's relative air diffusion efficiency[3] is

$$\varepsilon = \frac{\tau_x}{\tau_s}$$

If $\tau_x = \tau_m$ then $\varepsilon = 1$ representing the rapid complete mixing situation. In a stagnant region $\tau_s > \tau_x$ and $\varepsilon < 1$. Similarly values of $\varepsilon > 1$ imply removal of contaminants more effectively than for uniform mixing i.e. an amount of piston flow behaviour.

4. Experimental method

All the buildings of interest were mechanically ventilated. A short burst of tracer gas was released at various places in turn and the concentration measured as a function of time at the exhaust terminal or duct.

Sulphur hexafluoride was convenient as a tracer gas because it is harmless and equipment capable of measuring concentration of 10^{-9} is readily available, and therefore requiring only 10 ml of tracer gas in a 10,000 metre^3 building. At a pre-arranged

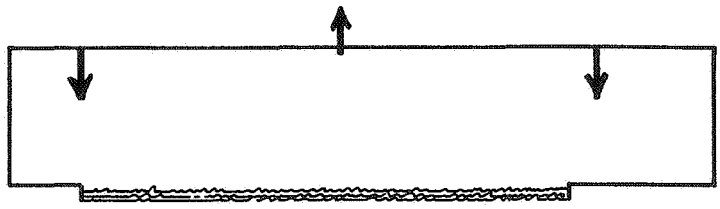
signal a measured volume of gas (usually 20 ml) was released at the place of interest from a syringe. The syringe was filled by its hypodermic needle by withdrawing gas through a septum on the gas bottle stored outside and downwind of the building. The gas analyser (AI Model 505, SF_6 Detector Chromatograph) was situated usually in the plant room at a convenient place for sampling to take place in the exhaust duct through a suitable existing inspection hole. Output from the analyser used in the sample mode is a series of pulses which were recorded on a strip chart recorder and analysed manually. Sampling interval was 1.5 to 2 minutes.

5. The buildings

As part of a larger survey, measurements were carried out in 10 public swimming pools.

The pool halls were all mechanically ventilated at an air change rate of about 4 air changes per hour although in many of the pools recycling of the air to conserve energy reduced the fresh air change rate to 1 or 2 air changes/hour.

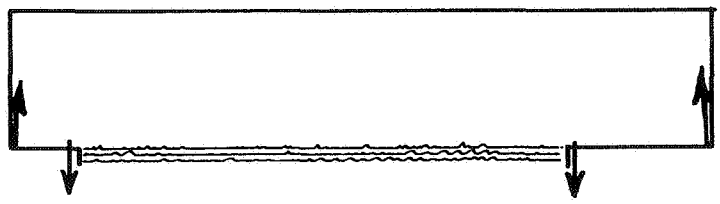
The air distribution systems were mainly of two types. The most common arrangement (6) was for air to be supplied more or less vertically downwards along the perimeter of the pool, with return air grilles also in the ceiling over the centre of the pool. Figure 3 shows this schematically and lists the dimensions of pools of this type.



Pool Code	l x b h (metres)	Volume (m^3)
A	39.7 x 18.5 x 3.6	2650
B	32.7 x 18.3 x 5.7	3070
C	28.7 x 24.6 x 7	5300
D	42 x 24 x 7.2	6500
E	51.2 x 23.3 x 8.9	12070
F	49.7 x 31.7 x 9.1	14000

Figure 3 Pools with ceiling mounted supply and extract positions

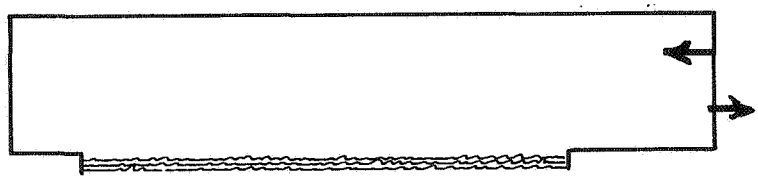
Some more recently built pools (3) have air supply slots in the floor adjacent to the perimeter walls so that the air is directed vertically upwards. The air return is combined with the pool water overflow grid at the pool side. These are all level deck pools. Figure 4 illustrates this type.



