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

PAPER 11

VENTILATION OF FACTORIES

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1. INTRODUCTION

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

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

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

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

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

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

2. EXPERIMENTAL DESIGN

2.1 Description of Factories

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

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

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

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

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

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

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

2.2 Project Objectives

The objectives of the project were as follows:

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

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

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

2.3 Measurement Programme

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

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

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

3. MEASUREMENT TECHNIQUES

3.1 Ventilation Rates

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

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

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

3.2 Air Leakage

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

Each unit consists of a cylindrical duct mounted on large wheels for manoeuvrability. The entrance to the duct is a bellmouth inlet followed in the downstream direction by a "Wilson" flow grid (Ref. 4), a honeycomb flow straightener and a variable-speed axial fan. The unit was specially designed for leakage measurements with the aims of achieving an instrument which could be used by inexperienced personnel, and which gave relatively high accuracy. An important contribution to achieving these aims is the choice of a proper flow measuring device, rather than simply measuring fan speed. The flow grid has the additional advantages that it is relatively insensitive to upstream conditions, and has a large pressure output and a low pressure loss. The flow rate through the unit is obtained from a calibration curve supplied by the manufacturers.

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

4. RESULTS

4.1 Infiltration rates of Factory 1

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

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

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

4.2 Leakages of Factories 1 and 2

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

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

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

4.3 Sealing loading bay door

In Factory 1 the effect of sealing the loading bay door was investigated with the Autovent system and the leakage tester. Figure 4 shows the substantial reduction in infiltration rate which was observed ($\sim$45%). The leakage results in Figure 6 are consistent with this observation, but for the reasons given above, it is not possible to evaluate a figure for the reduction. It should perhaps be noted that the two results in Figure 6 are consecutive measurements (it took only a few seconds to remove the sealing) in order to minimise errors in their comparison. Visual observation of the door showed a large opening at the top with gaps down the sides and the door itself.

