PAPER 3

EXPERIMENTAL TECHNIQUES FOR VENTILATION RESEARCH

D. K. ALEXANDER,[1]
D. W. ETHERIDGE[1] AND R. GALE[2]

1. British Gas Corporation
London
UK

2. Segas
London
UK

British Gas Corporation,
Research and Development Division,
Watson House,
Peterborough Road,
London, SW6 3HN

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D.K. Alexander*, D.W. Etheridge* and R. Gale+

* British Gas, Watson House, London.

\+ SEGAS, Central Laboratories, London.

1. INTRODUCTION

Ventilation has always been of interest to the Gas Industry, primarily for providing combustion air but more recently because of the desire for energy conservation. As a result of this British Gas has a continuing programme of research, and experimental techniques which have been used or developed during the course of this work form the subject of this paper. In addition, the opportunity is taken to comment on experimental techniques in general.

The paper is divided into the three main areas of experimental work, i.e. physical modelling, measurement of open areas and leakages, measurement of ventilation rates.

To be presented at AIC Conference "Instrumentation and Measuring Techniques", Cumberland Lodge, Windsor, October 1980.

2. PHYSICAL MODELLING TECHNIQUES

2.1 Pressure Distribution

The surface wind pressures on a dwelling are of considerable importance to an accurate ventilation prediction method. Rather than field measurements, which are held at the mercy of the weather, the pressure distributions are more easily derived from wind tunnel measurements on scale models. Provided that sufficient care is taken in the design of model and tunnel the results may be accurately applied to full scale (1,2). Attention must be given to the proper matching of the building model scales and wind profile and turbulence. British Gas, in a 2m x 1m wind tunnel, use a model scale of $^1/200$ which also allows a great deal of the surrounding environment to be included. Wind profile and turbulence are modelled in a manner similar to that described in (3).

The most usual forms of presentation are dimensionless coefficients, relating surface pressure to a reference pressure and air speed. Much work has been done on generalising these coefficients for simple shapes and arrays (4). These have been obtained for rather idealised cases however and their use would therefore seem to be limited to more general long-term predictions. Higher accuracy in ventilation predictions, such as are desirable for monitoring test houses, will require measurements on a specific scale model.

In addition to the mean surface pressures, there has been increasing awareness of the need for the fluctuating pressures to be known. Pulsating airflows will produce an effective ventilation which could not be accounted for in a method assuming only steady conditions. Provided that the turbulence and the surroundings are correctly modelled, pressure fluctuations may also be determined in a wind tunnel. Uncertainties arise because of difficulties in providing a suitable constant reference pressure and because the measurements only indicate surface fluctuations. It is the fluctuations of pressure differences across openings which are really required and at present these can only be estimated.

In spite of the above difficulties, the determination of surface pressure distributions from wind tunnel models seems to be an established procedure.

2.2 Ventilation Rates

Several techniques for determining ventilation rates in models have been described, e.g. tracer decay methods used by British Gas (5, 6), anemometers (7) and calibrated openings (8). However, there has been less consideration given to the problem of applying the results to full-scale. This problem is very important because one must question the value of model tests if the results cannot be extended with confidence to full-scale conditions.

In (9) it was argued that ventilation arising through cracks is influenced by viscosity even at full-scale and therefore one would expect the scale effect of Reynolds number to be evident in model results. This was demonstrated by tests carried out on simple model windows. Even for the wind direction for which ventilation was due mainly to turbulent pressure fluctuations, there was evidence of the same effect. Although this behaviour was not evident at low wind speeds, thus indicating no strong dependence on Reynolds number (see the preliminary presentation of results in (10)), later examination indicated that the ventilation rates measured at these speeds were not due solely to pressure fluctuations (see (9)). This was a manifestation of another problem with models, namely that the flow rates under investigation are often small.

When the tests were carried out with sharp-edged holes, as expected the results showed little dependence on Reynolds number. The mean pressure difference across the windows $\overline{\Delta p}$ also showed little variation with Reynolds number and this is also to be expected because of the geometry of the model.

Recent full-scale studies in a house (11) using a novel fluctuating pressurisation technique indicated that the expected effect of viscosity was not present. This is rather surprising, because it is difficult to think of a physical mechanism which could eliminate the effect at low Reynolds numbers. A possible explanation is that the openings in the dwelling which was tested were predominently of the purpose-provided type, so that even at the very low pressures the leakage was mainly comprised of flows with a constant discharge coefficient.

As far as is known only one comparison has been made between model-scale and full-scale results. This was done for openings with sharp edges and one might therefore expect good agreement. In the preliminary presentation of results (5), good agreement was indicated, but a recent re-examination suggests that this was incorrect. The data was not properly non-dimensionalised (a criticism not confined to (5))and when a proper comparison is made poorer agreement is found, as shown in Figure 1. The explanation for this lack of agreement probably lies with the pressure distribution. In the wind tunnel the surroundings of the building were not modelled, and it was not possible to model the wind turbulence accurately. Errors due to these factors could well be magnified because the openings were concentrated at two points on the building, thereby making extreme demands on the accuracy of the model pressure distribution. Another reason for the differences in Figure 1 is the fact that there were some adventitious openings in the full-scale building. However, the maximum allowance that can be made for this is to reduce the full-scale values by 25%.

To summarise all of the above, one must be pessimistic about the value of model-scale ventilation rates for providing full-scale data. For small cracks one is faced with the problem of the scale effect of Reynolds number. For sharp-edged openings which are concentrated at discrete points, an accurate pressure distribution is required. In both cases there is the additional difficulty of matching the model size and the turbulence length scales. Failure to do this introduces another scale effect. To achieve it however requires a very small model (at least $^1/200$ scale) and this makes construction of the model very difficult and introduces problems of measuring ventilation rates.

3. MEASUREMENT OF OPEN AREAS AND LEAKAGES

Open areas and/or leakages are required for two basic reasons, (i) as a means of characterizing the ventilation potential of buildings or components, and (ii) to provide data for prediction methods.

Leakages are usually measured with a steady pressure across the component and a variety of equipment has been developed for this purpose. The equipment currently in use by British Gas will be described in Section 3.4. Recently a novel alternating (AC) pressurisation technique has been used for determining the leakage of dwellings (11). It is claimed that this gives greater accuracy than the conventional DC technique at low pressures, because the noise introduced by external pressures (due to weather) can be eliminated. The leakage Q is not actually measured, but a value can be calculated from the pressure response of the structure at the driving frequency of the mechanical piston.

Although the above technique does not need a measurement of Q, it still requires measurement of very low pressures and this is often a source of error. The basic problem is that pressure differences encountered with natural ventilation are often very low, typically 2 Pa, and it can be argued that leakages should ideally be measured at this level.

There is however, a simpler alternative method for characterising the ventilation potential of components. It requires only one measurement of Q and $\overline{\Delta p}$, and this can be done at a pressure well above pressures induced by the weather. The result obtained however applies at very low pressures. The method relies on the fact that the geometry of a component is virtually independent of the flow rate passing through it and the pressure applied across it. Thus, if a parameter of the geometry is determined at a high flow rate, it will remain valid at all flow rates. The method is described in (10) and the geometric parameter is the open area A of the component, as determined from homogenous flow equations. Once A is determined, the flow rate Q at any steady pressure difference can be found from the flow equation. Whether or not the method can be generally applied to complete buildings remains to be seen, but it has been used with reasonable success for background leakage areas of rooms and this is encouraging.