Pool Code	l x b x h (metres)	Volume (m^3)
G	30.5 x 17 x 5.5	2850
H	34.2 x 14.4 x 6	2950
I	32.4 x 22.8 x 6	4350

Figure 4 Pools with floor mounted supply and extract positions

One of the pools had cross flow ventilation with air supplied horizontally at high level with the return air grille on the same side wall at low level, Figure 5.



Pool Code	l x b x h (metres)	Volume (m^3)
K	30 x 17 x 3.4	1770

Figure 5 Cross flow ventilated pool

Since the time available at each pool was limited to a few days, a definitive study of the advantages and performance of each system was not possible. The aim was to show the feasibility, and assess the practicalities of this assessment method.

In all cases there was no difficulty in placing the gas sampling tube in the return air duct. The SF_6 tracer (20 ml) was released from a syringe (needle removed) usually near the water level. The time of release was notified to the plant room via a two-way radio and marked on the chart. The time of tracer release was denoted zero time; the duration of release was at most a few seconds which is negligible on the time scale of measurement which was tens of minutes.

Typical response curves are shown in Figure 6.

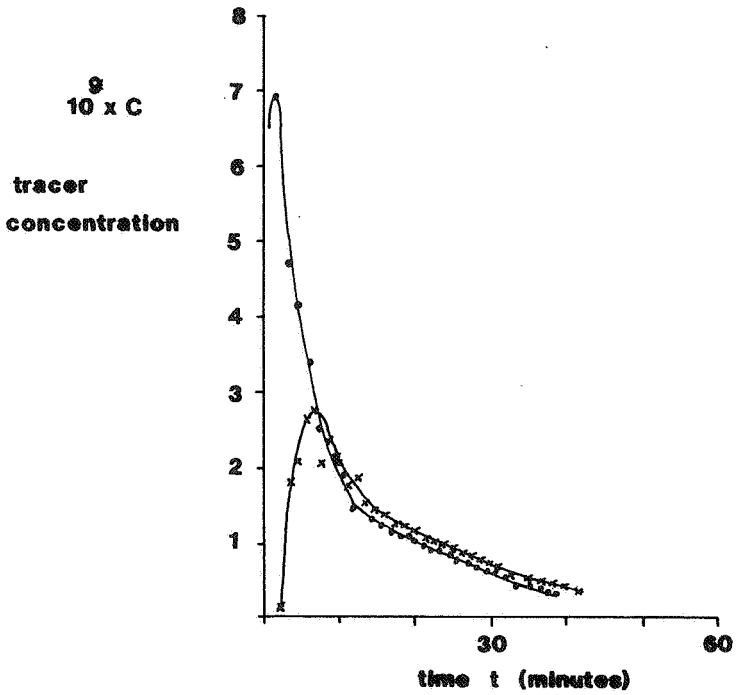


Figure 6 Measured concentration in extract duct for tracer released at pool side at time t = 0

A simple trapezium rule calculation on a programmable calculator enabled computation of $\int_o^t Cdt$ in each case, Figure 7.