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

4.4 Effect of roof vent

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

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

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

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

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

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

5. DISCUSSION

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

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

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

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

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

6. CONCLUSIONS

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

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

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

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

7. IMPLICATIONS

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

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

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

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

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

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

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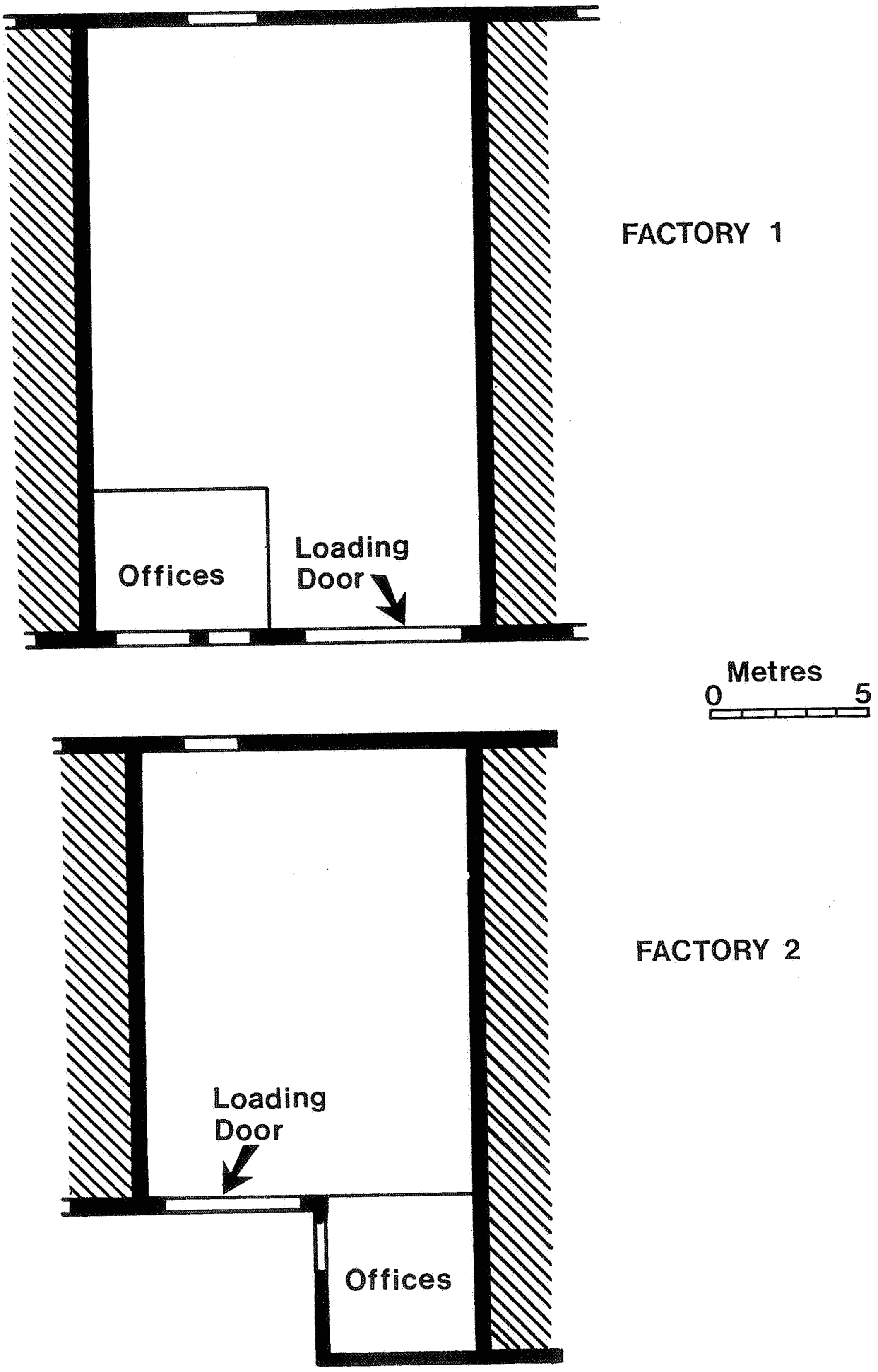