3.1 Purpose-provided openings

Purpose-provided openings such as air vents and open windows are fairly easy to treat. There is little ambiguity about the definition of their open area, and indeed this can be measured with a ruler, i.e. mensuration.

3.2 Component Openings

For simple components, the open area can be obtained from mensuration, but in general pressurisation will be required. The crack flow equations described in (10) apply to only fairly limited types of crack, but it has been found that they can be used for the complex openings which are encountered in practice. This is illustrated in Figure 2. The fundamental point to note is that A is independent of pressure difference.

In contrast an effective orifice area A_E, which is defined by taking a constant value for the discharge coefficient, varies with $\overline{\Delta p}$. Since the predicted flow rate is given by $Q = 0.6\ A_E\sqrt{2\ \overline{\Delta p}/\rho}$, Fig.2 shows that a value of A_E measured at 20 Pa say, can considerably overestimate the flow rate at 2 Pa. As a ventilation characteristic, A_E is therefore unsatisfactory and needs to be used with caution.

3.3 Background Leakage Areas

Background leakage areas are all those not accounted for by the previous two categories. They are by definition those leakage areas left over when the purpose-provided and component openings have been sealed. Taken globally, for it would be difficult and perhaps pointless to treat them singly, the background areas of rooms may be characterised fairly well by an effective open area and crack-flow equations (10).

The data necessary to derive these parameters comes in the main from pressurisation measurements on, say, a room in a house. By themselves such measurements would produce the total open area of the room. Purpose-provided and component openings may be sealed but those background areas which communicate between interior spaces will still be included. These areas may account for considerable leakage but are not of direct relevance to fresh air entry.

To aid in determining the distribution of background areas necessary for accurate prediction methods,* techniques allowing a more direct measure of the parameters of interest are being investigated by British Gas. The total exterior leakage of a room, neglecting complications due to cavity walls, may be determined if

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* the leakage distribution is an important part of the data required for "Vent", the British Gas method (17).

the rest of the building is balanced to the same pressure as the room under test. There will then be no flow to other interior spaces (leakage to adjoining houses may also be determined in this way). However, not all of the necessary information can easily be produced in this way. There are practical difficulties in distinguishing between external leakages through walls and through ceilings, or floors, but this needs to be done because the former will be more susceptible to wind pressures than to stack effect pressures.

A further technique, using a tracer gas in conjunction with pressurisation, has been developed. A tracer is injected into a communicating space, e.g. loft, to a constant concentration. The room under test is depressurized and the external leakage measured as described above. Now, however, the ratio of the steady-state tracer concentrations of the room and injected space gives the ratio of the leakages from the injected space (loft) and from the other areas (walls). This procedure is not much more complicated than the first and conceivably could be used to determine leakages to all communicating areas of a room. The technique may also be of use in determining the leakage characteristics of large buildings, where overall pressurisation may be difficult.

These techniques have been used successfully as shown in Figure 3, where the individual room leakage characteristics of a test house have been investigated.

3.4 Whole-House Leakage Characteristics

The whole-house leakage is the simplest and fastest quantity to measure and as such it provides the least information. The total leakage characteristic is generally measured at pressures large enough to overcome those generated by weather conditions. This is useful for purposes of comparisons, however the large pressures used may affect the relevance of the leakage measurement to ventilation characteristics.

The whole-house leakage is a global characteristic and as such would not seem to be a good basis of ventilation prediction, because no indication of the locations or communications of the measured leakage is given. For example, two houses with the same measured leakage, one of which has all the open area on external walls, the other dividing the area between floor and ceiling, would conceivably have quite different ventilation characteristics even if sited side by side.

Figure 4 shows the results of a preliminary investigation of the relation between measured leakage and ventilation. Ventilation measurements were to be done in a number of identical houses, concurrent with a measurement in a control house. Thus the ventilation rate of a house, relative to the ventilation measured simultaneously in the control, could be compared to its leakage relative to the control house. Practical difficulties experienced in the measurement of ventilation in occupied houses, and in organising sufficient access precluded any definite conclusions. A number of the comparisons needed to be done with data from a regression model of the control house (this is felt to be reasonable as the model was produced from nearly 60 hours of measurements under the weather conditions experienced for all tests). There does not appear to be any useable relation between leakage and ventilation. It is felt that long-term experiments similar to this, comparing simultaneous measurements to eliminate the effect of weather, will be needed to determine any useful relationship between these two characteristics.

A further complexity in relating leakage and ventilation is the apparent variation with time of the whole-house leakage. As well as a possible seasonal variation there appears to be considerable changes in a building as it settles and ages from its "new" state. Recent tests on several nominally identical houses showed, as well as large variations between houses, an average increase in total leakage of 70% over the first two years of occupancy, with most of this change apparently occurring in the first year. As, unfortunately, the easiest and most convenient time to make such measurements is before occupation, the leakages measured may not reflect those found in occupied homes.

The leakage equipment used by British Gas has advantages in occupied houses. It is small, easily transported and set up and as such causes little disruption in use. A high-pressure/high-volume centrifugal extractor is used, allowing an accurate conical inlet meter (12) and narrow flexible outlet ducting. Installation can be made through a small openable window. The equipment can be used as a module for leakier buildings (see Plate 1).

4. MEASUREMENT OF VENTILATION RATES WITH TRACER GAS

There are three main variants on the tracer gas theme, i.e. constant emission, tracer decay and constant concentration (13). Each method has strengths and weaknesses and each has suitable applications. The emphasis of our work has been on determining individual room ventilation rates and as such the constant concentration method has distinct advantages over the others. We have however made use of the other methods and these will be briefly discussed.

4.1 Constant Emission

In this method tracer gas is released at a fixed rate and after a suitable time lapse for the attainment of equilibrium the ventilation rate can be found from the tracer concentration. We have used the method to measure loft air change rates (14). CO_2 was used as the tracer and its concentration was sampled every minute. The average air change rate over 30 minute periods was found by averaging the concentrations.

4.2 Tracer Decay

The house is filled with a uniform concentration of tracer gas and the decay is monitored by discrete or continuous sampling at one or several points. For the measurement of whole-house ventilation rate, where the house is treated as a single cell, the method can give adequate results if the mixing in and between rooms is good. This mixing destroys information about the room rates and can influence the whole-house rate.

We have used a variation of the method to obtain simultaneous values of room ventilation rates and the whole-house rate. The difficulties which were encountered are described in (15). Although the method appeared to give reliable whole-house rates (it was possible to detect the effects of sealing windows), the room rates were much less reliable, and because these rates are of considerable interest to us it was decided to develop a system (see Section 5) based on the constant concentration method.

4.3 Constant Concentration

In this method tracer gas is released so as to maintain a constant concentration in each room of the house. During any accounting period (usually 30 or 60 minutes) the amount of fresh air that enters a room is directly proportional to the amount of gas injected to maintain the required concentration.

There are several advantages in this method for whole-house and for individual room rates. Firstly, the concentration of tracer gas is uniform in all rooms so that cross flow between rooms does not influence the measurements. Secondly, there is no need for any subjective assessment of the role of the room as an outlet or inlet of fresh air, because the technique measures the amount of fresh air coming into each room. This includes ventilation arising from turbulent pressure pulsations. Thirdly, it is relatively straightforward to use multiple tracer gases to measure flow from cell to cell within the house. Fourthly, the method is very suitable for automation, and one can take advantage of this by developing a computer controlled system which enables continuous monitoring of ventilation and on-line analysis of results.

