THE CHARTERED INSTITUTION OF BUILDING SERVICES

SYMPOSIUM

Natural Ventilation by Design

Tuesday 2nd December 1980
10.00 hours to 16.00 hours

at the Main Lecture Theatre,
Building Research Establishment
Garston, Watford.

Chairman of Symposium

J.B. Dick	CB, MA, BSc, FCIBS, FInstP, FIOB. Former Director — Building Research Establishment

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REQUIREMENTS FOR VENTILATION

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Ventilation criteria are viewed in terms of both the building and the occupants. Moisture control is necessary to preserve the building fabric. The occupants have additional sensitivity to chemical contamination such as odours and cigarette smoke. Criteria can be expressed in minimum acceptable concentrations for health reasons, or even lower concentrations for comfort. The ventilation needed to meet these criteria is derived from a knowledge of the generation rate of the pollutant, the effectiveness of ventilation mixing, the characteristics of the fresh air supplied, and the temperature of the occupied room.

INTRODUCTION

Contaminants can build up inside sealed buildings to create discomfort for the occupants and, in the long term, can both affect their health and spoil the integrity of the building fabric. Fresh air is therefore necessary to dilute these contaminants to an acceptable level. This paper reviews the contaminants individually and then, in terms of overall design, collectively.

CONTAMINANTS

Carbon dioxide

Breathing is controlled primarily by the carbon dioxide concentration in the lungs (Bell et al. (1)). When inspired air contains approximately 2% by volume of carbon dioxide, then the depth of breathing increases. When the concentration reaches 3-5% by volume, there is a conscious need for increased respiratory effort and the breathing rate increases and the atmosphere becomes objectionable. Concentrations over 6% are dangerous. The maximum allowable concentration for 8 hour exposures for healthy adults is 0.5% by volume.

The usual source of carbon dioxide is the occupants themselves. The generation rate is directly proportional to the number of people and their activity. The ventilation needed for carbon dioxide dilution is illustrated in Table 1 (BS 5925: 1980 (2)).

TABLE 1 - Outdoor air requirements for respiration (BS 5925: 1980)

Activity	Metabolic rate (watts)	Requirements for oxygen (16.3% O_2 in expired air) (m^3/h)	Requirements for carbon dioxide at 0.5% by volume (m^3/h)
Seated quietly	100	0.36	2.9
Light work	160-320	0.7-1.1	4.7-9.4
Moderate work	320-480	1.1-1.3	9.4-14
Heavy work	480-650	1.8-2.5	14-19
Very heavy work	650-800	2.5-3.2	19-23

Flueless heating appliances are also a source of carbon dioxide. A 3 kW paraffin heater is equivalent to 20-30 people in the room (BRE Digest No. 206 (3)).

Odours

Healthy, clean people give off odours even immediately after a bath (Yaglou et al. (4)). Such odours are not known to be harmful but can be unpleasant and diminish appetite. Odour generation is proportional to the size of the adult (Lehmberg et al. (5)) and the time elapsed since the last bath. Children younger than 14 years old are more powerful generators than adults (Figure 1).

Odour concentration cannot always be measured chemically and so empirical ventilation rates are prescribed. An unusual feature of body odours which distinguishes them from simple chemical odours is that acceptability is influenced both by concentration and by personal space. Much more fresh air is needed as the personal space declines (Figure 2).

Empirical data suggests a minimum air extract rate from the W.C. should be 20 cu. metres per hour (BRE Digest 170 (6)).

Smoking

In normal cigarette smoking, more tobacco burns during the smoulder period and escapes to the room than during the inhaling period, when the smoker absorbs the combustion products himself. This sidestream smoke requires dilution (Brundrett (7)).

While the tobacco type, its treatment, the cigarette size and smoking pattern are very varied, an approximate value of 20m^3 of fresh air is needed to dilute the sidestream smoke from a cigarette to an acceptable air quality. Since the average British smoker consumes 1.3 cigarettes an hour, then a fresh air allowance of 26 m^3/h is needed for each smoker. In small offices, the probability of an office containing mainly smokers is high and so this fresh air is needed for each occupant. In large offices of 50-100 occupants, it can be assumed that the population in the office will reflect the normal adult population, of which half smoke. The ventilation rate can therefore be halved, since only half the occupants will be expected to smoke (Halfpenny & Starrett (8)). If the cigarette consumption is known to be much lower or much higher, then appropriate changes in the ventilation rate will be necessary. Experience suggests that the values given in Table 2 are adequate for Britain (CIBS (9)).

TABLE 2 - Ventilation to dilute cigarette smoke

Smoking	Space	Minimum outdoor air m^3/h per person	Recommended outdoor air m^3/h per person
some	open plan office	18	29
heavy	private offices	29	43
very heavy	board rooms	65	90

Lower quantities of fresh air introduce irritation to the eyes and respiratory passages. When this occurs, there is the risk that the maximum permitted concentration of acrolein has been exceeded (Figure 3).

Moisture

Moisture has two kinds of effect. The first is related to relative humidity, while the second is related to vapour pressure.

Organic materials such as wool, paper, cotton and leather, absorb moisture as a function of the relative humidity in the atmosphere (Hearle & Peters (10)). If this relative humidity becomes low, then fabrics become less flexible and less electrically conducting. Electrostatic shocks can be expected from walking on carpets when the relative humidity falls below 40% (Brundrett (11)). When the relative humidities rise above 70%, then fabrics become damp to the touch (Lake & Lloyd-Hughes (12)), mould spores can develop (Brundrett & Onions (13)), and house mites thrive (Cunnington (14)). Unfortunately, the relative humidities involved are those immediately adjacent to the fabric rather than the bulk air in the centre of the room. This means, for example, that wallpaper on a cold wall could have very high relative humidities immediately adjacent to it, while the values in the room centre are low. In practice, moisture problems are avoided if the bulk air in the room does not rise above 70% relative humidity (HMSO (15)).

Physiological factors such as dry throats, cracking skin, and sultriness, depend more upon the absolute water vapour pressure. While work is limited in this area, illustrations of these relationships are given in Figure 4 (Brundrett (16)). The generation rate of moisture within the house is summarised in Table 3 according to activity, and is typically 7 kg a day unless clothes are dried in the house, when this value is doubled (Loudon (17)). Ventilation requirements needed to prevent excessive relative humidity depend on both the moisture generation rate in the house and the moisture content in the outdoor air. The moisture in the outdoor air depends in turn upon the outdoor air temperature (Figure 5) (Heap (18)). This means that for a constant moisture generation rate in the house, the ventilation will need to increase progressively with outdoor temperature to maintain a chosen relative humidity (Figure 6). Local extraction of moisture vapour at source, such as with a cooker hood, or any form of dehumidification, could significantly reduce this ventilation requirement (Brundrett (19)).

TABLE 3 - Moisture generation rates in five person houses (Loudon 1971)

Activity	Generation rate
Moisture from the occupants (perspiration and respiration)	1.7 kg/day
Clothes washing	0.5 kg/day
Clothes drying	5 kg/day
Cooking (gas)	3 kg/day
Baths and washing	1 kg/day
Daily average	7.2 kg/day 14.4 kg on washday

Radon

Minute traces of uranium are present in most rocks, soils and common building materials. Uranium is radioactive and decays down to a stable lead isotope. One of the products of this chain is the gas radon. Radon has a half-life of 3.8 days, which is sufficient for it to diffuse from building materials and from the sub-soil underneath a house into the buildings. The radon gas decomposes into four short-lived daughters, which can be inhaled. Inhaled daughters can decay within the lung and could increase the incidence of lung cancer (Davies (20), Doll & Hill (21)). The health risk is proportional to the radon concentration and the time exposed to it (Table 4). Present evidence suggests that the minimum ventilation rate for a house in Britain should be 0.2 air changes an hour.

TABLE 4 - Predicted lung cancer incidence in the UK due to environmental $222R_n$ daughter concentrations as the mean winter (7 months) ventilation rate is reduced: the summer (5 months) mean ventilation rate is assumed to be constant at 2 air changes per hour

Winter ventilation rate h^{-1}	Mean population exposure WLM y^{-1}	Lung cancer incidence predicted per 10^6 population per year	Number of cigarettes smoked per week to give the same lung cancer incidence (Derived from Ref. 20)
0.8	0.15	15	1.5
0.5	0.22	22	2.2
0.4	0.28	28	2.8
0.3	0.38	38	3.8
0.2	0.58	58	5.8
0.1	1.15	115	11.5

VENTILATION REQUIREMENTS FOR DESIGN

The four design factors are:

1. extract contaminants at source
2. ventilate for the worst pollutant
3. avoid by-passing of the supply and extract air
4. control the flow route

When the sources of pollution are known, the first design requirement is to remove as much as possible at source. Once that is done the generation rates of the pollutants into the room can be estimated. For all practical purposes, the common pollutants can be considered to be independent of each other. The ventilation needed for each pollutant should then be calculated and the highest ventilation rate chosen. When air is supplied at low rates, it slowly but intimately mixes with the room air. The relative positions of the inlet and outlet grilles are not very important. However, at high ventilation rates, some correction is needed for the inefficiency of the air mixing. The chances of short-circuiting increase with the higher ventilation rates and more care is needed in positioning and distributing the inlet and extract air (Yaglou & Witheridge (22)).

Finally, while in general it is desirable to provide each room with fresh air, exceptions can be made for buildings such as houses. The conventional house has two types of rooms, clean residential rooms and service rooms. The residential rooms, which include living rooms and bedrooms, can be supplied with fresh air to ensure pleasant conditions during the long periods these rooms are occupied. However, the service rooms such as kitchen, bathroom and toilet, are occupied for shorter periods and it is the traditional approach in mechanically ventilated houses to supply the fresh air to the clean rooms and extract the same air from the kitchen and other service areas. Routing the air this way saves much ventilation.

FUTURE NEEDS

As the importance of ventilation becomes recognised, we will need to strengthen five weaknesses. The first is to refine the ventilation criteria. Most work has concentrated on the adult population and for eight hour exposure as in a working day. Buildings can contain children, the elderly and the infirm, and often for continuous occupancy. More research is needed to assess suitable criteria for these common circumstances.

The second is the need for simple sensors which will guide the occupants of the building on whether or not they have gross under- or over-ventilation. The need for such instrumentation is strongest for those pollutants such as radon or carbon monoxide, or carbon dioxide, which the occupants themselves cannot sense. However, low cost detection of the more recognised pollutants, such as cigarette smoke or moisture, could be valuable as the starting point for more advanced energy saving controlled ventilation schemes.

The third is an educational exercise to show the importance of removing contaminants at source. This includes cooker hoods venting to the outside to remove moisture and odours, and also proper use of venting kits for appliances such as tumble dryers. It also includes the dangers of unflued heaters.