FIG. 1 FLOOR PLANS OF FACTORIES

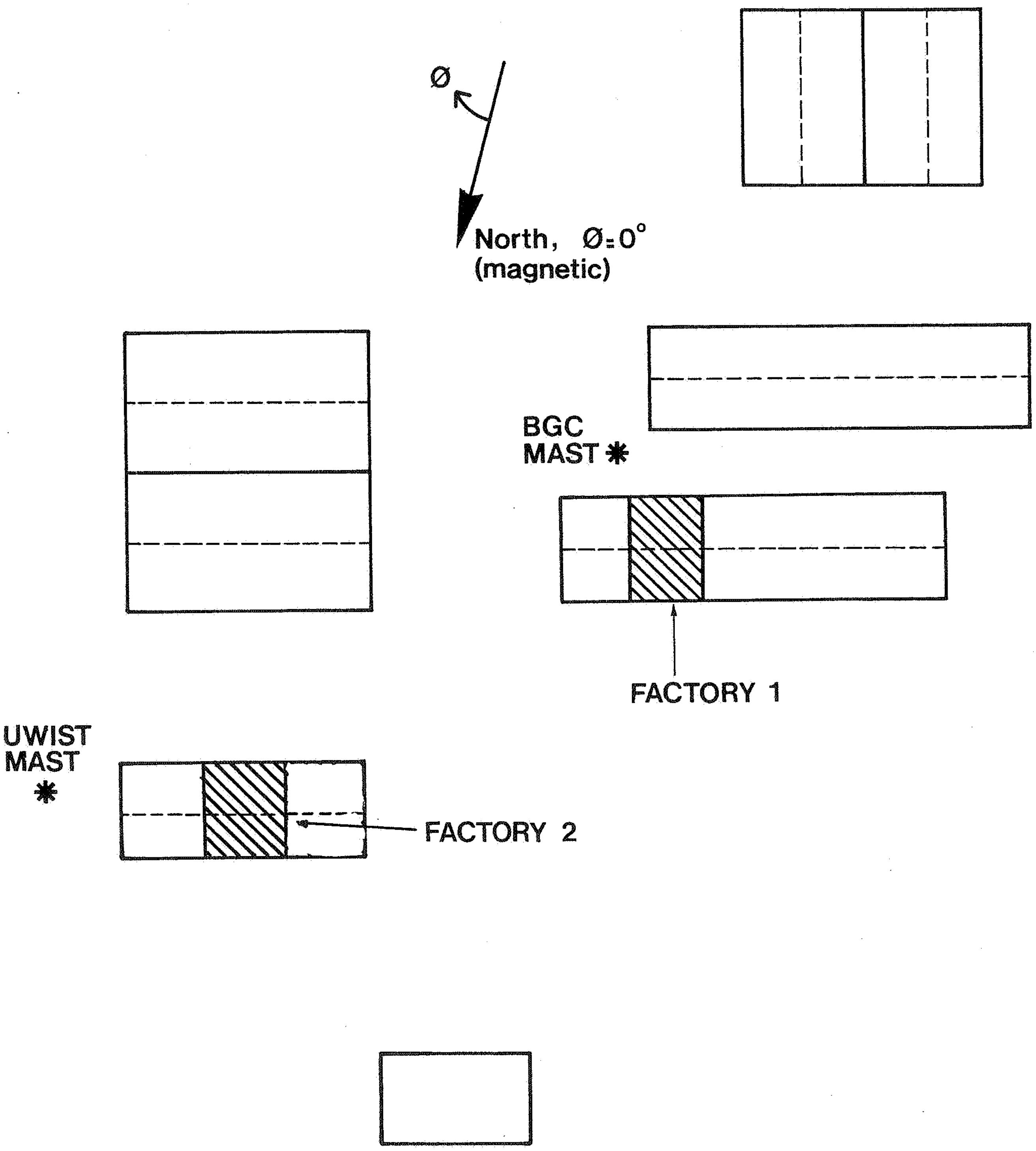

FIG. 2 PLAN OF SITE

