VENTILATION SYSTEM PERFORMANCE

11th AIVC Conference, Belgirate, Italy
18-21 September, 1990

Paper 44

USING PRESSURISATION MEASUREMENTS TO PREDICT VENTILATION PERFORMANCE AND HEATING ENERGY REQUIREMENTS OF A LARGE INDUSTRIAL BUILDING

M D A E S Perera[1], G Powell[2], R R Walker[1] and P J Jones[2]

1. Building Research Establishment
Garston, Watford,
HERTS., WD2 7JR, UNITED KINGDOM

2. Dept of Architecture
University of Wales College of Cardiff
P O Box 25, CARDIFF CF1 3XE, UNITED KINGDOM

SUMMARY

A single whole building pressurisation test using robust and easy to use equipment can, in a very short time, quantify the air-leakiness of the building envelope. However, such measurements do not give a direct measure of the ventilation characteristics of the building which normally requires time-consuming and specialist tracer gas tests.

This paper provides a model which makes the link between leakage measurements and ventilation characteristics and applies it to a large, industrial building constructed according to 1979 UK Building Regulations. Air leakage measurements with the building 'as found' and then with its loading doors sealed showed a 14% reduction at an inside/outside pressure differential of 25 Pa. Using these leakage characteristics, the model predicted ventilation rates which corresponded well with measured values.

Meteorological data at the site for the heating season were combined with the ventilation characteristics of the building (given by the model) to predict the ventilation performance of the building over that period. The results indicated that the building 'as-found' would have, on average, an air change rate of 0.5 h^{-1} during the heating season. Sealing the loading doors would reduce this rate by 24%, i.e. to 0.38 h^{-1}.

This paper shows that space heating energy requirements for the heating season can be assessed using either the combined hourly-predicted ventilation rates and meteorological data for the site or using the mean predicted ventilation rate with existing design guidance. The two approaches agreed to within 10% of each other. The results also indicated that ventilation heat losses accounted for 44% of the total required energy. Calculations also show that replacing the loading doors with ones which are more air tight and better insulated will reduce by 25% the energy required for ventilation losses and by 5% the losses through the building fabric. This results in an overall reduction of 14% of the total requirement.

1. INTRODUCTION

A major factor in the ventilation of buildings and their energy performance is the leakiness of the building envelope. While adequate ventilation is essential for the health, safety and comfort of the occupants, the adventitious ingress (infiltration) of air through the building envelope can be a source of excessive ventilation and can lead to energy waste and, in some cases, to discomfort.

A single whole building pressurisation test[1] using robust and easy to use equipment can, in a very short time, quantify the air-leakiness of a buildings's external envelope. However, such a measurement does not give a direct measure of the ventilation characteristics of the building. This is usually assessed by tracer gas techniques[2] using sophisticated equipment and specialist expertise. It would also be time-consuming if a proper assessment of the ventilation performance of the building is needed, i.e. an assessment of how often specific ventilation rates occur over a specified period. This is because, at any moment, the ventilation rate of a naturally-ventilated building depends (among other factors) on the prevailing meteorological conditions (i.e. wind speed and direction and outside air temperature) and a proper assessment would require many tracer gas measurements to be carried out over a wide range of weather conditions.

A building pressurisation test is normally used to;

(a) compare the air tightness of different buildings and
(b) identify and quantify rates of leakage through different paths in the same building.

However, the value of a pressurisation test would be considerably enhanced if the results can be linked through a simple procedure to the ventilation performance of the building, bypassing ventilation measurements. This would then make it possible to assess whether there is adequate ventilation within the building and, if excessive, to;

(c) assess the potential for reducing air infiltration and,
(d) determine the cost-effectiveness of retrofit measures in reducing the energy used for the space heating of the building by reducing its ventilation heat loss.

The use of a simple correlation becomes even more attractive in the case of naturally-ventilated and large non-domestic buildings where tracer gas measurements can be fraught with difficulties[2]. As a starting point to provide similar correlations for more complex building-types like offices, this paper describes a preliminary attempt to make this link for a large single-space industrial building.

As said above, such a link could result in the identification of energy conserving opportunities. At the moment, UK industry as a whole consumes about 2600 PJ of primary energy annually[3] accounting for about 30% of the UK total. Of this, the 0.5 million or so industrial premises account for some 600 PJ (at a cost of £1400 million) for space and water heating and lighting with space heating being by far the largest component. A recent study[4] has shown that one of the most important factors in any energy savings in this type of industrial building is the impact of loading doors on air infiltration rates.

This paper covers a three-stage process to relate air leakage measurements to ventilation performance and energy use for a naturally-ventilated large single-space industrial building. The effect of sealing the loading doors is considered. In the first stage, a simple theoretical model is derived to predict the ventilation characteristics of the building from its measured whole building air leakage characteristics. The predicted values are then compared with field measurements (in which tracer gas techniques were used).

Given a specific wind direction, wind speed and an external air temperature, the ventilation rate of the building can be predicted from its ventilation characteristics. However, the ventilation characteristics of the building makes no reference to the local climatic conditions expected at the site. This is achieved in the second part of this paper by combining the ventilation characteristics of the industrial building with the local meteorological data to predict the ventilation performance of the building, i.e. how often various ventilation rates would be expected to occur. In this paper, the assessment was constrained to the ventilation performance expected over a typical heating season between the beginning of October until the end of March.

Finally, the effect of sealing the loading door on the heating energy requirements of the industrial building is assessed using the predicted ventilation performance. The energy requirements obtained are also compared against current guidance procedures[5].

2. PREDICTING VENTILATION CHARACTERISTICS FROM PRESSURISATION MEASUREMENTS

2.1. Theoretical Model

In a naturally-ventilated building, air enters either through design (e.g. through purposely provided openings like windows) or adventitiously by uncontrolled leakage (infiltration) through cracks and gaps in the building envelope. The air is driven through the openings by the pressure difference between inside and outside set up by the combined influence of wind and inside/outside temperature difference.

The pressure difference ΔP (Pa) across the opening can be expressed as[6],

$$\Delta P = (\frac{1}{2}\rho_o U^2 C_p + P_o - \rho_o g z) - (P_i - \rho_i g z) \qquad .... (1)$$

where C_p is the wind pressure coefficient referenced to a freestream wind speed U (m/s) measured at a reference height,
ρ_o is the outside (external) air density (kg/m^3),
P_o and P_i are the outside and inside static pressures (Pa) at height $z = 0$ m and
g is the gravitational constant (= 9.80665 m/s^2).

For large openings like windows, the air flow rate Q (m^3/s) through that component is given by the simple formula

$$Q = A\, C_d \sqrt{\frac{2\, \Delta P}{\rho}} \qquad .... (2)$$

where A is the area (m^2) of the opening, C_d is the discharge coefficient (usually given a value of 0.61) and ρ is the density (kg/m^3) of air flowing through the opening.

Using a derivation similar to that of Warren and Webb[6], the adventitious leakage Q (m^3/s) through any single element of the building facade, i.e. a roof or wall element, for a pressure differential ΔP can be obtained from a whole-building leakage measurement. For brevity, this is not derived here but it can be shown that this relationship is given by

$$Q = \rho_o \left[\frac{k\rho_{pr}}{g(n+1)}\right] \left(\frac{A}{A_T}\right) \left(\frac{1}{h_U - h_L}\right) \left[\left| a - bh_L \right|^{n+1} - \left| a - bh_U \right|^{n+1}\right] \qquad .... (3)$$

where k and n are respectively the coefficient and exponent obtained from a pressurisation test and related by an equation of the form, $Q = k.\ \Delta P^n$,
ρ_{pr} is the outside air density during the pressurisation test.
A (m^2) is the area of the facade element,
A_T (m^2) is the total external permeable area of the building and
h_L and h_U are the lower and upper heights of the facade element above ground level.