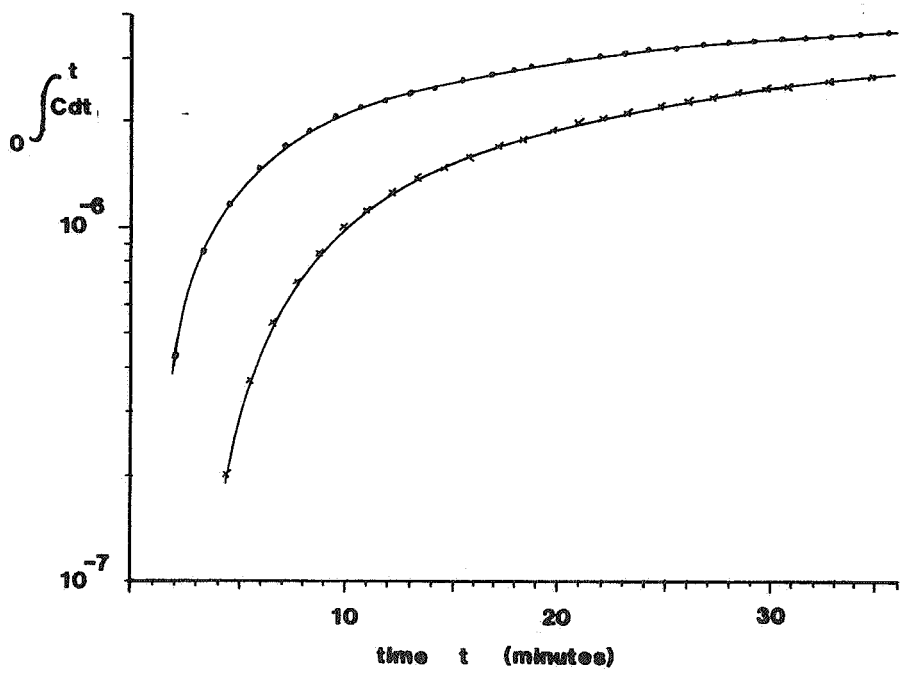


Figure 7 Integrated concentration versus time at extract duct

The time when measurements stopped t_m was typically after 30 to 60 minutes.

From the decay part of the tracer in Figure 6 on a plot of logarithm (concentration) versus time the decay rate before time t_m can be found, hence assuming that the same exponential decay rate persists until all the tracer is removed it is possible to calculate $\int_{tm}^{\tau} C\,dt$ thus:

Let $C_t = C_o\, e^{-At}$ represent the exponential decay process then

$$\int_{tm}^{\infty} C_o e^{-At} = \frac{C_o}{-A} \left[e^{-At}\right]_{tm}^{\infty} = \frac{C_o e^{At_m}}{A} = \frac{C_m}{A}$$

where C_m is the tracer concentration at time t_m.

By adding these calculated values to the measured value of $\int_o^{tm} C\,dt$ the values of $\int_o^{\infty} C\,dt$ were obtained.

The median residence time is then $\frac{1}{2} \int_o^{\infty} C\,dt$.

If the decay rate as measured in the latter part of each test is assumed to represent the actual mean fresh air ventilation rate in the space then this can be used as a basis for the fully mixed performance and τ_x is given by the value of t for which

$$\int_o^t C\,dt = \tfrac{1}{2} \int_o^{\infty} C\,dt$$

$$\text{if } C = C_o\, e^{-At}$$

$$\text{i.e. } e^{-At} = \tfrac{1}{2}$$

$$\text{i.e. } \tau_x = \frac{0.693}{A}$$

The value of the measured median residence time τ_s is obtained from Figure 7.

6. Results

In comparing one mechanically ventilated space with another the most significant factor, in the absence of local extract, is the actual fresh air ventilation rate, i.e. τ_s correlated well with τ_x, Figure 8. Actual values of median residence time were in the range 10 to 60 minutes.

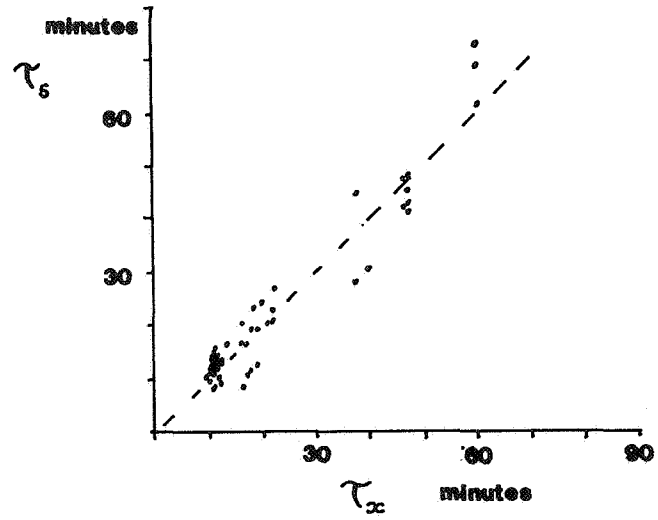


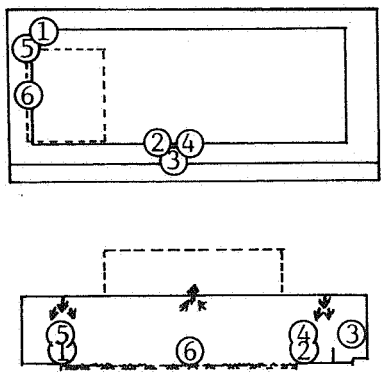
Figure 8 Measured τ_s and fully mixed τ_x residence times

Within each pool hall the value of $\Sigma = \tau_x/\tau_s$ was found at various locations around the pool, mostly near the water level. The results are given in Table 1 and summarised in Figure 9.