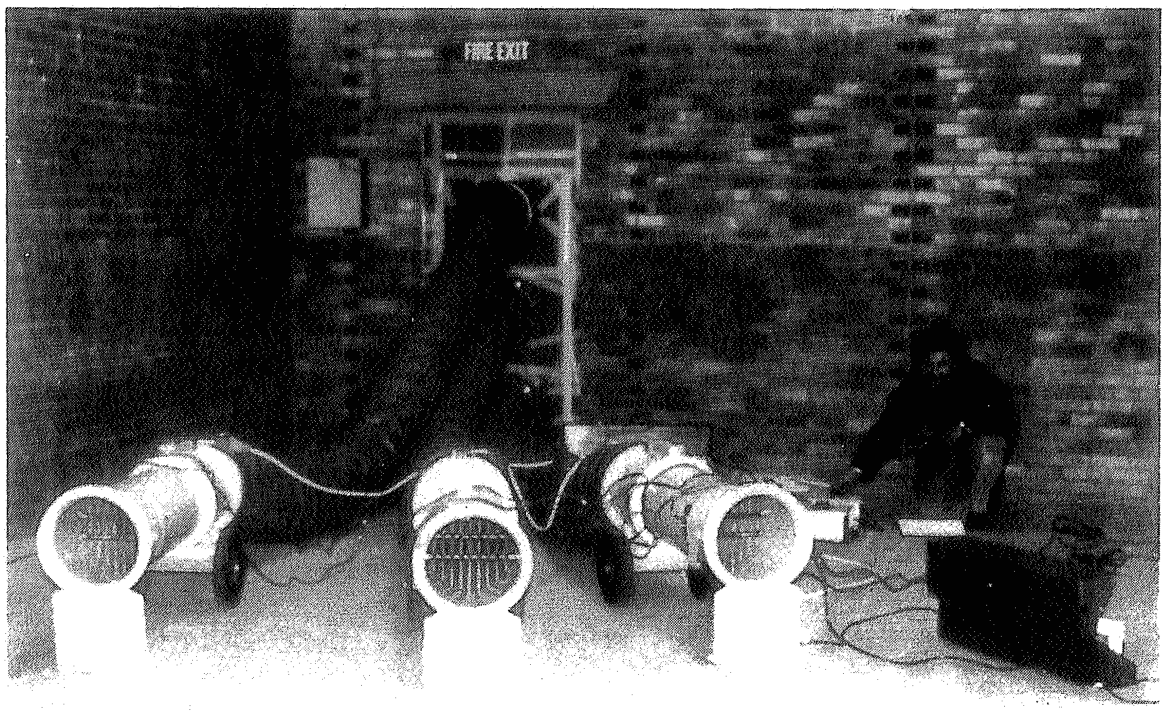

FIG. 3 LEAKAGE MEASUREMENT IN FACTORY 2

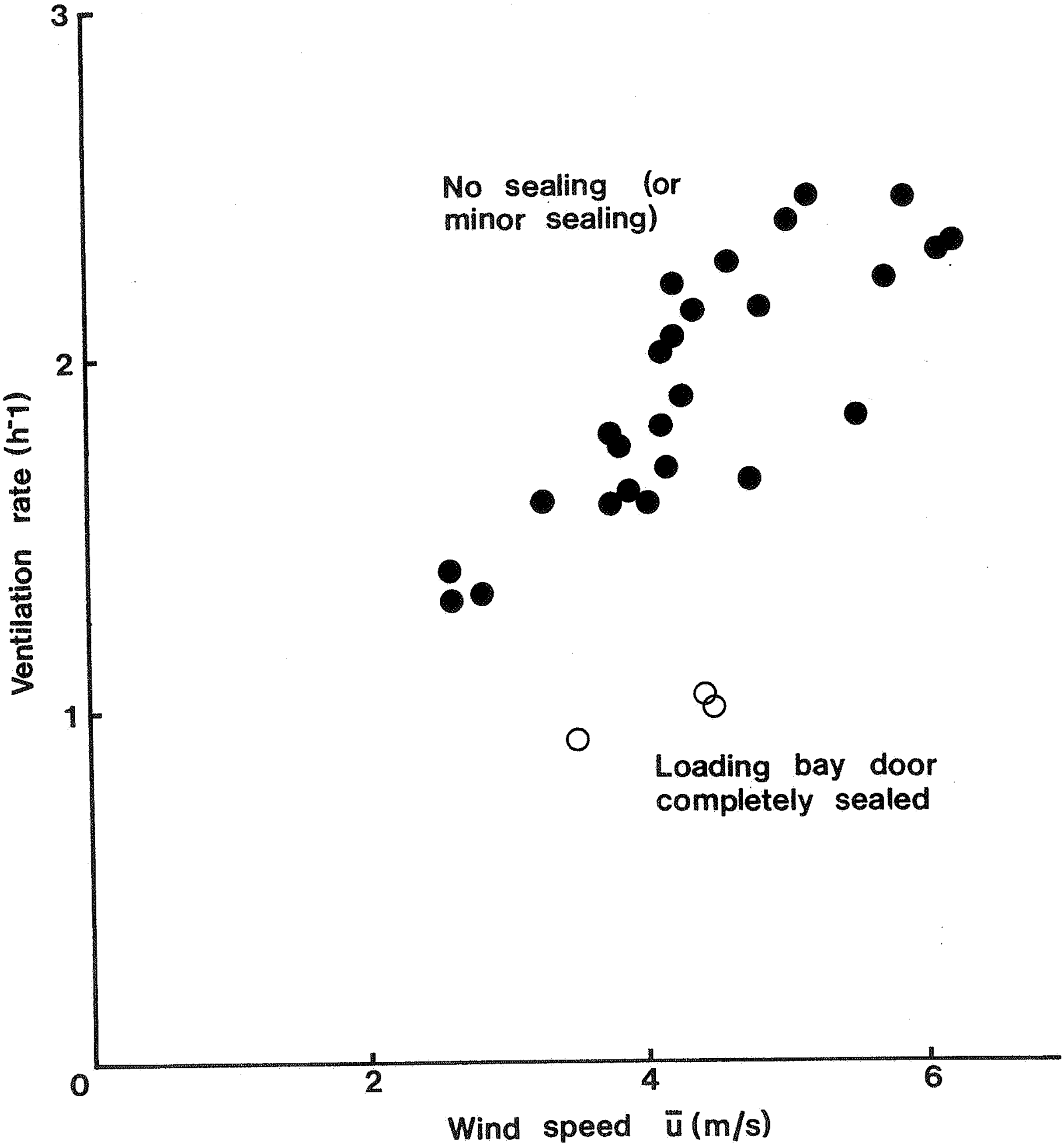