Here, $a = 1/2\ \rho_o U^2 C_p - p_i$ where p_i (= $P_I - P_e$) is the inside pressure and
$b = g\ (\rho_o - \rho_i)$ in which ρ_i is the air density inside.

The main assumption[6] inherent in deriving the above equation is that the pressure generated by the wind and the air leakage through the envelope is uniformly distributed across each surface. However, a weighting factor (totalling 1.0 over all surfaces) can be ascribed, if necessary, to each of the surfaces to take into account variations in air permeability.

A computer program BREAIR, similar to the domestic model BREVENT[7], was written to solve the above equations. The inside air pressure is the unknown parameter to be found. The program uses an iterative procedure to calculate this pressure for which there is mass balance. Volume flows are then calculated using the appropriate air densities.

2.2. Field Measurements

Whole building pressurisation tests and tracer gas measurements of ventilation flow rates were carried out in an industrial building in Cwmbran, Wales. Measurements in this building formed part of a larger programme of seven similar studies undertaken in a variety of single-celled industrial buildings to provide, amongst other things, data sets for validating prediction procedures. In each building, measurements were made before and after sealing various identifiable air leakage paths.

Industrial building

This detached single-cell building (Fig. 1) is located in the Ty-Coch Industrial Estate, Cwmbran in Wales. Figures 2 is a site plan showing the location of the building relative to its neighbours and showing that the factory faces east and is oriented on a north-south axis.

The volume of the building was estimated as 15063 m^3 with a production floor area of about 1950 m^2. The walls and roofs were built to Part FF standard of the 1979 UK Building Regulations which required wall and roof U-values of 0.7 W/m^2K. The wall comprised of a metal clad outer leaf with a fibre board inner leaf containing 60 mm of glass fibre insulation with a band of single glazing at high-level. On the east wall, there were two standard roller-shutter loading doors, each with an area of 18 m^2.

There were two working areas or bays with duo-pitch metal clad roofs with an asbestos panelled inner leaf containing 60 mm of glass fibre insulation. There was approximately 5% roof lighting but no roof ventilators.

Whole-building pressurisation tests

A pressurisation rig consisting of four large fans was used to pressure test the building. Two tests were carried out in calm conditions; one with the building 'as-found' and the other with both loading doors sealed with polythene sheeting. The outside air temperature during the test was about 8°C with the inside temperature ranging between 8 and 9°C.

The generally accepted relationship

$$Q = k \cdot \Delta P^n \qquad \text{.... (4)}$$

between air leakage Q (m^3/s) and inside/outside static pressure difference ΔP (Pa) was fitted to the measured data. Best-fit regression lines (with correlation, $r^2 > 0.99$) on the measured data gave the following results:

Condition of Building	Coefficient, k $m^3/s.Pa^n$	Exponent, n
'as-found'	4.162	0.497
loading doors sealed	3.300	0.521

For large buildings, it is usual[1] to consider the air leakage rate at 25 Pa. Calculations at this pressure show that the air leakage rate is reduced by 14% when the loading doors were sealed.

Ventilation rate measurements

An automated tracer gas system[8] was used to measure the ventilation rates within the building as-found and with the loading doors sealed. The measurements were carried at various intervals over a period of one month to cover varying outside weather conditions. Both 'decay' and 'constant-concentration' measurements[2] were made using nitrous oxide as the tracer. However, only a portion of this data - sufficient to evaluate the predictions - is used in this paper. An analysis of the full data set will be the subject of a future report.

Inspection of the full data set showed that there was sufficient information available from the constant-concentration tests to compare the performance of the factory as-found and also with loading doors sealed for winds blowing from the south. Figure 3 shows the data corresponding to this direction. The outside air temperature for this set averaged at 8°C, while the inside temperature averaged around 11°C for the building as-found and 12°C with the loading doors sealed.

Wind pressure coefficients for predicting ventilation

Wind pressure coefficients are necessary to carry out any prediction. In the absence of specific wind-tunnel measurements, it is sometimes possible to use published wind tunnel data which may have been gathered for other purposes, such as for wind loading calculations when the measurements have been made on isolated buildings.

However, it is known[9] that such pressures are substantially reduced when the building is sheltered or surrounded by buildings of similar height and previous work[6,9,10] have shown that these coefficients could be halved for predicting ventilation in buildings which are sheltered by others of similar height. In this paper, wind pressure coefficient for this type of industrial buildings (multi-bays with 5° duo-pitch roofs) were obtained from published wind-loading data[11] and then modified. These amended values, used in the present prediction, are given in Table 1.

2.3. Comparing Predicted with Measured Ventilation Rates

The input data for BREAIR comprised of the estimated wind pressure coefficients for southerly winds, the measured envelope air leakage data and the individual permeable areas of the roof and wall areas (estimated from Figure 1). The model was run through a range of wind speeds using air temperatures appropriate to the measured data (shown in Fig 3).

In Figure 3, the predicted curves are superimposed over the measured values for both the building 'as-found' and also with the loading doors sealed and shows good comparison between measured and predicted. The predictions appear to identify correctly not only the magnitude of the rates but also the point at which the ventilation switches over from being buoyancy-induced (as a consequence of the inside/outside temperature difference) to wind-induced.

Ad-hoc spot checks were also carried out on the rest of the measured data corresponding to other wind directions. In all, the results were as good as for the specific wind direction considered here. This gives confidence in using the prediction model in this instance. Further comparisons will need to be carried out later on other industrial buildings to confirm the general validity of the model.

3. ASSESSING VENTILATION PERFORMANCE

These ventilation predictions, although specific to the building, make no reference to local climatic conditions at the site. To assess the ventilation performance and to predict how often various levels of ventilation could be expected, the predicted ventilation characteristics of the building have to be combined with the weather frequency distribution, i.e. the joint occurrence of wind direction, wind speed and outside air temperature.

3.1. Compressing Ventilation Flows

To assess the overall ventilation performance of the industrial building, it is necessary to compute the ventilation flow Q for winds blowing from each direction ϕ for a range of wind speeds u and air temperature differences $\Delta\theta$ between inside and outside. To avoid generating a large and unmanageable set of data, the results can be presented in a compressed form, in which the temperature dependence has been removed, without any loss of generality.

Previous work[12] has shown that, for each wind direction ϕ, all the predicted or measured air flow rates $Q(u,\Delta\theta,\phi)$ can be collapsed into such a form by scaling both the ventilation flow and the wind speed by the factor $1/\Delta\theta^{1/2}$. Using predicted values from BREAIR, this was carried out for the industrial building with and without the loading door sealed. Dividing the flow rates by the volume (V) of the building, the air change rates I (per hour) were calculated and scaled accordingly and Figure 4 shows the results for, in this instance, a temperature difference of 1°C. Note that all directions are not represented because of symmetry (about the north-south and east-west axis) for the building 'as found' and (along the east-west axis) with the loading doors sealed.

This compressed form makes the data more manageable when used as input to assess the ventilation performance of the building. This aspect is further enhanced by being able to represent them with polynomial expressions[12] of the form,

$$I(\phi) = a_0(\phi) + a_1(\phi)\overline{u} + a_2(\phi)\overline{u}^2 + a_3(\phi)\overline{u}^3 + a_4(\phi)\overline{u}^4 \quad .... (5)$$

where

$$I(\phi) = \frac{Q(u,\Delta\theta,\phi)}{V\sqrt{\Delta\theta}}$$

and,

$$\bar{u} = \frac{u}{\sqrt{\Delta\theta}}$$

Using regression analysis, best-fit (correlation $r^2 > 0.99$) of the above form were fitted to the predicted curves (Fig 4). The polynomial coefficients obtained are tabulated in Table 2.