The fourth is recognition of the importance of the ventilation route. In many circumstances, the fresh air can be designed to serve two purposes. In a house, for example, if fresh air is introduced into the living room to dilute body odours, the same air can be extracted from the kitchen, taking with it the added moisture and cooking smells.

The fifth is the development of alternative methods of lowering the pollution concentration. Research is already exploring deodorising techniques to remove or destroy malodorants and advanced dehumidification techniques to solve moisture problems.

CONCLUSION

Ventilation is necessary to dilute common contaminants to acceptable concentrations for health and comfort, and to protect buildings.

The ventilation requirements are mainly a function of the generation rate of the pollutant and the maximum allowable concentration. Unoccupied buildings need a minimum ventilation rate to prevent a build-up of radon. This is mainly a function of the building materials. The minimum for occupied buildings depends upon the carbon dioxide generation. This generation is directly related to activity level. Cigarette smoke is proportional to the cigarette consumption although the criterion of acceptability varies from the relatively sensitive one of a visitor, to the much less sensitive one of a smoker. Body odours are unusual in being related not only to the elapsed time since the last bath, but also to the allocated volume of personal space. Designing for moisture control is the most difficult, since it is a complex function, not only of the outdoor vapour pressure and the indoor moisture generation rate and location, but also of the temperatures of individual parts of the rooms, which should remain above the air dew point.

Further work is needed on ventilation routes so that fresh air can be introduced to the living rooms and extracted from the service rooms, which are usually more contaminated. Separate fresh air supply is then not necessary in the service room. The air flow is then in opposition to the contaminant gradient. More attention must be paid to local contamination control. This includes cooker hoods and vented clothes dryers to prevent moisture and odours escaping into the room. It also includes dehumidifiers, which can not only reduce the ventilation requirement but also transduce latent heat into sensible heat.

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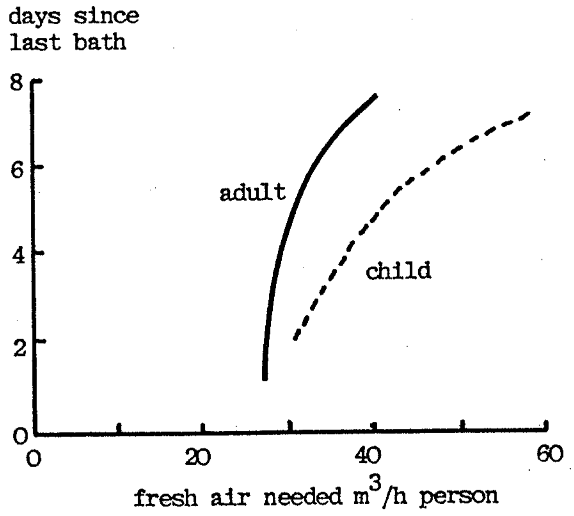


Figure 1 Fresh air needed for acceptable body odour

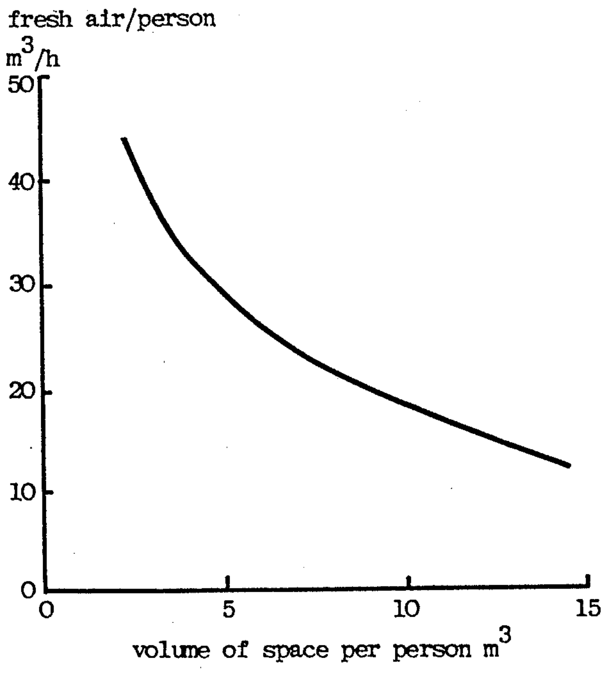


Figure 2 Fresh air needed for acceptable body odour as a function of personal space

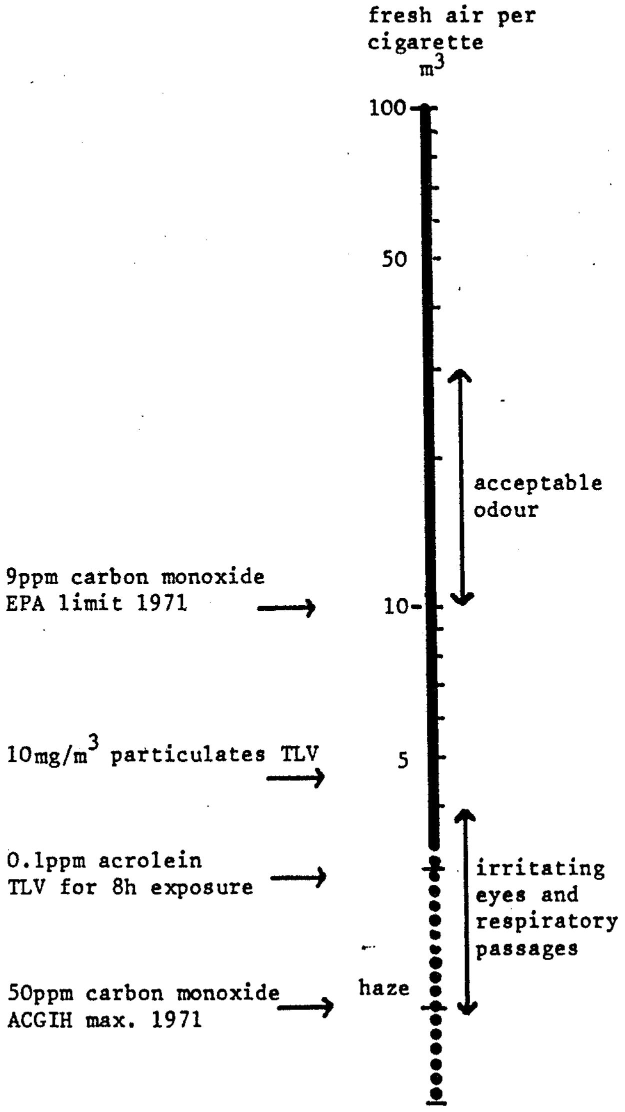


Figure 3 Fresh air needed to dilute cigarette smoke

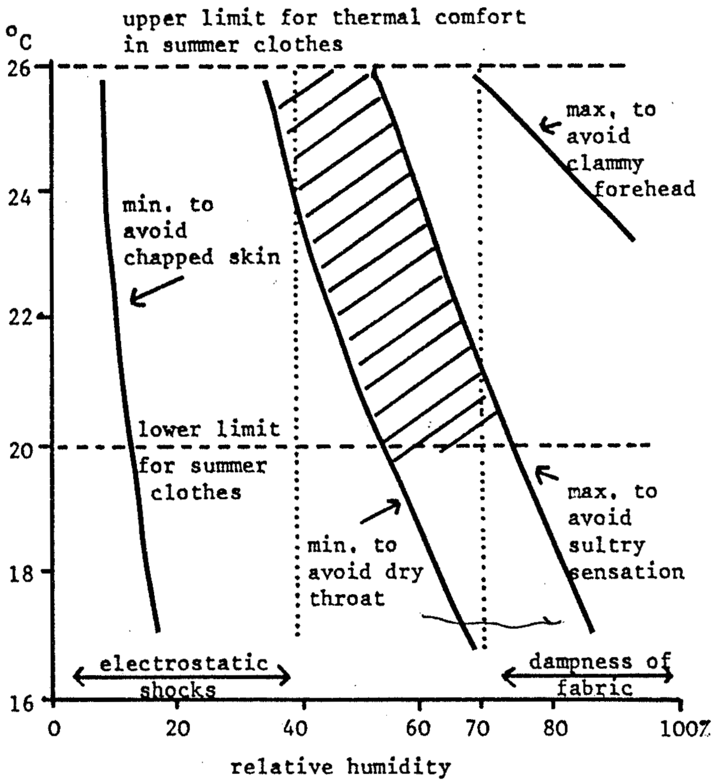
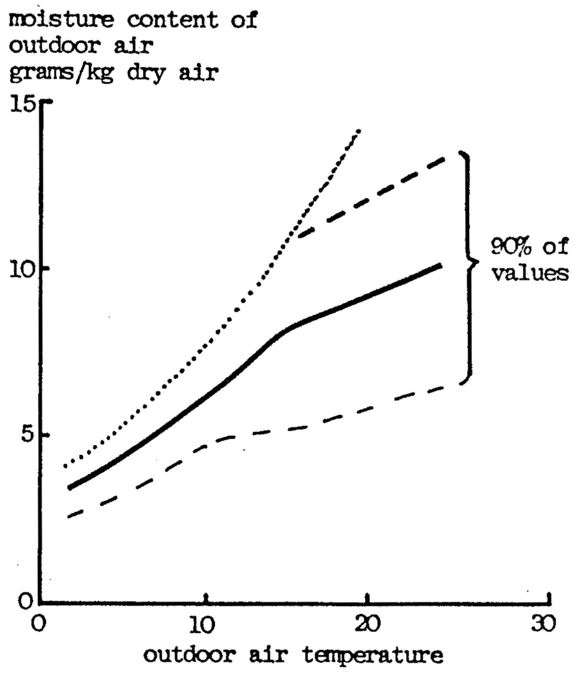


Figure 4 Comfort zone for sedentary people (shown hatched)



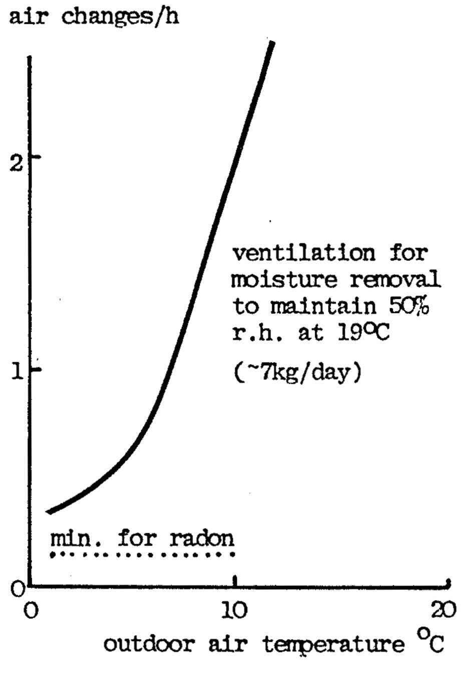


Figure 5 The relation between moisture content and outdoor air temperature

Figure 6 Ventilation requirements for domestic moisture control and radon in the house

NATURAL VENTILATION PRINCIPLES IN DESIGN

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The requirement for better methods of predicting infiltration and natural ventilation rates has been reinforced by the incentive to reduce energy consumption in buildings.