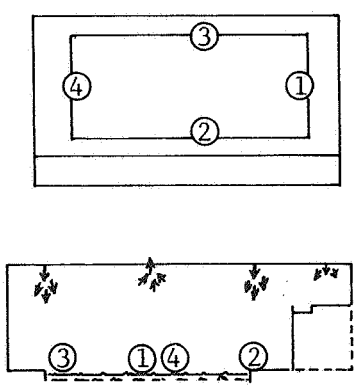
Variations in ε were found in the region 0.75 to nearly 2. No definite pattern emerged and no system proved significantly more efficient than any other. Poor local ventilation tends to occur at central locations over the water and in the shelter of balconies. Better than average efficiency occurred very close to extracts on level deck pools where the air return and water overflow are combined.

Table 1 Results of ventilation efficiency measurements in ten public swimming pool halls

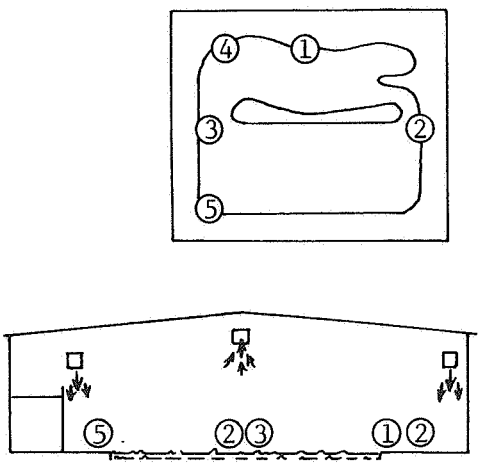
Pool Code	τ_x (minutes)	τ_s (minutes)	τ_x/τ_s
A 1	10.6	11.5	0.92
2	10.2	10.2	1.00
3	11.1	10.3	1.08
4	10.0	9.5	1.05
5	10.0	10.3	0.97
6	10.2	11.7	0.87



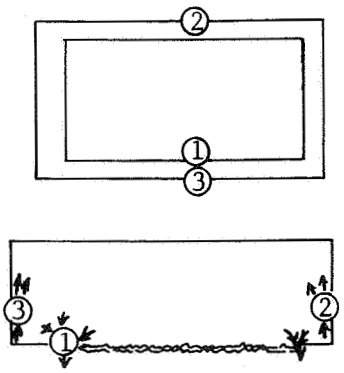
B 1	13.6	16.4	0.83
2	11.2	14.4	0.78
3	11.1	8.4	1.32
4	12.2	9.7	1.26



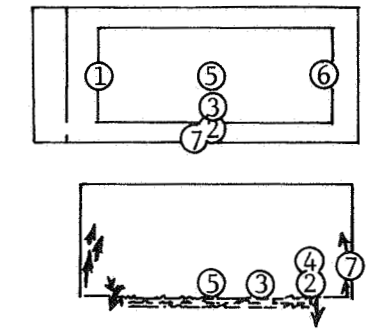
C 1	11.6	13.0	0.89
2	12.1	13.5	0.89
3	10.9	12.0	0.91
4	11.8	9.5	1.24
5	11.1	12.0	0.93



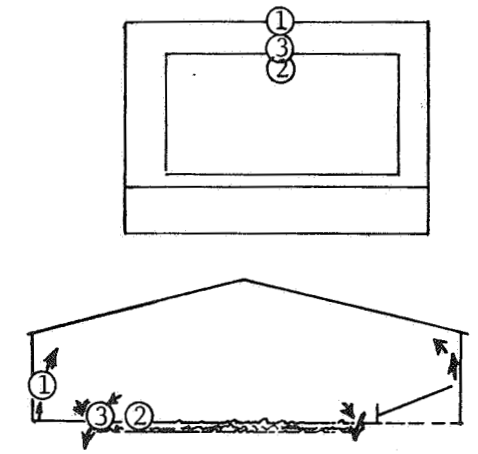
Pool Code	τ_x (minutes)	τ_s	τ_x/τ_s
G 1	16.5	8.5	1.94
2	16.1	17.0	0.95
3	16.4	16.5	0.99



