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VENTILATION WITH OPEN WINDOWS

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SUMMARY

While some fresh air ventilation is necessary for comfort and health, excessive ventilation can result in more heat being lost from a house as hot air than by thermal conduction through the walls and roof.

The ventilation rate and energy consumption of one of the ECRC Test Houses with one bedroom window open by various amounts was monitored continuously during one heating season.

The results show that a very small window opening is sufficient to satisfy ventilation requirements most of the time.

While air flow paths in and out of the house are mainly determined by wind direction, air flow between rooms is temperature induced and a very large air interchange takes place even for temperature differences of one or two degrees.

The energy cost of ventilation can be calculated provided that the temperature of the air leaving the house is known. This will usually be the bedroom temperature.

The measured ventilation rates could be related to the measured house leakage only by assuming that stack effect ventilation took place mainly through openings into the basement and loft while wind induced ventilation took place through other openings in the front and back of the house.

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CONTENTS

1. INTRODUCTION

The opening and closing of windows represents the most common way of controlling ventilation. However, ventilation in the heating season uses energy because the cold fresh air from outside displaces an equal volume of warm air from the house and the fresh air must then be heated up to room temperature. The energy required to heat the fresh air is generally known as the 'ventilation heat loss'.

For a typical house of volume 200 m^3, thermal insulation by readily available methods can reduce the heat loss by conduction through the walls, ceiling and floor to about 3 kWh per degree day. In this type of house the ventilation heat loss will exceed the fabric heat loss if the ventilation rate is greater than 1.8 air changes per hour, which as will be shown can often be exceeded by moderate window opening. Thus, excessive ventilation can negate the effectiveness of thermal insulation.

Ventilation rates arising from open windows have been measured in the two houses shown in Figure 1. House A (Kemnay) is a well-insulated detached wooden house with weather-stripped, wood-framed windows hinged at the top. House B (10 Manorfield Close) is a more conventional brick semi-detached house, with weather-stripped, metal-framed windows which are horizontally pivoted at the mid-points of the vertical sides. Thermal insulation of house B is to 1975 Building Regulations. The windows are shown in Figure 2.

2. VENTILATION NEEDS

Ventilation is required mainly to remove objectionable odours and excessive moisture(1). Water vapour is associated with washing and cooking, and requires intermittent local high ventilation for its removal. Odour removal in an average size room (30 m^3) with three or four people in it requires more than 2 room air changes per hour of fresh air, but if the room is intermittently occupied one third to one half of an air change per hour will probably be sufficient to avoid discomfort.

Thus, in a domestic environment it is necessary to be able to vary the local ventilation rate between about one third of an air change per hour and 3 to 4 changes per hour. For more details refer to ECRC/M1197.

Unless heat is recovered from exhaust air, minimising ventilation heat losses is achieved by minimising ventilation rates.

3. EXPERIMENTAL METHODS

Tracer decay methods were used to measure ventilation rates in individual rooms. Both carbon dioxide and nitrous oxide have been used as tracers using a Hampden Gas-O-Mat and Miran 103 Infra-Red Gas Analyser respectively.

A uniform tracer concentration was first established throughout the house, with the assistance of mixing fans mainly in the internal doorways. The fans were then switched off, the appropriate window opened and the decay rate measured in the appropriate room. The decay rate was calculated from a chart recorder trace of gas concentration versus time.

Internal doors were open and the houses were heated electrically to 19^{o}C throughout.

The ventilation rate was also monitored continuously under various window and weather conditions by the equilibrium concentration method in which the tracer gas is introduced into the house at a known flow rate. Mixing fans ensure a uniform tracer concentration throughout the house. The tracer concentration recorded on a chart recorder gives a continuous measurement of the ventilation rate.

House and individual room leakage were also measured using the pressurisation technique.

Details of all these methods are given in reference (2).

4. NATURAL VENTILATION WITH WINDOWS CLOSED

Even when all windows and external doors are closed, a house is ventilated through fortuitous cracks in the structure. The ventilation rate will be weather-dependent since wind and temperature differences are the driving forces. The size of fortuitous cracks may also undergo seasonal variations particularly where there are timber/brick interfaces.

Ventilation rates in these houses, with all windows and doors closed, as measured by tracer decay, are given in Figure 3 and Tables 1 and 2. Both houses would be classed as fairly 'tight' by British standards; neither has a flue. It is seen that under normal conditions the background ventilation rate is less than 0.5 air changes per hour.

The significance of these data is that they represent minimum possible ventilation rates set by the structure under the prevailing weather conditions. The air change rate can only be increased.

Further measurements in House B by the continuous method produced ventilation rates for a wide range of weather conditions: ΔT from $5^{o}C$ to $23^{o}C$ and mean wind speed up to 8 metres per second, Figure 4.

With windows closed the ventilation rate is influenced by wind and temperature over the whole range of conditions encountered. Wind direction, however, was relatively unimportant, Figure 5.

5. VENTILATION WITH WINDOWS OPEN

When the ventilation rate with open windows is considered, the immediate problem is the wide range of possible options of which windows to open and by how much. The position of internal doors will also be significant but to reduce the number of variables, these doors were left open throughout.

Surveys have shown that bedroom (i.e. upstairs) windows are commonly left open for long periods. The present investigation was therefore restricted to open windows in upstairs rooms.

The ventilation rate considered relevant was an average fresh air rate for the whole house, since this will determine the energy cost. Individual room rates depend on whether the room is ventilated from outside or with air from other rooms in the house.

It is convenient to categorise rooms in relation to the wind direction as:

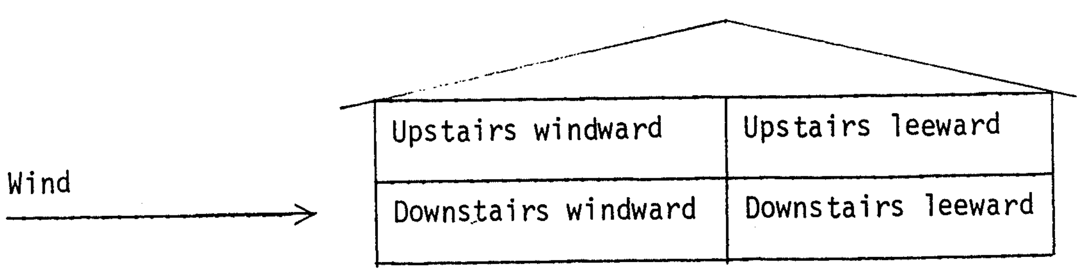


TABLE 1 - Data for Figure 3 (House A)

Wind speed m/s	Wind (from) direction	Outside temp. °C	Inside temp. °C	ΔT °C	Ventilation ac/h
1.5	345	10	18	8	0.14
0.8	330	9	18	9	0.14
0.5	variable	9	18	9	0.13
1.0	150	12	18	6	0.12
1.9	150	11	18	7	0.17
3.3	150	14	18	4	0.17
4.0	140	14	18	4	0.25
3.1	160	13	18	5	0.14
1.2	140	14	19	5	0.14
4.8	240	12	19	7	0.36
1.2	210	5	17	12	0.16
1.0	230	4	17	13	0.17
0.1	variable	6	18	12	0.19
0.2	"	3	17	14	0.19
2.9	100	5	17	12	0.43
4.0	90	4	17	13	0.47
4.0	80	2	17	15	0.49
4.0	100	3	19	16	0.50
3.8	150	7	18	11	0.25
1.5	260	3	19	16	0.33
1.2	270	6	17	11	0.22

House faces 100° (i.e. approximately East), detached.

Windows all on front and back of house, except landing window and back door which are on North side.

House sheltered by other houses on North and West.

Ventilation measured by CO_2 decay, Hampden Gas-O-Mat Analyser.

TABLE 2 - Data for Figure 3 (House B)

Wind speed m/s	Wind (from) direction	Outside temp.°C	Inside temp. °C	ΔT °C	Ventilation ac/h
6.7	180	8.0	19.5	11.5	0.48
6.7	315	10.0	21.1	11.1	0.33
5.3	315	9.5	20.8	11.3	0.25
3.5	315	10.0	20.5	10.5	0.23
6.3	340	10.5	20.8	10.3	0.25
6.3	315	10.5	21.2	10.7	0.32
4.4	315	10.0	20.9	10.9	0.23
5.3	200	9.0	20.2	11.2	0.26
1.1	170	6.2	19.8	13.6	0.22
4.5	150	7.5	20.0	12.5	0.27
5.3	220	8.6	20.0	11.4	0.39
2.5	152	3.2	19.8	16.6	0.28
1.1	170	6.2	19.8	13.6	0.22

House faces 135° (SE), and is semi-detached.
Windows are on front and back of house.
House is sheltered on the SW side by its semi-detached neighbour and on the NE side by the next house in the row. There is a 2 metre fence on the NW boundary.
Ventilation measured initially by CO_2 decay and Hampden Analyser, the last five by N_2O decay and Miran 103 Infra-red gas analyser.

Some early results from Kemnay (House A) during which the wind remained very conveniently directly onto the front of the house are given in Figure 6 and Table 3, because they illustrate clearly the magnitude of the ventilation changes that open windows can produce. The windows were opened to the stop - about 8°. It can be seen that under average wind (3 to 4 m/s) and temperature conditions ($\Delta T \sim 10°C$), opening two leeward upstairs windows doubled the ventilation rate upstairs.
When instead two windward upstairs windows were opened, the ventilation increased to about 4 air changes per hour or eight times the closed window amount. When all upstairs windows were opened, through ventilation of about 20 air changes per hour occurred upstairs and also 2 to 3 air changes per hour downstairs - where the windows remained closed.

More detailed measurements were carried out at 10 Manorfield Close, Capenhurst (House B). The large front bedroom window was opened and the average whole house ventilation rate measured continuously. Three open window conditions were used:

(01) catch on first notch (approximately 2^{o})
(02) back of catch resting on window frame (approximately 4^{o})
(03) window open to main stop (approximately 11^{o})

By leaving this one window open all the time both leeward and windward orientations of the opening were achieved as the wind direction varied from day to day.

With the window open (01) the ventilation rate was not significantly greater than with the windows closed, except at high wind speeds, Figure 7.

With the window open (03), the most likely position that would be used in practice, the ventilation rate was very variable up to 7.5 air changes per hour throughout the house but sometimes as low as 0.5 air changes per hour depending on the wind speed and direction, Figure 8. During these tests the wind blew either on the end of the adjoining house or almost directly onto the front facade. With wind blowing on the end of the house the ventilation rate was 0.5 to 1 ac/h with very little weather dependence. With wind blowing on the front of the house ventilation increased linearly from 1 ac/h at 2.5 m/s wind to 7 ac/h at 8 m/s wind. Temperature difference appeared relatively unimportant in the range $\Delta T = 7$ to $13^{o}C$.

At the intermediate open window position (02) the ventilation was increased by a useful amount without being excessive. The ventilation rate throughout the house varied between 0.5 and 2 air changes per hour depending on the weather as shown in Figure 9(a). Wind direction now influenced the ventilation rate. End-on winds of 2 to 10 metre/second gave ventilation rates of 0.5 to 1 ac/h, almost independent of wind strength (Figures 9(d) and 9(e)). When the wind direction was onto the back of the house (i.e. on the opposite side to the open bedroom window) the ventilation rate increased approximately linearly with wind speed from 0.7 ac/h at 2 metres/second wind to 1.5 ac/h at 10 m/s wind (Figure 9(c)). Wind on the front of the house (i.e. directly into the open window) produced marginally lower ventilation rates at very low wind speeds (wind and stack effects opposed at the open window) but the ventilation increased rapidly with wind speed to more than 2 ac/h throughout the house when the wind reached 8 m/s (average speed) (Figure 9(b)).

6. EFFECTIVE LEAKAGE AREAS

6.1 Whole House

Ventilation takes place through a large number of intentional and unintentional openings in the house envelope. The pressurisation technique has been used for measuring and locating this leakage.

The room by room distribution of leakage in House B is shown in Figure 10. All internal doors were sealed and then unsealed one at a time so that, with the fan installed in the front door, the leakage of each room plus hall plus landing was measured. It is seen that the leakage is almost equally distributed between upstairs and downstairs and between front and back of the house. However, the kitchen/diner has rather more than 25% of the whole house leakage.

TABLE 3 - Data for Figure 6 (House A)

Open windows	Measured ventilation	Wind speed m/s	Wind direction	ΔT ^{o}C	Ventilation ac/h
all upstairs	upstairs	2.4	120^{o}	12.0	14.4
		4.4	90^{o}	9.0	22.6
		3.1	110^{o}	9.5	16.8
front upstairs	upstairs	3.4	120^{o}	14.5	3.4
		3.6	90^{o}	10.5	4.2
		3.3	130^{o}	10.2	2.8
all upstairs	downstairs	3.8	90^{o}	10.0	2.4
		4.6	90^{o}	9.5	2.8
		2.8	110^{o}	9.3	1.6
back upstairs	upstairs	1.3	90^{o}	15.5	1.1
		4.1	90^{o}	12.0	1.0
		3.1	110^{o}	11.5	0.94
none	whole house	2.9	90^{o}	11.7	0.43
		4.0	90^{o}	13.0	0.47
		4.0	80^{o}	14.5	0.48

Wind close to directly on front throughout

Windows opened to stop i.e. about 8^{o}

Hinged at top 875 mm wide x 980 mm high

It is convenient to express the leakage as an effective area defined as the area of an orifice which would allow the same air flow under the same pressure difference. This gives an effective leakage area of 0.115 metre^2 for House B with all windows and doors closed.

Another way of expressing the effective leakage is in terms of an air flow at a standard pressure difference, usually 50 Pa. However the maximum pressure difference Δp achieved was 30 Pa. By fitting a relationship of the type air flow rate = $m\Delta p^n$ with m = 246 and n = 0.655 an extrapolated value of air flow is obtained of 3180 m^3/h at 50 Pa.

On the same basis the effective leakage of House A is 0.061 metre^2 or 1650 m^3/h at 50 Pa (without extrapolation).

6.2 Open Window

The effective area of the open window in House B was measured by the same pressurisation technique with the fan installed in the bedroom doorway. The pressure difference Δp across the open window was measured, i.e. from inside the bedroom to outside the house.

The bedroom leakage was measured for the four possible situations:

window closed
window open on first notch (01)
window open resting catch on frame (02)
window open to main stop (03)

The flow versus pressure relationships are shown in Figure 11. In principle, these could be expressed as equivalent leakage areas using the previous calibration but the pressure dependence of the flow is now different because the open window does not behave like a crack.

To recalibrate the apparatus for open window type flow the window was replaced by an adjustable slot of the same width as the window opening (700 mm) and 10 to 150 mm wide in steps of 10 mm. Figure 12 shows the resulting flow versus pressure difference curves. Since the areas of the slots are known, comparison with Figure 11 enables an equivalent slot area to be assigned to each window condition as follows:

(01) 0.013 m^2
(02) 0.026 m^2
(03) 0.11 m^2

It is noted that the equivalent leakage when the window is open to the main stop (03) is comparable to the total house leakage, with all windows closed.

7. AIR FLOW AT OPEN WINDOWS

The air flow patterns at open windows was investigated qualitatively using smoke.

On the windward facade the wind pressure is such that air enters through small openings. However, since the wind blows along the outside wall surface the detailed air flow at an open window will be influenced by the aspect the open window presents to the air flow. In particular, a window which when open protrudes beyond the outer wall surface may cause both inward and outward flow. This contributes to the very high local air change rates occurring in a room with an open windward window. However such high air change rates do not represent air flow through the house of this magnitude as was confirmed by measuring the ventilation rates in other rooms, and so a two-way flow must be taking place at the open window. Figure 13 shows the results of the smoke tests. Cold air entered the house at the lower edge of the window whereas at the top of the open window both inward and outward flow took place from time to time. The flow is turbulent and variable. A cold draught along the floor into the room is inevitable, while warm air escapes from the top of the window, apparently against the wind direction.

On the leeward side of the house, there is suction outwards at any opening or crack resulting in air flow out of the house. On the outside the air is turbulent with eddies but the air flow through the open window is very smooth. However, if the wind speed is less than 1 or 2 m/s temperature effects may dominate giving a flow out at the top and in at the bottom of the open window, resulting in a cold downdraught at the window, similar to the windward case, and a draught into the room along the floor of typically 0.3 metre/second, as shown in Figure 14.