Natural ventilation is basically dependent on the effects of wind and temperature difference and on the resistance to airflow through the building. These factors are discussed in detail and those areas requiring further study are highlighted.

Some calculations of the effect of applying controlled natural ventilation and mechanical ventilation illustrate the potential energy savings of such measures.

INTRODUCTION

As far back as 1850, the fundamentals of ventilation design were given by Walker who announced[1]:

(i) windows were to admit light; ventilation should be catered for separately.

(ii) both inlets and outlets were necessary.

(iii) incoming air should be warmed to avoid draughts.

(iv) inlets and outlets should be well distributed.

(v) ventilating openings should be permanent, realising that once closed they will remain closed.

It is not easy to find fault with such fundamentals but the major problem in applying these over the years has been to predict quantitatively the size and distribution of ventilation inlets and outlets to ensure an adequate fresh air supply when relying on natural forces.

In the past the design emphasis for naturally ventilated buildings was two-fold. First, to provide sufficient open or openable area to facilitate adequate ventilation. Second, to determine the ventilation heat loss under winter design conditions and so enable it to be taken into account when sizing the main boiler plant and individual heat emitters.

The basis for the selection of the required openable area, whether vents or windows, seems to have been mainly a matter of judgement gained from experience, perhaps backed up by the use of basic information such as that in the British Standard Code of Practice CP3 published in 1950[2].

The general recommendation that the absolute minimum openable window area should be 5% of the room floor area appears to stem from a similar recommendation by Bedford[3] in 1948, and is the same as the value for the area of ventilation openings specified for habitable rooms in the Building Regulations[4]. In practice, however, the range of variation was considerable as may be judged from a survey of naturally ventilated offices[5] in 1964 which revealed a variation in the proportion of openable window area to floor area from 3½ to 27%.

More specific information has been derived for the calculation of ventilation or infiltration heat loss at specific design conditions. One method involves the assumption of an appropriate rate of air change for the particular type of building and its expected use. Recommended air change rates are tabulated in the CIBS guide[6]. A more detailed method also presented in the CIBS Guide, uses known relationships between leakage rate and pressure differential for components such as windows, doors and vents. These relationships are applied for pressure differentials generated by wind or stack effects at the selected design condition.

IMPLICATIONS OF ENERGY CONSUMPTION

The requirement to reduce energy consumption has changed the design emphasis so that it is now necessary to ensure not only that an acceptable level of ventilation is provided but also that the ventilation rate throughout the season is at or as little as possible above the minimum acceptable level. Seasonal energy consumption has become a major criterion.

The significance of ventilation in relation to energy consumption has also increased because of the change in the ratio of fabric to ventilation heat loss brought about by the application of improved standards of thermal insulation. As shown in Figure 1, the proportion of ventilation heat loss to the total for a heating season has typically risen from less than 25% for an older dwelling to about one half for a well-insulated house.

This increased significance and the need to minimise seasonal energy consumption has led to a requirement for more reliable and accurate methods of predicting air infiltration and ventilation rates and the associated energy losses. These methods need on the one hand to be soundly based on the principles governing natural ventilation processes and on the other to be readily applicable by the design team in their quest for optimum energy and cost effectiveness.

PRINCIPLES OF NATURAL VENTILATION

Natural ventilation is basically dependent on two factors (1) the motive forces and (2) the resistance to airflow through the building. However, this simple statement disguises a multitude of complexities which make the prediction of the magnitude of each factor very difficult.

The Motive Forces

The two motive forces primarily responsible for natural ventilation are caused by wind and air temperature differences.

Wind. Wind impingement on a building produces higher-than-ambient pressures on the windward faces and lower pressures on the others. The pressure differences so generated give rise to a movement of air from the higher to the lower pressures through any cracks, gaps or openings in the building.

Wind is turbulent and both its speed and direction undergo continual change. The wind speed and direction are measured at frequent intervals at a large number of sites in the UK by the Meteorological Office. From these measurements hourly mean wind speeds applicable to a standard height of 10m above ground in open countryside are derived.

Wind speeds are, however, affected by the roughness of the terrain over which the wind passes and it is therefore necessary to make a correction to the 'meteorological' wind speed to determine an equivalent value appropriate to the specific location in question. Figure 2 illustrates the effect on wind velocity of various types of terrain. From the exponential profiles of wind speed and height, the factors required to determine the local wind speeds at various heights above ground from the meteorological wind speed have been derived. They are presented in Reference 11.

Prominent topographical features and obtrusive buildings close to the building being considered will further modify the structure of the wind. Taking account of such effects is particularly difficult without resorting to wind tunnel testing.

The pressure distribution on a building exposed to wind is not only dependent on the local wind speed and direction but also on the size and shape of the building itself. However, the pattern of distribution is comparatively independent of wind speed, provided the building has sharp corners.

The pressure on a building generated by wind is thus usually expressed in terms of the dynamic (or stagnation) pressure of the wind by the use of a pressure co-efficient, C, so that

$$p = C\,(\tfrac{1}{2}\rho u^2) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ρ = density of air (kg/m^3)

u = local wind speed (m/s) (conventionally taken as the wind speed at a height equal to that of the buildings)

As is shown in the example in Figure 3, there is a wide variation in the value of the pressure coefficients over the surfaces and with change in wind direction, even for a simple building shape. Such detailed information for simple rectangular building shapes is available from many sources and may be used in a comprehensive study of natural ventilation. For a less critical approach, pressure coefficients averaged over each surface may be used. Such data for two wind directions are presented in Reference 7.

For other than the standard building shapes or where other adjacent buildings may affect the pressure distribution, wind-tunnel tests with a scale model of the building and its surroundings will be required, although for some specific building layouts wind pressure distribution data is now available[8].

The use of mean wind speeds in determining the pressures generated on building surfaces is not a strictly accurate method because of the turbulent character of the wind. The effect of fluctuating pressures on the rate of ventilation has been shown to be significant[9] but, at present, there is insufficient information to quantify the magnitude other than for the particular situations studied.

Another feature which gives rise to some uncertainty is the effect of relatively small irregularities in the surface of the building. For example, the pressure distribution around the edge of a window set in a rebate may be somewhat different from that in equivalent circumstances but with the window flush with the facade. The effects of external mullions has been studied[10] but not in sufficient depth to produce comprehensive data.

Temperature Difference. The difference in temperature, and hence in density, between the air inside a building and that outside causes a movement of air vertically through the building. This temperature motivated transfer of air is called 'stack effect'. In the heating season, for example, when the air temperature within the building is higher than that outside, pressure differences are created such that air flows into the lower levels of the building and out of the upper levels. The reverse occurs when the indoor temperature is lower than outdoors. The 'stack effect' can also generate ventilation in a single room where, for example, cool outside air may flow in through the lower section of an open window and out through the upper part.

The magnitude of the pressure differences caused by 'stack effect' is a function of the indoor and outdoor temperatures and the vertical distance between the openings, as follows

$$\Delta p_\theta = 3462h\left(\frac{1}{\theta_o} - \frac{1}{\theta_i}\right) \quad \ldots\ldots (2)$$

where Δp_θ = pressure difference caused by stack effect (Pa)

h = vertical distance between openings (m)

θ_o = external absolute temperature (K)

θ_i = internal absolute temperature (K)

A much more complex analysis is required in cases where severe temperature gradients exist within the building and where there is a multiplicity of openings at various heights.

Combined Effects of Wind and Temperature Difference. The effects of wind and temperature differences usually act simultaneously but they cannot simply be added together. The reason for this can perhaps be best illustrated by considering a window in an upper level on the windward side of a building. The wind tends to cause a movement of air inwards through the window, whereas stack effect produces an outward air movement. The two forces are acting contrary to each other. On other parts of the building, for example at the lower levels on the windward side they are complementary.

The overall ventilation rate is generally equivalent to that of the higher of the two effects when acting alone. Thus, at low wind speeds, when stack effect is predominant, the rate of ventilation may be calculated on the basis of temperature difference alone. At high wind speeds, only the effect of the wind needs to be taken into account. Figure 4 illustrates this for a two-storey house.

Although the overall ventilation rate may be determined by considering the predominant force only, the distribution of ventilation air throughout the building may be affected, so for detailed room-by-room analysis, the two effects need to be considered in combination.

Another reason for taking account of the coincidence of conditions of wind and temperature is the calculation of the energy loss attributable to infiltration or natural ventilation. Over the heating season, this energy loss is that required to heat the incoming cold air to the temperature maintained indoors.

i.e $$W = \int_0^T q_v \rho c_p (\theta_i - \theta_o) dt \quad (3)$$

where W = energy required (kJ)

q_v = volume flow rate of infiltration/ventilation (m^3/s)

ρ = air density (kg/m^3)

c_p = specific heat capacity of air (kJ/kg K)

θ_i = indoor absolute air temperature (K)

θ_o = outdoor absolute air temperature (K)

For a proper analysis of the ventilation energy loss over a heating season, it is thus, necessary to analyse the climatic conditions in terms of the coincidence of specific temperature, wind speeds and directions.

The Resistance to Airflow Through the Building

A building may be regarded as a network of air flow paths which interconnect at nodes. The nodes represent spaces inside and outside the building where substantially uniform pressure occurs. The interconnections comprise the components through which air may pass, such as gaps around windows and doors. Figure 5 shows a typical network superimposed on a plan drawing. The air flow paths have a characteristic resistance to air flow dependent on their type.

For large openings such as ventilator grilles and open windows, the following formula may be used:

$$q_v = Cd\ A \left(\frac{2\Delta p}{\rho}\right)^{\frac{1}{2}} \quad (4)$$

where q_v = volume rate of flow (m^3/s)

Cd = coefficient of discharge

A = area of opening (m^2)

Δp = pressure difference across opening (Pa)

ρ = air density (kg/m^3)

The discharge coefficient Cd is normally given the value appropriate to a sharp-edged opening and an equivalent orifice area is prescribed for the particular opening in question. This equivalent area may be taken as the same as the physical area for plain openings (e.g. open windows) but for more complex openings such as air-bricks or ventilation grilles, derived values of equivalent area will be needed. Some are given in Reference 11.

For small openings, such as gaps around closed windows and doors, the relationship between flow and pressure is much more dependent on Reynolds number but over a limited range corresponding to normal conditions the following relationship applies:

$$q_v = C_L (\Delta p)^{\frac{1}{n}} \quad (5)$$

where C_L = leakage factor = $k \times \ell$ where k = leakage coefficient in m^3/s per metre of gap length at a Δp of 1 Pa, and ℓ = total gap length (m)

$\frac{1}{n}$ = exponent where n is normally between 1.4 and 1.6

Typical values of k for windows are also given in Reference 11.