3.2. Meteorological Data

A record of local weather conditions was obtained from the nearby meteorological station at Cilfynydd, Wales. Although not the nearest, it was located in a terrain similar to the building site. Calculations[13] to take account of change in site and height (required since the pressure coefficients were referenced to the eave height of the building) of the meteorological anemometer showed that the wind speeds at the site had to be reduced to 56% of that measured at the station.

The meteorological data (collected over the period October 1982 to March 1990) was constrained in the analysis to the winter heating season, i.e. beginning of October to the end of March and to the time period between 0600 and 1800 GMT when the building would be heated. Since measurements were collected only at three-hourly intervals, some refinement of the data was carried out to translate them into representative hourly values. No attempt was made to further segregate the weather data to exclude week-ends since the standard occupancy pattern of a full week is used to calculate energy demands in factories[5].

Figure 5 shows the weather conditions monitored at the meteorological station for this constrained period. Winds from the north predominate even though there is some substantial occurrence from the south-west. The mean wind speed and the outside air temperature exceeded for 50% of the time are about 3.7 m/s and 7.5°C respectively.

3.3. Statistical Assessment of the Ventilation Performance

The design or required inside temperature was taken as 19°C, a value normally used[5] to assess heating energy requirements. Using the polynomial expressions given in Equation 5, the air change rates were determined for combinations of wind direction, speed and outside air temperature. The number of hours that these combinations occurred were then read from joint frequency tables (of wind speed, outside air temperature and wind direction) and placed in 'bins' corresponding to various intervals of ventilation flows to build a frequency distribution. Figure 6 shows the evaluated percentage frequency of the ventilation air change rate within the building as-found. Figure 7 shows this translated to a frequency of exceedance. Figure 7 also shows the corresponding information for the case when the doors were sealed.

Figure 7 shows that the mean air change rate within the building as-found is 0.5 h^{-1} corresponding to the recommended[14] design value for calculating energy demands. Figure 7 also shows quite clearly that sealing the loading doors reduces this mean (50% exceedance) rate to 0.38 h^{-1}, i.e. a 24% reduction in the mean ventilation rate.

4. PREDICTING HEATING ENERGY REQUIREMENTS

4.1. Using Predicted Ventilation Rates

The heating energy E_V (GJ) required for losses by natural ventilation over the heating season is given by,

$$E_V = \rho_r \, c \sum_{\text{heating period}} Q \, (\theta_r - \theta_o) \, 10^{-6} \, \Delta t \qquad \text{.... (6.a)}$$

where c (= 0.988 kJ/kg.K) is the specific heat of air,

θ_r and θ_e are the required (design) inside and outside air temperatures respectively,

ρ_r is the air density corresponding to the required air temperature,

Q (m^3/h) is the ventilation rate predicted for a particular wind speed, wind direction and outside temperature, and

Δt is the individual time period (h) during which this occurs.

This calculation is carried out only when the inside air temperature is greater than that outside.

The energy required E_F (GJ) for fabric heat losses over the heating season is similarly given by,

$$E_F = 3.6 \, 10^{-6} \sum_{\text{heating period}} (\Sigma AU) \, (\theta_r - \theta_o) \, \Delta t \qquad \text{.... (6.b)}$$

where Σ(AU) is the product of all areas A (m^2) of surfaces separating the heated space from the outside and their U-values (W/m^2K). The areas and the U-values for each major component of the industrial building are given in Table 3. Note that the U-value for the floor relates[14] to the outside air temperature and not to the surface ground temperature.

Using the meterological data, the energy requirements given in Equations 6 were evaluated for the building as-found and with the loading doors replaced with higher performance doors which are more air tight and better insulated. The results were obtained for each of the major building components and are given in Table 4.

4.2. Compensating the Predicted Heating Energy Requirement for Intermittent Heating

According to design guide[5], when a reduction in the required temperature is allowed at night, the mean inside temperature, θ_{im}, can be taken as the mean temperature calculated for an intermittently heated building. This mean temperature is a function of:

(i) The required inside temperature, θ_r, during the heating period.
(ii) The average daily heating period, including pre-heating, H.
(iii) The response factor, f, of the building.

The equations relating these[5], re-written here for completeness, are as follows:

$$f = \frac{\Sigma(AY) + \rho c Q}{\Sigma(AU) + \rho c Q} \quad \text{.... (7.a)}$$

and.

$$\theta_{im} = \theta_{om} + \frac{H f (\theta_r - \theta_{om})}{H f + (24 - H)} \quad \text{.... (7.b)}$$

where Q is the design ventilation rate (m^3/s),
$\Sigma(AY)$ is the sum of products of areas of all exposed surfaces and their appropriate thermal admittances (Table 3) and
θ_{om} is the 24-hour mean outside air temperature (°C)
and all other symbols as previously defined.

A mean outside air temperature θ_{om} of 7°C was estimated for Cwmbran from design guidance[5], a value close to that identified from the meteorological data (Section 3.2). Using air change rates of 0.5 (building as-found) and 0.35 h^{-1} (loading doors sealed), f was evaluated from Equation 7.a. as about 3. This value for the response factor is typical[14] for thermally lightweight buildings of this type. A more massive building will have a higher response factor. Using Equation 7.b., θ_{im} was evaluated as 15.9°C.

The total energy requirement E_H (comprising of requirements for both ventilation and fabric losses) evaluated in previous Section 4.1. covered only the heating period H from 0600 to 1800 hrs. It is therefore necessary to correct to a 24-hour requirement, $E_{24,}$ to compensate for thermal storage effects of the construction and loss during the unheated overnight period. This can be obtained from the equation (Harrington-Lynn, private communication),

$$\frac{E_H}{E_{24}} = \frac{H (\theta_r - \theta_{om})}{24 (\theta_{im} - \theta_{om})} \quad \text{.... (8)}$$

Substitution of the appropriate values, evaluated for the present case, in the above equation shows that 33% of the energy input during the heating period is carried over due to thermal storage and lost during the unheated overnight period. This 33% carry-over means that the estimates of energy use predicted earlier need to be increased by 50% resulting in the following revised estimate:

Component	**HEATING ENERGY REQUIREMENTS (GJ)**	
	building as-found	**with higher-performance loading doors**
FABRIC	496	469
VENTILATION	392	295
TOTAL	888	764

This shows that approximately 44% of the heating energy required for this building is for ventilation losses with over half lost through the fabric. Even though sealing the loading door reduces the losses through ventilation by 25%, the reduction through the fabric is only 5% (as a consequence of reducing the U-value of the loading doors) but overall there is a 14% reduction in the total energy requirement.

The effect of sealing the loading doors in this factory, built to present UK Standards, can be compared with a low energy factory building (with much higher levels of thermal insulation) where a nominally similar measure[4] was also carried out. In this instance, it was estimated that ventilation losses were reduced by 52%, fabric losses by 21% and the total by 32%.

4.3. Using Design Guidance

As a check against the above predicted values, a standard design procedure[5] was used to calculate the energy demand for space heating of the industrial building. Using the transmittance and admittance values given in Table 3, design air change rates of 0.5 and 0.38 h^{-1} were used in calculations for the building as-found and with the leading doors sealed and the results are summarised below:

Component	**HEATING ENERGY REQUIREMENTS (GJ)**	
	building as-found	**with higher-performance loading doors**
FABRIC	465	451
VENTILATION	**346**	**270**
TOTAL	**811**	**721**

The comparison between these design values using a ventilation rate averaged over the heating season and those obtained from the hourly predictions are within 10% of each other with the hourly predictions over-estimating the energy requirements. These comparisons give confidence, at least for this building, that predicted energy demands for space heating could be estimated from whole-building air leakage measurements or obtained from existing design guides provided the air change rate for the building is correctly identified.