At a leeward window the turbulence is outside, but the flow out of the window is much more predictable and smooth than at a windward window.

8. AIR TRANSFER WITHIN THE HOUSE

The flow from room to room within the house through open doorways was investigated with smoke. It was found that even when a room had an open window a two-way flow existed at the doorway, out of the hotter room at the top and out of the colder room at the bottom. A typical measured air speed distribution with a temperature difference between the rooms of 1°C is shown in Figure 15 for a windward room with window open. Even if the rooms are initially at the same temperature, the opening of a window will soon result in non-uniform temperatures between rooms. These findings agree with Bouwman[3] who predicted an air flow each way of 350 m^3/h, i.e. more than 10 air changes per hour, when the temperature difference is 1°C.

The flow between rooms on account of temperature differences can thus be much greater than the air flows caused directly by ventilation. A similar situation was observed on stairs with cold air flowing downstairs at stair level and a corresponding warm air flow upstairs at ceiling level. This explains why the influence of an open window is felt very quickly throughout a house whether the window is leeward or windward.

Room to room interchange of air was measured between lounge and kitchen/dining room (House B) by releasing a measured volume of tracer gas (nitrous oxide) in one room and measuring the resulting increase in concentration in the other room. With a moderate wind on the front of the house (2 m/s 180°) and all internal doors open, 5 litres of tracer gas was released in the centre of the lounge over 10 seconds. Within 6 minutes the tracer gas was detected in the centre of the kitchen, the concentration increased to a maximum value of 30 ppm in 15 minutes, thereafter decaying at a rate indicating fresh air ventilation of 0.17 air changes per hour.

Five litres of gas uniformly distributed throughout the house would give a concentration of 25 ppm, almost the maximum value attained in the kitchen, suggesting that the gas had dispersed throughout the house and hence mixing between most of the rooms in the house takes place within about 15 minutes.

With the wind on the opposite face of the house, i.e. opposing the tracer direction, similar results were obtained. With a 300° 5 m/s wind, tracer gas injected into the lounge produced a concentration in the kitchen after 12 minutes equivalent to the whole house mean value, followed by a decay in the kitchen equivalent to 0.62 air changes per hour and in the rest of the house of 0.2 air changes per hour, with tracer gas concentration being uniform throughout the house at the end of 1 hour, except in the kitchen where it was less.

Similar measurements were made with the lounge door closed. With wind on the front of the house (180^0 2 m/s) and gas injected into the lounge, virtually no tracer gas was detected in the kitchen/diner (a few ppm after 2 hours), while in the lounge concentration decayed at less than 0.1 ac/h. With wind on the back of the house, tracer was injected into the kitchen. With the lounge door closed, the concentration in the kitchen fell very rapidly (since it was open to the rest of the house) to about twice the mean whole house value after 10 minutes and then decayed more slowly while the tracer gas concentration in the lounge (door closed) rose to one third of the mean whole house value over 1½ hours at which time the upstairs was at one half of the mean whole house value. The kitchen meanwhile, being ventilated by fresh air from outside, showed the lowest tracer concentration (one fifth of the whole house mean value).

9. ENERGY COSTS OF OPEN WINDOWS - EXPERIMENTAL

House B was heated to a uniform temperature of 20^oC by thermostatically controlled panel heaters in the main rooms, hall and landing, supplemented by a fan heater in the large front bedroom when the window was open.

Energy consumption was monitored by kWh meters, one on each heater. Temperature was continuously recorded on 6 thermohygrographs in the kitchen/diner, lounge, hall, landing and both large bedrooms.
The ventilation rate was measured continuously at those same places and averaged to give a whole house value.

Table 4 gives the data for the period November 1978 to June 1979 in blocks of approximately 10 days.

The house energy balance can be written as:

$$\text{Electrical} + \text{Solar} = \text{Ventilation} + \text{Fabric}$$

where convenient units are kWh/day averaged over 10 days to even out thermal storage effects.

The electrical energy input was measured directly. The solar energy input must be estimated from an appropriate calibration procedure and the solarimeter reading of kWh per m^2 on the horizontal plane.

Since the temperature difference between inside and outside is varying continuously and also since heat loss from the house is proportional to this temperature difference, it is convenient to work in kWh per degree per day thus:

$$\frac{\text{Elec - Vent}}{\Delta T} = \frac{\text{Fabric}}{\Delta T} - \frac{\text{Solar}}{\Delta T}$$

where Elec, Vent, Fabric and Solar are expressed in kWh/day. Thus if $\frac{\text{Elec - Vent}}{\Delta T}$ is plotted against the integrated solarimeter reading of kWh per m^2 horizontal surface per day divided by ΔT, the intercept at Solar = 0 will give the fabric heat loss coefficient in kWh/(K day) and the slope will give the effective solar energy input to the house as a function of the daily integrated solarimeter reading. However, first a relationship between the measured ventilation rate and the associated energy loss is required.

Let the air in the house be at a uniform temperature T_1 and the outside temperature be T_0. If V = house volume = 200 m^3, A = ventilation rate (ac/h), ρ = density of air = 1.25 kgm^{-3} at 10^oC and Cp = specific heat of air = 990 J kg^{-1} K^{-1} then the ventilation heat loss is:

$1.65 \times A \times (T_1 - T_0)$ kWh/day

or $1.65\ A$ kWh/(K day)

If it is assumed that this estimate of the ventilation heat loss may be in error by as much as 30% then by selecting periods when the estimated ventilation heat loss is less than 20% of the total heat loss the maximum error due to wrongly estimating the ventilation heat loss is 6% With this proviso $\frac{\text{Elec - Vent}}{\Delta T}$ versus $\frac{\text{Solarimeter reading}}{\Delta T}$ is plotted in Figure 16.

A fitted straight line (correlation coefficient 0.97) gives:

$$\frac{\text{Elec - Vent}}{\Delta T} = 4.46 - \frac{4.08\ \text{Solarimeter}}{\Delta T}$$

TABLE 4 - Experimental Data: Energy Use

Dates 1978-1979	Window condition	Electrical kWh/day	Solar $kWh/m^2/day$	Ventilation ac/h	Temperature difference ^oC	
7-20 Nov	closed	45.34	0.562	0.219	9.94	
20 Nov-5 Dec	closed	75.55	0.530	0.314	15.31	
5-11 Dec	open to stop (03)	86.55	0.309	2.95	10.89/7.87	*
15-27 Dec	1st notch (01)	83.93	0.386	0.334	17.71	
27 Dec-8 Jan	1st notch (01)	92.71	0.478	0.362	18.18	
8-22 Jan	various	75.98	0.478	0.430	15.75	
12-23 Feb	back of catch (02)	108.53	0.755	0.728	19.03	
23 Feb-8 Mar	back of catch (02)	81.05	1.615	0.736	15.84	
12-22 Mar	back of catch (02)	90.38	1.666	0.637	17.50	
22 Mar-2 Apr	back of catch (02)	82.85	1.956	0.769	15.63	
4-12 Apr	closed	67.84	1.804	0.323	14.48	
12-20 Apr	closed	39.79	3.585	0.319	11.49	
20-30 Apr	closed	5.42	3.619	0.503	5.11	**
4-14 May	closed	44.07	3.857	0.30	11.76	
14-24 May	closed	37.86	3.768	0.281	11.44	
24 May-3 June	closed	37.13	3.481	0.230	9.81	
12-21 June	closed	17.58	4.778	0.241	7.74	

Notes: (1) Open window was in the front large bedroom

(2) *temperature differences refer to whole house and front bedroom respectively

(3) **house unheated, mixing fans account for electrical consumption.

Thus the fabric heat loss coefficient is 4.46 kWh/(K day) and the conversion factor from solarimeter daily integrated kWh/m^2 horizontal to useful kWh into the house is 4.08.

This solar heating factor is now used to replot the data in the form (Figure 17):

$$\frac{\text{Elec + Solar}}{\Delta T} = \frac{\text{Vent}}{\Delta T} + \frac{\text{Fabric}}{\Delta T}$$

This time data points are omitted in which the estimated solar heating effect is more than 20% of the total energy into the house. A fitted straight line (correlation coefficient 0.90) gives:

$$\frac{\text{Elec + Solar}}{\Delta T} = 4.45 + 1.70 \times \text{air change per h}$$

showing the fabric heat loss coefficient confirmed as 4.45 kWh/(K day) and the ventilation heat loss coefficient of 1.70, very close to value 1.65 assumed above.

The energy balance for the various 10 day periods is given in Table 5, showing that gains and losses balance within ± 5%. Table 6 shows the ventilation heat loss as a percentage of the total energy input to the house and the increase in heating energy required to maintain the house temperature when the bedroom window is opened by various amounts.

10. ENERGY COSTS OF VENTILATION - THEORETICAL

The heat loss associated with ventilation was estimated in the previous section assuming all the air in the house was at a uniform temperature. However, all the rooms in a house are seldom at the same temperature and opening a window may cause local cooling unless the heating system is responsive and of sufficient capacity.

Consider a house at a non-uniform temperature in which the ventilating air passes in turn through regions of temperature T_1 T_2 ... T_n. Let the air flow through each in turn be Q kg/s.

Consider the mth region. The power required to maintain its temperature at T_m is:

$$Q\, C_p\, (T_m - T_{m-1}) + \text{Fabric heat loss}_m$$

For the whole house the power required to maintain existing temperatures is:

$$\sum_{m=o}^{n} Q\, (T_m - T_{m-1})\, C_p + \text{Fabric loss}_m$$

$$= Q\, (T_n - T_o)\, C_p + \text{whole house fabric loss}$$

i.e. the ventilation heat loss depends only on the outside air temperature and the temperature of the air which is leaving the house. Intermediate temperatures do not matter.

TABLE 5 - Energy balance, daily averages over 10 day (approx.) periods

Date 1978/1979	Electrical kWh	Solar kWh	Fabric Loss kWh	Ventilation kWh	Unbalance kWh	
					+	-
7-20 Nov	45.34	2.29	43.74	3.70	0.19	
20 Nov-5 Dec	75.55	2.16	67.36	8.17	2.18	
5-11 Dec	86.55	1.26	47.92	*39.47	0.42	
15-27 Dec	83.93	1.57	77.92	10.06		2.48
27 Dec-8 Jan	92.71	1.95	79.99	11.19	3.48	
8-22 Jan	75.98	1.95	69.30	11.51		2.88
12-23 Feb	108.53	3.08	83.73	23.55	4.33	
23 Feb-8 Mar	81.05	6.59	69.70	19.82		1.88
12-22 Mar	90.38	6.80	77.00	18.95	1.23	
22 Mar-2 Apr	82.85	7.98	68.77	20.43	1.63	
4-12 Apr	67.84	7.36	63.71	7.95	3.54	
12-20 Apr	39.79	14.63	50.56	6.23		2.37
20-30 Apr	5.42	14.77	22.48	4.37	**	6.66
4-14 May	44.07	15.74	51.74	∿ 6.0	2.07	
14-24 May	37.86	15.37	50.34	5.46		2.57
24 May-3 June	37.13	14.20	43.16	3.84	4.33	
12-21 June	17.58	19.49	34.06	3.17		0.16

Notes: (1) Solar kWh = 4.08 x solarimeter kWh m^{-2} horizontal

(2) Fabric kWh = 4.4 x $(T_{in} - T_{out})$

(3) Ventilation kWh = 1.70 x (air change $hour^{-1}$) x $(T_{in} - T_{out})$

(4) Unbalance: + means gains > losses

- means losses > gains

(5) * uses bedroom temperature in place of house temperature

(6) ** house was unheated so heat gain from cavity significant but not metered

TABLE 6 - Ventilation heat loss

Window condition	Measured Ventilation heat loss / Total heat loss	Increase in heating energy as a result of open window	Mean ventilation rate ac/h
Closed	10%	0	0.30
01	12%	3%	0.35
02	21%	14%	0.73
03	45%	64%	3.0

To a first approximation air leaves the house upstairs leeward which means that heat loss due to ventilation should be related to bedroom rather than whole house temperatures. In strong wind conditions however air will also leave the house downstairs leeward.

To check this experimentally requires that the bedrooms be at a different temperature to the rest of the house. This occurred when the front bedroom window was open to its widest position (03) and the room heater was unable to maintain the set temperature. Energy balance is achieved (see Table 5) when the bedroom air temperature rather than the whole house temperature is used to calculate the ventilation heat loss.

Figure 18 shows how ventilation heat loss relates to ventilation rate and outside temperature for House B.

11. INDIVIDUAL ROOM VENTILATION RATES

Results so far have referred to whole house ventilation rates. Useful ventilation is fresh air ventilation. Rooms on the windward side are ventilated with fresh air, especially downstairs, whereas rooms on the leeward side, especially upstairs, may be ventilated entirely by stale air from other rooms of the house.

Individual room ventilation rates were measured by tracer decay. The whole house was initially charged with tracer gas and then the individual room rates measured. As before, rooms can be classified as:

upstairs	windward
upstairs	leeward
downstairs	windward
downstairs	leeward

Table 7 shows individual room ventilation rates for both leeward and windward open upstairs windows. The data are shown graphically in Figure 19.

The results are insufficient to draw more than very general conclusions but it can be seen that opening any one window increases ventilation approximately threefold throughout the house. If the open window is on the windward side of the house the ventilation rate in that room will be increased approximately tenfold.

12. STACK AND WIND EFFECTS COMPARED

The pressure differences causing flow of air into and out of a house arise from wind pressure and the temperature difference between inside and outside the house - known as 'stack effect'.

The wind pressure is $\frac{1}{2}\rho v^2$ where ρ is the density of air (1.25 kgm^{-3} at 10^oC) and v is the wind speed. The actual pressure exerted across any opening depends on the size and shape of the house together with the nature of its environment. As a reasonable approximation for houses like these the pressure exerted on the windward side is 0.7 of $\frac{1}{2}\rho v^2$ with a suction on the leeward side equal to 0.4 of $\frac{1}{2}\rho v^2$ so that the effective total pressure difference driving air through the house is $1.1 \times \frac{1}{2}\rho v^2$.

The stack effect arises due to the difference in air density between inside and outside. If these densities of air are ρ_1 and ρ_0 respectively, and the vertical separation between two openings is h, then the stack pressure difference is

$$\rho_0 gh - \rho_1 gh$$

where $g = 9.81\ ms^{-2}$.

Stack and wind pressures are given in Figure 20. It is apparent that except at very low windspeeds, wind pressures are much greater than stack pressures. Figure 21 shows this in another way.

The strong temperature dependence of ventilation rate shown in Figure 9 is thus rather surprising since it occurs at wind speeds where the stack pressure is less than 10% of the wind pressure.

13. CALCULATION OF VENTILATION RATES

Since the total house leakage is known from pressurisation tests it should be possible to calculate the ventilation rate for any given wind and stack pressures.

The ventilating air flow takes place through numerous openings in series and parallel with wind-induced flow taking place from one side of the house to the other and temperature-induced flow from downstairs to upstairs.

Table 7 Individual room ventilation rates

House	Room location	Open window	Wind speed	Wind direction	Temperature °C out	Temperature °C in	Temperature °C ΔT	Ventilation ac/h
N, 270, 90, 180	wind ▷		1.0	270	4.0	19.4	15.4	0.50
			3.8	176	6.3	20.0	13.7	0.56
			3.0	195	7.0	19.0	12.0	0.40
			3.3	90	2.0	18.0	16.0	1.09
			2.7	100	1.0	17.5	16.5	1.50
			5.3	173	8.9	20.0	11.1	14.1
			2.7	180	14.5	19.3	4.8	1.2
			2.8	150	12.0	19.8	8.0	2.0
			4.2	231	7.0	19.8	12.8	3.9
			0.9	222	4.2	19.7	15.5	0.56
			4.0	60	4.0	20.0	16.0	0.50
			3.2	85	2.2	18.3	16.1	0.44
			3.4	127	8.0	19.9	11.9	2.6
			2.5	150	12.0	20.0	8.0	0.58
			3.8	120	17.0	22.4	5.4	0.91
			2.0	0	2.0	17.4	15.4	0.98
			5.8	222	8.0	19.6	11.6	1.2
			2.4	249	5.5	19.6	14.1	1.1
			2.6	100	1.0	18.8	17.8	0.76
			3.9	190	9.3	20.0	10.7	1.0
			3.3	150	13.0	18.8	5.8	0.83
			3.1	20	3.2	18.9	15.7	0.52
			5.8	206	7.0	19.7	12.7	0.67
			1.4	142	6.2	19.7	13.5	0.57
			3.0	75	2.5	17.5	15.0	0.50
			3.3	196	8.6	20.0	11.4	0.90
			1.3	150	10.0	20.0	10.0	0.64
			3.0	150	16.5	23.0	6.5	0.96

o window open 3°

O window open 10°

If the leakage area of the house is divided into:

A(WU) = Area windward upstairs
A(WD) = Area windward downstairs
A(LU) = Area leeward upstairs
A(LD) = Area leeward downstairs

then the wind-induced flow takes place through A(WC) and A(WD) (in parallel) in series with A(LU) and A(LD) (in parallel). The temperature induced flow is through A(WD) and A(LD) (in parallel) in series with A(WU) and A(LU) (in parallel).