FIG. 4 MEASURED EFFECT OF SEALING LOADING DOOR OF FACTORY 1

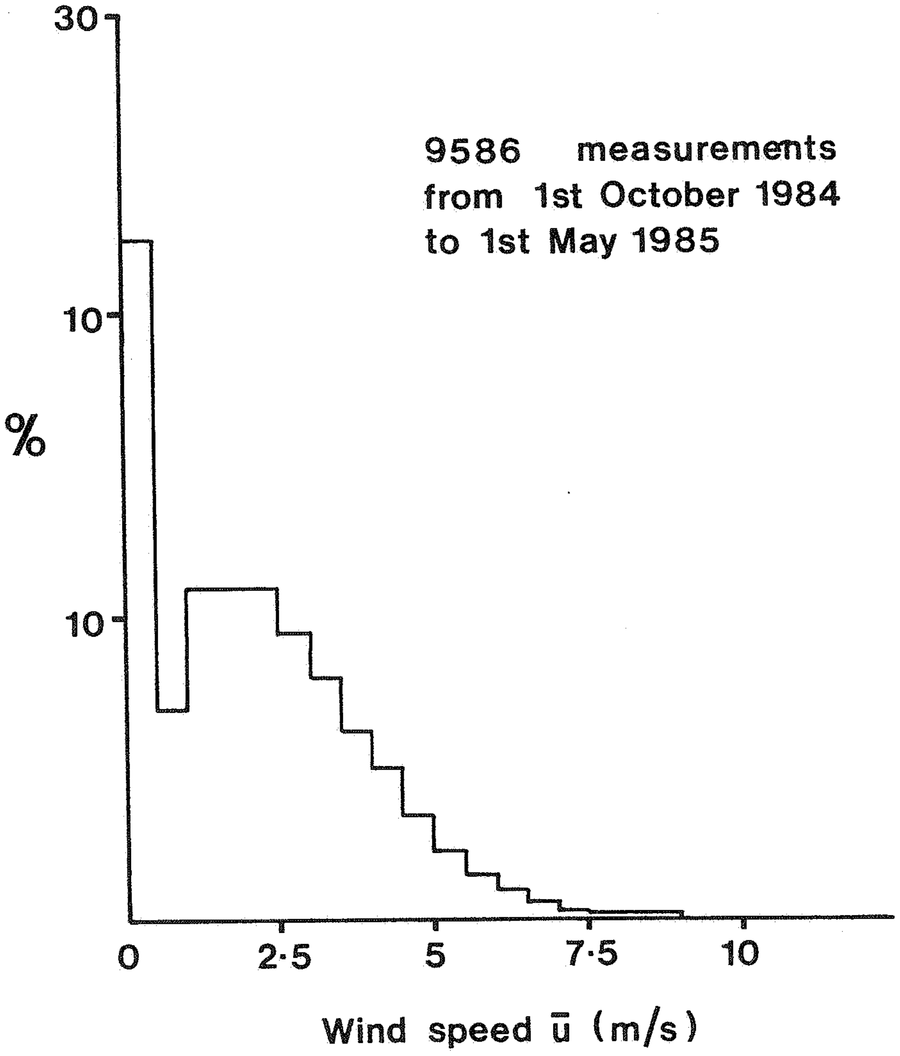