At British Gas we have developed such a system, known as "Autovent". The current version is shown in Plate 2.

5. DESCRIPTION OF THE AUTOVENT SYSTEM

The system consists of two networks of solenoid valves. One network of valves controls the sampling of air in each room, the other controls the injection of tracer gas to maintain the target level. The solenoid valves are activated by a command from the central computer logger which controls both the sampling and the injection sequences. The sampling lines are purged continuously to ensure that a fresh sample of room air reaches the analyser and all lines are of equal length to minimise differences in flow resistance. The rooms are sampled in sequence for 6 seconds each.

At the end of that period the analyser output is read by the computer and the injection period necessary to maintain the target concentration in that room is calculated. The relevant injection valve is then opened and the next room in the sequence is sampled. When the injection period has elapsed the computer closes the valve and stores the time for which the valve was open. Every half hour the results are summarised and the volume of air entering each room together with the relevant temperature and weather data is printed. A more detailed description of this system has been published in (16) and a full one is in preparation.

Mixing between the injected tracer gas and the room air is very important to the accuracy of the method. We adopt three measures to increase the effectiveness of mixing. Firstly, injection of gas into a room ceases six seconds before the room is next sampled. Secondly, a purge pump is used on the sample line to ensure a fresh sample, accurately reflecting the present state of the room, is available to the analyser. Thirdly, the injection lines are terminated in areas of high air speed, either near radiators or behind small mixing fans. These measures appear adequate in most circumstances where we have tested them by sampling room air at several points.

To illustrate the power and potential of the Autovent system, examples of its application are given in the following.

5.1 Continuous monitoring of ventilation

One advantage of continuous monitoring over discrete measurement is that it is possible to observe subtle variations due to wind speed and direction changes more quickly, more accurately and with less effort. Figure 5 shows some typical results obtained in an end-of-terrace house with all doors and windows sealed. The weather conditions and the corresponding changes in whole-house ventilation rate over nine consecutive 30-minute periods can be seen.

Another advantage of continuous monitoring of ventilation rates over long periods is that it is sometimes possible to isolate the effects of individual weather parameters. Figures 6 and 7 give two examples of this.

Figure 6 shows the effect of wind direction on the ventilation rate of a room in an end-of-terrace house. Also shown is the effect on the whole-house rate, which is much less pronounced.

Figure 7 shows the effect of wind speed on the whole-house rate for three wind directions, for two of which stack effect is clearly dominant.

Results like these illustrate the value of the 'Autovent' system for investigating the complex nature of house ventilation.

5.2 Multiple gas experiments

To illustrate this aspect of the system, we use the example of loft ventilation. The loft seems to be a very important route by which air can leave a house. Sealing some of the obvious leakage paths to a loft might make a significant contribution to energy conservation.

Using two tracer gases, we used N_2O and CO_2, it is possible to measure simultaneously the whole-house ventilation rate, the loft ventilation rate and the proportion of air escaping from the house to the loft. Figure 8 shows loft air change rates as a function of wind speed and direction measured in a detached house. It is interesting that a strong directional effect was observed, with winds blowing directly at the roof tiles causing much higher ventilation rates. It was also found that the proportion of house air escaping through the loft depended on wind speed. In low winds, 80% escaped through the loft. This is probably because at low wind speeds the stack effect is dominant and acts on the cracks in the ceiling. As the wind increased, so the proportion of air leaving through the loft was found to decrease. At 5 m/s wind speed it was 40% of the total leaving the house.

Multiple gas experiments could be extended to measure the flow from or to any room or area within a house.

6. CONCLUSIONS

6.1 Wind tunnel models appear to be suitable for obtaining external pressure distributions. There are considerable problems however associated with the measurement of ventilation rates in models. Such measurements are probably restricted to pure research rather than general design purposes.

6.2 Leakage measurements at steady high pressures are relatively easy to do, but they suffer from the disadvantage that they may not be very meaningful for natural ventilation which occurs at low pressures. High-pressure leakage characteristics can be used as a basis for comparison, but it remains to be seen whether they can be usefully correlated to natural ventilation rates.

6.3 Techniques for determining the low-pressure leakage characteristics of dwellings could prove valuable. The method for determining open areas developed by British Gas has proved useful for component areas, but has yet to be developed for complete buildings.

6.4 As a general rule, measured open areas should be independent of flow rate. This is particularly true when they are used as data for a prediction method. The prediction method developed by British Gas also requires the spatial distribution of background leakage areas to be specified. Methods for determining this have been devised with encouraging results.

6.5 For measurement of whole-house ventilation rates, techniques based on tracer decay, constant emission or constant concentration can be used. However, when simultaneous measurements of room ventilation rates are also required, the constant concentration technique is much superior.

6.6 The 'Autovent' system developed by British Gas is a computer controlled automatic ventilation monitoring rig based on the constant concentration technique. It has been used with considerable success for investigating the complex features of multi-cell ventilation, with single and multiple tracer experiments.

ACKNOWLEDGEMENTS

The permission of British Gas to publish this paper is gratefully acknowledged.

Some of the work described has been carried out by British Gas in dwellings at the Abertridwr test site, which is being monitored by UWIST under the sponsorship of the Housing Development

Directorate of the Department of the Environment. Their co-operation is gratefully acknowledged.

DWE/JW
18.6.1980

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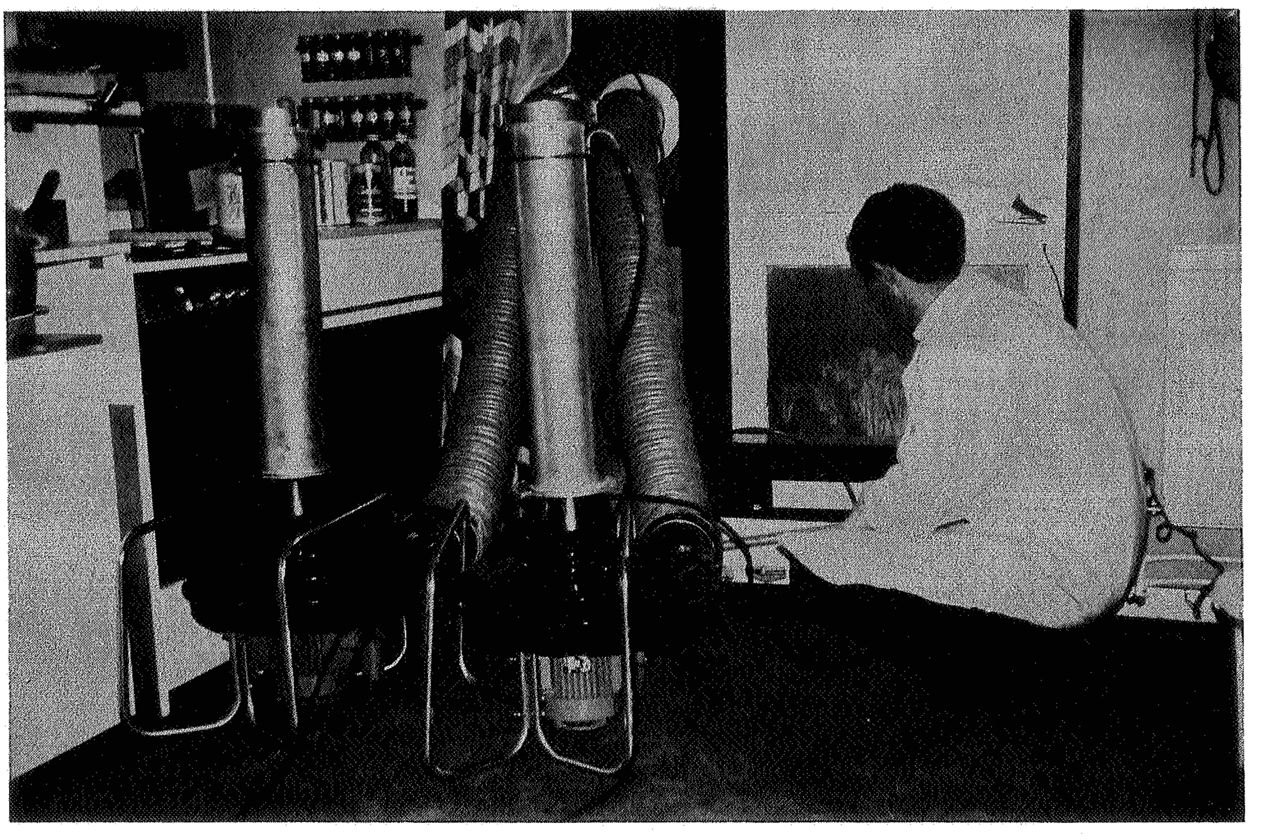