The total effective area of a number of areas in parallel is simply their sum:

$$A_{eff} = A_1 + A_2 + \dots + A_n$$

The effective area of two openings in series is given by

$$\frac{1}{A^2_{eff}} = \frac{1}{A_1{}^2} + \frac{1}{A_2{}^2}$$

assuming flow proportional to $\Delta p^{0.5}$.

If flow is proportional to Δp^n then

$$A_{eff} = \frac{A_1 A_2}{(A_1{}^{1/n} + A_2{}^{1/n})^n}$$

The flow through an orifice of area Am^2 is usually taken to be

$$Q = 0.827\ A\ \Delta p^{0.5} \quad m^3/s$$

$$= 2977\ A\ \Delta p^{0.5} \quad m^3/h$$

Tests in House B showed that for crack flow (windows closed)

$$Q = 2139\ A\ \Delta p^{0.655} \quad m^3/h \qquad (1)$$

and for combined open windows + residual crack flow

$$Q = 2960\ A\ \Delta p^{0.53} \qquad (2)$$

To a first approximation take A(WU) = A(WD) = A(LU) = A(LD) = A(i.e. the whole house leakage is 4A).

The measured ventilation rate with a small inside to outside temperature difference and a wind speed of 5 m/s is 0.3 air changes per hour. From equation (1) the effective leakage area required to give this ventilation rate is 0.018 m^2, which is only one sixth of the measured leakage area of the house (0.115 m^2).

It is therefore concluded that only a small part of the measured leakage area takes part in wind-induced ventilation.

From the experimental data the ventilation rates for predominantly wind and predominantly stack effect conditions were obtained, Table 8.

TABLE 8 - Wind and stack ventilation - experimental

Window condition	Air changes per hour			
	Stack only		Wind only	
	Δt = 10°C	20°C	v = 4 m/s	8 m/s
Closed	0.2	0.35	< 0.2	< 0.3
01	0.22	0.37	0.2	0.6
02	0.4	0.55	0.75	2 wind on front
			0.85	1.4 wind on back
03	0.5 to 1	?	2.5	7

The pressure differences corresponding to ΔT = 10°C and 20°C are 1.67 and 3.46 Pa respectively.

Since the wind is measured at the top of a 10 metre mast it is likely that the wind strength at house level will be less. From the IHVE Guide the wind strength at house level is estimated to be 77% of the 10 metre mast value and so the corresponding wind pressures for 4 m/s and 8 m/s are 5.7 and 22.8 Pa respectively.

The effective leakage areas to satisfy the measured ventilation rates at these pressure differences are given in Table 9, using equation (1) for windows closed or (01) and equation (2) for windows (02) or (03).

TABLE 9 - Effective leakage areas for measured ventilation rates

Window condition	Effective leakage area			
	Stack ventilation		Wind ventilation	
	ΔT = 10°C	20°C	v = 4 m/s	8 m/s
Closed	0.0134	0.0145	0.0060	0.0036
01	0.0147	0.0153	0.0060	0.0072
02	0.0206	0.0192	0.0202	0.0258 wind on front
			0.0229	0.0180 wind on back
03	0.0257 to 0.0515	?	0.0672	0.0902

When the windows are closed (or nearly closed) the effective leakage areas are 0.0145 m^2 for stack effect flow and 0.006 m^2 for wind induced flow which suggests that only a part of the whole house leakage area (0.115 m^2) is involved in each type of ventilation and probably that the actual openings are different in each case.

The stack effect encourages air flow in at lower levels and out at upper levels. Since the basement and loft of the house are ventilated to outside it may be that the leakage paths associated with the stack effect ventilation are mainly in the downstairs floor and upstairs ceiling. Assuming these leakage areas (in series) are equal, the area of each is 0.0228 m^2. So that the downstairs floor and upstairs ceiling together comprise 2 x 0.0228 = 0.0456 m^2 leakage area or 40% of the total house leakage (0.115 m^2), leaving 60% of the house leakage associated with the walls.

If the wind induced ventilation with windows closed is the resultant air flow through two openings in series, the area of each would have to be 0.0094 m^2, or only 8% of the total house leakage, which is much too small to account for the 60% of the leakage area associated with the walls.

However, if two leakage openings are in series and one is much larger than the other (in practice more than four times) then the effective area is equal to the smaller of the two. The pressurisation test showed that the house was very leaky downstairs at the back. The wind results can be explained by the house being very leaky at the back and comparatively 'tight' at the front so that, until windows are opened on the front, the effective wind leakage area of the house (0.006 m^2) is equal to the effective leakage area of the front only.

From the pressurisation tests the rooms at the back of the house account for 55% of the total house leakage = 0.0633 m^2. Assuming the floor and ceiling leakage is proportional to floor area accounts for 0.018 m^2 of this leaving 0.045 m^2 associated with the back wall.

As the front bedroom window is opened in stages the leakage of the front wall is increased in stages as shown in Table 10.

TABLE 10 - Effective leakage areas for wind induced ventilation

Window condition	Back wall leakage m^2	Front wall leakage m^2	Total effective leakage m^2 of front and back in series
Closed	0.045	0.006	0.006
(01) 0.013 m^2	0.045	0.019	0.016
(02) 0.026 m^2	0.045	0.032	0.026
(03) 0.11 m^2	0.045	0.116	0.042

where for windows closed and (02) the effective leakage area is given by

$$A_{eff} = \frac{A_1 A_2}{(A_1{}^{1.53} + A_2{}^{1.53})} 0.655$$

and for windows open (02) and (03)

$$A_{eff} = \frac{A_1 A_2}{(A_1{}^{1.89} + A_2{}^{1.89})^{0.53}}$$

Comparison of Tables 8 and 9 shows that effective leakage areas for wind ventilation as calculated from the pressurisation tests and as estimated from measured ventilation rates are as in Table 11.

TABLE 11 - Effective leakage areas from pressurisation tests and ventilation measurements compared

Window condition	Effective leakage area m^2	
	Pressurisation tests	Ventilation measurements
Closed	0.006	0.006
01	0.016	0.007
02	0.026	0.022
03	0.042	0.079

Agreement is reasonable considering the nature of the measurements. The effective area when the window is wide open (03) is larger than the measured area, confirming that in that situation the ventilating air flow is not all through the house but also in and out of the wide open window giving more ventilation than if all the ventilating air had to leave the house through the residual crackage in the rest of the house.

14. CONCLUSIONS

Windows are capable of providing the widely varying requirements for ventilation in a house. If not used carefully they are also likely to provide too much ventilation, resulting in excessive energy consumption. Open window ventilation could easily cancel the advantages gained by high levels of thermal insulation.

The common habit of opening bedroom windows can result in several air changes per hour throughout a house, including the downstairs rooms in which the windows may be closed. The amount of open window required for sufficient ventilation is much less than most window catches are designed for. In a house built to current (1975) Building Regulations, one bedroom window permanently open was found to increase heating energy requirements by 64%.

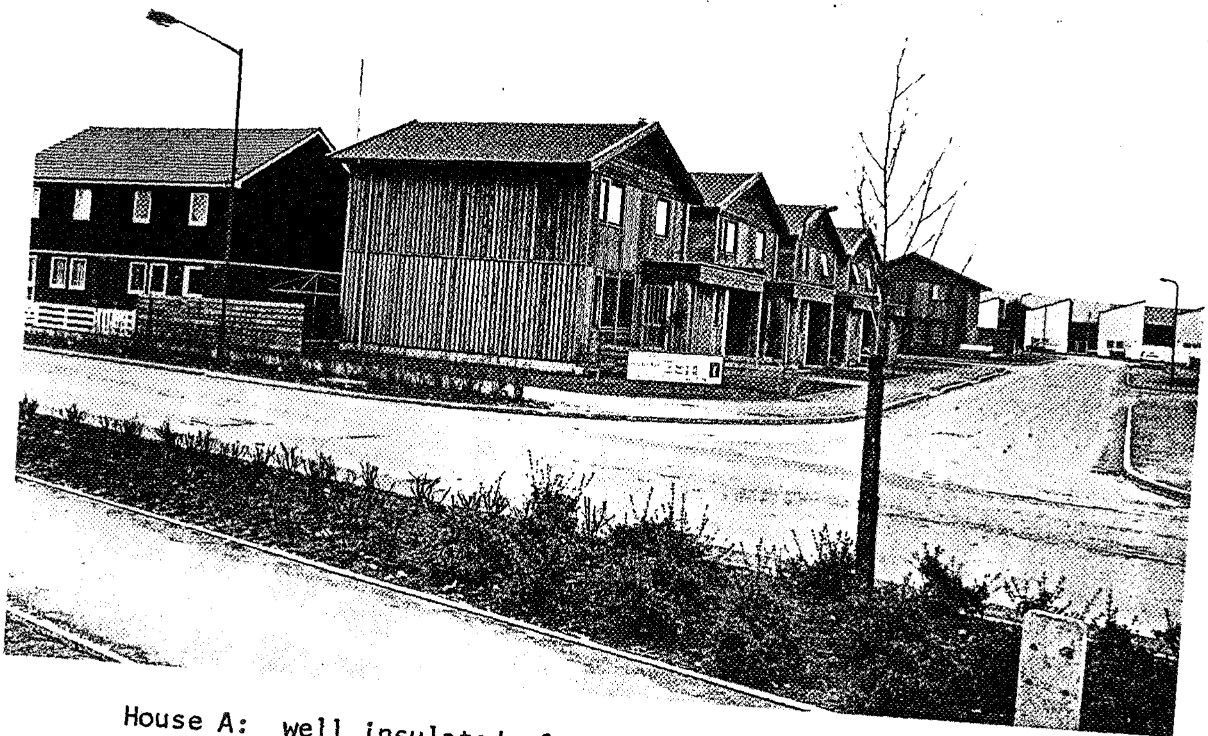
Temperature differences between rooms result in very large air interchange through open doorways (e.g. the equivalent of 10 air changes per hour in each direction for a $1^{o}C$ temperature difference). This emphasises the importance of removing contaminants at source since otherwise they will spread throughout the house regardless of the wind direction.

15. REFERENCES

(1) Building Research Establishment Digest No. 206, Ventilation Requirements.

(2) Dickson, D.J., Ventilation measurements in the ECRC Test Houses (in preparation).

(3) Bouman, H.B., Air flow through an open door. O.A. Translation No. 1761 (ECRC Capenhurst).



House A: well insulated, facing East, volume 260 m3

House B: Brick semi, facing South East, volume 200 m^3

Figure 1(a) The houses in which measurements were carried out

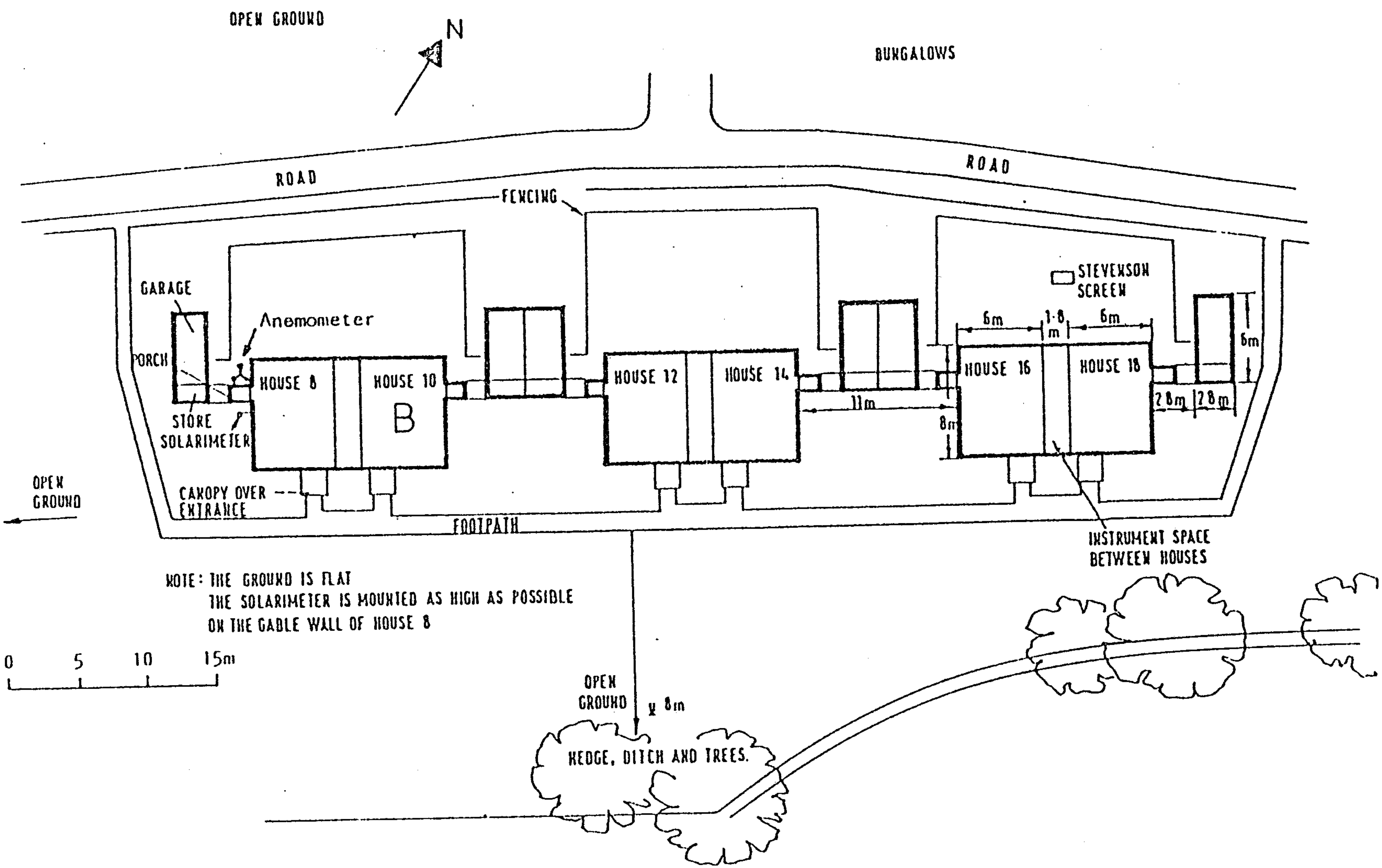


Figure 1(b) Site plan of Test House (B)

House A: 875 x 980 mm.

House B: 700 x 900 mm.

Figure 2.   Windows of the houses

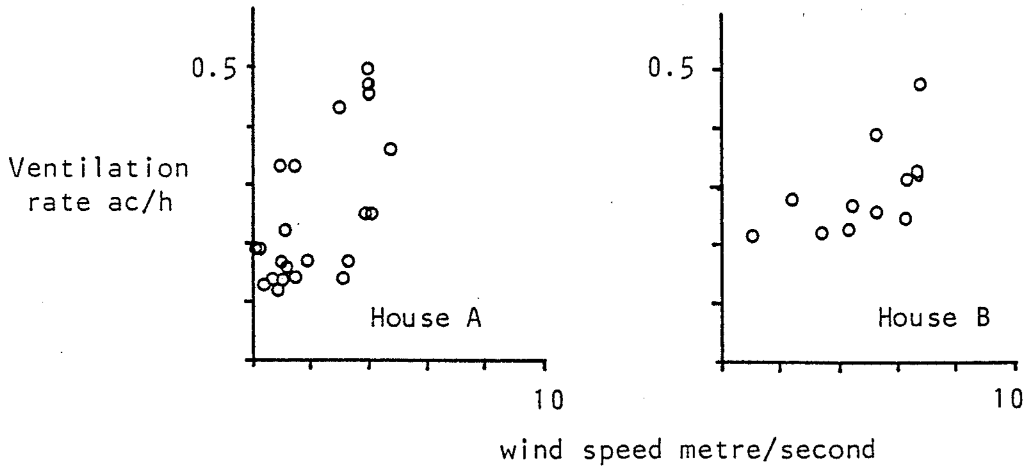


Figure 3. Measured ventilation rates with windows and external doors closed (tracer decay).