5. CONCLUSIONS

The whole building pressurisation tests on the industrial building showed that the air leakiness of the external building fabric was reduced by 14% (at a 25 Pa pressure difference between inside and out) when both loading doors were sealed.

A simple ventilation prediction model which used the building's leakage characteristics was shown to compare well with measured (using tracer gas methods) ventilation data. The predictions were combined with the meterological weather conditions expected during the heating season to predict the ventilation performance of the building. Results indicate that the mean (exceeding for 50% of the time) ventilation rate was 0.5 air changes per hour (ach) with the building 'as-found'. This rate was reduced to 0.38 ach when the loading doors were sealed, i.e. a reduction of 24%.

The ventilation model was also used to predict (on an hourly basis) the space heating energy requirements for the heating season. These values were within 10% of that given by standard design procedures using the predicted ventilation rates averaged over the heating season. The predictions showed that replacing the loading doors with higher-performance doors would reduce the energy requirement for ventilation from 392 to 295 GJ (reduction of 25%), those due to fabric losses from 496 to 469 GJ (a 5% reduction) and the total from 888 to 764 GJ (i.e. reduced by 14%).

Using a database of field measurements, additional work will be carried out to validate further this approach of using measured external wall leakage characteristics to estimate the ventilation performance of naturally ventilated, large non-domestic buildings and to predict their space heating energy demands.

ACKNOWLEDGEMENTS

Thanks are due to Andrew Cripps for help with the BREAIR algorithms. The considerable help and guidance given by John Harrington-Lynn in the energy prediction aspect of this work is gratefully acknowledged. The field measurements described in this paper were carried out by the Welsh School of Architecture under contract to the Building Research Establishment. The work described here has been carried out as part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Chief Executive.

REFERENCES

1. Perera, M D A E S, Stephen, R K and Tull, R G, Use of BREFAN to measure the airtightness of non-domestic buildings, BRE IP 6/89, Building Research Establishment, (1989).

2. Perera, M D A E S, Review of techniques for measuring ventilation rates in multicelled buildings, Published in Energy Conservation in Buildings - Heating, Ventilation and Insulation (Ed. Ehringer, H, Hoyaux, G and Zegers, P), Reidl Publishing Co., Dordrecht, (1982).

3. Wozniak, S J, Energy efficiency in industrial buildings, BRECSU Information Leaflet 9, Building Research Establishment, (1988).

4. Jones, P J and Powell, G, Low Energy Factory Development, Energy Efficiency Demonstration Scheme Final Report No. ED 256/173, Energy Efficiency Office, (1989).

5. CIBS, CIBS Building Energy Code, Part 2: Calculation of Energy Demands and Targets for the Design of New Buildings and Services; Section (a) Heated and Naturally Ventilated Buildings, The Chartered Institution of Building Services, London (1981).

6. Warren, P R and Webb, B C, The relationship between tracer gas and pressurisation techniques in dwellings, Proceedings of the 1st Air Infiltration Centre Conference on Infiltration Measurement Techniques held in Windsor, UK (1980).

7. Edwards, R, Hartless, R and Gaze, A, Measurements of sub-floor ventilation rates - comparison with BREVENT predictions, To be presented at the poster session of the 11th AIVC Conference on Ventilation System Performance (Sept. 1990).

8. Etheridge, D W, Application of the constant concentration technique for ventilation measurements in large buildings, Building Services Engineering Research and Technology, Vol 6(3), pp 129-33, (1985).

9. Lee, B E, Hussain, M and Soliman, B, A method for the assessment of the wind-induced natural ventilation forces acting on low-rise building arrays, Building Services Engineering Research and Technology, Vol 1(1), (1980).

10. Perera, M D A E S and Warren, P R, Influence of open windows on the interzone air movement within a semidetached dwelling, Proceedings of the 6th AIC Conference on Ventilation Strategies and Measurement Techniques (1985).

11. BRE, BRE Digest 346 - The assessment of wind loads; Part 6: Loading coefficients for typical buildings, Building Research Establishment, (1989).

12. Perera, M D A E S, Walker R R and Tull, R G, Natural ventilation for a Crown Court: Developing statistical assessment techniques at the design stage, Proceedings of the 9th AIVC Conference on Effective Ventilation, (1988).

13. British Standards Institute, Code of practice for Design of Buildings: Ventilation principles and Designing for Natural Ventilation, BS 5925, (1980).

14. CIBSE, CIBSE Guide - Volume A (Design Data), CIBSE, London (1988).

TABLE 1 - PRESSURE COEFFICIENTS, C_P

	Wall area				Roof area			
Wind direction (°N)	**North-facing**	**East-facing**	**South-facing**	**West-facing**	**North-facing outer**	**South-facing inner**	**North-facing inner**	**South-facing outer**
0	0.43	-0.21	-0.11	-0.21	-0.29	0.00	-0.23	0.00
30	0.35	0.20	-0.13	-0.23	-0.30	0.00	-0.24	0.00
60	0.20	0.35	-0.23	-0.13	-0.21	0.00	-0.17	0.00
90	-0.21	0.43	-0.21	-0.11	0.00	0.00	0.00	0.00
120	-0.23	0.35	0.20	-0.13	0.00	-0.17	0.00	-0.21
150	-0.13	0.20	0.35	-0.23	0.00	-0.24	0.00	-0.30
180	-0.11	-0.21	0.43	-0.21	0.00	-0.23	0.00	-0.29
210	-0.13	-0.23	0.35	0.20	0.00	-0.24	0.00	-0.30
240	-0.23	-0.13	0.20	0.35	0.00	-0.17	0.00	-0.21
270	-0.21	-0.11	-0.21	0.43	0.00	0.00	0.00	0.00
300	0.20	-0.13	-0.23	0.35	-0.21	0.00	-0.17	0.00
330	0.35	-0.23	-0.13	0.20	-0.30	0.00	-0.24	0.00

All coefficients referenced to freestream dynamic pressure measured at eave height

TABLE 2 - POLYNOMIAL COEFFICIENTS

Factory - as found:

Wind direction (°N)	a_0	a_1	a_2	a_3	a_4
0	0.1381	-0.0707	0.0747	-0.0114	0.0006
30	0.1303	-0.0089	0.0422	-0.0053	0.0002
60	0.1207	0.0296	0.0131	-0.0004	0.0000
90	0.1256	-0.0121	0.0230	-0.0033	0.0002
120	0.1207	0.0296	0.0131	-0.0004	0.0000
150	0.1303	-0.0089	0.0422	-0.0053	0.0002
180	0.1381	-0.0707	0.0747	-0.0114	0.0006
210	0.1303	-0.0089	0.0422	-0.0053	0.0002
240	0.1207	0.0296	0.0131	-0.0004	0.0000
270	0.1256	-0.0121	0.0230	-0.0033	0.0002
300	0.1207	0.0296	0.0131	-0.0004	0.0000
330	0.1303	-0.0089	0.0422	-0.0053	0.0002

Loading doors sealed:

Wind direction (°N)	a_0	a_1	a_2	a_3	a_4
0	0.1032	-0.0530	0.0578	-0.0086	0.0004
30	0.0969	-0.0080	0.0348	-0.0044	0.0002
60	0.0910	0.0192	0.0117	-0.0003	0.0000
90	0.0942	-0.0120	0.0186	-0.0026	0.0001
120	0.0910	0.0192	0.0117	-0.0003	0.0000
150	0.0969	-0.0080	0.0348	-0.0044	0.0002
180	0.1032	-0.0530	0.0578	-0.0086	0.0004
210	0.0973	-0.0039	0.0319	-0.0037	0.0002
240	0.0900	0.0198	0.0161	-0.0017	0.0001
270	0.0938	-0.0095	0.0192	-0.0026	0.0001
300	0.0900	0.0198	0.0161	-0.0017	0.0001
330	0.0973	-0.0039	0.0319	-0.0037	0.0002

TABLE 3 - THERMAL TRANSMITTANCE AND ADMITTANCE PROPERTIES

COMPONENT	AREA, A m²	TRANSMITTANCE, U W/m² K	ADMITTANCE, Y W/m² K
Wall	1283.8	0.70	0.75
Wall glazing	44.6	5.60	5.60
Loading door	36.0	5.60 (**0.70**)	5.60 (**0.75**)
Roof	1851.4	0.70	0.75
Roof lights	97.4	3.50	3.50
Floor	1830.6	0.21	6.00

(Note: Figures in bold for the loading doors give relevant values when the doors are sealed)

TABLE 4 - ENERGY REQUIREMENTS WITHOUT COMPENSATING FOR INTERMITTENT HEATING

COMPONENT	HEATING ENERGY REQUIREMENTS (GJ)	
	building as-found	loading doors sealed
Wall	89	89
Wall glazing	25	25
Loading door	20	2
Roof	129	129
Roof lights	34	34
Floor	38	38
VENTILATION	264	199
TOTAL	599	516