PLATE 1 PRESSURISATION EQUIPMENT DEVELOPED FOR WHOLE-HOUSE LEAKAGE MEASUREMENT (AS SHOWN) AND FOR MEASUREMENT OF LEAKAGE DISTRIBUTION.

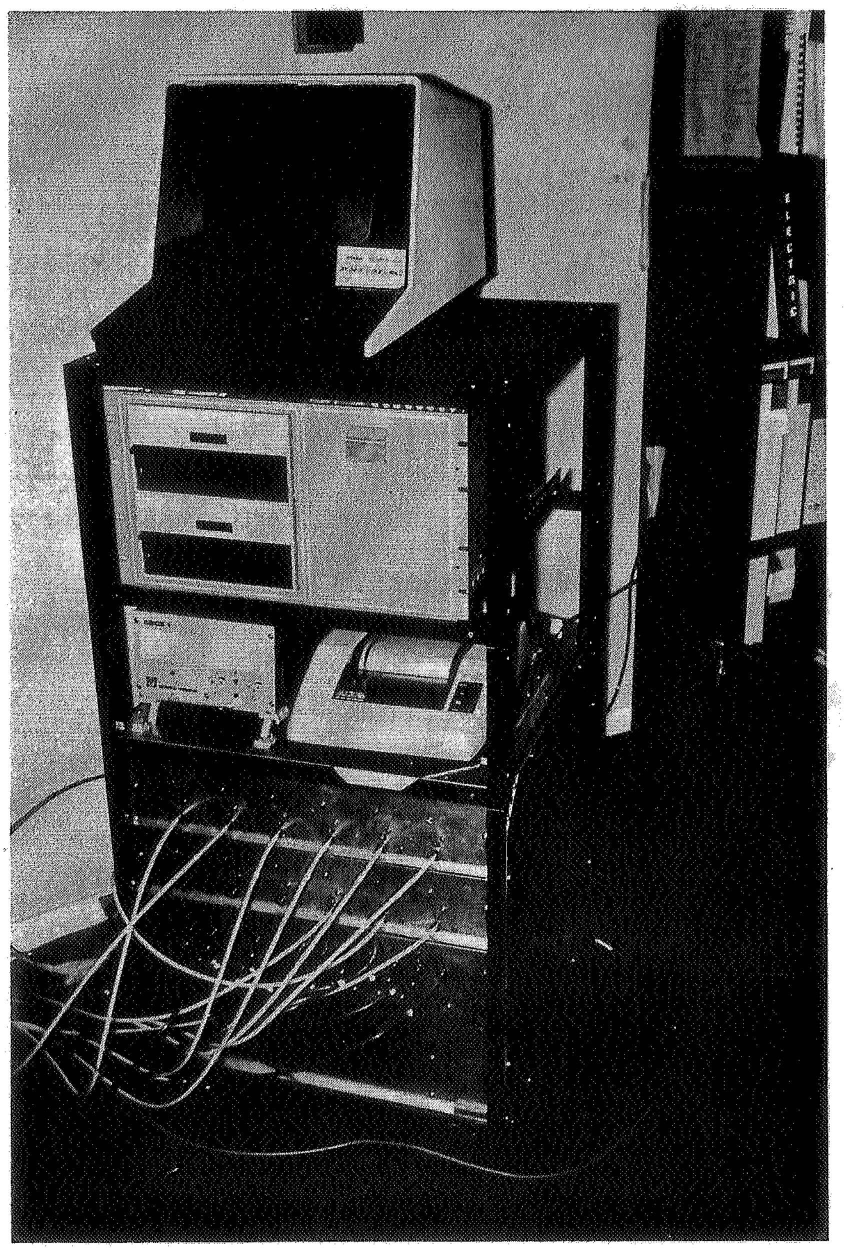
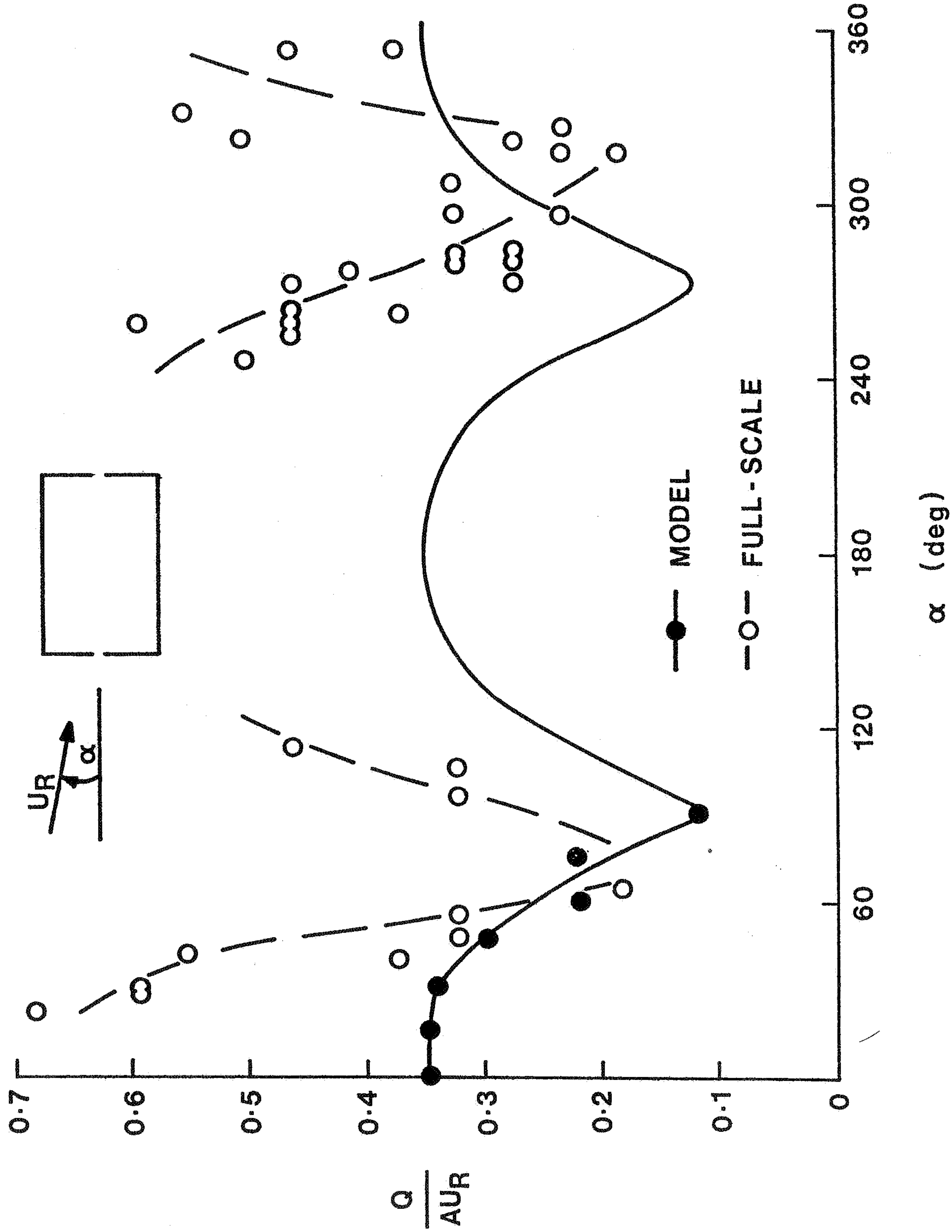
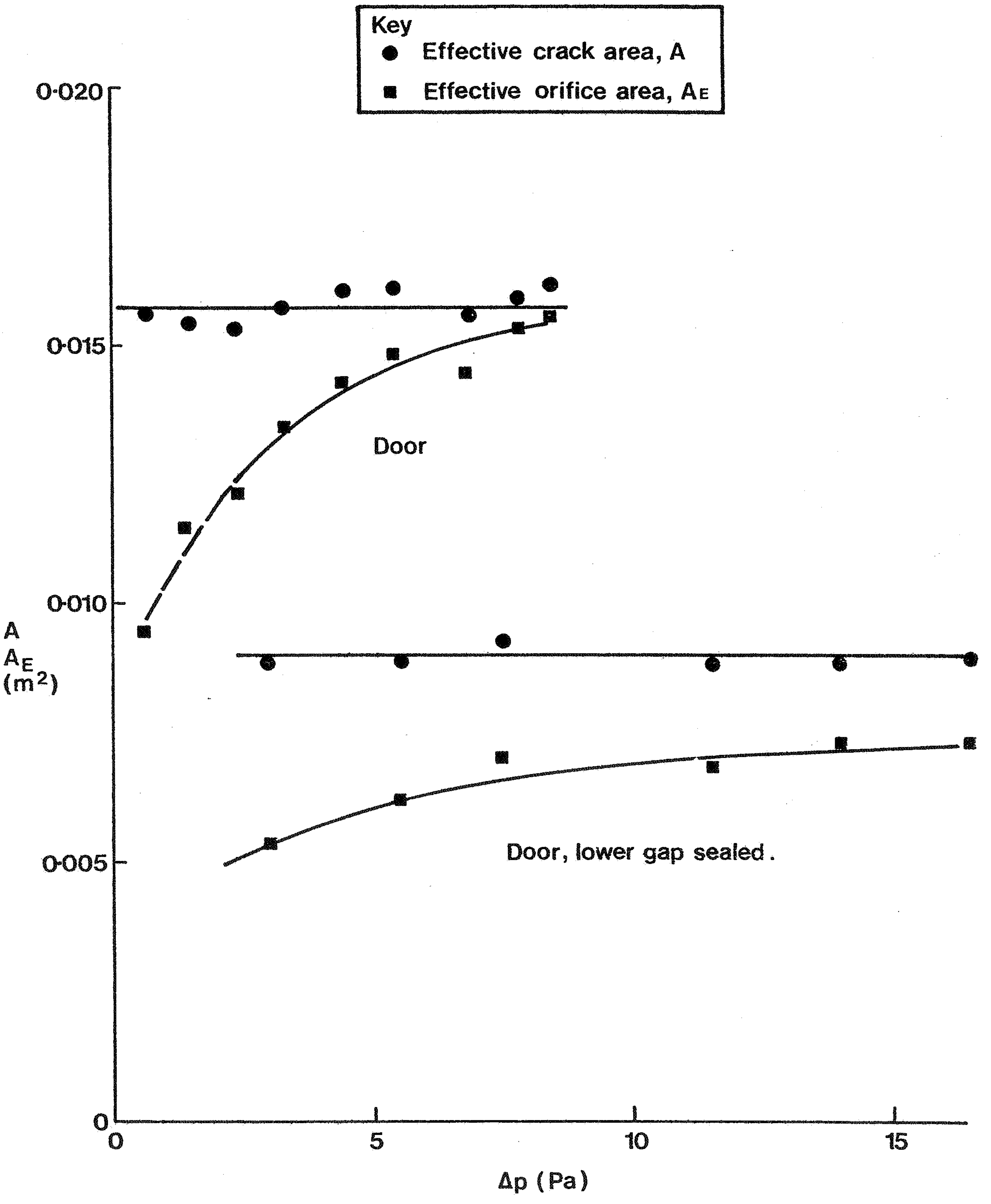