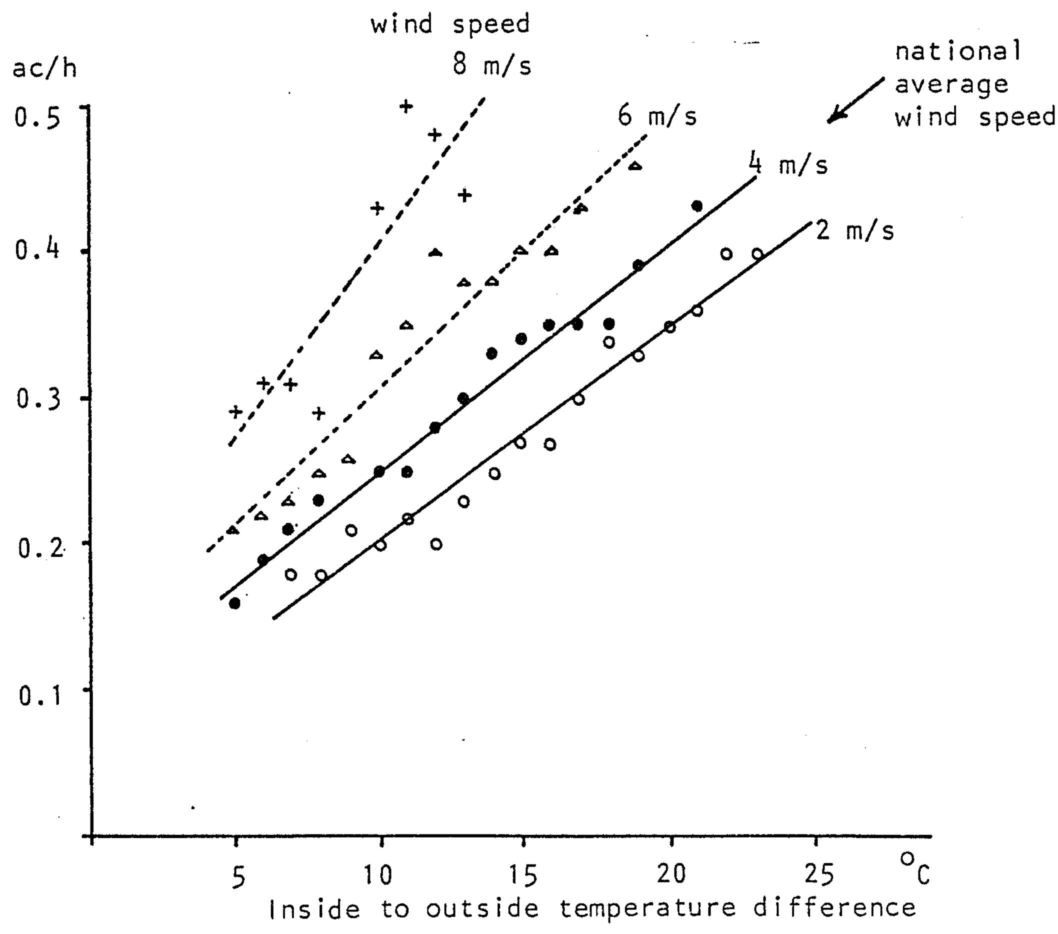


Figure 4. Measured ventilation rates with windows closed. House B. (Equilibrium concentration method.)

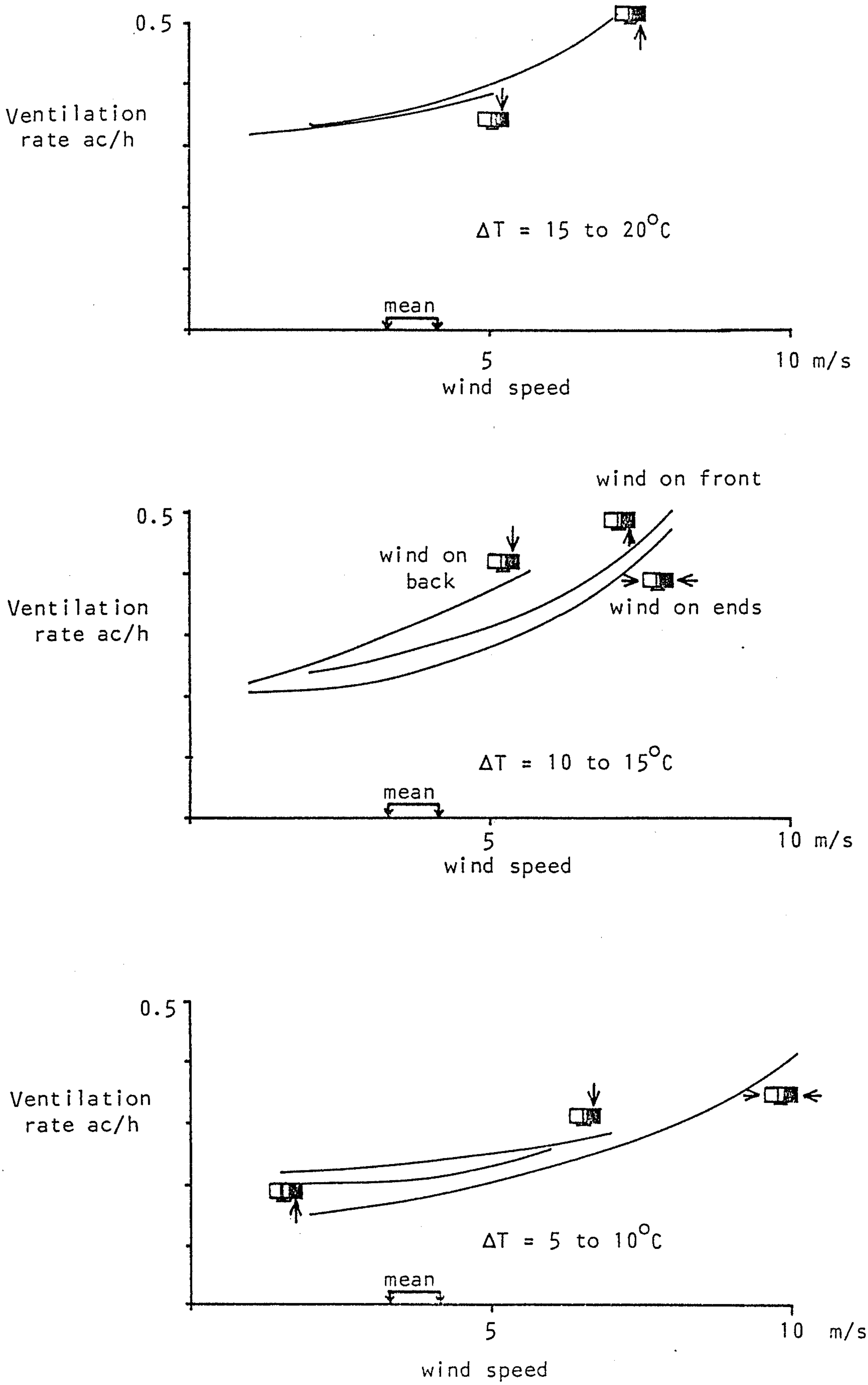
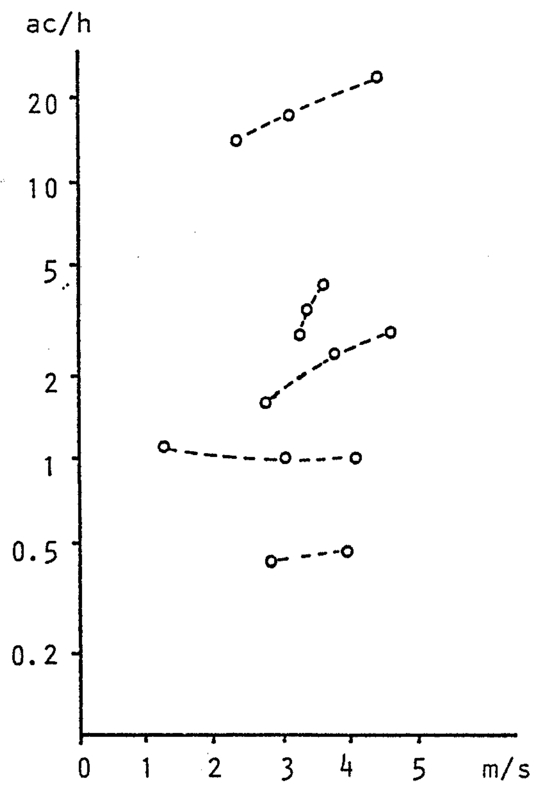


Figure 5. Wind direction effect on ventilation rate, House B, windows closed.



open windows	measured ventilation
all upstairs	upstairs
upstairs windward	upstairs
all upstairs	downstairs
upstairs leeward	upstairs
none	whole house

Figure 6. Ventilation rates floor by floor with upstairs window open

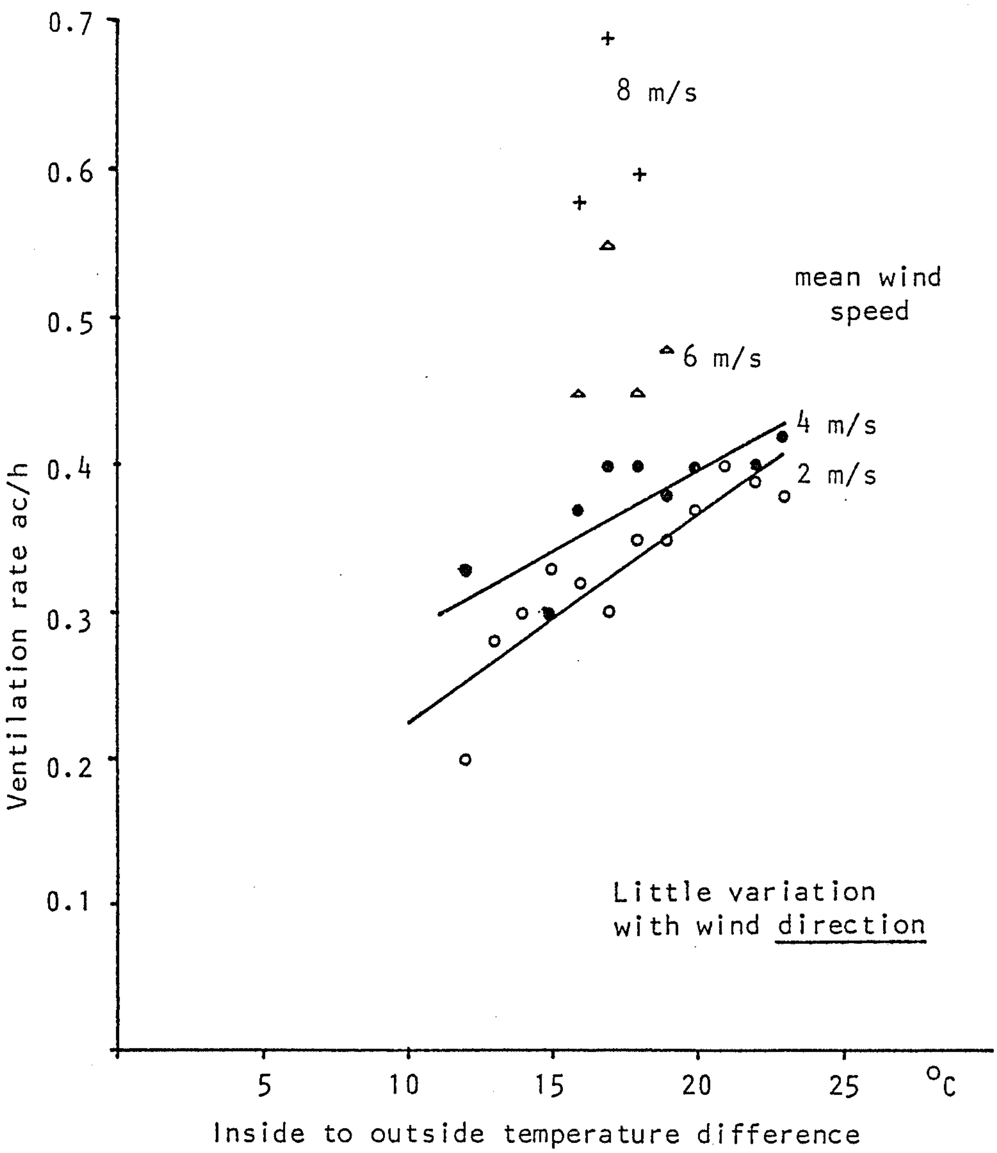


Figure 7. Ventilation rates with front bedroom window open on first notch (01)

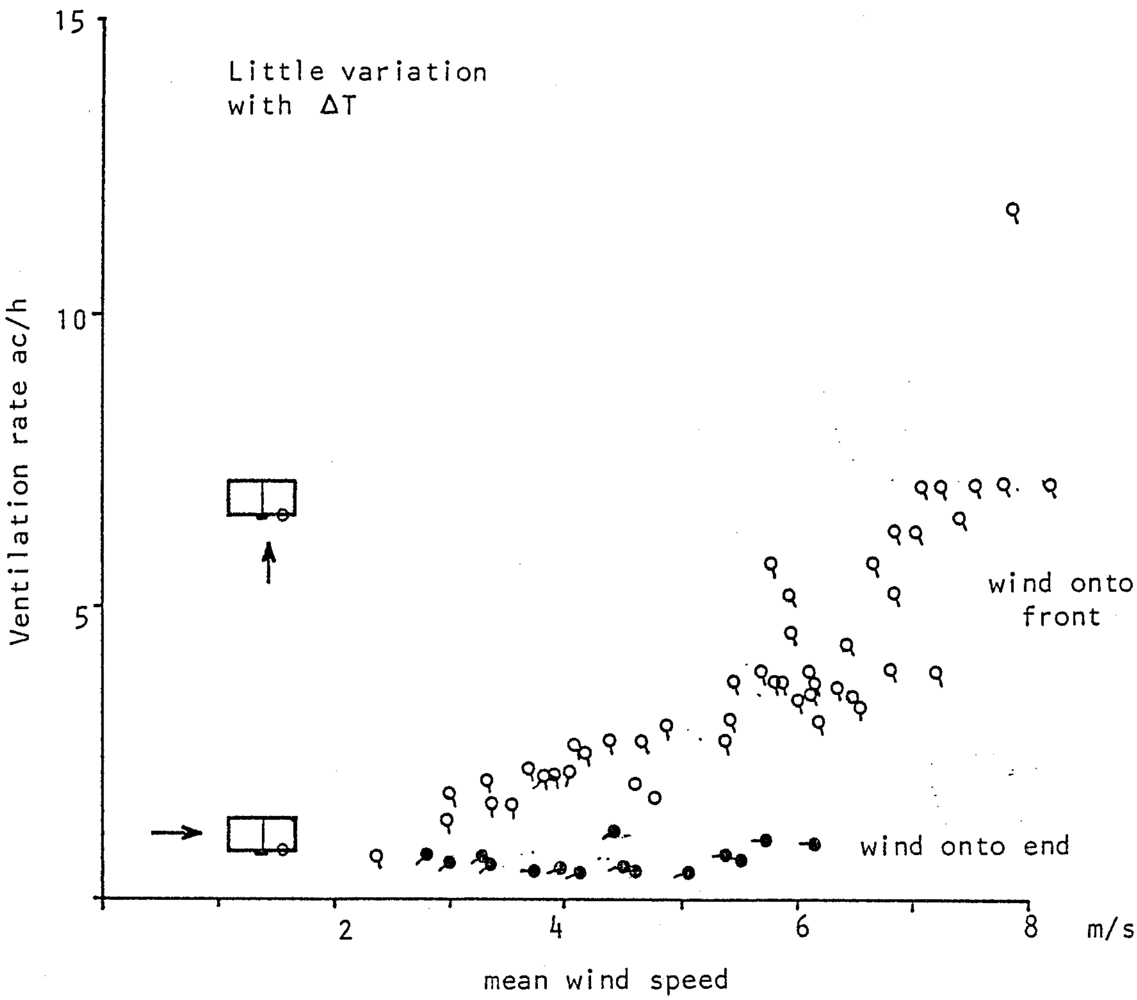


Figure 8. Ventilation rates with front bedroom window open to main stop (03).