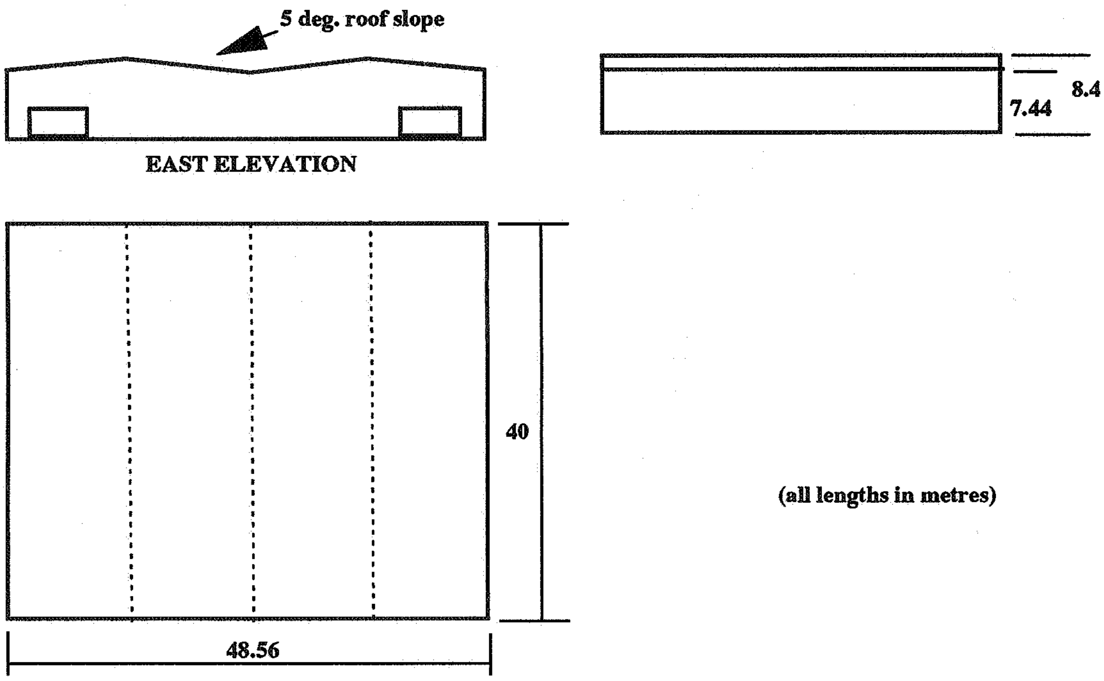


FIGURE 1 - PLAN AND ELEVATIONS OF THE INDUSTRIAL BUILDING

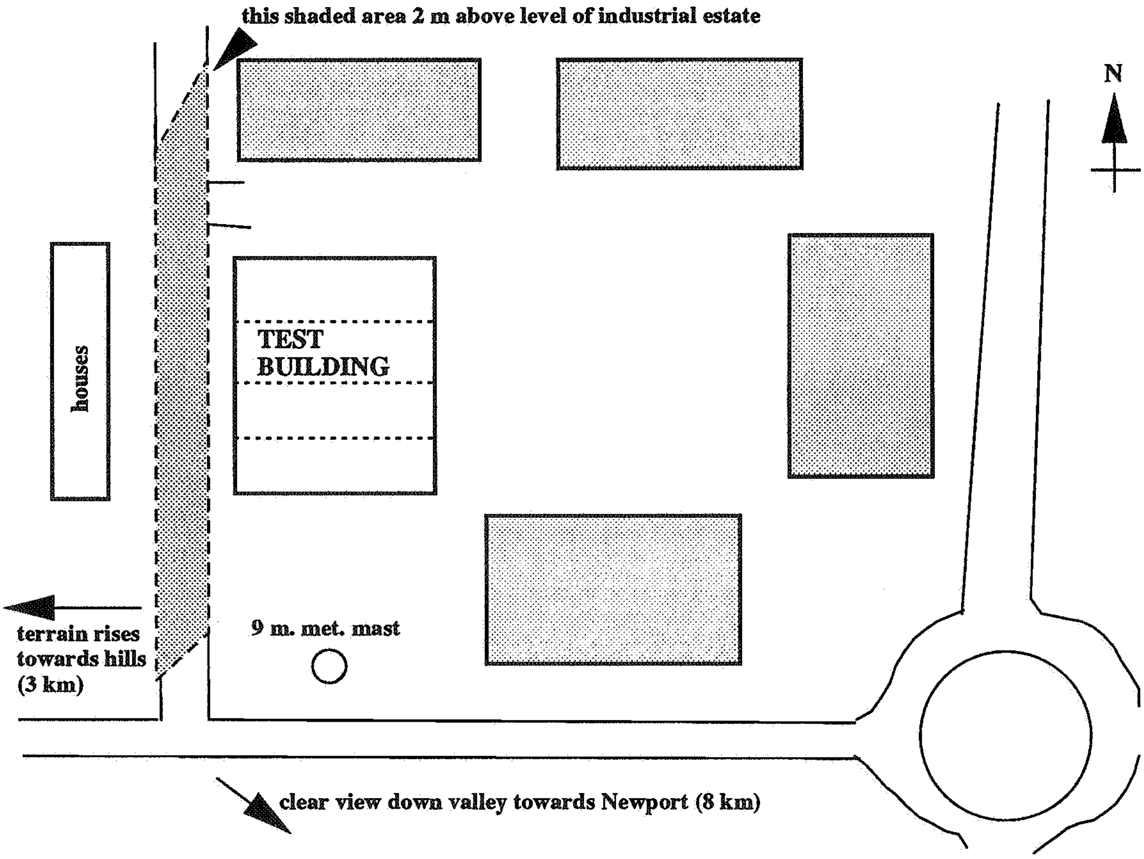


FIGURE 2 - SITE PLAN OF TEST INDUSTRIAL BUILDING