PLATE 2 'AUTOVENT' CONTROL AND ANALYSIS SYSTEM, DEVELOPED FOR CONTINUOUS MONITORING OF VENTILATION RATES (ROOMS AND WHOLE-HOUSE).



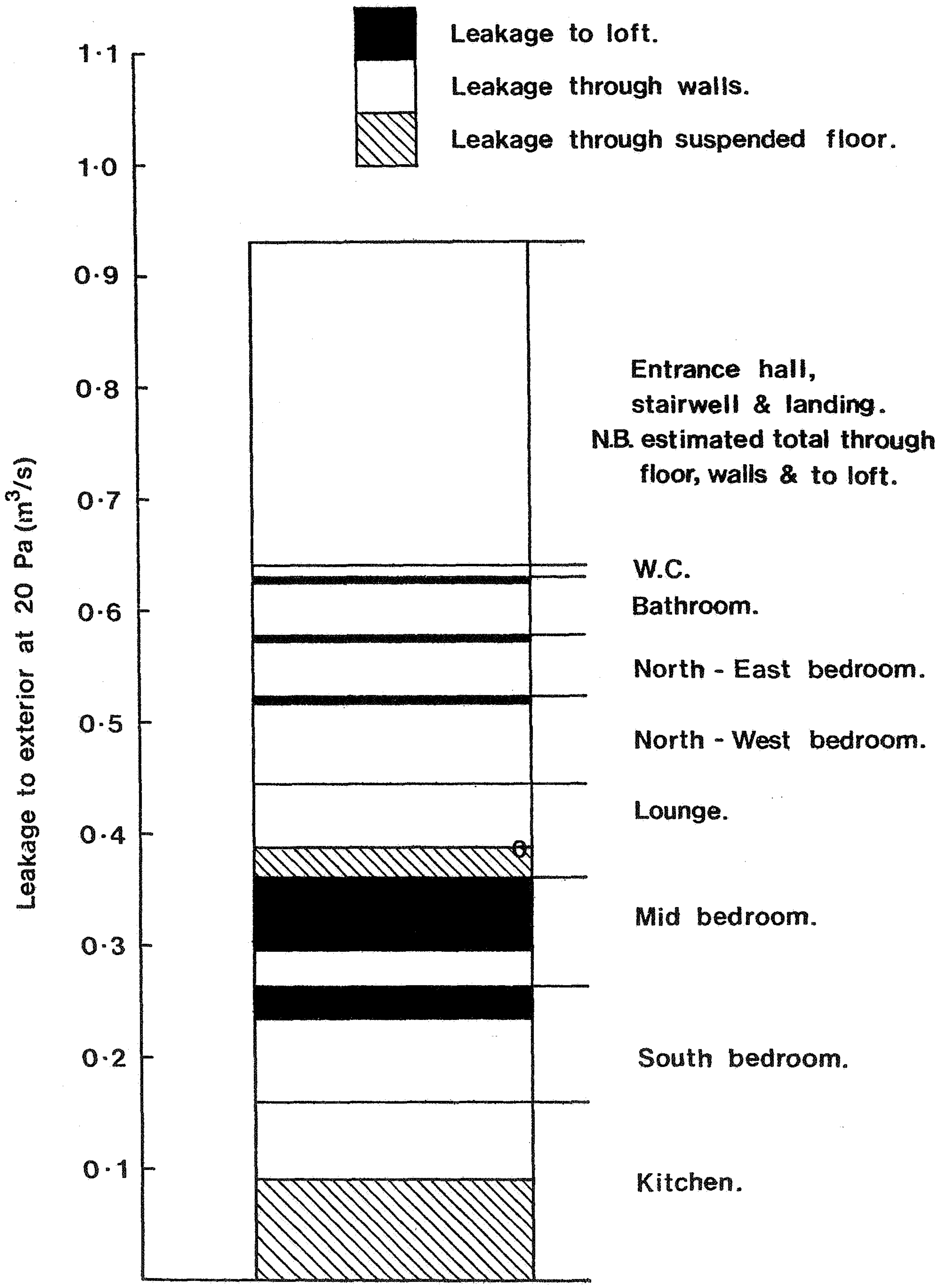
COMPARISON BETWEEN FULL-SCALE AND MODEL-SCALE VENTILATION RATES FOR A SINGLE-CELL STRUCTURE WITH SHARP-EDGED OPENINGS