Note: Wind comes from direction in which flag points, assuming front of house is at bottom of page.

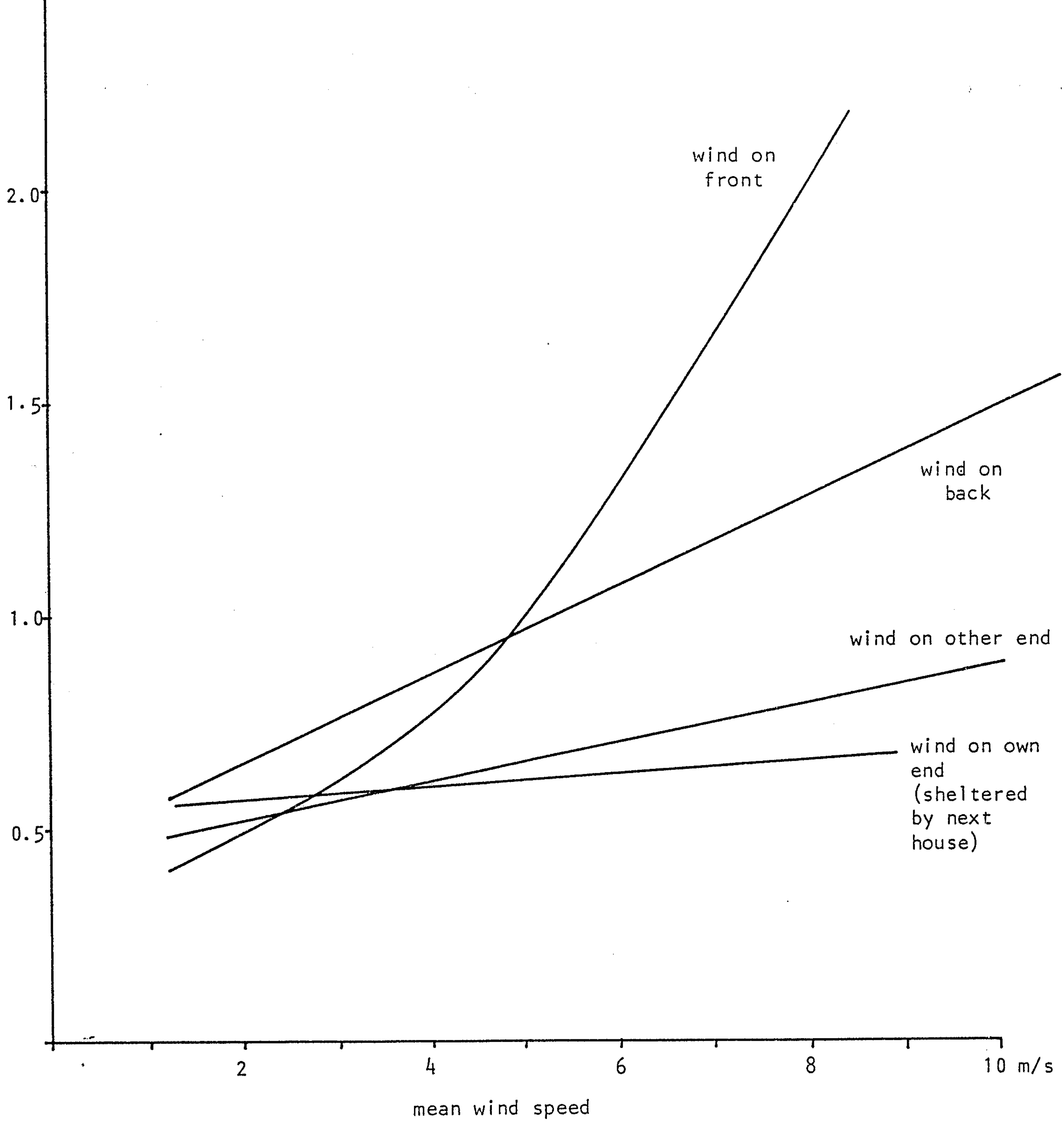


Figure 9(a) Ventilation rate with front bedroom window open on back of catch (02)
Summary of Figures 9(b) to 9(e)

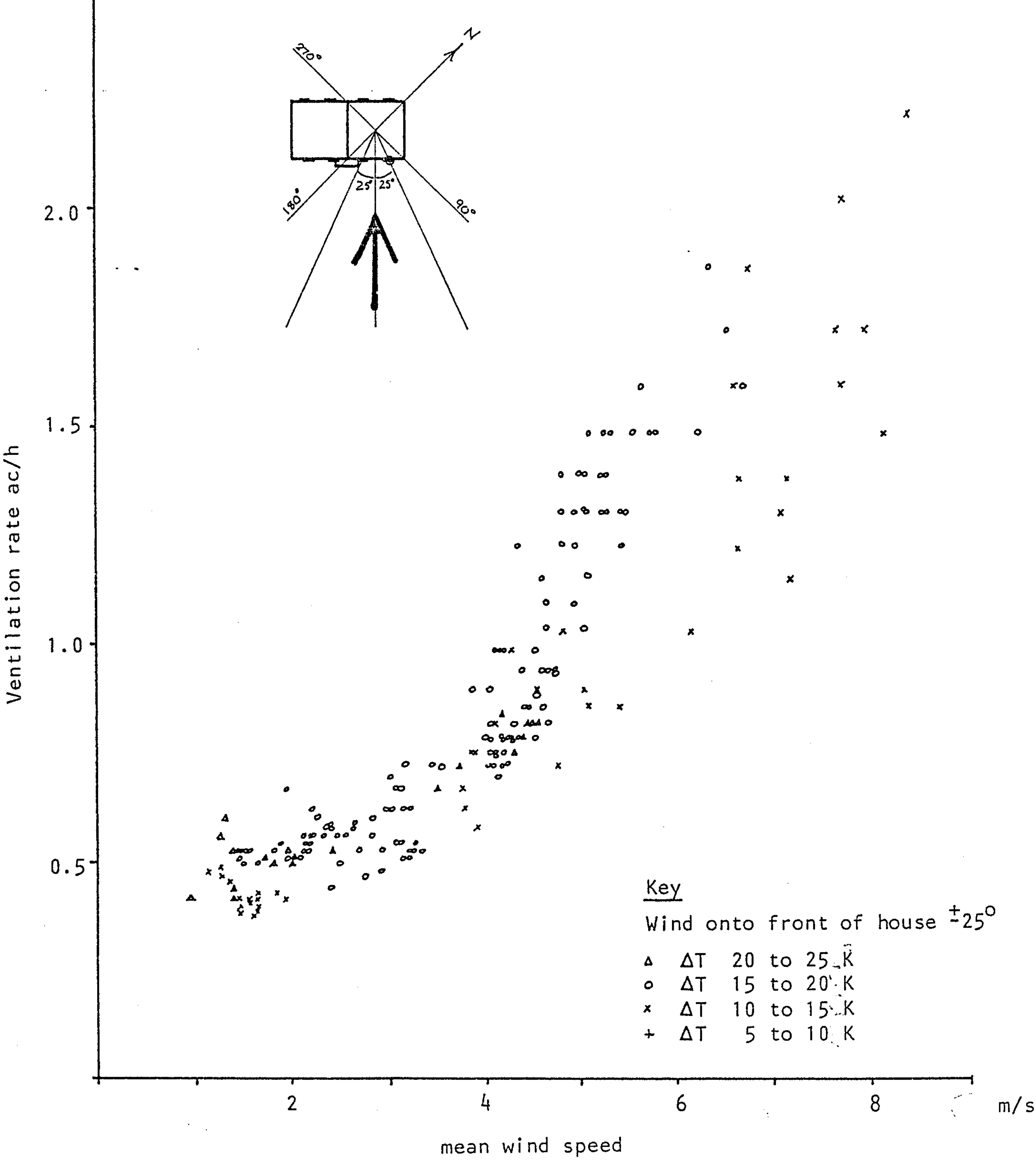


Figure 9(b). Ventilation rate with wind onto front of house.
Front bedroom window open (02).

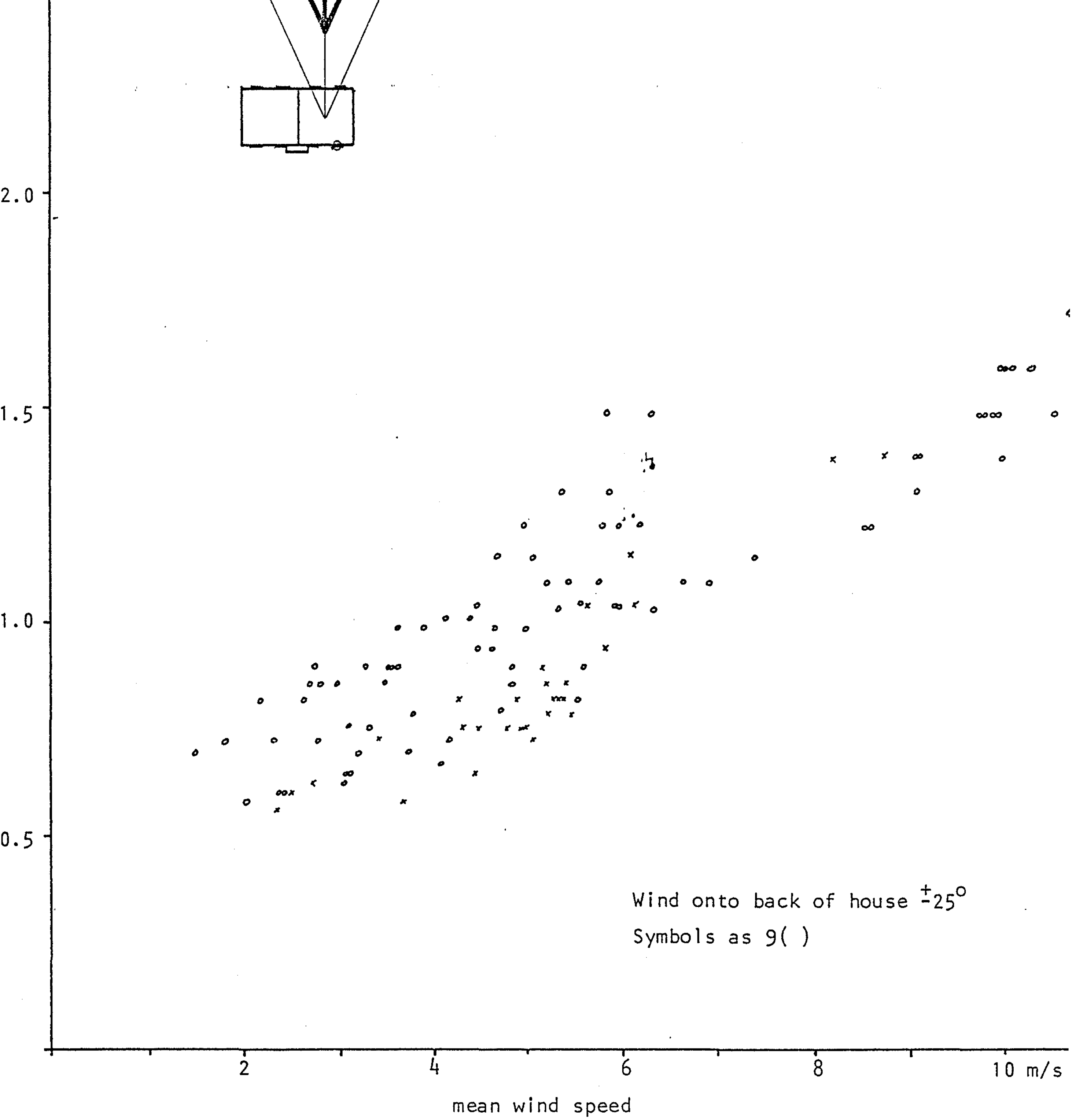


Figure 9(c) Ventilation rate with wind onto back of house.
Front bedroom window open (02).

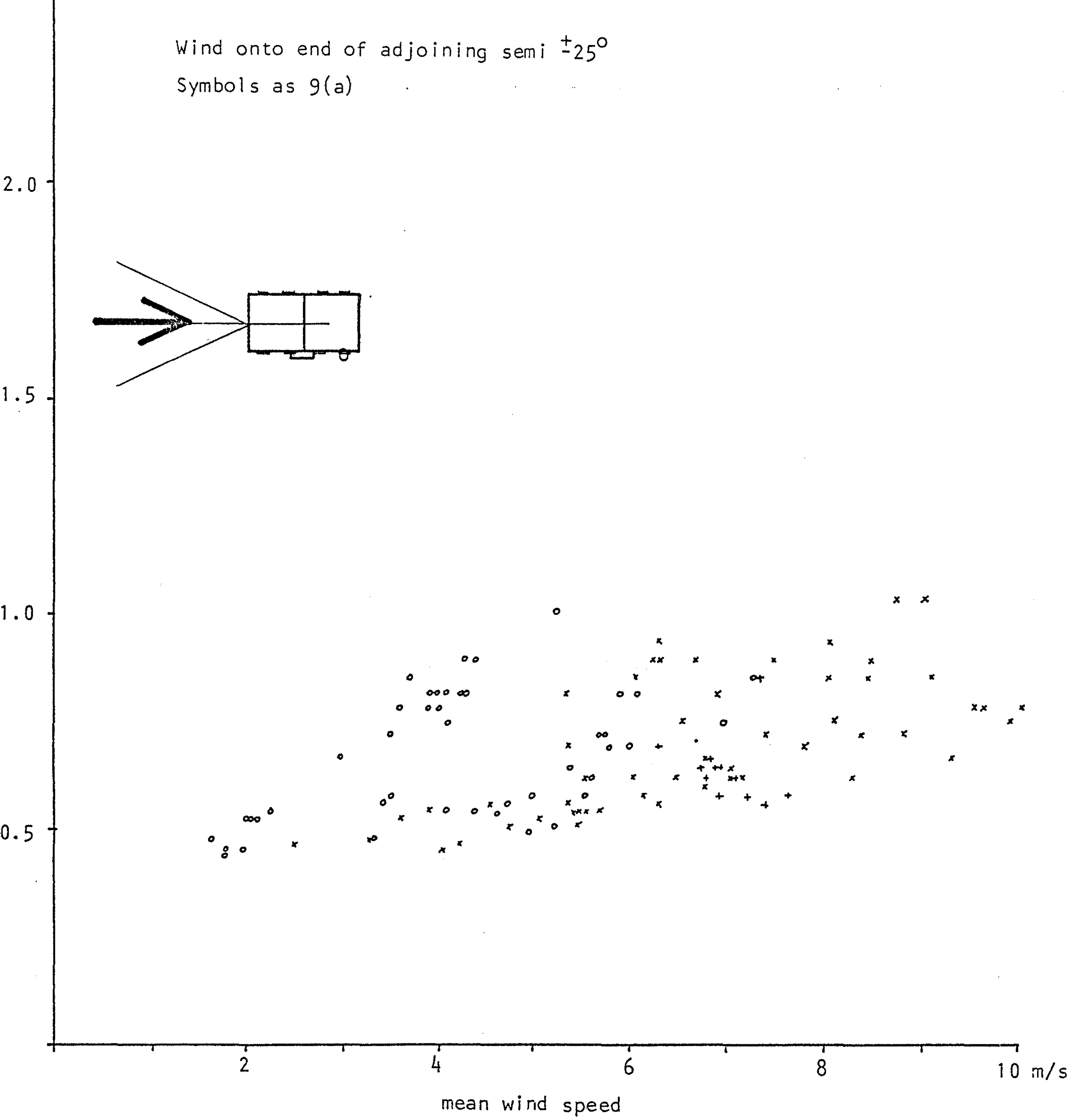


Figure 9(d) Ventilation rate with wind onto end of adjoining semi-detached house. Front bedroom window open (02).