In addition to the types of opening described, air leakage occurs through other gaps and cracks in the building fabric. It may be through cladding components, structural cracks, and even through electrical conduits and where other services penetrate the structure. The magnitude of this 'background' leakage has been found to be significant. Measurements have revealed equivalent areas of similar magnitude to the areas of gaps around closed doors and windows in the building.

These measurements of background leakage area involved pressurising or evacuating the inside of a building using a fan passing a known rate of flow into or out of it. With any purpose-provided ventilation openings blanked-off and the gaps around the windows and external doors sealed, the relationship between internal-to-external pressure difference and air flow rate was established for the background leakage. To fully take account of it, the location of the background leakage paths must also be known and such information is extremely difficult to obtain for an existing building and virtually impossible to predict for a projected building. Much more experimental data are required before information suitable for design purposes can be provided, and even then the wide variations in building workmanship will make its application questionable.

DESIGN DATA

The move towards reduced energy consumption in buildings cannot be undertaken without recognition of the need to maintain safe and comfortable conditions for the occupants and of the economic considerations affecting the relationship between capital and running costs. For ventilation, this requires the ability to design buildings and systems to achieve the minimum ventilation rate criteria, to assess the energy consumption involved and to evaluate the economic advantages (or otherwise) of possible energy saving measures.

There is an urgent need for sufficient information to be made available to enable the designer to achieve these requirements by the application of the principles already outlined. In this section, the shortfall in the available data is highlighted. There is also a need for an understanding of the effectiveness of alternative measures to reduce energy losses as well as an appreciation of the economic criteria for evaluating an increase in capital outlay against the potential long-term savings. Some examples of alternative ventilation control measures are presented but the economic aspects, important though they may be, are not considered within the scope of this paper. The effects of occupant behaviour with respect to openable windows are also not considered.

Prediction of Ventilation Performance

The designer requires information to enable the estimation of ventilation rates from known building design data, or, conversely, the determination of provisions required in the building from knowledge of the ventilation criteria. Associated with both approaches, is the requirement for the calculation of corresponding energy losses.

Figure 6 illustrates how, by the application of the principles of natural ventilation, the gulf the designer has to cross can be spanned. As the diagram shows, the bridge-building is not yet complete. Highlighted as weak links are those relationships for which sufficient reliable data are, as yet, unavailable. These include the relationship between meteorological wind data and wind-generated pressure distributions on a building taking into account fluctuations, local disturbances, characteristics of the building surface; and the magnitude and distribution of 'background' leakage through gaps and cracks in the building fabric. Additionally, specific criteria for minimum ventilation rates are required. There is an obvious need for continuing reseach to strengthen these weaker links.

One of the further important requirements is the translation of these principles of ventilation, involving multiple and complex parameters, into a procedure easily applied by designers.

With the facilities offered by modern computers, it is tempting to opt for the retention of sophisticated procedures for design predictions. However, the required detail and precision of the prediction method is governed not only by the use that is made of the end result, but also by the form of the available supporting information. For example, a calculation precision of 1% is hardly justifiable when constructional tolerances may produce variations of much higher magnitude. Nor is there any point in developing a minute-by-minute analysis of ventilation rates, when available meteorological data is expressed in hourly mean values. The aim perhaps can best be expressed as the achievement of a design process which is comparable in precision, proven reliability and ease of use with those available for the other energy transfer processes in buildings.

Energy Saving Potential

The requirement to maintain ventilation rates at or as little possible above the minimum acceptable value while relying on natural forces presents real difficulties. If the minimum ventilation rate is achieved under mild, still climatic conditions then under all cooler, windier conditions the rate will be in excess of that required with the consequent wastage of energy. To demonstrate the magnitude of the unnecessary energy loss and to examine the potential of alternative measures to reduce energy wastage, comparative calculations of ventilation rates and energy loss have been made for a modern, two-storey dwelling.

Calculations were made to derive, for this particular building, the relationship between ventilation rate and the combination of wind speed and indoor-outdoor temperature difference. In this case, variation in wind direction was not taken into account, because tests had shown that overall ventilation rates were relatively independent of wind direction. These calculations were based on selected pressure distribution data applicable to an urban area, an assumed constant indoor temperature of 19°C and various component and background air leakage characteristics. It was assumed that the windows and doors were always closed. The example shown on Figure 4 illustrates the predominant effect of temperature difference at low wind speeds and of wind at speeds above 3.5 m/s.

Seasonal ventilation rates and the associated energy loss was then calculated by using the derived relationships and specific meteorological data. The meteorological data consisted of a table giving the frequency of occurence of mean hourly wind speeds within 2 K outdoor temperature bands. The wind speeds were modified to relate them to an urban environment and to the height of the dwelling. The data for Birmingham (Elmdon) covered the heating seasons, September to May, over a 10 year period, 1969 to 1979.

Table 1 presents the results of these calculations for a number of conditions and these are discussed below. In this discussion, it has been assumed that the rate of ventilation should not fall below 0.3 air changes per hour. This value has been chosen for demonstration purposes only - whether or not it is an acceptable criteria may be considered in the light of the previous paper.

Natural Ventilation - Variation in Leakage Values. For the same dwelling, two levels of leakage were considered. The first corresponded to the situation as found on site in which window, door and background leakage were taken into account. This could be considered as a house of typical construction with good quality windows and doors. Over the heating season the air change rate was always at or above 0.3 times per hour with a mean rate of 0.81. It was above 0.5 changes per hour for 93% of the time. The associated seasonal energy loss was calculated to be 16.6 GJ. In comparison, the equivalent energy loss for an air change rate of 0.3 and 0.5 air changes per hour consistently over the heating season was 6.1 GJ and 10.2 GJ respectively. There is thus considerable potential for reducing the ventilation energy loss in such a naturally ventilated building provided some control can be applied to reduce the range of ventilation above the minimum rate. This theoretical potential for energy saving is up to 20% of the total seasonal energy loss of the dwelling assuming it to have the thermal insulation values given in the 1976 Building Regulations[4].

The second level of leakage was that with the background leakage eliminated and a reduction in the leakage through windows and doors so that the building met the air leakage requirements of the 1978 Swedish Building Code, i.e. 3 air changes an hour at a pressure difference of 50 Pa. The seasonal energy consumption was reduced to a level that corresponded to a mean air change rate of just less than 0.3 times per hour but for over 60% of the season the ventilation rate was below that level. Simply reducing the leakiness of the structure is clearly not a satisfactory method of minimising ventilation energy losses.

Controlled Natural Ventilation. There are several ways by which the rate of natural ventilation in a building could be controlled if the resulting energy savings were found to be worthwhile.

For example, providing shelter to eliminate the effects of wind on the original dwelling under consideration would, while still maintaining an air change rate consistently above 0.3 times per hour, reduce the ventilation energy loss from 16.6 GJ to 10.8 GJ, a potential saving of just over 30%. Experiments in the United States[12] have demonstrated savings of the order of 10% with shelter provided by evergreen trees.

Another approach might be the control of ventilation openings by devices sensitive to outdoor temperature so that as the temperature outside reduced so the open area of the vents also reduced. Again, the calculation shows that savings of over 30% could be realised while maintaining adequate ventilation at all times.

The control of ventilation opening areas in response to the pressure differential across them could theoretically produce a consistent ventilation rate at the required minimum level and so reduce the associated energy loss to 6.1 GJ. Although such devices were evidently available as long ago as 1948[3], it is unlikely that effective performance could be achieved economically.

The effective adoption of some form of automatic control of ventilation openings implies that other routes of potential leakage must be minimised and this requires detailed attention to structural design.

Mechanical Ventilation. The application of mechanical ventilation systems in dwellings is worthy of consideration. It is being used as an energy saving measure in some countries with climatic conditions more severe than ours, but further studies on its potential in this country are required.

The advantage of mechanical ventilation is that it ensures fresh air supply at a required rate. However, the influences of wind and stack forces can still result in ventilation rates above the required level. Table 1 includes the results of calculations for mechanical ventilation applied to the low-leakage dwelling. With a balanced ventilation system, i.e. both supply and extract fans, providing 0.3 air changes per hour, the ventilation energy loss was twice the value that would result if the natural forces were eliminated. At a mechanical ventilation rate of 0.5 air changes per hour the corresponding ratio was 1.5:1. With extract ventilation the ratios were lower at 1.5:1 and 1.12:1 respectively.

This demonstrates that structures must be well sealed for the effective application of mechanical ventilation systems. In the original naturally ventilated dwelling, a reduction of energy of 7.5 GJ per year would involve not only the purchase, installation and running cost of the mechanical ventilation system but also a five-fold reduction in the leakiness of the structure.

The balanced type of mechanical ventilation system offers the potential of heat recovery by preheating the incoming air with the outgoing air. This may be achieved by a plate heat exchanger or more sophisticated heat transfer equipment. If it is assumed that 75% of the heat in the extract air was recovered, the seasonal ventilation energy loss would reduce by 4.3 GJ but again the cost implications need careful assessment.

CONCLUSIONS

Natural ventilation is a complex process affected by many parameters, the values of which are difficult to accurately predict. There is a need for further experimental work to provide more reliable data for the improvement of design procedures. This experimental work should include detailed studies on various building types with measurements of local climatic conditions, wind-generated pressure differences and infiltration rates. The results of such work should be related to the leakage characteristics of the buildings and meteorological data and be used in the development of refined design models.

The results of some sample calculations demonstrate the orders of magnitude of energy savings that could theoretically be achieved by the use of controlled or mechanical ventilation in dwellings. The value of these savings needs to be assessed in relation to the expenditure required to construct buildings with lower air leakage than is usual at present and that required for additional capital equipment.

It is appreciated that the effects of the occupants' use of openable windows has been ignored. This will have a significant influence on the energy consumption but it should nevertheless be the aim of the designer to promote buildings which inherently provide ventilation at a minimum acceptable level while allowing occupants the facility to increase the rate of ventilation for special circumstances.