Fig.



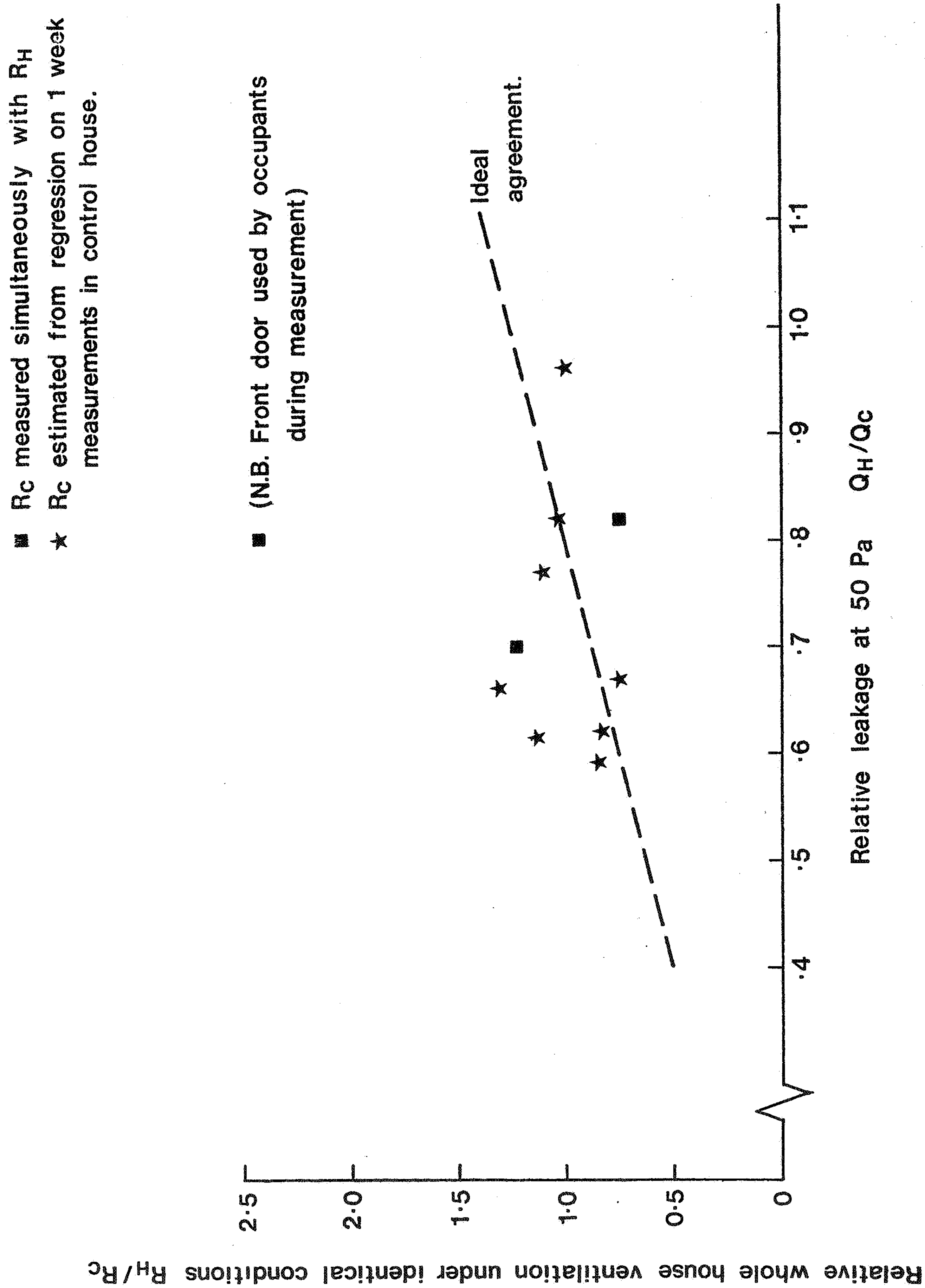
EFFECTIVE CRACK AND EFFECTIVE ORIFICE AREAS DETERMINED FROM LEAKAGE TESTS

Fig. 2



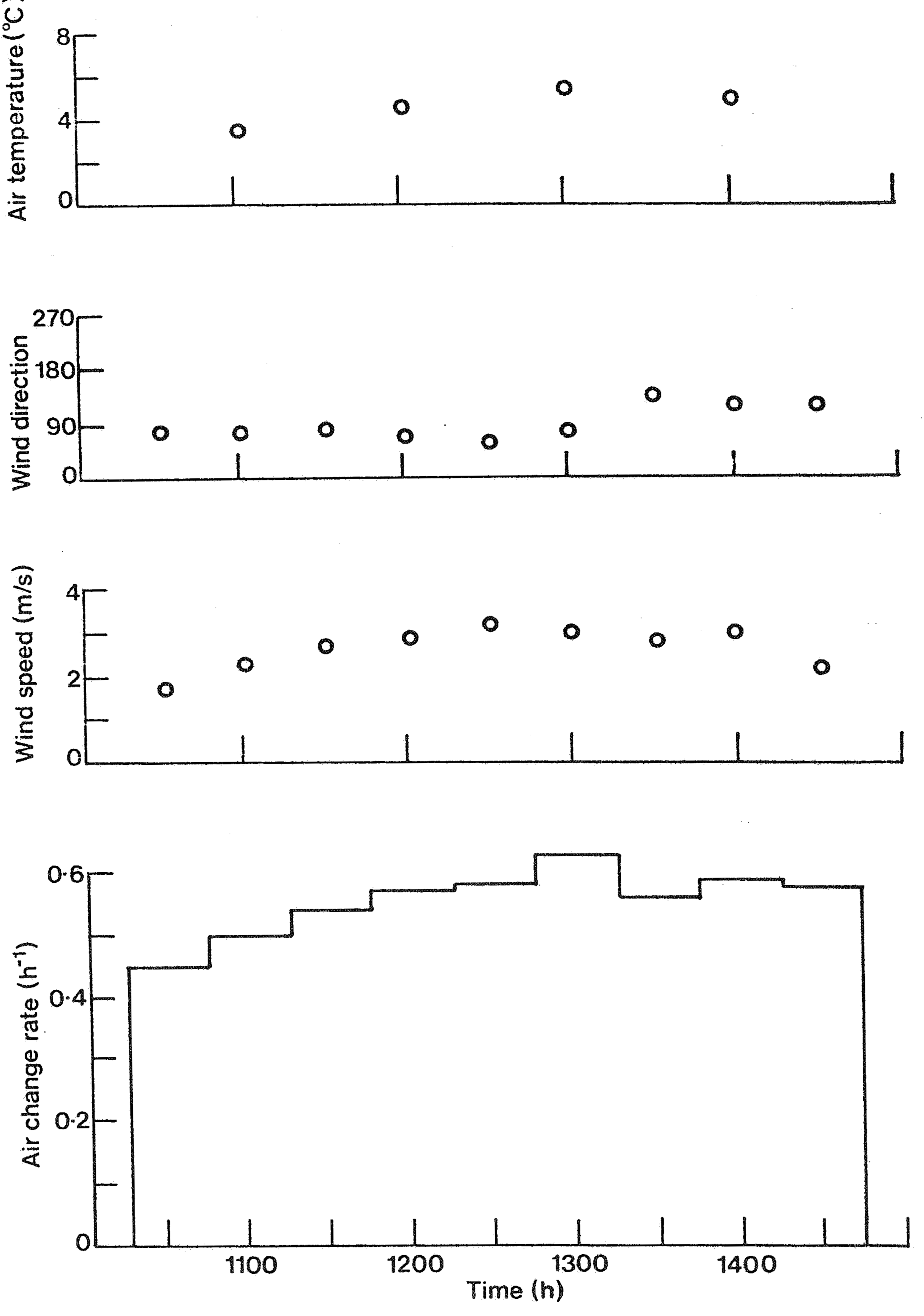