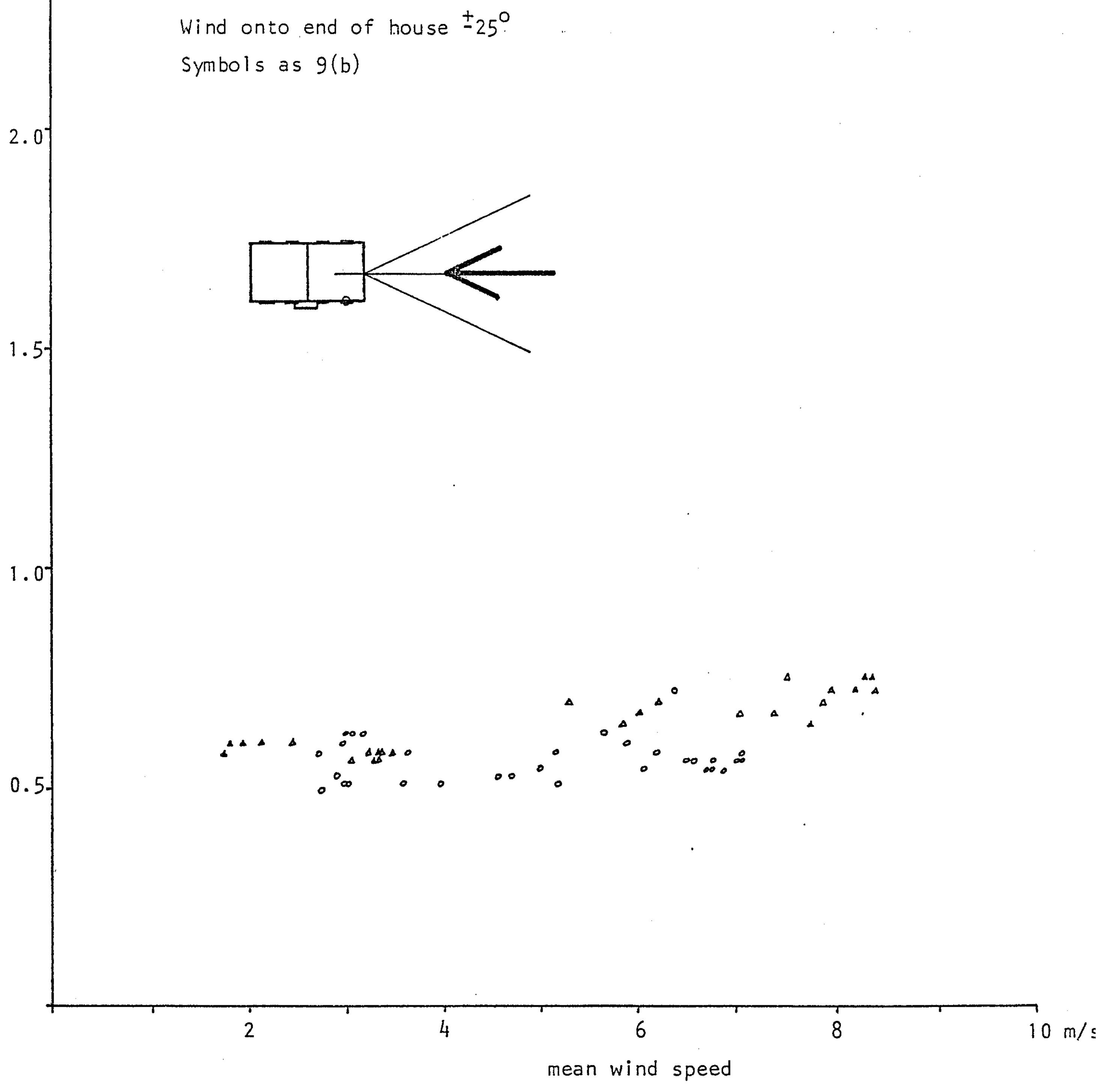


Figure 9(e) Ventilation rate with wind on end of house, partially sheltered by the next house in the row which is about 12 metres away.
Front bedroom window open (02).

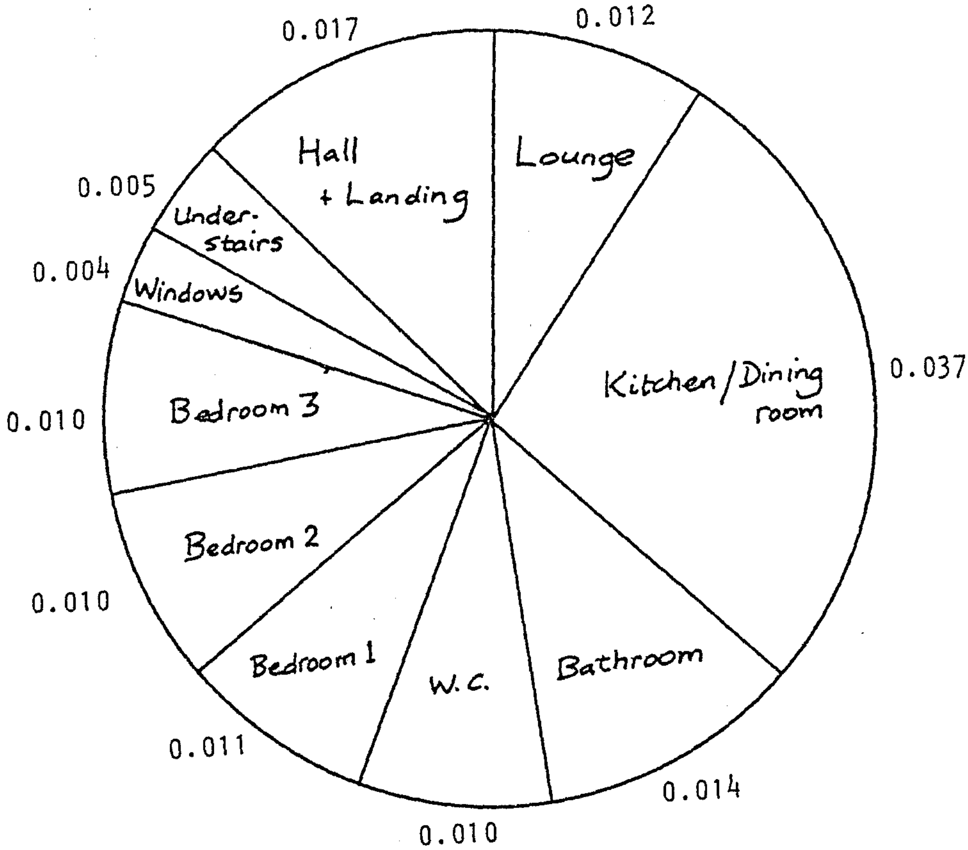


Fig.10 Leakage areas of House B, room by room (metre^2)

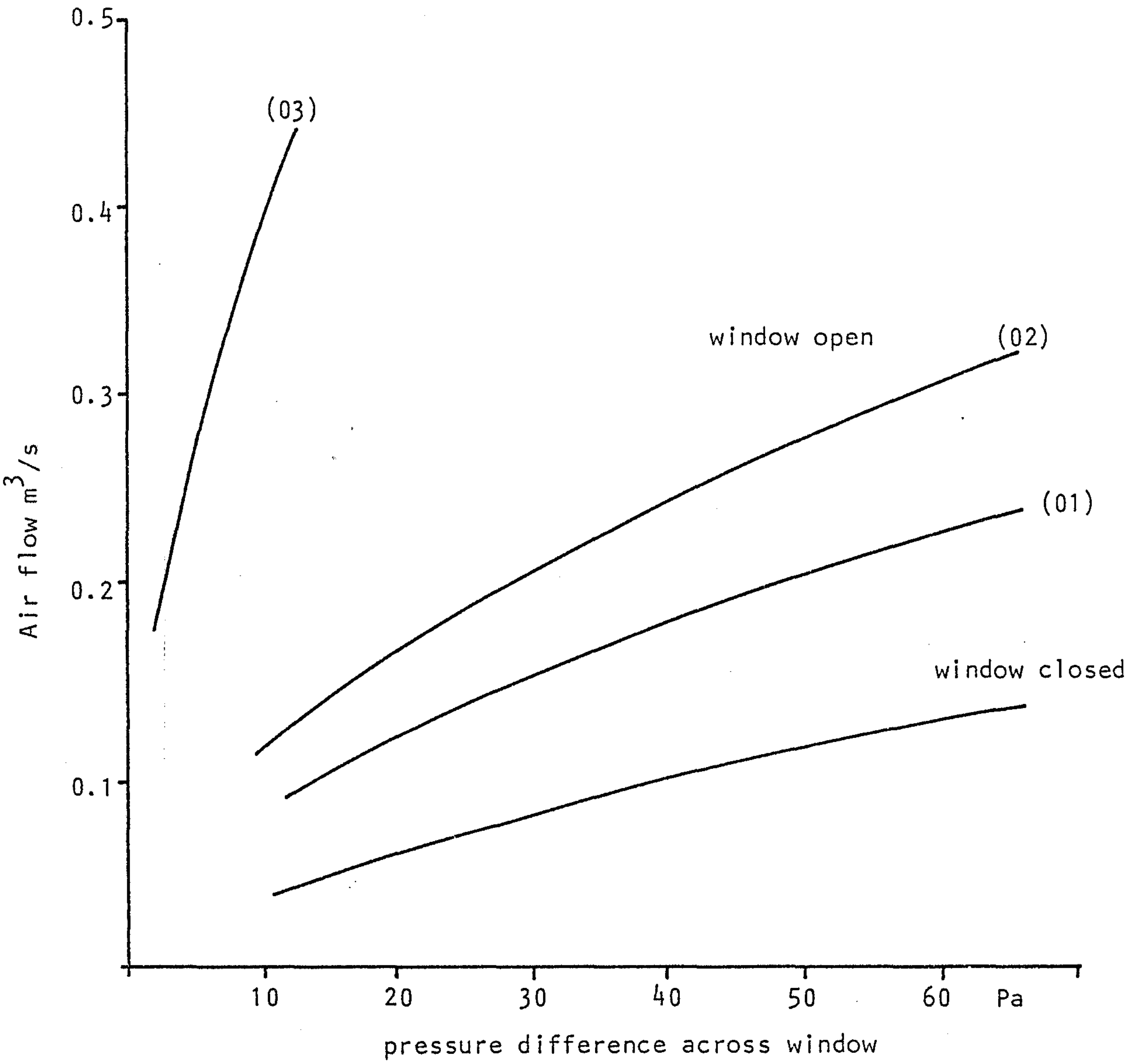
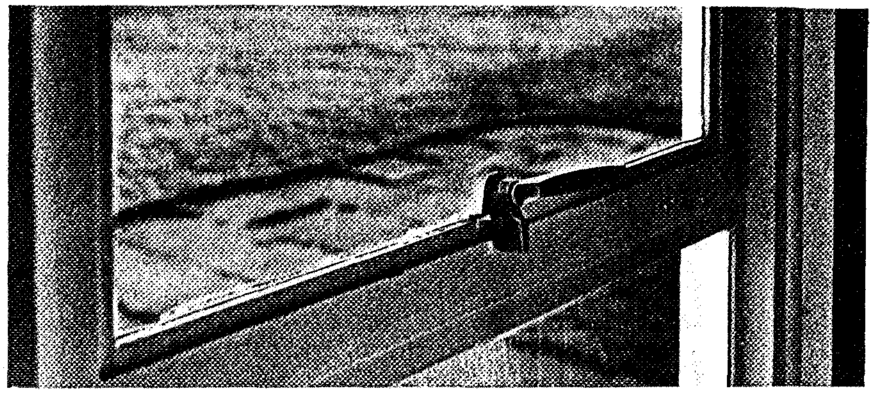
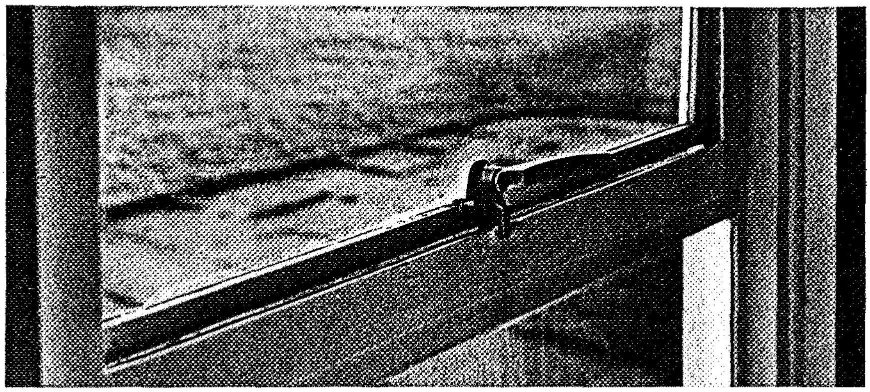


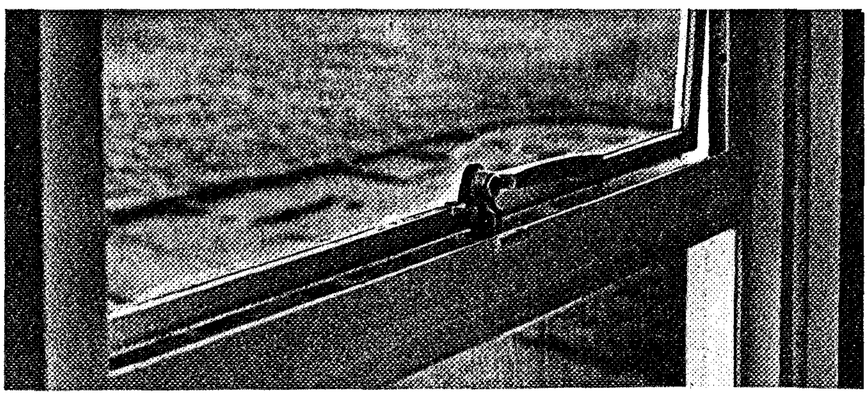
Figure 11a. Flow-pressure characteristics of open window in front bedroom, interpreted as effective areas according to the calibration data in Figure 12