TABLE 1 - Calculated seasonal ventilation performance and energy loss

	Ventilation energy loss GJ	Average ventilation rate air changes/hour	Time > 0.3 changes/hour %	Time > 0.5 changes/hour %	Total leakage at 50 Pa air changes/hour
Constant ventilation (theoretical)					
1. 0.3 air changes/hour	6.1	0.3	100	0	-
2. 0.5 air changes/hour	10.2	0.5	100	100	-
Natural ventilation					
3. House of typical construction	16.6	0.81	100	93	14.6
4. House to 1978 Swedish Building Code (low leakage)	5.4	0.27	37	8	3
Controlled natural ventilation					
5. Typical house fully sheltered	10.8	0.53	100	41	14.6
6. House with temperature-sensitive ventilation control	10.8	0.53	100	49	14.6 at $\Delta\theta$ of 4K 4.6 at $\Delta\theta$ of 20K
7. House with pressure-differential-sensitive ventilation control (theoretical optimum)	6.1	0.3	100	0	-
Mechanical ventilation					
8. Low leakage house with balanced ventilation at 0.3 air changes/hour	11.5	0.56	100	67	3
9. Low leakage house with balanced ventilation at 0.5 air changes/hour	15.6	0.77	100	100	3
10. Low leakage house with extract ventilation at 0.3 air changes/hour	8.9	0.44	100	32	3
11. Low leakage house with extract ventilation at 0.5 air changes/hour	11.5	0.56	100	100	3

SYMBOLS USED

A = area of opening (m^2)

C = wind pressure coefficient

Cd = coefficient of discharge

C_L = leakage factor (m^3/s at a Δp of 1 Pa)

c_p = specific heat capacity of air (kJ/kgK)

h = vertical distance between openings (m)

k = leakage coefficient (m^2/s at a Δp of 1 Pa)

ℓ = length of gap (m)

n = characteristic exponent

p = pressure on a building generated by wind (Pa)

Δp = pressure difference across opening (Pa)

Δp_θ = pressure difference caused by stack effect (Pa)

q_v = volume flow rate of infiltration/ventilation (m^3/s)

T = time (s)

u = local wind speed (m/s)

W = energy requirement (kJ)

ρ = density of air (kg/m^3)

θ_i = internal absolute temperature (K)

θ_o = external absolute temperature (K)

$\Delta\theta$ = indoor to outdoor temperature difference (K)

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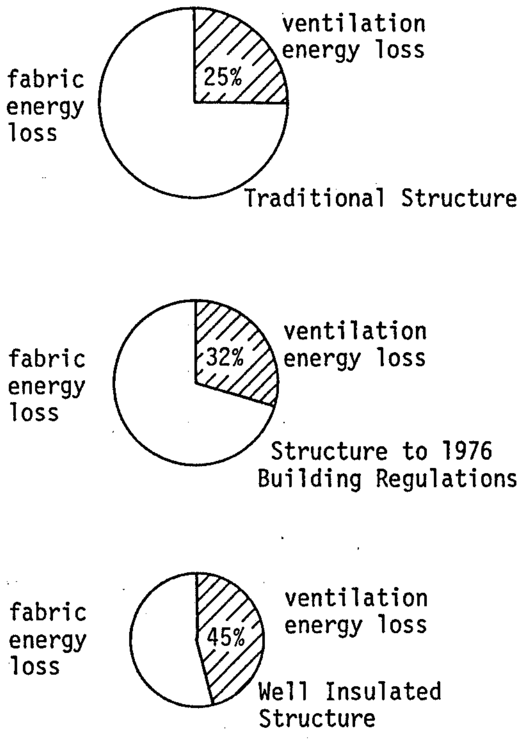