SPATIAL DISTRIBUTION OF LEAKAGE TO EXTERIOR MEASURED IN A DETACHED HOUSE.

Fig. 3



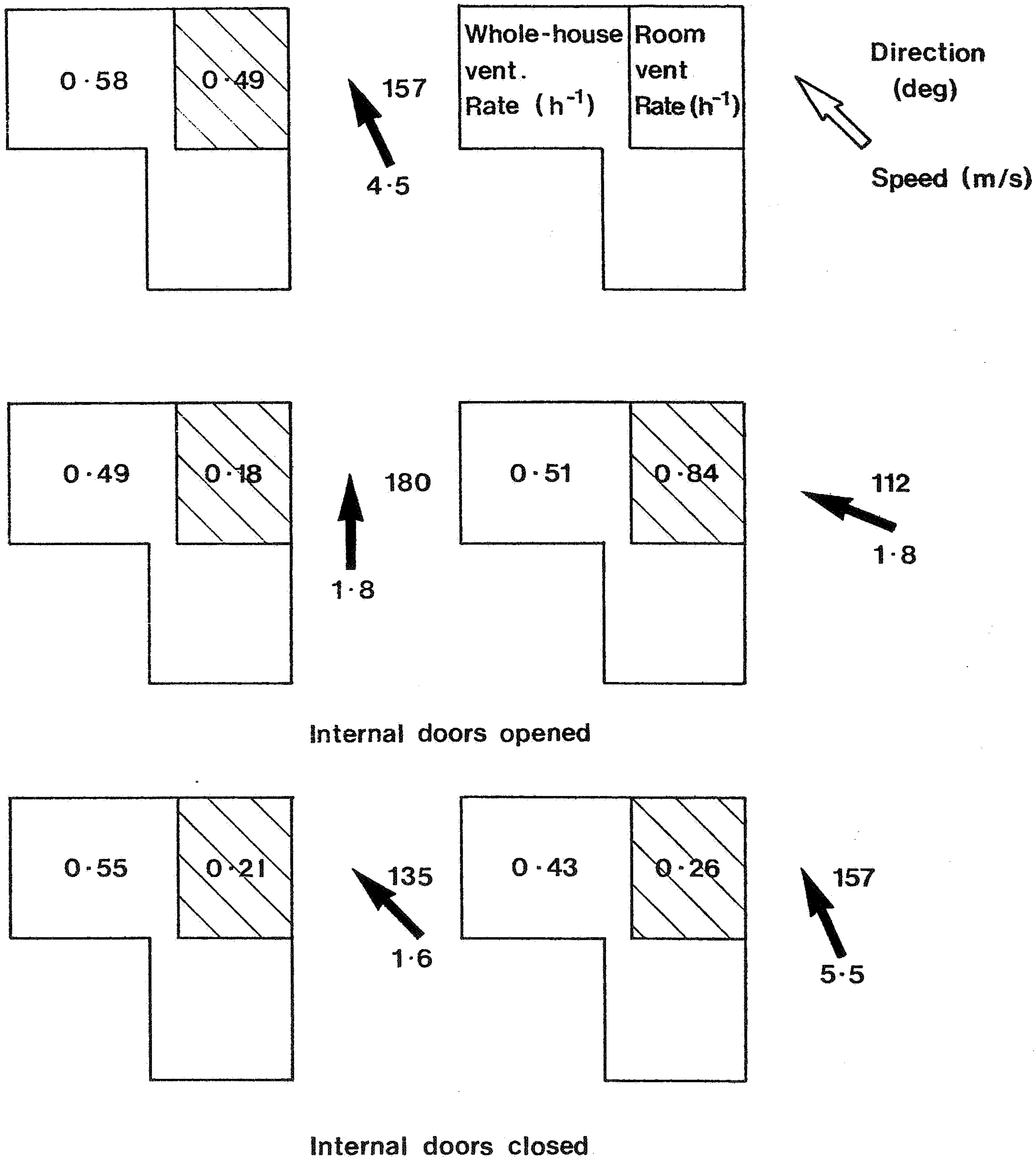
INVESTIGATION OF POSSIBLE RELATION BETWEEN VENTILATION AND LEAKAGE.