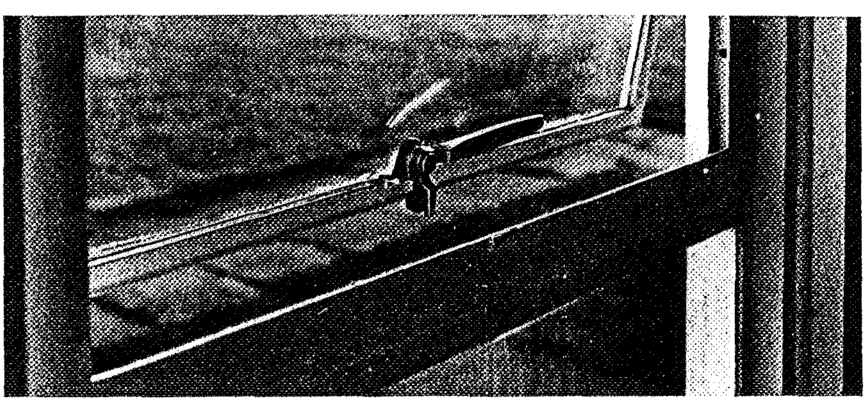
CLOSED



01



02



03

Figure 11(b) Definition of window positions

ECRC/M1329

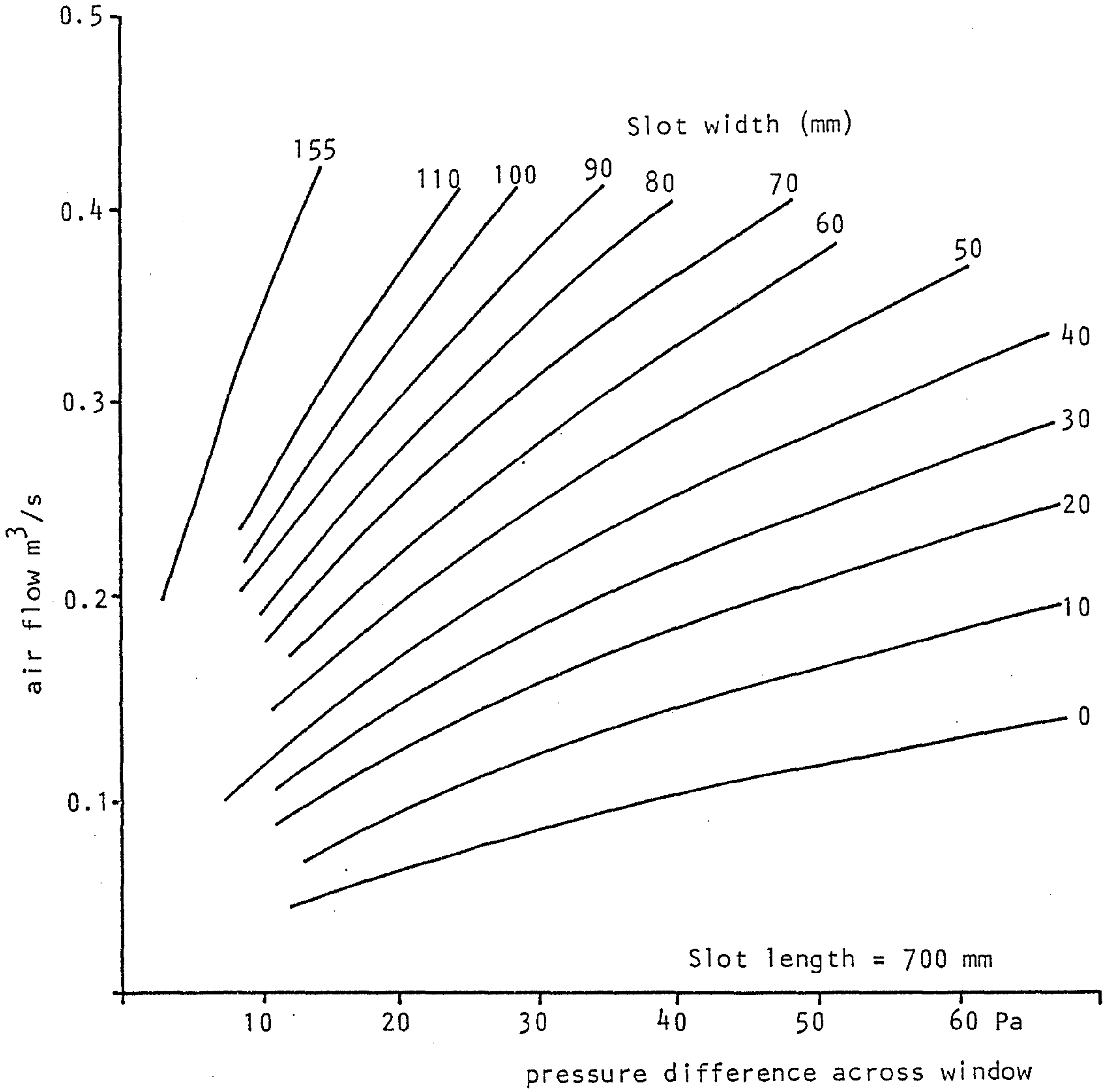


Figure 12. Calibration for window effective area using slots of known dimensions

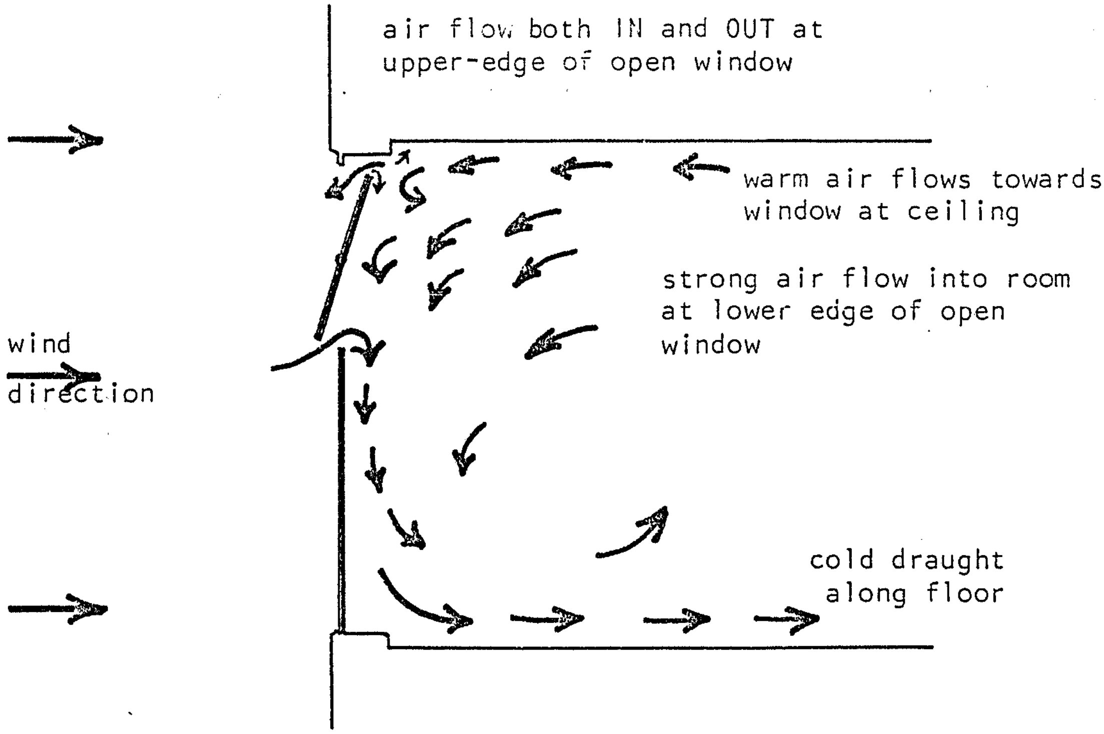


Figure 13. Air flow at an upstairs windward open window

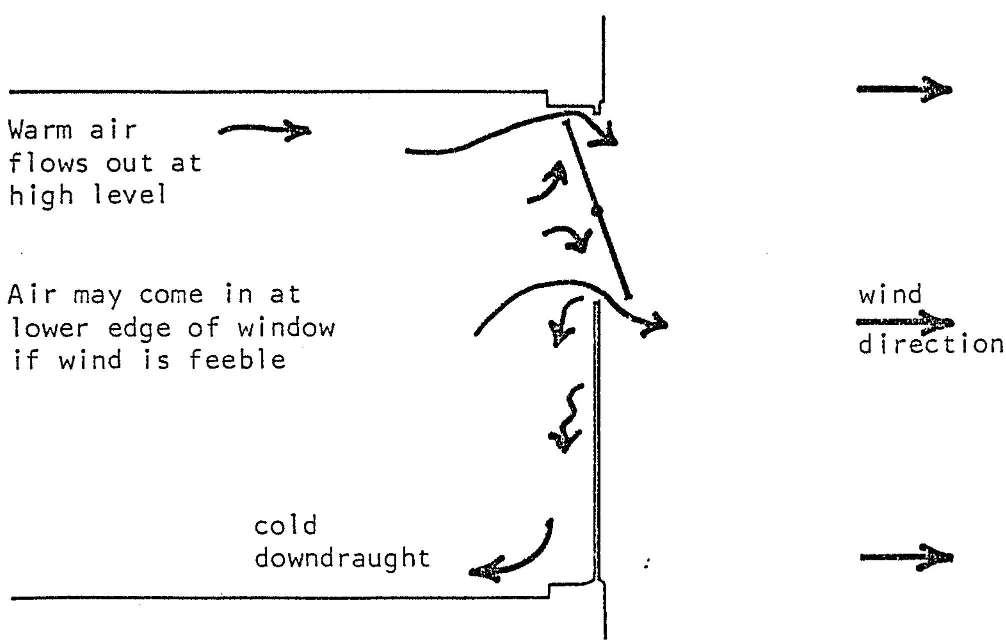


Figure 14. Air flow at an upstairs leeward open window

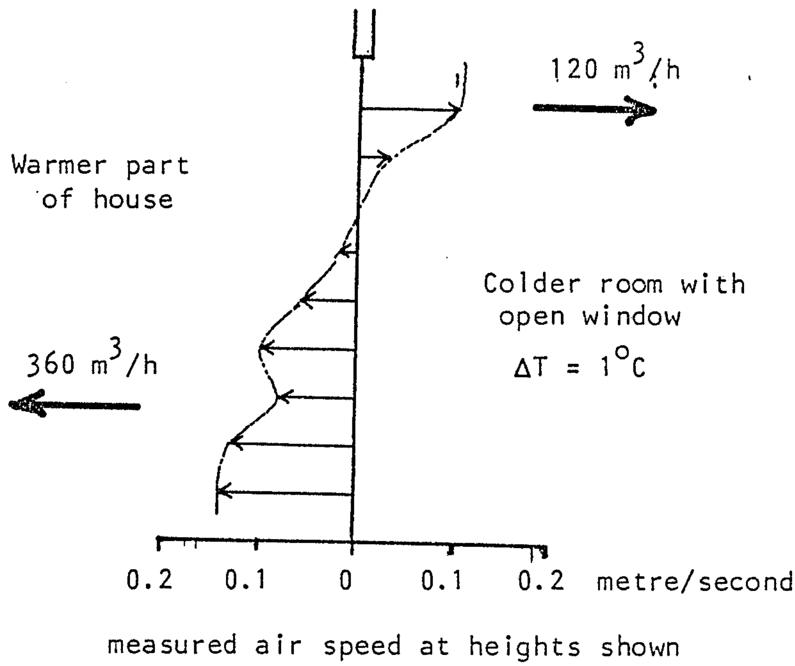
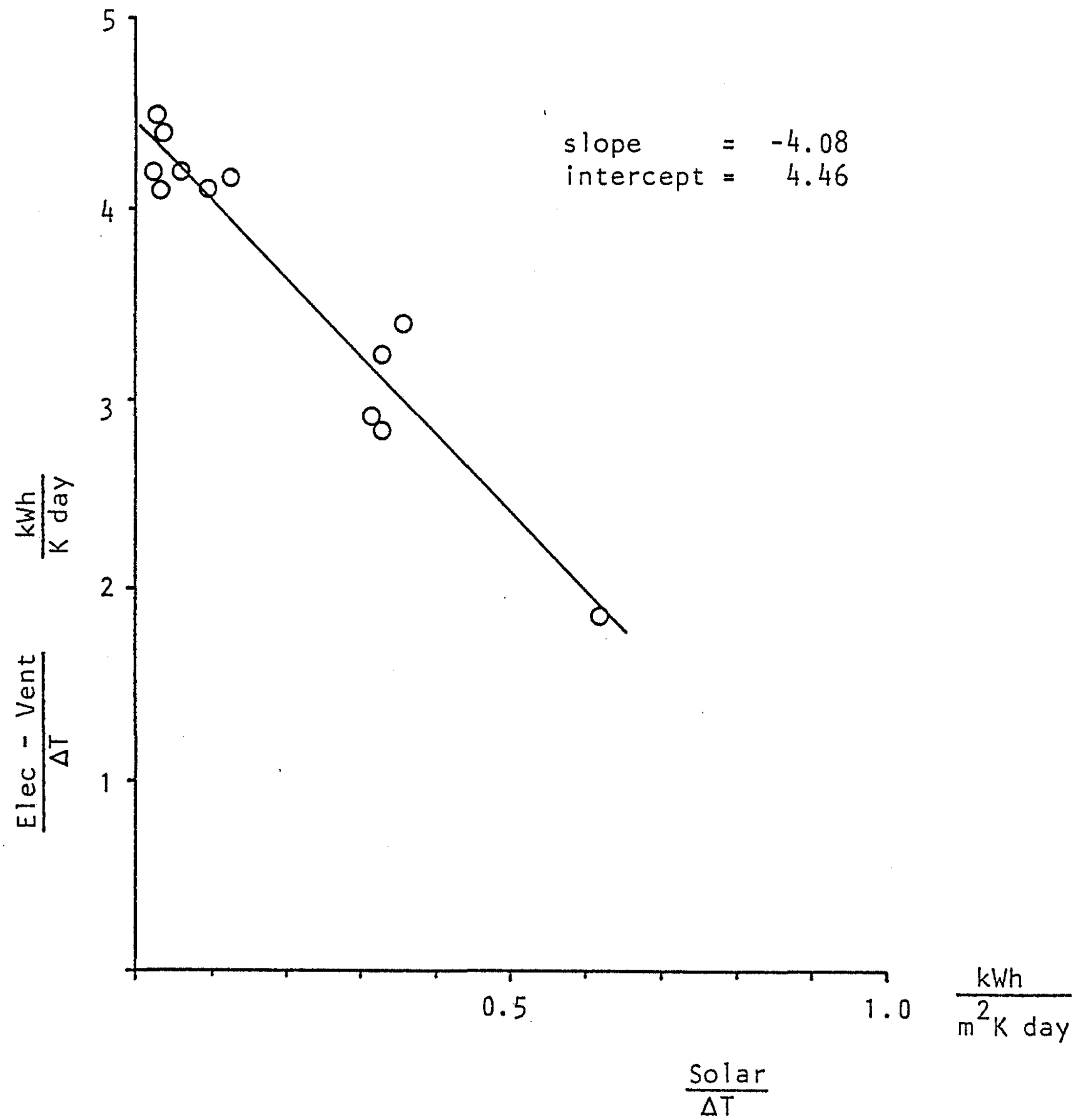


Figure 15. Air speeds measured at a bedroom doorway when the bedroom window was open.