Figure 1 Typical proporations of seasonal energy losses from dwellings

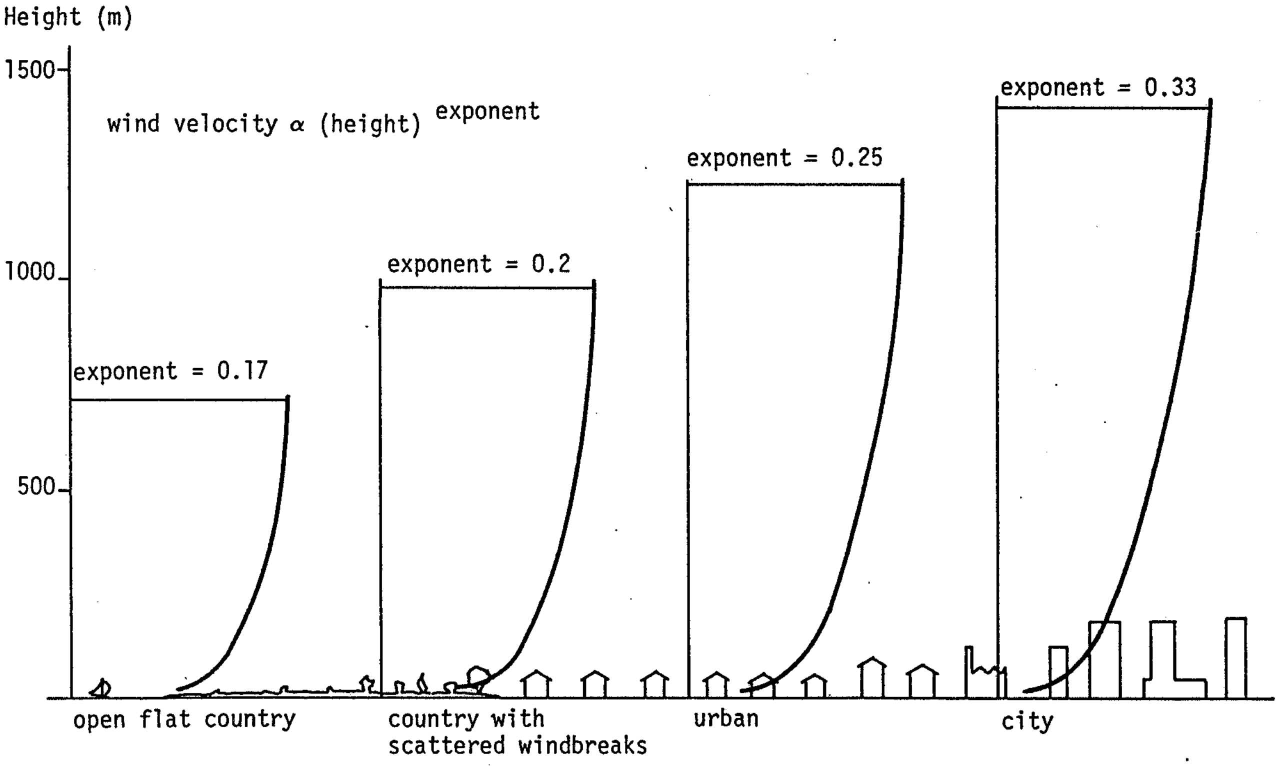


Figure 2 Variation of wind velocity with height over various types of terrain

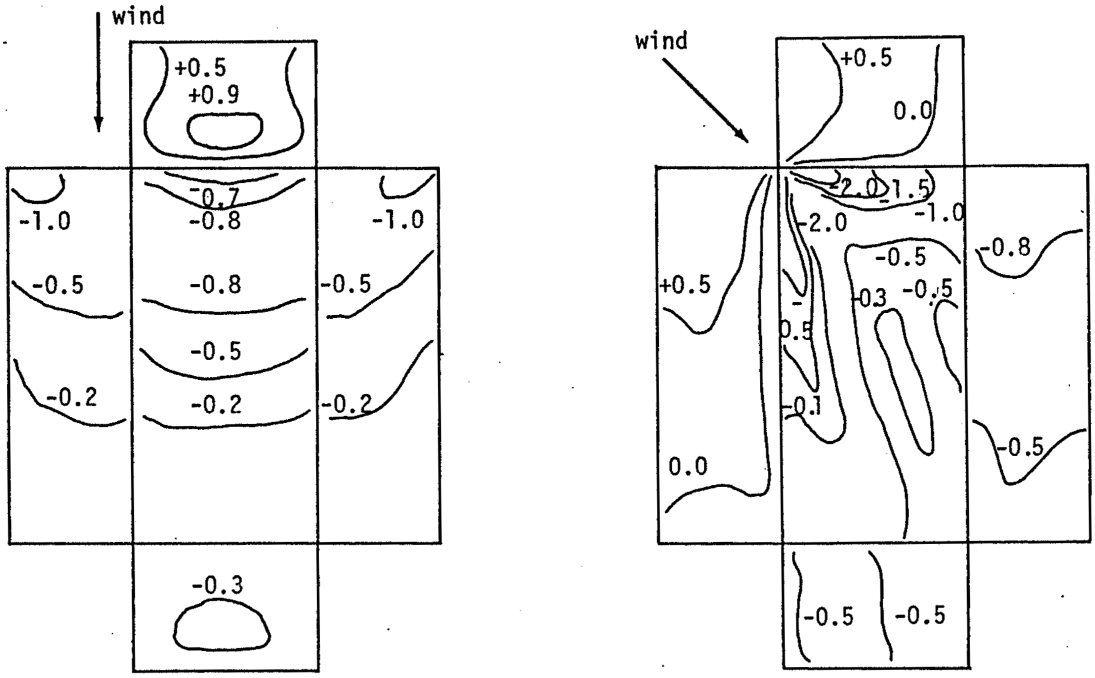


Figure 3 Wind pressure coefficient contours on the surface of a building

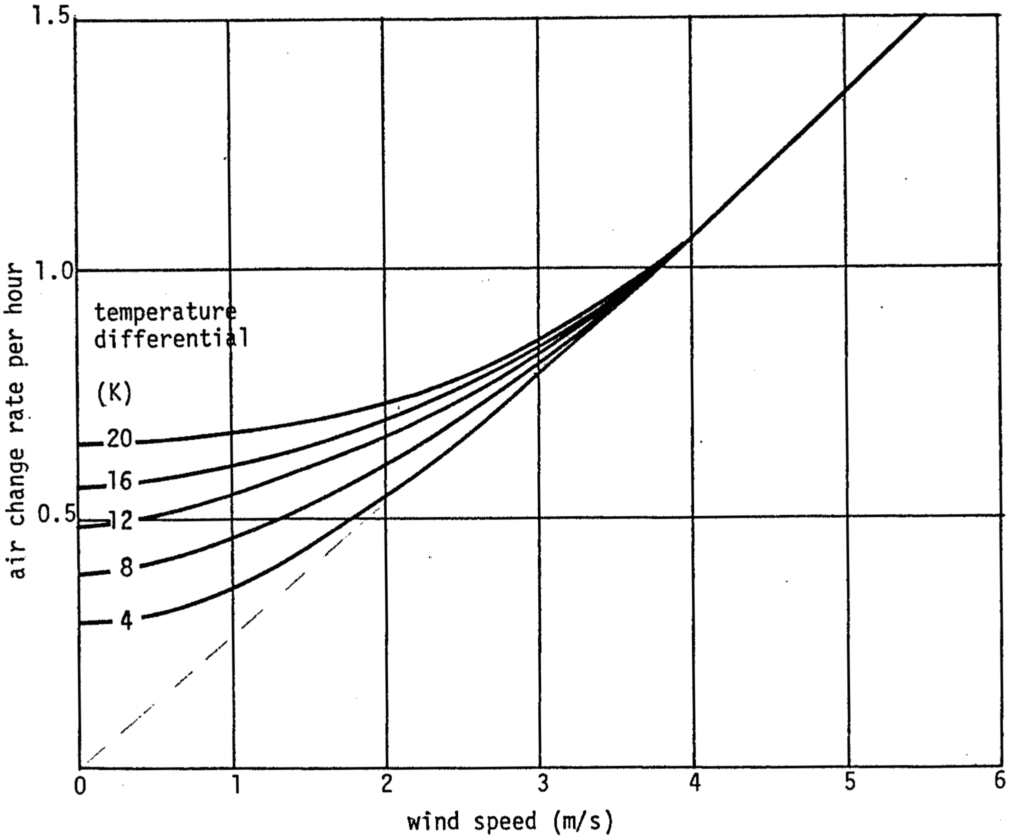
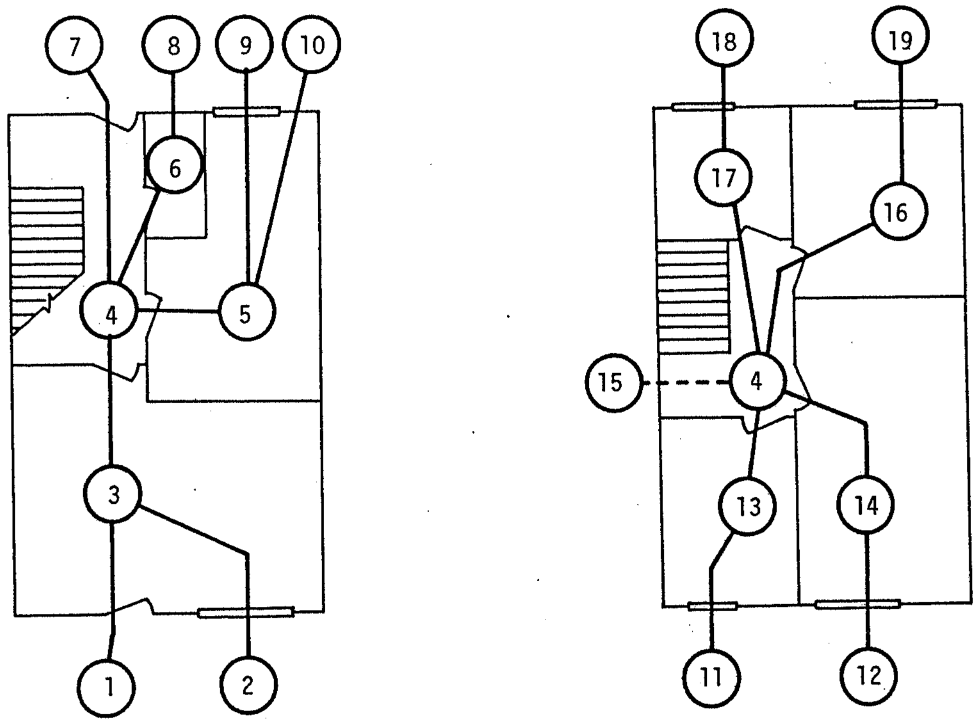


Figure 4 Typical relationship between ventilation rate, wind speed, and temperature differential



Ground Floor

First Floor

Figure 5 Air flow network of a typical dwelling

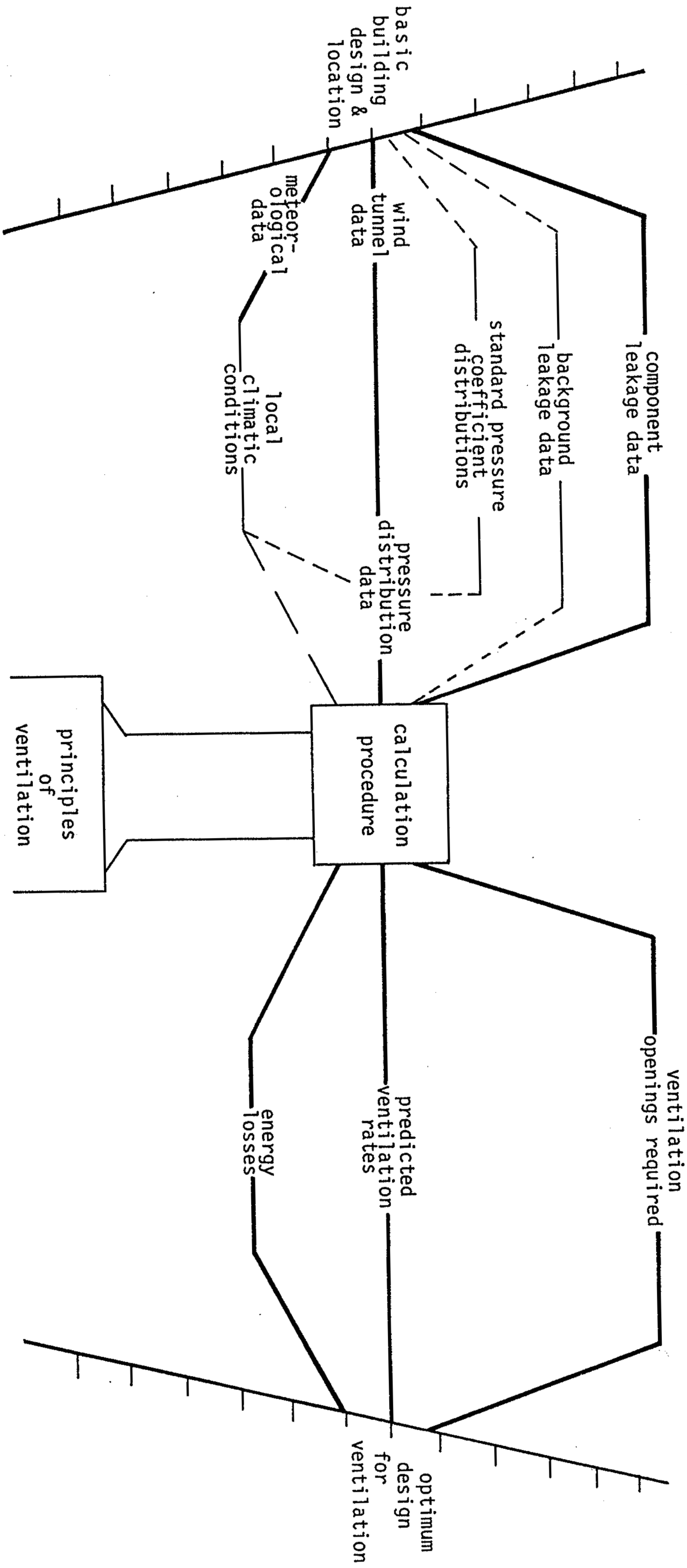


Figure 6 Ventilation design process

VENTILATION MEASUREMENTS IN HOUSING

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Despite the fact that the majority of buildings, particularly in the domestic sector, are naturally ventilated, natural ventilation and infiltration remain amongst the most intractable aspects of building design. The need for improved guidance has become of increasing importance with the need for energy conservation.

As a first step to providing a better understanding of natural ventilation in housing this paper presents results of recent measurements of ventilation rates and air leakage characteristics in dwellings. These are used to show typical magnitudes of ventilation rates and the way in which they are influenced by meteorological parameters, such as wind speed and direction, and air temperature, and the characteristics of the fabric and form of the building.

1 INTRODUCTION

Natural ventilation is one of the most intractable features of building design. Despite the fact that the majority of buildings, particularly in the domestic sector depend upon natural ventilation to maintain internal air quality and, in summer, to limit the incidence of thermal discomfort, current knowledge of the rates of ventilation which occur in practice and the way that these are related to design parameters is very limited. In the past when heating fuel was relatively cheaper, excessive ventilation was comparatively unimportant, provided that it did not give rise to discomfort. The current need to reduce energy consumption has provided an impetus to reduce ventilation rates to the minimum levels necessary to ensure health, safety and comfort. This has lead to the demand for improved guidance on design and the development of methods for readily assessing the ventilation performance of buildings.

The purpose of this paper is to present the results of recent measurements in housing in order to illustrate typical magnitudes of ventilation rate and the way in which these are influenced by meteorological parameters and the characteristics of building fabric and form. Examples are taken from a recent survey by the Building Research Establishment of ventilation rates in unoccupied housing, a fuller report of which will be published in due course.

2 FACTORS WHICH INFLUENCE NATURAL VENTILATION RATES

It is proposed to review the theoretical principles of natural ventilation only briefly as these have been dealt with in many published papers, of which references (1, 2 and 3) are examples. In respect of natural ventilation a building may be considered to consist of a number of individual 'cells' connected to each other and to the outside air by openings through which air can flow. In a house these 'cells' may represent rooms or other spaces such as those beneath suspended floors, under the roof or even wall cavities. The connecting openings may be large and well-defined, such as doors, open windows, air-bricks and flues, or small, and not always immediately apparent, such as gaps around the opening lights of windows and cracks at the junction of floors and walls or where electrical fittings and other services penetrate the fabric. Air will flow through these openings when a pressure difference is created across them. This may be due to the action of the wind or to differences between the temperature of the air within the house and outside. It has been conventional in the past to consider only mean pressures but recent studies have indicated the importance of the fluctuating component of wind-generated pressures where the mean pressures difference across an opening in the external fabric is small(4,5). In addition, for large openings such as open windows, mechanisms dependent upon the local air speed, rather than the applied pressure difference, may be the dominant cause of air exchange between inside and outside(6).

The natural ventilation rate of a house therefore depends upon the following factors:

a) The meteorological variables - wind speed and direction and air temperature .

b) The shape of the house and the nature of its surroundings. These determine the distribution of wind-generated pressure at the external surfaces.

c) The positions and airflow characteristics of all openings and flow paths.

In addition, some openings, in particular windows and doors, may be controlled by the occupants. Dick(7) and, more recently, Brundrett(8) have demonstrated that window opening behaviour in dwellings can be correlated closely with external air temperature. A further factor which should therefore be added to those given above is the behaviour of occupants.

It is the wide range and the difficulty in determining the effects of some of these parameters which make the prediction of natural ventilation rates and the interpretation of field measurements so difficult.

3 MEASUREMENT TECHNIQUES

3.1 Air flow characteristics of openings

(i) Theoretical considerations

The relationship between the flow rate through an opening and an applied pressure difference depends upon Reynolds Number and the geometry of the opening. For large openings such as open windows, which approximate to a sharp-edged orifice the following simple relationship applies:

$$Q = C_d . A . \sqrt{\frac{2\Delta p}{\rho}} \qquad (1)$$

where, Q is the volume flow rate resulting from the applied pressure difference Δp; A is the area of the opening, ρ is the density of air and C_d the discharge coefficient. For other types of opening it is necessary in general to determine the relationship empirically. It is convenient to fit the measured values to a simple expression and the following power law is generally used

$$Q = K . \Delta p^n \qquad (2)$$

More complex expressions, which can be more readily justified theoretically, have been developed, notably by Etheridge(9). These cannot, however, be easily used where the shape and dimensions of an opening are not known and this is generally the case in real situations.

The value of the exponent, n, will lie between 0.5, for flows which are independent of viscosity, and 1.0, for flows which are dominated by viscosity. For any given range of applied pressure the smaller the cross-stream dimension of the opening, the closer n will approach to 1.0.