FIG. 5 FREQUENCY DISTRIBUTION OF HALF–HOUR AVERAGE WIND SPEED

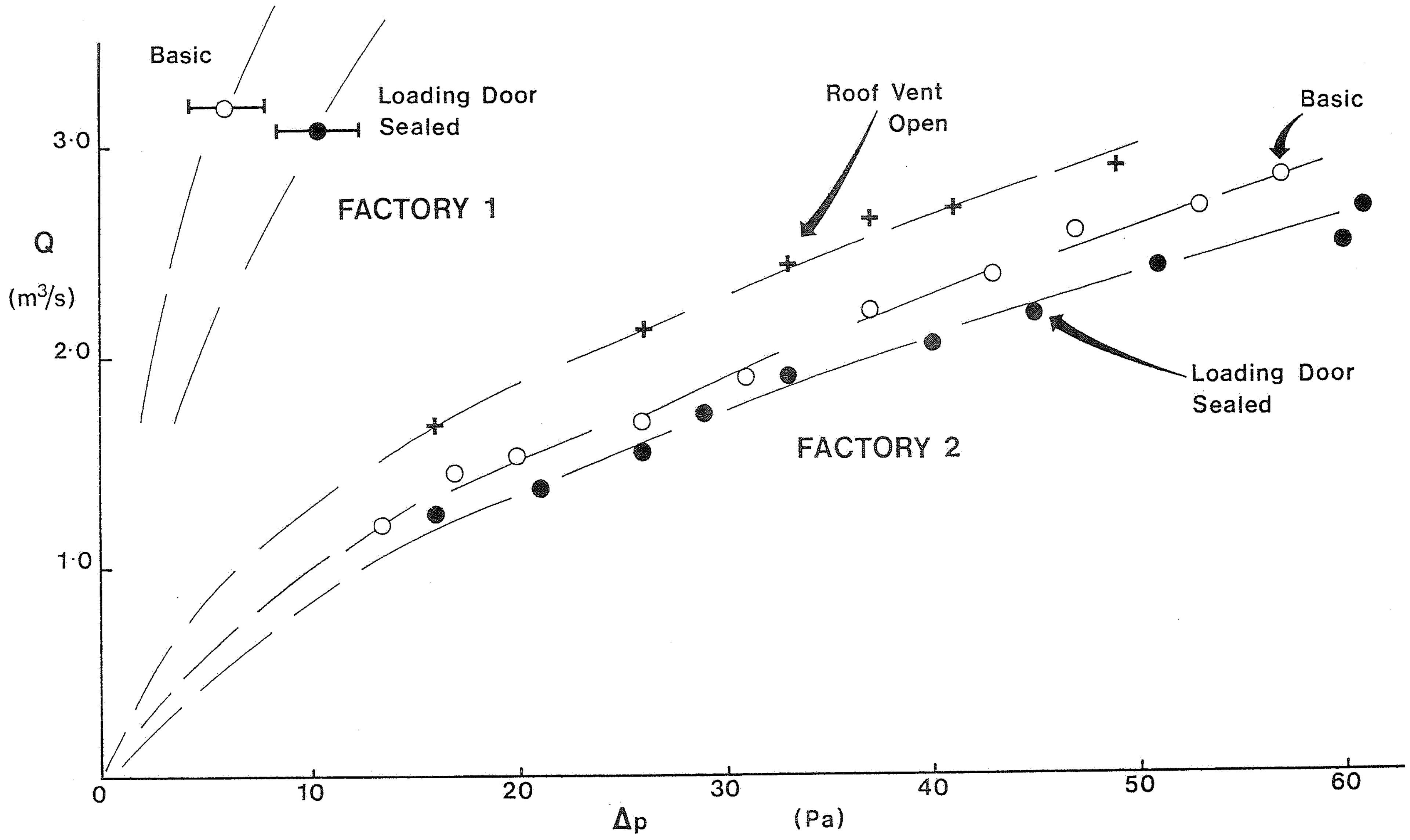

FIG. 6 AIR LEAKAGE OF FACTORIES 1 & 2