Solar = integrated kWh per metre^2 horizontal surface per day

Figure 16. Estimate of solar heating effect

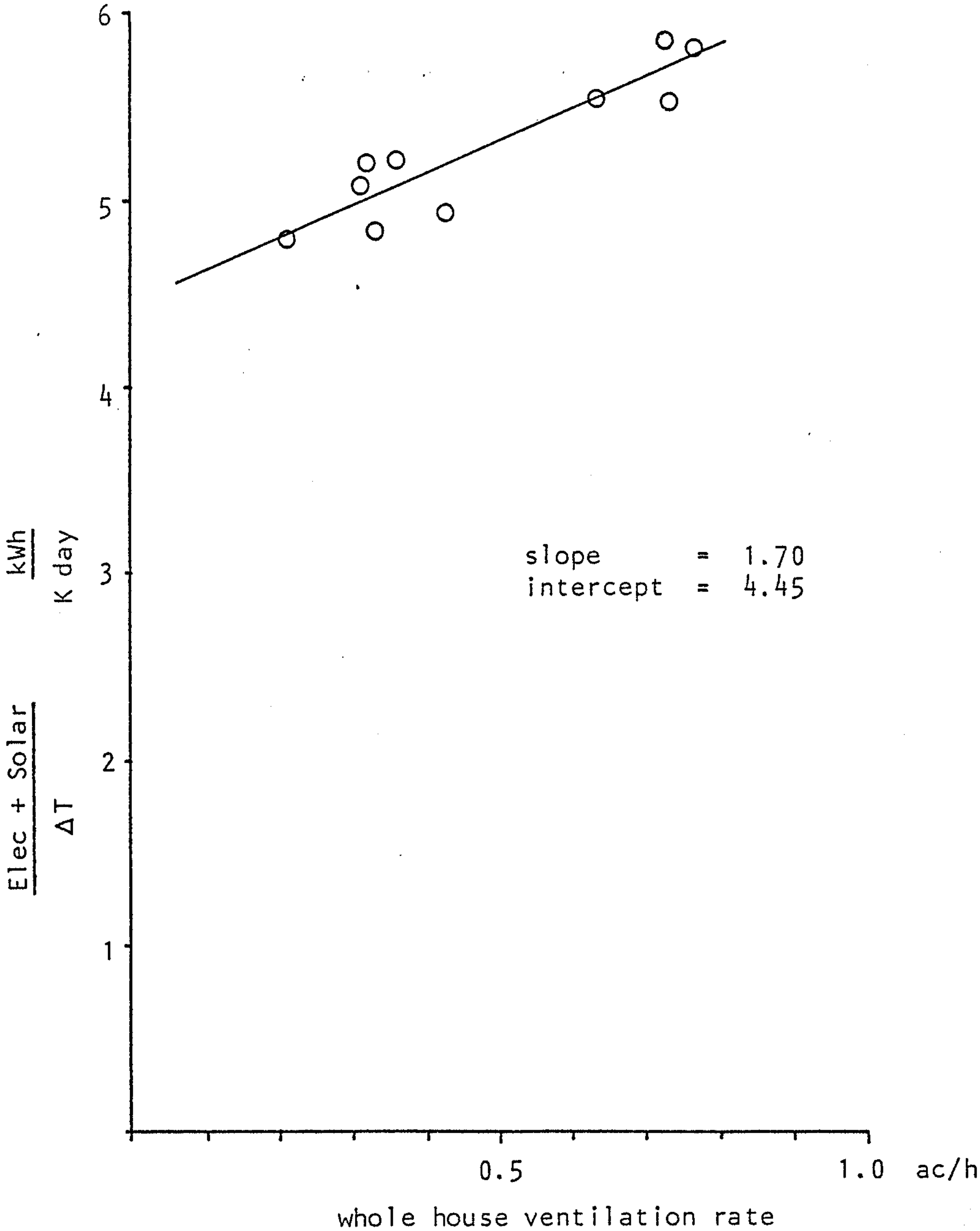


Figure 17. Estimate of ventilation heat loss coefficient

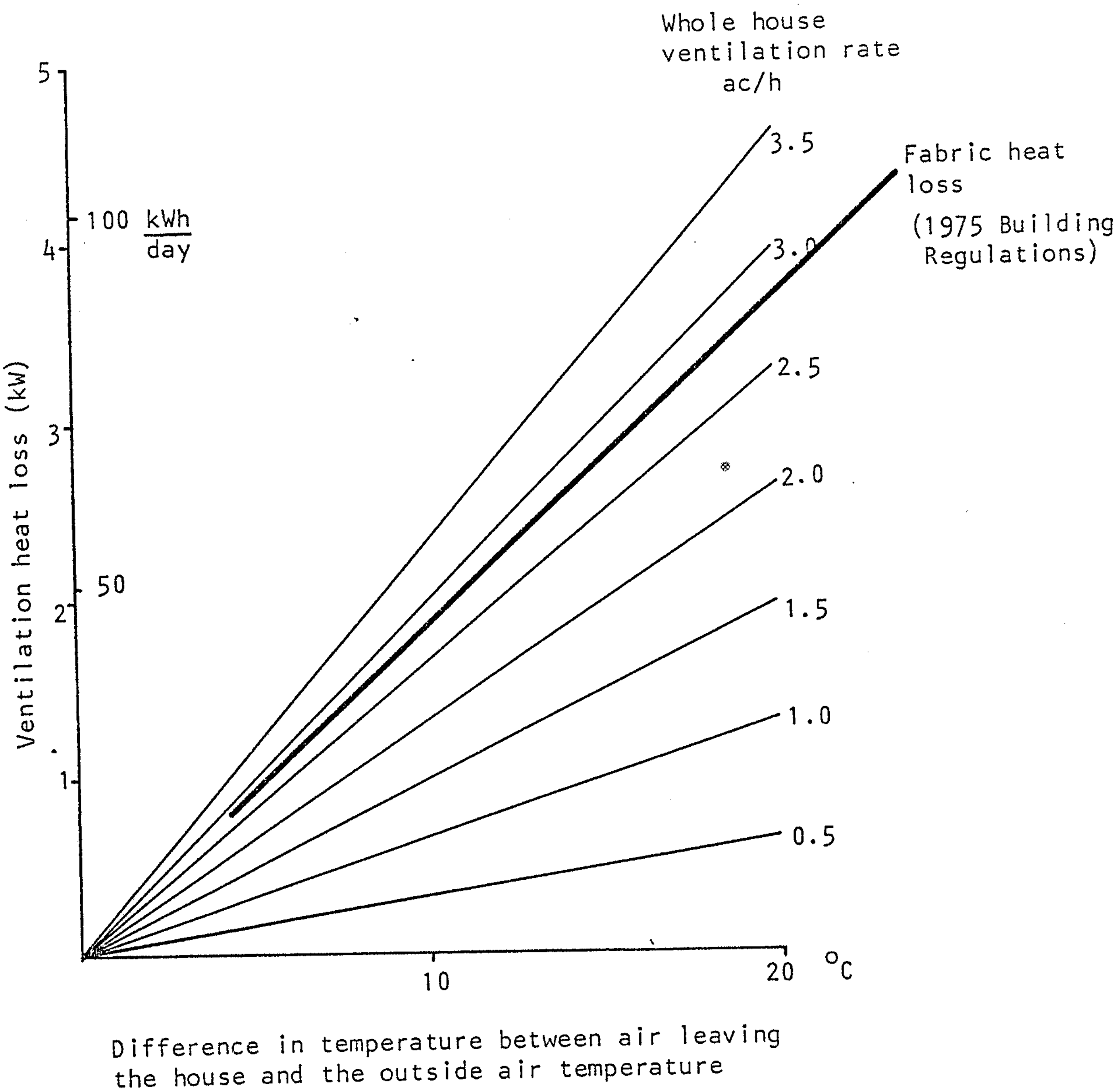
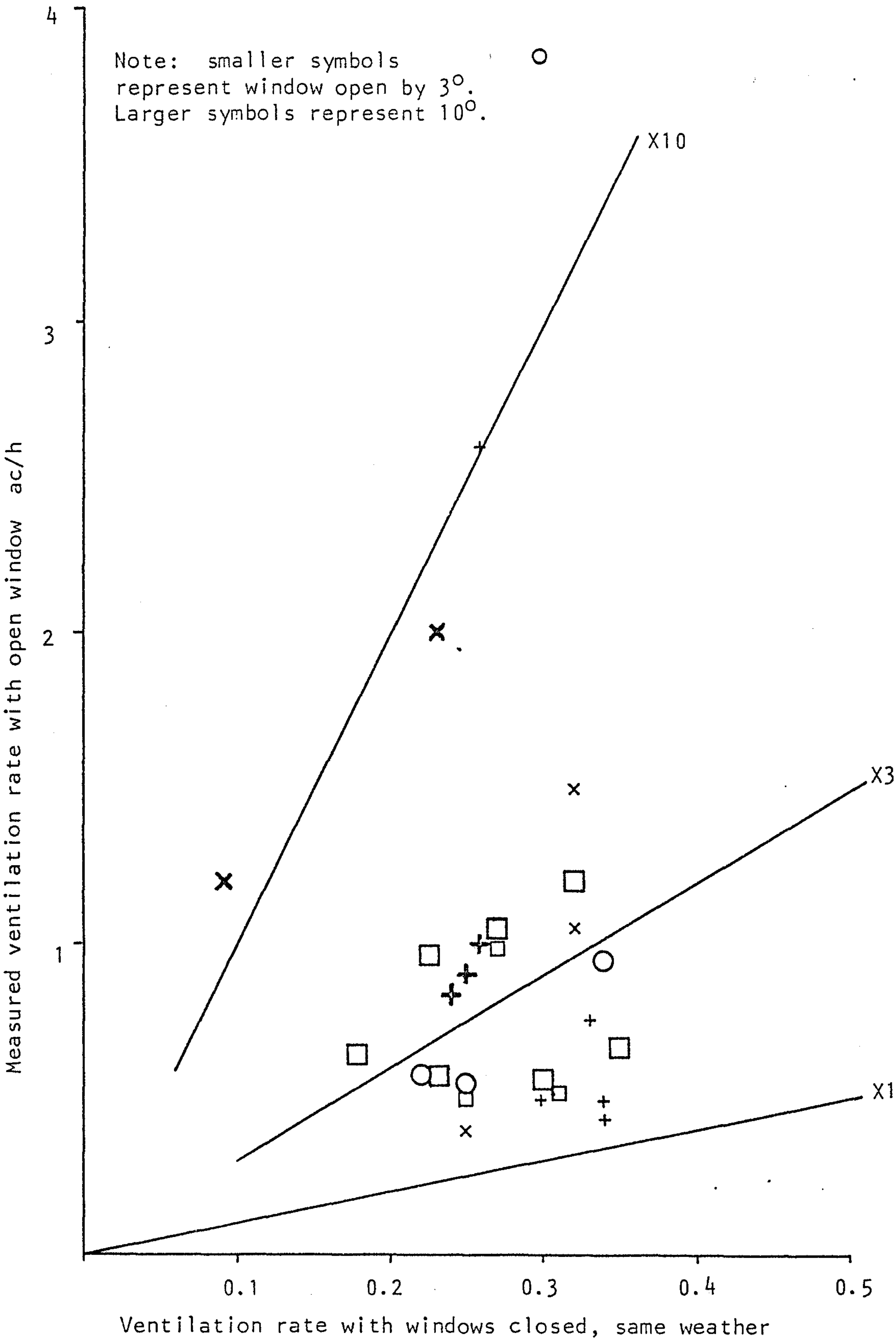


Figure 18. Ventilation heat loss, House B



Key:
- × windward room, window open
- o leeward room, window open
- + windward window open in another room
- □ leeward window open in another room

Figure 19. Individual room ventilation rates with a window open either in that room or in another room

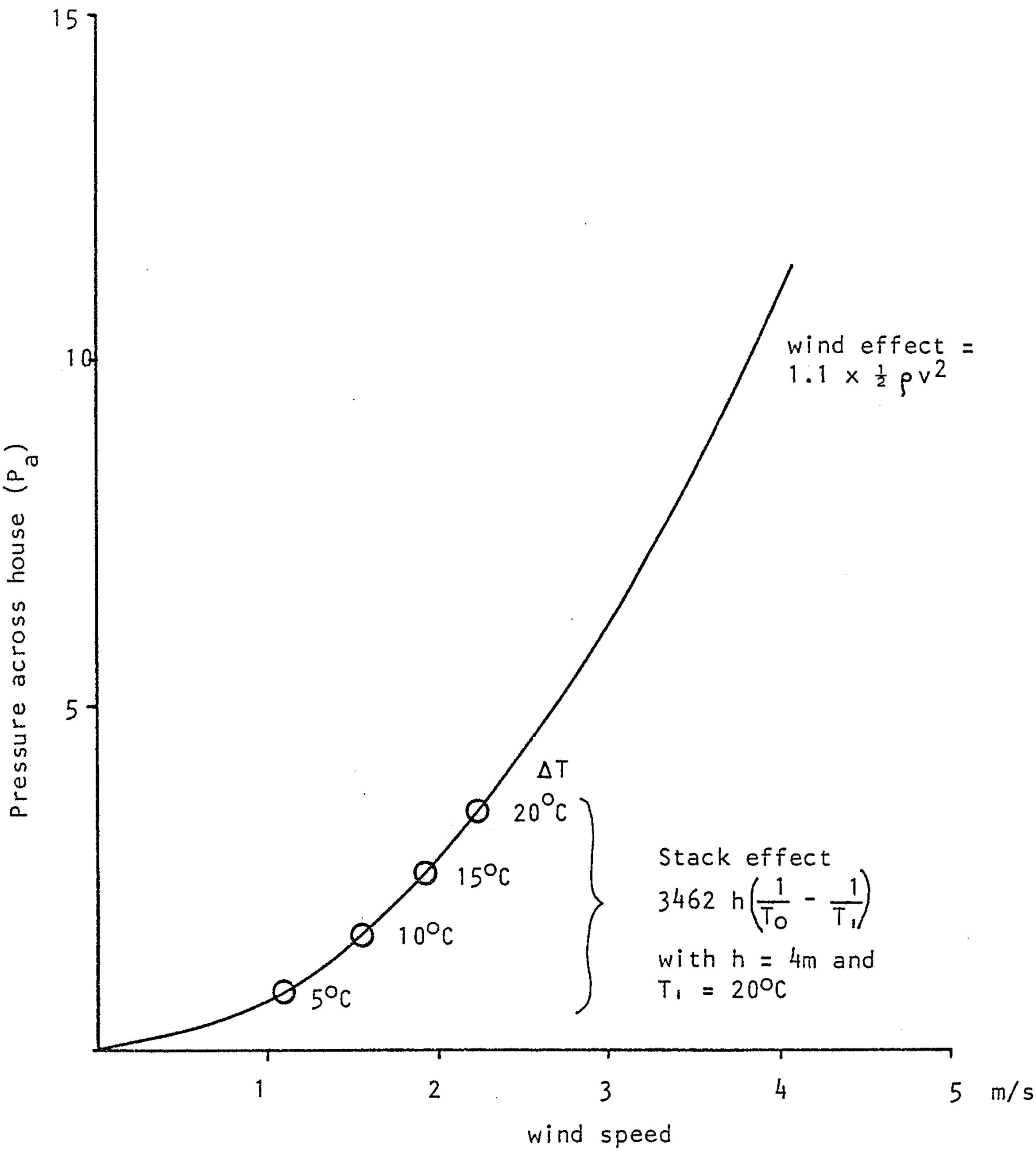


Figure 20. Pressure differences resulting from stack and wind effects

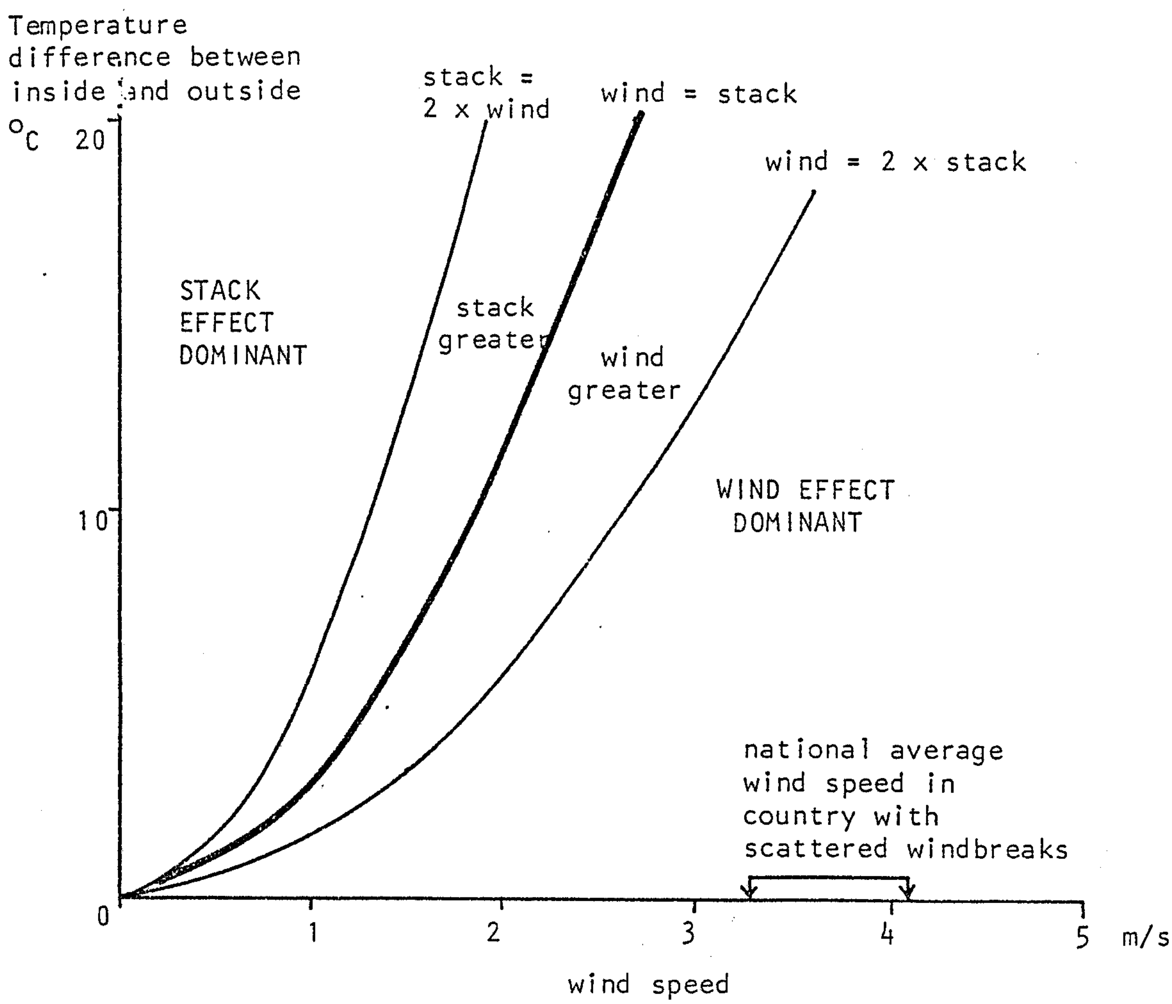


Figure 21. Comparison of wind and stack effects