(ii) Measurement techniques

Laboratory 'pressure box' techniques have been used for many years for testing the air leakage characteristics of building components such as windows. Van Gunst and den Ouden(10) extended the method to field use by developing a portable pressure box for measuring the in situ performance of windows in experimental houses. The technique is essentially simple. An enclosure is sealed around the component of interest. Air is extracted at a known rate and the pressure difference developed across the component measured with a manometer.

More recently the measurement of the leakage performance of individual components has been extended to measuring the 'whole house' leakage characteristics. Development of suitable equipment by Skinner(11) in the United Kingdom was accompanied by similar developments in Canada, Denmark, the USA and Sweden. Although the techniques used by various experimenters differ in detail, the essential method is the same. A large fan unit is sealed into a suitable opening in the external fabric of the house, usually an open doorway or window. The flow rate through the fan and the applied pressure difference are measured. In some cases the equipment is designed so that the flow can be reversed and the leakage measured for both positive and negative pressure differences.

Large openings whose equivalent areas can be determined by alternative methods are sealed during testing. Progressive sealing of chosen components and repetition of the measurements allows the distribution of leakage to be determined.

Provided a variable speed fan unit is used, results may be presented as a curve of volume flow rate against applied pressure difference and a simple power law expression, of the form given in equation (2), may be fitted. In fact this expression will represent the aggregate of the various flow paths through the fabric:

$$Q = K . (\Delta p)^n = \Sigma K_i . (\Delta p)^{n_i} \qquad (3)$$

A simpler alternative which is also used is to give the leakage at a fixed pressure difference, usually 50 Pa. The two approaches may be readily combined, by writing equation (3) in the following form, which has the additional merit of being dimensionless:

$$Q/Q_T = \left[(\Delta p)/(\Delta p_T)\right]^n \qquad (4)$$

where Q_T is the flow rate at the applied pressure, Δp_T.

The technique has achieved considerable interest because of its simplicity and ease of use on site and because of the possibility that it could be used as an indicator of the general natural ventilation performance of a dwelling. To determine the validity of this proposal it is necessary to compare the results obtained using this pressurisation technique with the results of tracer gas measurements of ventilation rates and this will be discussed further in a following section. In this context it is worth noting the following points:

a) Pressures generated by wind and stack effect are not uniformly applied across the building envelope, as they are in the pressurisation test.

b) Relatively high pressure differences are used, usually in the range 20 to 60 Pa, in comparison with typical pressures generated across the fabric at average wind speed, which are of the order of 1 to 5 Pa. (In an attempt to overcome this limitation, techniques using alternating pressures are under development(12) but have not reached the stage when they can be used with confidence.)

3.2 Ventilation rate measurements

(i) Tracer gas methods

Because the air flow paths in a naturally ventilated building are not well defined conventional anemometric techniques cannot be used to measure the volume flow rate of air entering a space. The only satisfactory techniques employ the use of a tracer substance, usually a gas. Two methods of operating may be employed:

a) the exponential decay method, and
b) the constant injection rate method.

These may be illustrated by considering a single 'cell' of volume V. Air enters and leaves the cell at a rate Q. If tracer gas is introduced into the cell at a constant rate, q, its concentration after a period of time, t is given by:

$$c = q/Q\left[1 - e^{\frac{-Qt}{V}}\right] \qquad (5)$$

After a sufficiently long period the concentration tends to an equilibrium level, c_e, given by

$$c_c = q/Q \qquad (6)$$

If c_e and q are measured then the ventilation flow rate, Q, may be determined. This is the basis of the constant injection rate method. If the injection of tracer is stopped then the concentration rate decays exponentially according to the following equation:

$$c = c_o.e^{-Qt/V} \qquad (7)$$

The ventilation rate R(= Q/V) is readily determined. Both methods require that the tracer gas should be uniformly mixed within the space.

A recent development of the constant injection technique(13) employs a microprocessor in a feedback loop from the measuring instrument to the injection device and maintains the concentration of tracer gas constant, while monitoring the amount of tracer injected. The average ventilation rate of the space under consideration is obtained by dividing the total volume of tracer gas injected over a given period by the value at which the concentration is held constant.

(ii) Tracer gas characteristics

To be suitable as a tracer gas must possess the following characteristics:

a) It should neither be created or removed from the space under test, other than by ventilation (ie it should be stable and not absorbed or emanated by surfaces within the space).

b) It should be capable of being readily mixed with air.

c) It should be non-toxic.

d) It should be capable of being measured over an appropriate range of concentration.

A number of gases have been employed as tracers including carbon dioxide, hydrogen, helium, ethane and krypton-85. The two gases most commonly used at present are sulphur hexafluoride and nitrous oxide. These may be measured in concentrations as low as 10^{-4} and 10 parts per million respectively using an electron capture chromatograph in the first case and an infra red gas analyser in the second case.

(iii) Measurements in dwellings

The type of tracer gas measurements to be made in dwellings depend upon the reason for which the ventilation rate is required. If the concern is with energy consumption, and temperatures are reasonably uniform throughout the house, then whole house ventilation rates are of interest. If substantial temperature differences are likely to occur then concern is the fresh air entering a particular room. The constant concentration technique is most useful in this case since it allows the air entering each room to be separately determined. Alternatively the major concern may be the movement of some contaminant, such as water vapour, from one part of the house to another, in which case it is necessary to know the rate of air exchange between rooms, which is obscured in the constant concentration method. A second tracer using the exponential decay method is required. Individual room measurements, made by injecting tracer gas into a single room are less easy to interpret since the incoming air may come from elsewhere within the house as well as from outside. However this may be overcome in part by observing the points of entry and exit of the air using smoke filament indicators. Although such measurements obscure the origin of the air entering the room they are useful;

(i) for comparison with theoretical predictions, and

(ii) in situations where a contaminant is produced in the room in question only. This is often the case in housing because of the diversity of use of rooms and the range of contaminants that need to be controlled.

4 MEASUREMENTS IN DWELLINGS

4.1 BRE measurements

In order to provide basic data on the ventilation of dwellings in practice a programme of air leakage and ventilation rate measurements has been carried out in 25 dwellings. In addition measurements in a further 13 houses of ventilation rates and component characteristics have been carried out under contract by the Building Services Research and Information Association. Full sets of leakage characteristics and ventilation rates were made in nineteen of the houses and brief details of these are included in Table 1.

Where possible the ventilation rate measurements were carried out over a period of three to four weeks in order to obtain a range of wind speeds and directions, and, generally less successfully, temperatures. In order to limit the range of variables the measurements were carried out with windows and doors closed, although in a few of the houses a limited number of additional measurements were made with windows and other controllable ventilation openings set to particular positions of opening. All measurements were made in unoccupied dwellings. A full analysis of the results referred to in the following sections will be published in due course.

4.2 Air leakage measurements

(i) Method

Whole house air leakage measurements were made using the pressurisation equipment described by Skinner(11). This allowed measurements to be made with both positive and negative pressure differences. The measurements were carried out during periods of low wind speed in order to reduce any interference by wind generated pressures.

Air leakage through individual items was determined separately using a portable rig consisting of an adjustable frame capable of being set up to fit over any component up to the size of a double door. Polythene sheet was sealed over this to form an airtight enclosure from which air was extracted using a small fan. The pressure difference applied across the component and the rate of flow of the extracted air were measured.

(ii) Whole house air leakage measurements

Measurements were made of whole house air leakage for both positive and negative applied pressure differences for each of the nineteen dwellings listed in Table 1. Power law curves were fitted to each set of results and the mean values K and n from the positive and negative results calculated for each dwelling. Using the form given by equation (4), Table 1 lists the values of air leakage, Q_T in m^3/h, at an applied pressure difference of 50 Pa, and of the exponent, n. As expected the values of n lie within the range 0.5 to 1.0. The maximum value is 0.69 and the minimum 0.53. The mean value is 0.60, with a standard deviation of 0.04. Table 1 also

TABLE 1 - Whole House Air Leakage Characteristics

	House data			Air leakage characteristics at 50 Pa					Ventilation rates at mean wind speed for the site
No.	Date	Type	Volume m^3	Q_T m^3/h	(Q_T/V) ach	(Q_T/A_p) m^3/hm^2	n	Percentage background leakage	ach
1	1971	2 B	197	2310	11.7	12.4	0.57	64%	0.44
2	1957	2 B	254	2205	9.7	11.9	0.69	52%	-
3	1957	2 B	249	2910	11.7	16.6	0.55	64%	0.45
4	1976	2 C	196	3090	15.8	23.3	0.64	67%	0.58
5	1976	2 C	196	2810	14.4	21.2	0.57	69%	0.77
6	1956	2 D	164	2210	13.5	22.2	0.67	42%	0.72
7	1975	2 D	200	2440	12.4	22.6	0.66	57%	0.70
8	1977	2 D	77	1330	17.3	40.2	0.58	60%	0.72
9	1947	2 A	195	3530	18.1	19.3	0.61	-	-
10	1978	2 D	179	1760	9.9	13.9	0.58	72%	0.49
11	1977	2 C	196	4130	21.8	31.5	0.64	72%	1.27
12	1960	2 B	261	3782	14.5	22.3	0.58	69%	0.50
13	1960	2 B	261	3990	17.4	23.5	0.58	67%	0.58
14	1977	2 C	247	3570	14.5	16.6	0.63	76%	-
15	1976	1 E	148	1350	9.1	16.1	0.55	48%	-
16	1976	2 F	169	1620	9.6	16.7	0.54	57%	-
17	1976	2 G	179	3400	19.0	39.2	0.53	54%	-
18	1977	3 D	220	3240	14.7	32.6	0.63	56%	-
19	1970	2 C	221	2310	10.4	17.3	0.58	70%	0.36

House type_ 1, 2, 3 - Number of storeys:

A - detached
B - semi-detached
C - end terrace
D - mid-terrace
E - flat
F - maisonnette
G - quad.

shows the air leakage flow rate scaled by the house volume (Q_T/V), and scales by the permeable area (Q_T/A_p). For this purpose the latter is defined as the sum of the areas of the external walls of the house together with the area of the ground floor, provided that this is permeable to air flow, and the area of the surface between the house and the roof space. (Q_T/A_p) is an index of the overall permeability to air flow of the building envelope.

It is of interest to compare these results with those obtained in typical dwellings in other countries. The mean of the results for the nineteen houses, together with similar results obtained in Canada(14), Sweden(15,16), Denmark(17) and the United States(18) are shown in Table 2. The air leakage rates at 50 Pa for the British house compare favourably with all but the Swedish houses which have much lower values. However when a comparison is made taking into account the different average volumes for each data set the British houses are clearly considerably less tight than those in Canada and Sweden. This is further reflected in a comparison of fabric permeability - (Q_T/A_p), which shows Swedish houses to be four times as tight as the United Kingdom sample.