Fig. 4



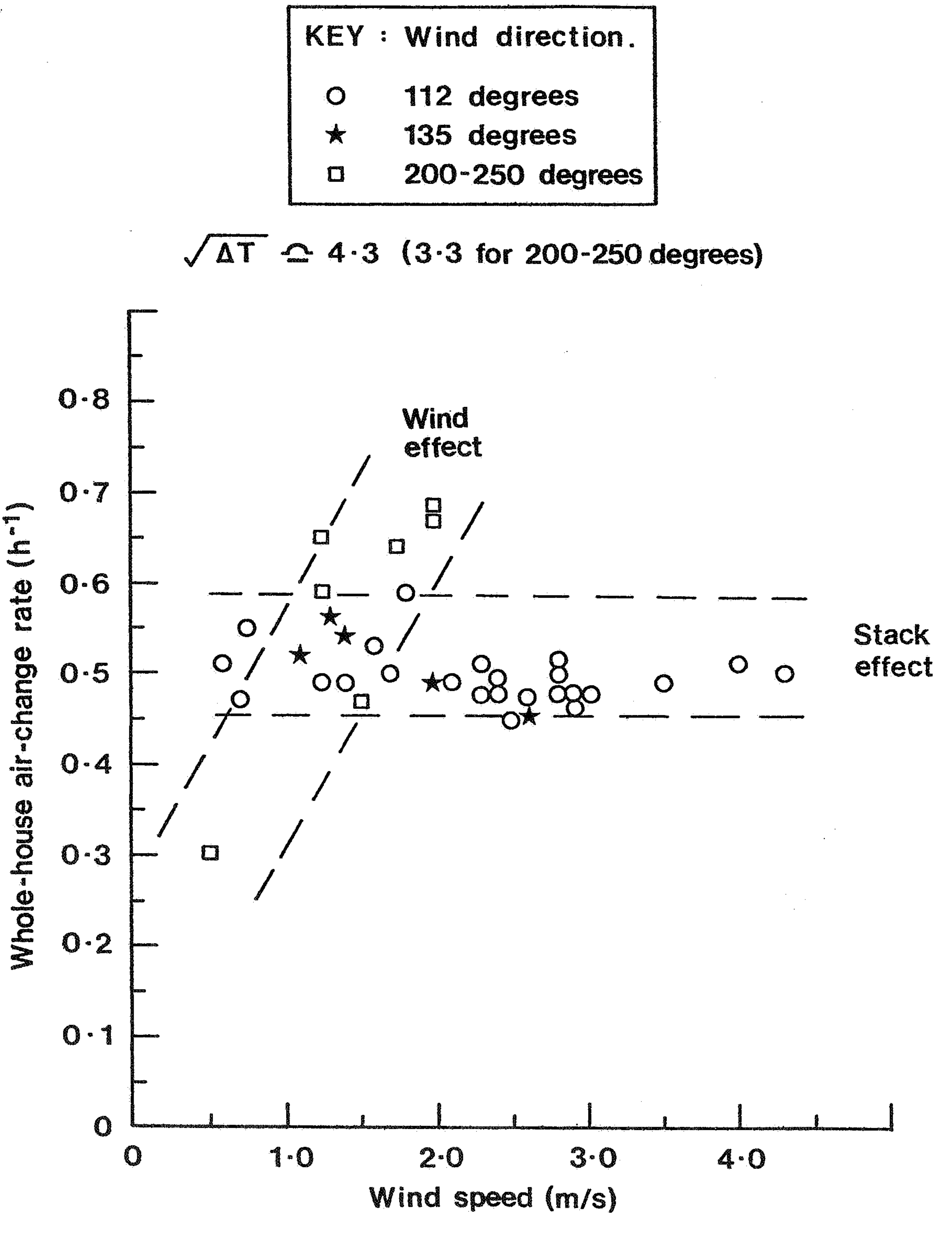
CONTINUOUS MEASUREMENT OF WHOLE-HOUSE AIR CHANGE RATE WITH 'AUTOVENT', AND CORRESPONDING WEATHER CONDITIONS

FIG. 5



VARIATION OF WHOLE-HOUSE AND ROOM VENTILATION RATES WITH WIND SPEED AND DIRECTION ($12°C < \Delta T < 16°C$)

Fig. 6



WHOLE HOUSE VENTILATION: EFFECT OF WIND SPEED FOR CONSTANT STACK EFFECT (0 DEGREES = BUILDING AXIS)

Fig. 7

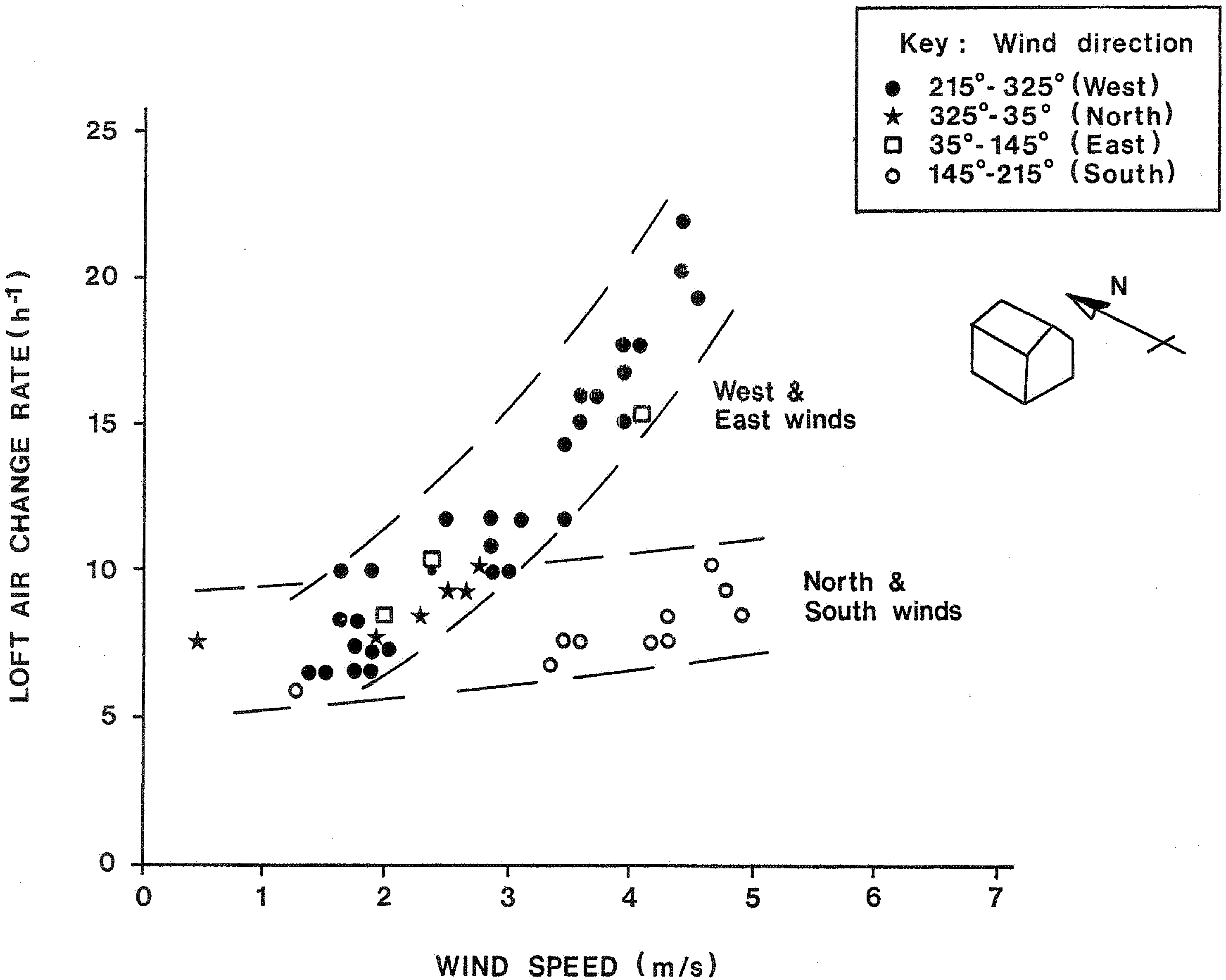


Fig.8

VARIATION OF LOFT AIR CHANGE RATE WITH WIND SPEED AND DIRECTION FOR A DETACHED HOUSE