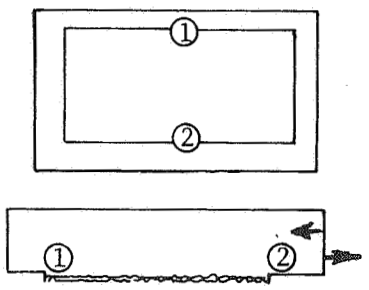
H 1	16.2	20.5	0.79
2	17.8	11.2	1.60
3	18.2	19.5	0.93
4	19.8	24.5	0.81
5	21.9	21.0	1.04
6	18.9	19.5	0.97
7	18.1	24.0	0.75



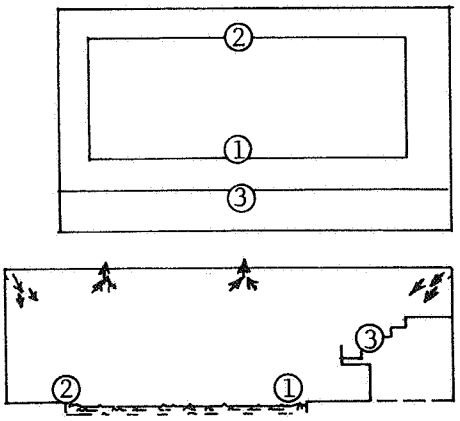
I 1	60	62	0.97
2	60	73	0.82
3	60	69	0.87



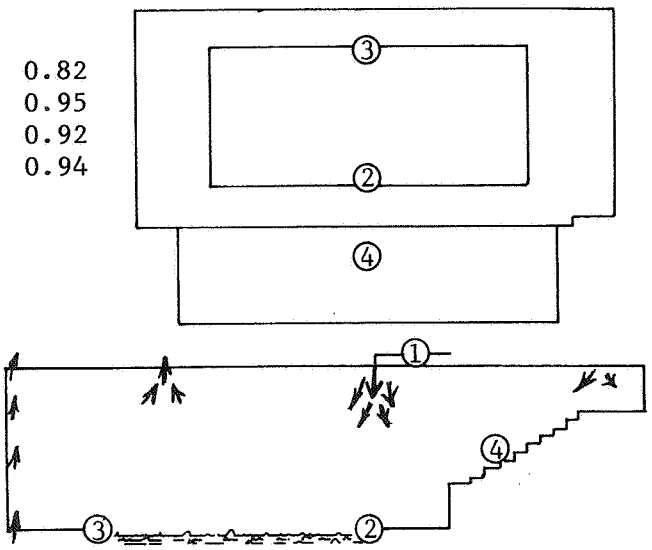
K 1	22.0	23	0.96
2	22.6	27	0.84



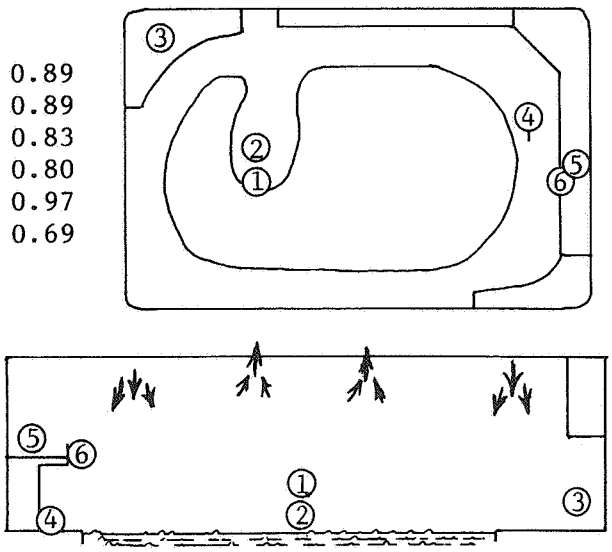
Pool Code	τ_x (minutes)	τ_s	τ_x/τ_s
D 1	37.8	28.5	1.33
2	40.0	41.0	0.98
3	37.8	45.0	0.84