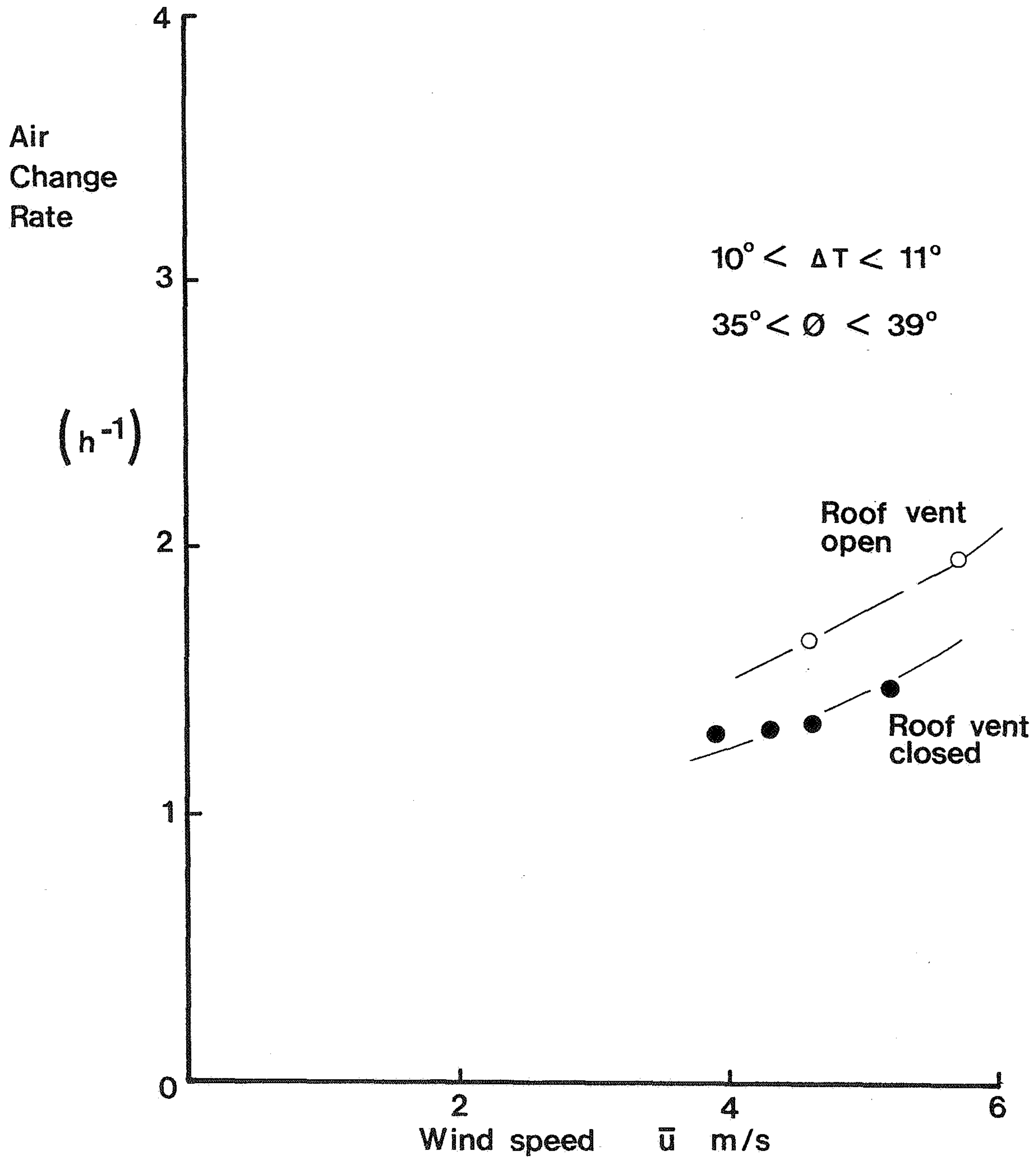

FIG. 7 EFFECT OF ROOF VENT ON AIR CHANGE RATE OF FACTORY 1