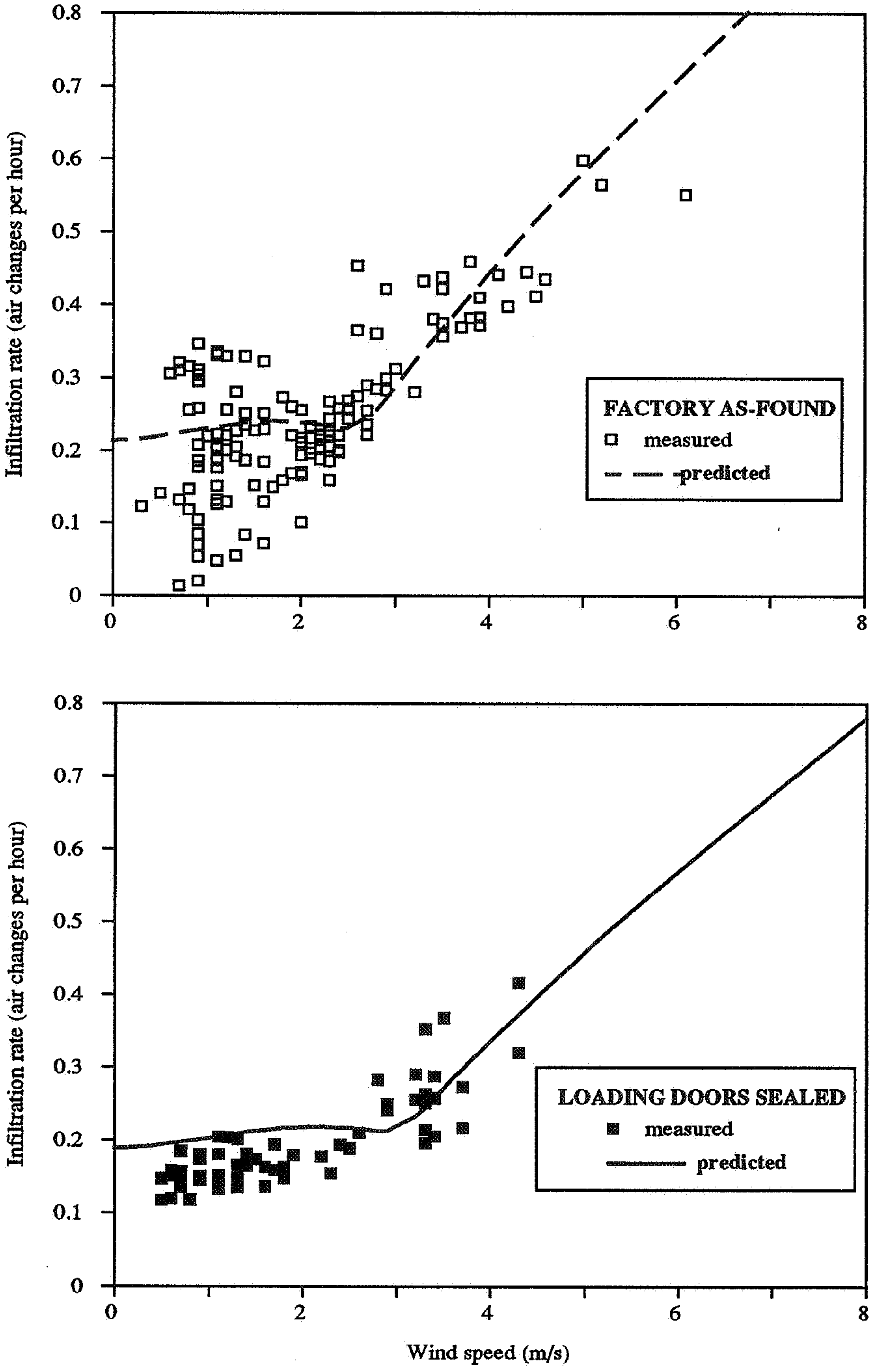


FIGURE 3 - VENTILATION RATES FOR SOUTH WINDS

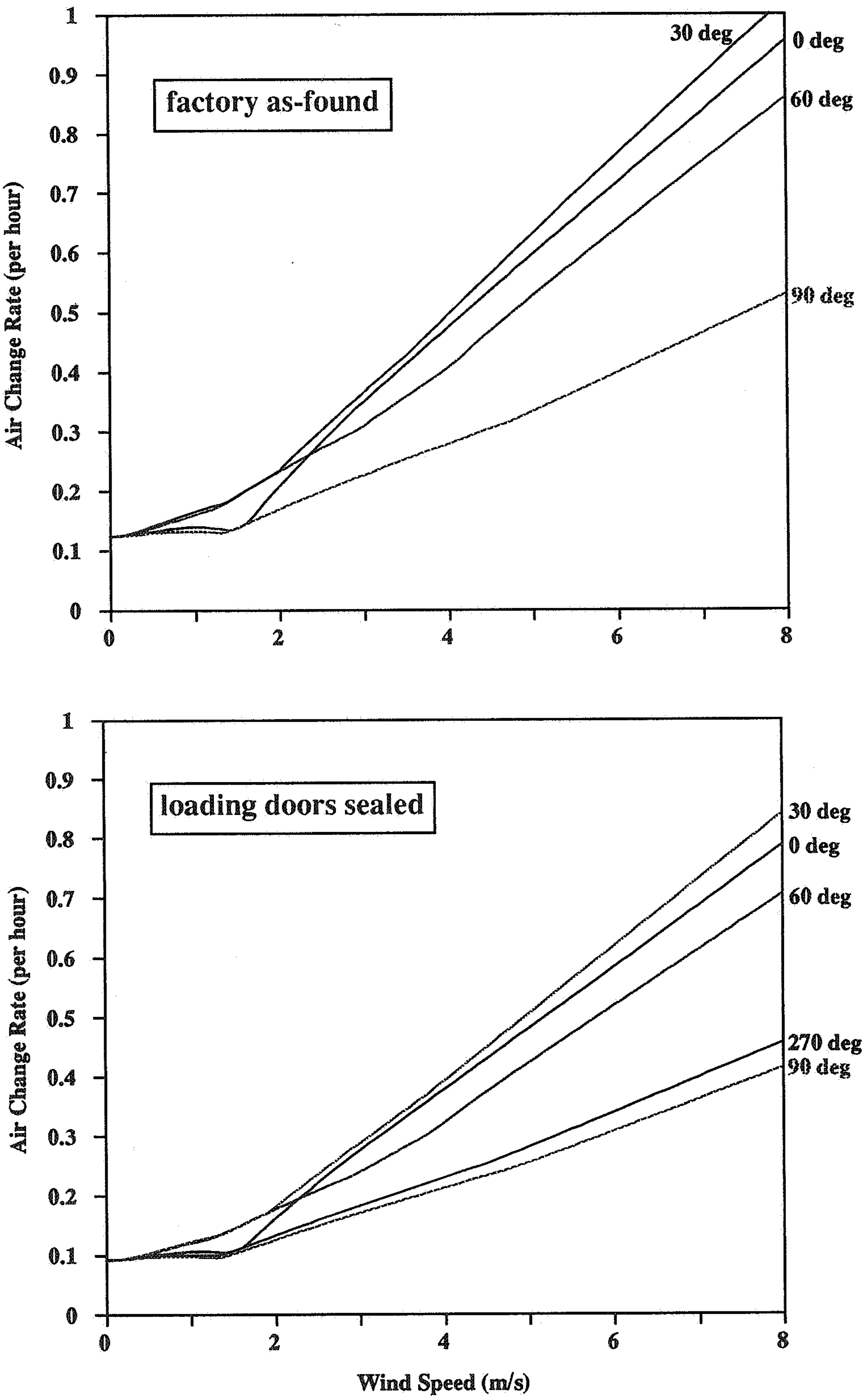
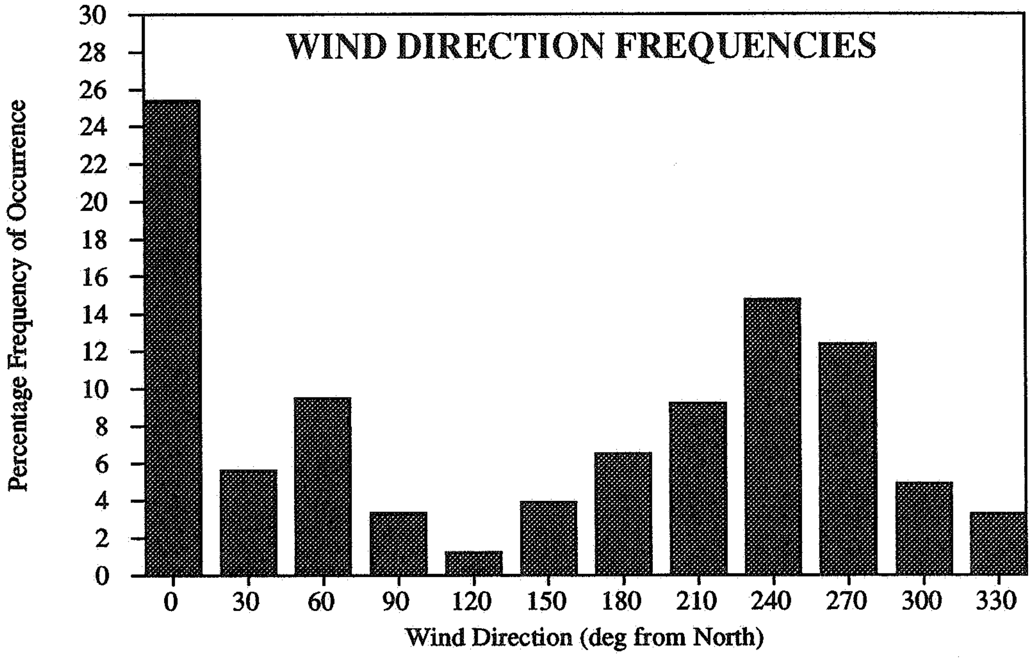