E	1	21.0	25.5	0.82
	2	21.5	21.5	0.95
	3	21.7	23.5	0.92
	4	18.8	20.0	0.94



F	1	10.7	12.0	0.89
	2	10.7	12.0	0.89
	3	10.7	12.9	0.83
	4	11.6	14.5	0.80
	5	11.2	11.5	0.97
	6	10.7	15.5	0.69



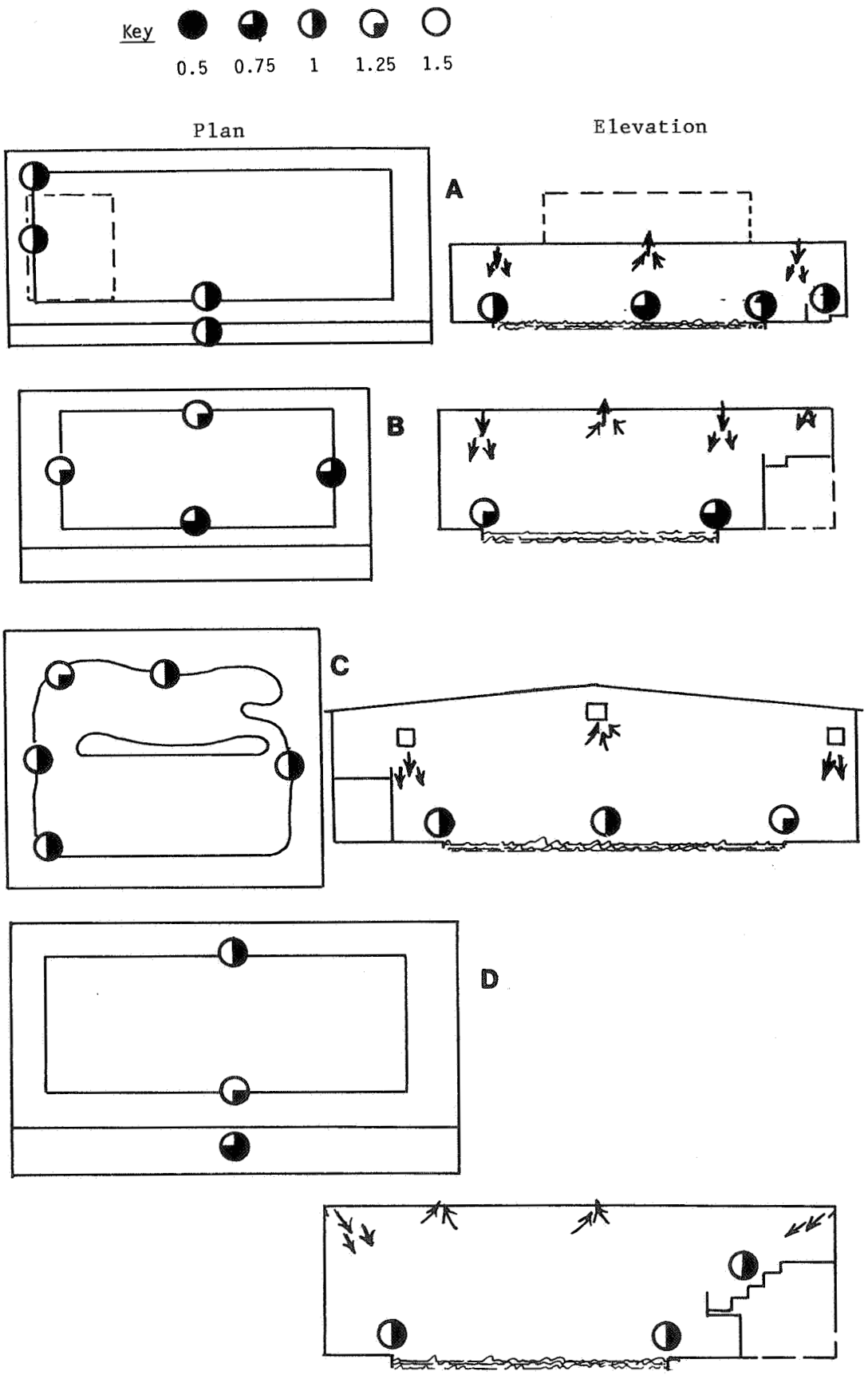


Figure 9 Measured values of τ_x/τ_s

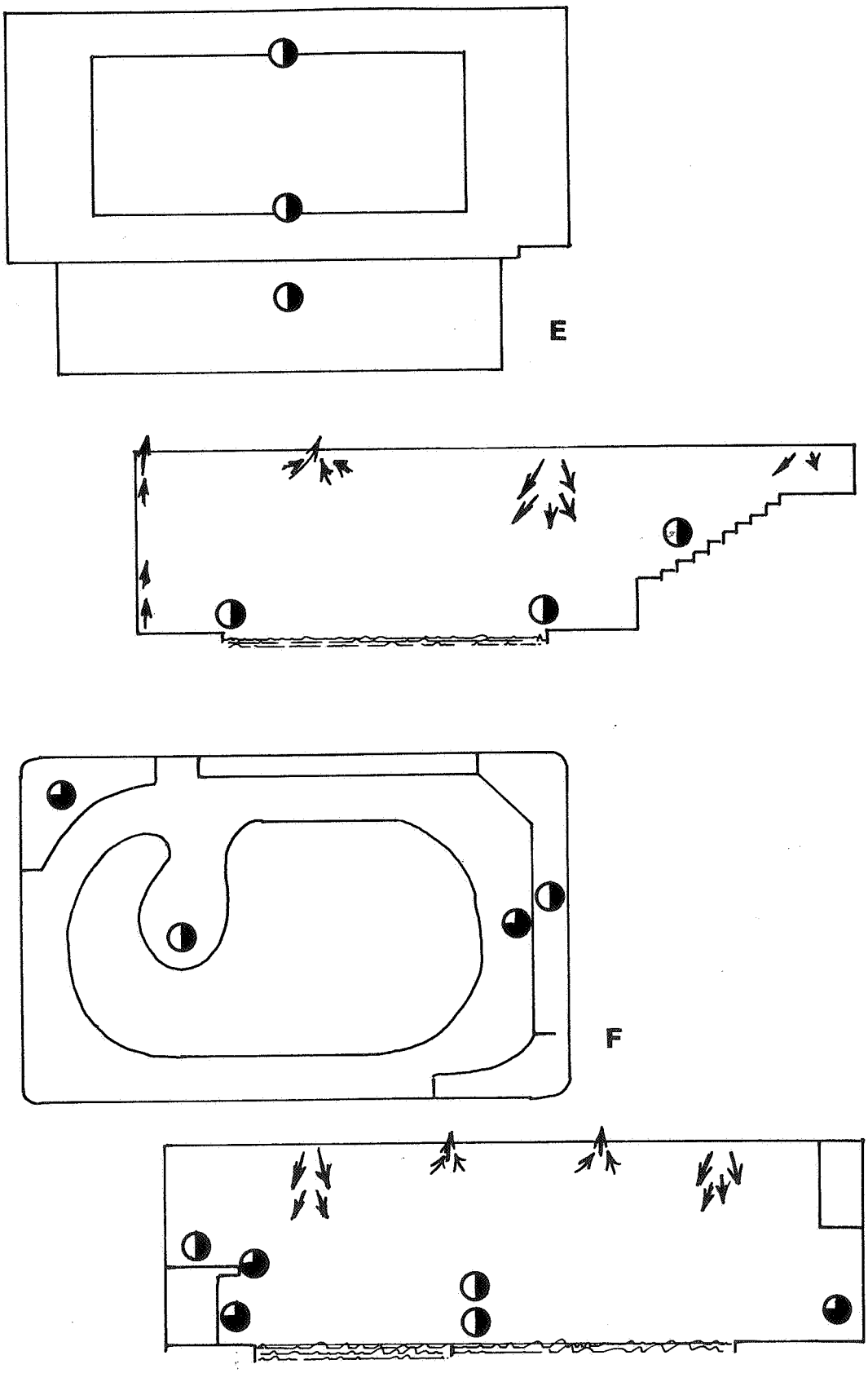


Figure 9 continued