FIGURE 4 - PREDICTED VENTILATION RATES



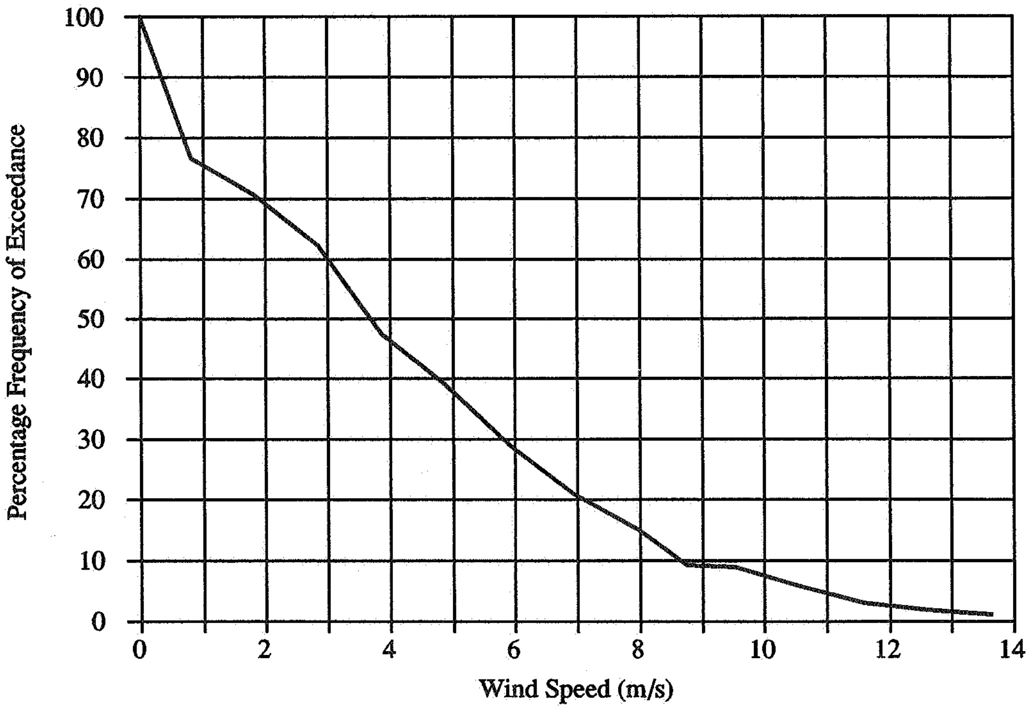


FIGURE 5.a. - WIND CONDITIONS AT THE MET. STATION

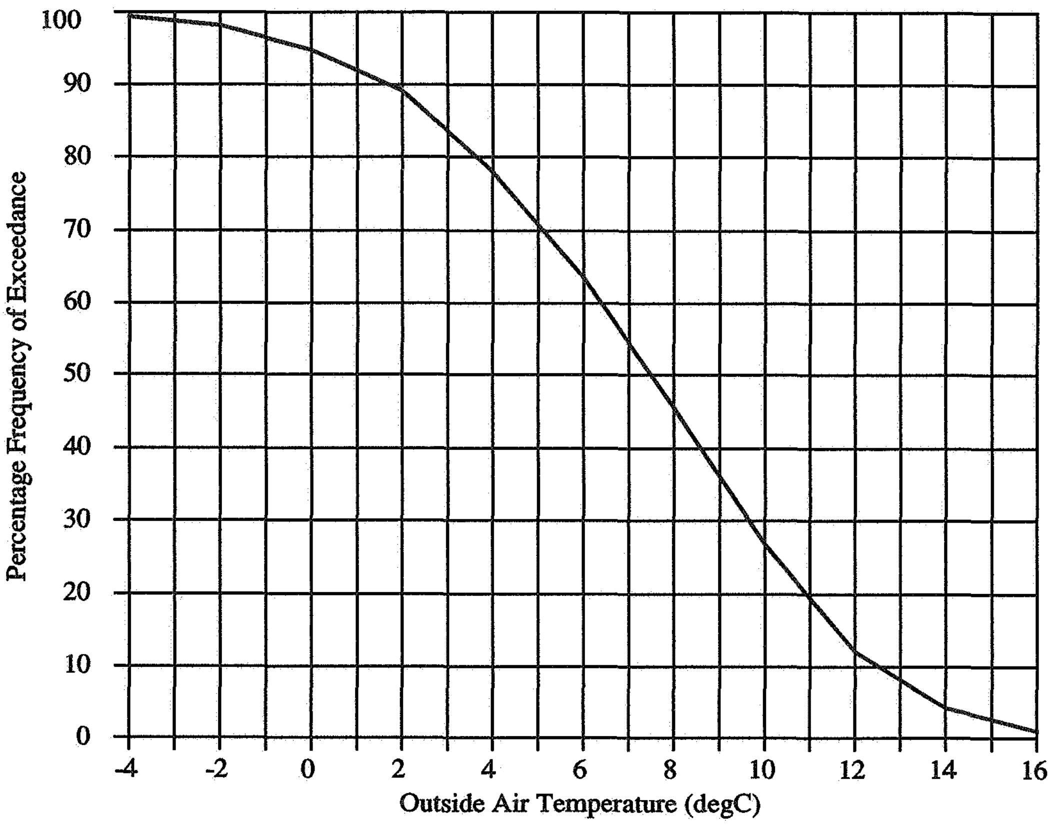


FIGURE 5.b. - OUTSIDE AIR TEMPERATURE AT MET. STATION

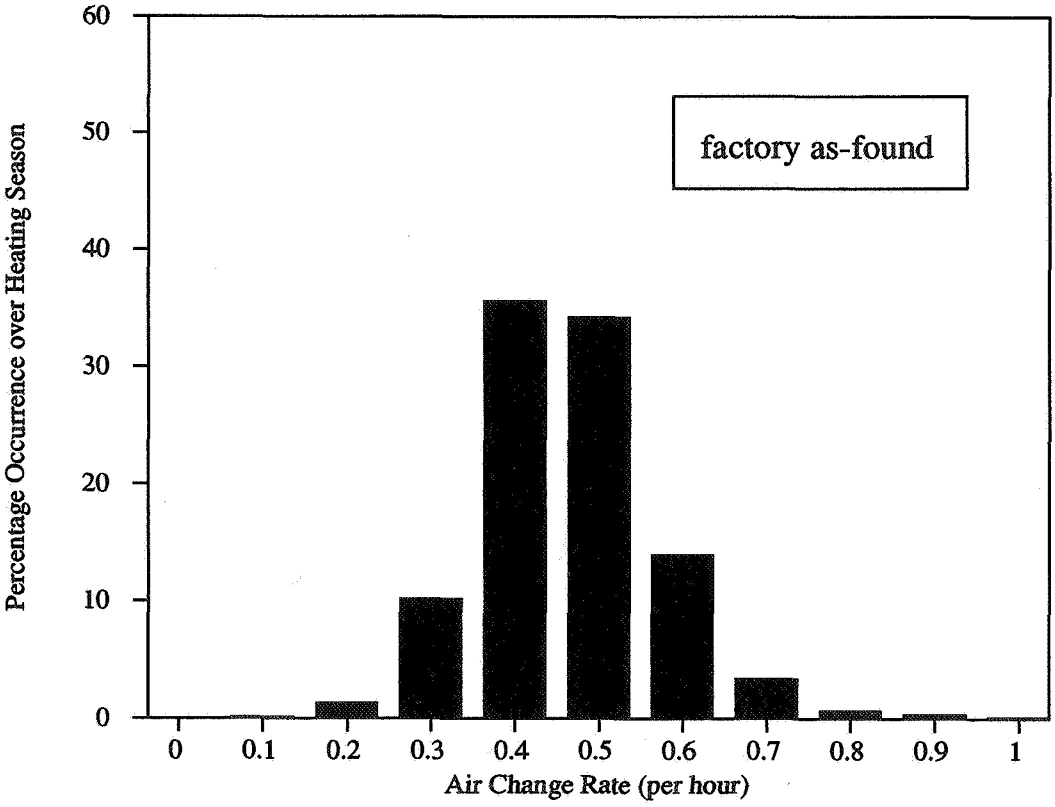


FIGURE 6 - PREDICTED VENTILATION PERFORMANCE

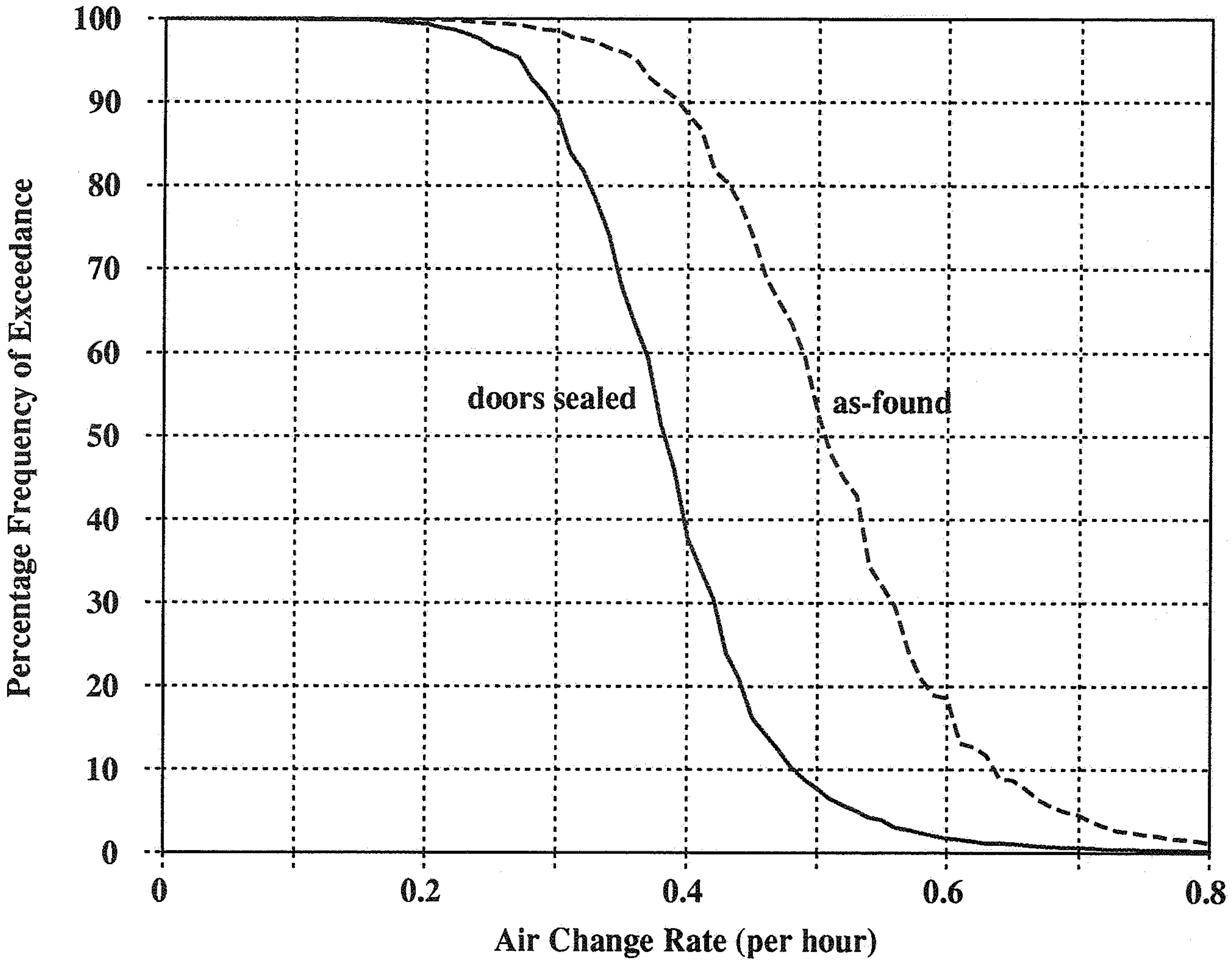


FIGURE 7 - EFFECT OF SEALING DOORS ON VENTILATION PERFORMANCE

Discussion

Paper 44

J Van Der Maas, LESO, Switzerland

What is the relative influence of wind and stack effect in your calculation? Can you estimate the effect of shielding by trees e.g.?

Earle Perera, BRE, UK

The relative effects are not explicitly identified within the paper. However, it is comparatively easy to modify the prediction programme to identify these individual contributions if it is so required. Shielding by trees will reduce the localised pressure coefficients on the building fabric and hence the flow through discreet openings, and the computer model can account for this. Background leakage calculation, which requires an area-weighted average pressure coefficient, would be affected only by a substantial amount of tree shading.

Bas Knoll, TNO, The Netherlands

Did you account for a vertical temperature-gradient in the building because it may influence energy-demand if the warmest air at top is exhausted?

Earle Perera, BRE, UK.

No, we supposed a uniform distributed temperature and leakage. However, it is not a problem to modify Equation (1) and (3) in the paper to account for this effect.