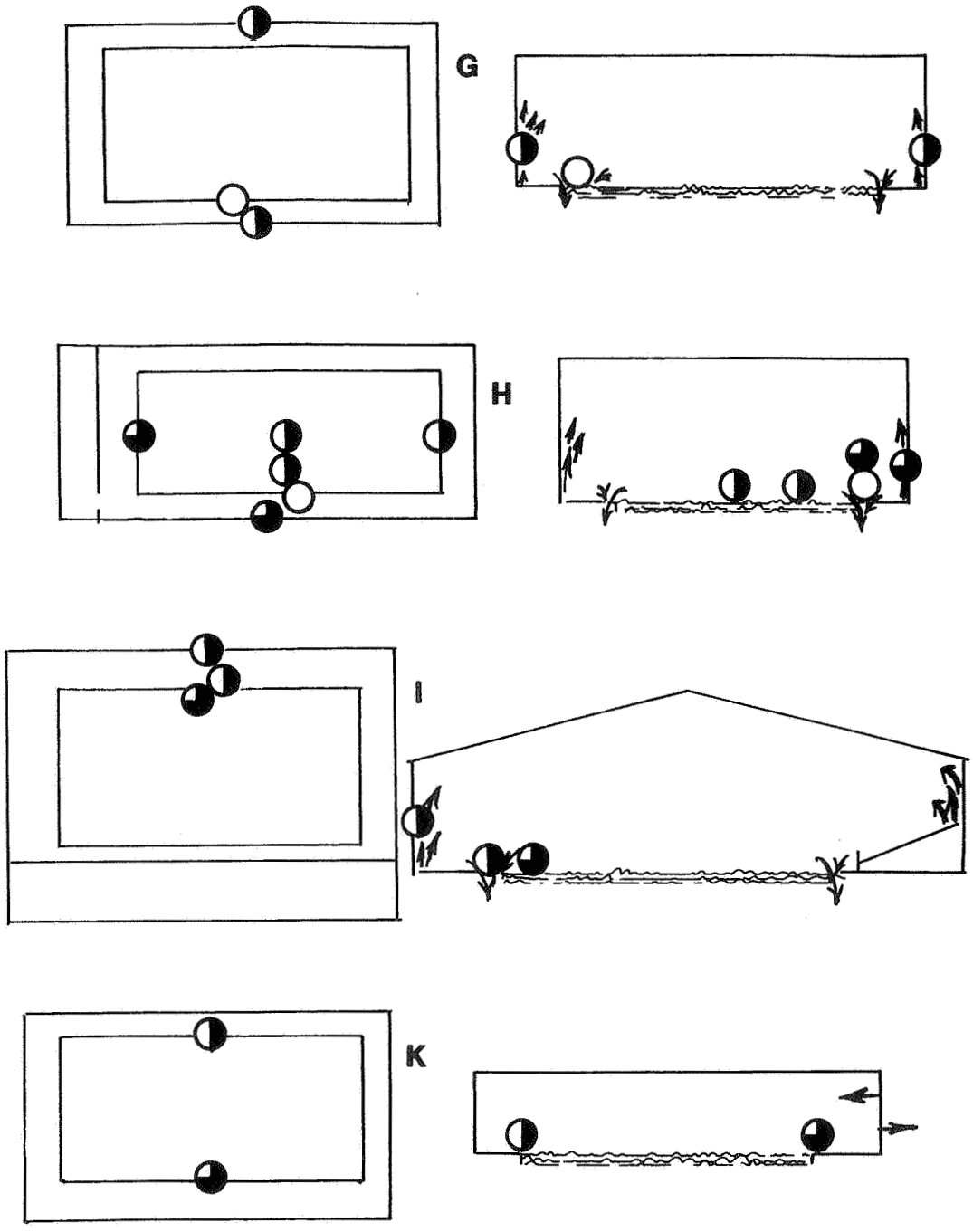


Figure 9 continued

7. Conclusions

The 'ventilation efficiency' can be defined in terms of contaminant residence times.

Measurements are possible in occupied mechanically ventilated buildings without interfering with the normal usage patterns.

Conditions in mechanically ventilated swimming pool halls are consistent with the existence of good mixing.

8. Acknowledgements

The co-operation of the pool staff and Local Authorities is gratefully acknowledged.

9. References

[1] Sandberg, M. Building and Environment, 16 (2), 1981, pp 123-135.
[2] Lidwell, O.M. J. Hyg. 58 (3), 1960, pp 297-305.
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