(iii) Variation of air leakage rates with time

In order to determine whether any variation occurred in the air leakage characteristics, measurements were made in one of the dwellings (no 11, Table 1) and repeated at regular intervals over a period of eighteen months. The results are shown in Figure 1 in the form of the whole house leakage rate, Q_T, at 50 Pa, subdivided between leakage through the windows and doors, and background leakage. The house concerned was unoccupied during the test period, but was heated to normal temperatures during the heating season. Figure 1 indicates a very substantial seasonal change in overall leakage with a maximum in winter and a minimum in the summer months. In view of the

TABLE 2 - A Comparison of Air Leakage Characteristics of Dwellings in Different Countries

Author	Country	Sample size	Average house volume	Air leakage characteristics at 50 Pa				
				Q_T	Q_T/V	Q_T/A_p	n	Applied pressure direction
			(m^3)	(m^3/h)	(ach)	(m^3/m^2h)		
Present results	United Kingdom	19	200	2740	13.9	22.1	0.60	Mean
Grimsud et al (18)	United States (California)	13	378	3330	9.4	-	-	Mean
Colet et al (17)	Denmark	6	303	2730	8.6	-	0.70	Positive
Holmgren et al (16)	Sweden	10	307	1580	5.1	-	0.71	Positive
Kronvall (15)	Sweden	25	317	1360	4.5	5.0	0.77	Negative
Beach (14)	Canada (Ottawa)	63	553	2420	4.4	8.4	0.66	Positive

fact that the house was not occupied internal relative humidities were relatively low during the winter, there being no moisture input, and, in consequence, drying out of the timber in the structure may be a contributory factor to the observed change in tightness. The measurements will be repeated during the coming heating season when typical moisture levels will be maintained in the house.

Recent measurements in Swedish houses(19) indicated a very substantial change in air leakage characteristics in the first year of occupation of new houses. Leakage rates measured in five houses increased on average by 70%. Measurements made a further year later showed no significant change. Similar measurements were made in the present series of tests on three identical British houses. The mean leakage at 50 Pa at completion was found to be 1870 m^3/h. Approximately one year after the houses had been occupied the leakage rate had increased to a mean value of 3420 m^3/h, an increase of 83%. Possible reasons for this include drying out of the fabric, settling of the structure, changes carried out by the occupants and general wear and tear during use, particularly of the doors and windows.

Before any general conclusions can be drawn from these results they will need to be substantiated by further work and if possible related to form of construction. Nevertheless there is a clear indication that the interpretation of whole house air leakage measurements should take into account the time when the measurements are made.

(iv) Distribution of airleakage between components

A useful indication of the distribution of leakage between components may be obtained by expressing, at a common applied pressure of 50 Pa, the leakage of each component, obtained either by individual measurement or selective sealing during whole house tests, as a proportion of the total leakage at the same pressure. Figure 2 shows a typical example obtained for House 18. The proportions of the air leakage at 50 Pa attributable to background air flow paths, ie not through identifiable flow paths such as gaps around windows and doors, have been measured for the houses in Table 1 and are included as percentages in the Table. The average value is approximately 60% with a range from 40 to 80%.

Although expressing air leakage in this way emphasises the importance of background leakage some care should be taken in placing too much importance on detailed figures, bearing in mind the qualifications concerning the technique expressed in Section 3.1. The overall air leakage is an aggregate of many individual leakage paths with different values of the exponent, n. Components with higher values of n will be more dominant at the higher end of the pressure difference range. This is illustrated in Figure 3 which shows the percentages of the overall air leakage flow attributable to windows, doors, and background flow paths over a range of applied pressure difference from 5 Pa to 50 Pa, for House 17 in Table 1. Whereas at 50 Pa the background areas contribute 54% of the leakage, at 5 Pa the proportion is reduced to 27%.

4.3 Tracer gas measurements

(i) Method

Measurements were made of whole house and individual room ventilation rates using the exponential decay technique described in Section 3.2. Nitrous oxide was used as the tracer gas and its concentration was measured using an infra-red gas analyser. Simultaneously with the tracer gas concentration wind speed and direction, were measured using a lightweight cup anemometer and wind vane mounted on a 10 m high mast at a suitable position near the house under test, and together with internal and external air temperatures were recorded and automatically logged on to paper tape. This was subsequently processed on an ICL 1905 mainframe computer to calculate the ventilation rate, R, and the mean wind speed, U , wind direction, ϕ, and average temperature difference between inside and outside air, ΔT, for each test.

The whole house ventilation rates were obtained by the expedient of artificially mixing the air within the house using fans mounted in the open doorways, thus effectively reducing the house to a single 'cell'. The results are therefore representative of conditions of use when internal doors are normally kept partly open, or present very little resistance to flow. The results are likely to slightly overestimate the actual rates in occupied house in which the internal doors are kept closed. Individual room rates, determined by the decay rate technique, must be interpreted with care since, as noted in Section 3.2(iii) the incoming air may enter from other parts of the building as well as from outside.

(ii) Whole house ventilation rates

In order to indicate the general magnitude and range of whole house ventilation rates found in practice the results of 430 measurements in 25 different houses have been aggregated and presented in the form of a histogram in Figure 4a. The mean ventilation rate is 0.7 ach. Additional information is obtained from the cumulative frequency diagram, Figure 4b which shows that the median value is 0.6 ach and that a ventilation rate of 1.3 ach is exceeded only on 10% of occasions. In view of the substantially lower air leakage in Swedish housing it is of interest to compare these results with a similar analysis of results reported by Kronvall(20) of 97 measurements in 70 different houses. These lead to a mean value of 0.16 ach, a median of 0.14 ach and a rate of 0.3 ach exceeded on 10% of occasions.

Aggregating the results, however, obscures the effects of the individual factors, outlined in Section 2, which influence natural ventilation rates. The results for individual houses may be characterised by fitting regression lines to the data. Various combinations of the main meteorological variables, U , ΔT, and ϕ have been considered by previous workers. In general wind speed has been found to be the dominant variable and for present purposes the results for each house have been fitted to wind speed by simple regression analysis. Cases with significance levels less than 5% were rejected. The resulting regression equation enables the ventilation to be determined for any chosen wind speed and the values at the mean wind speed for each site have been calculated. These are listed in Table 1 for comparison with the leakage measurements. For the full sample of houses which satisfied the significance criterion, the mean value was found to be 0.74 ach with a range from 0.36 to 1.70 ach.

Another approach to the analysis of the results which yield more information is to isolate the results for each house which are dominated by wind or by stack effect. Using a simple single cell model it is shown in reference (21) that this may be achieved by plotting the results in the form $(Q/\Delta T^n)$ against $(U^{2n}/\Delta T^n)$. Those measurements which are substantially dominated by stack effect will lie in the range, for two storey houses,

$$0 \leqslant \left[\frac{U^{2n}}{\Delta T^n}\right] < 0.3$$

and those dominated by wind will lie in the range,

$$\left[\frac{U^{2n}}{\Delta T^n}\right] > 1.5$$

As an example of this approach the results of the whole house ventilation rate measurements for house 6 have been analysed and the wind dominated results identified. Since for any specific house these are a function of wind direction and wind speed only, plotting (Q/U^{2n}) against ϕ, will indicate the variation of ventilation rate with wind direction. This has been done and results shown in Figure 6. House 6 is in the centre of a row of terraced houses and the results give a clear indication of the effect of wind direction for this building arrangement. Ventilation rate, at a given wind speed, with the wind perpendicular to the row of houses is twice that when the wind is parallel to the row.

TABLE 3 - Room Ventilation Rates at Mean Wind Speed for Different Types of Room Use

Room description	Number of rooms in the sample	Ventilation rates (ach) Mean value	Range Minimum		Range Maximum
Living room	16	0.89	0.24	-	1.64
Kitchen	17	1.43	0.43	-	3.50
Bathroom	18	1.81	0.25	-	3.19
Large Bedroom (Volume ⩾ 15 m^3)	29	0.65	0.25	-	1.19
Small Bedroom (Volume < 15 mm^3)	14	0.87	0.28	-	2.90

(iii) Room ventilation rates

Room ventilation rates may be analysed in the same way as for the whole house results. Figure 5a for instance shows a histogram for large bedrooms (defined as those with a volume greater than 15 m^3) based upon 290 individual measurements in 25 houses. The associated cumulative frequency diagram is shown in Figure 5b. The mean ventilation rate is 0.73 ach, but the skewed nature of the distribution results in a median value of 0.55. A rate of 1.5 ach is exceeded in only 10% of cases. As with the whole house results the ventilation rate measurements for each room were fitted to wind speed by a simple regression analysis. Results with a significance level of less than 5% were rejected and the subsequent regression lines were used to calculate the ventilation rate for each room at the appropriate site mean wind speed. The mean values of ventilation rate for each type of room are shown in Table 3.

4.4 Comparison of pressurisation and tracer gas measurements

Although the tracer gas technique provides a direct measurement of natural ventilation rate considerable effort is required to set up the associated equipment and to carry out the measurements. To obtain sufficient results to establish the variation of ventilation rate with the main climatic parameters takes a long time. The instrumentation is expensive and requires specialist knowledge to operate it. In contrast the equipment for whole house pressurisation measurements is relatively inexpensive, robust and requires little experience to use. Measurements can be made in a few hours. Its usefulness would be considerably enhanced if it can be demonstrated that the natural ventilation rate of a dwelling can be related to leakage characteristics. The measurements, using both types of equipment in a range of houses, which have been briefly described in this paper offer an opportunity for testing this proposition.

One possibility is to compare the whole house leakage rate, Q_T, measured at 50 Pa, with a suitably chosen ventilation rate. For this purpose the simple regression fit against wind speed may be used for those cases where the significance levels were better than 5%. Using this to obtain the ventilation rate correspondingly to a standard wind speed of 3.5 m/s (this is approximately the mean wind speed at 10 m for most inland suburban sites in the United Kingdom) for each house these have been plotted against Q_T in Figure 7. The corelation is sufficiently encouraging to proceed to a more detailed analysis based upon the simple theoretical model discussed in reference (21).

5 CONCLUSIONS

1) Measurements in typical modern British housing indicate that average ventilation rates, with windows and other controllable openings closed lie in the range 0.3 to 1.7 ach with a mean value of 0.7 ach. The distribution of aggregated data from all houses gives a similar mean value of 0.7 ach and also indicates a median level of 0.6 ach and an upper decile value of 1.3 ach.

2) In comparison with housing in countries with much more severe winter climates British housing is much less resistant to air flow through the fabric and components. Swedish dwellings for instance, are three to four times tighter. However the levels of natural ventilation found in British houses are close to the minimum air requirements for fresh air supply. Any general reduction in air leakage, without alternative provision for fresh air supply could lead to an increase in problems such as condensation.

3) Pressurisation measurements indicate that a substantial proportion of the infiltration of air into a dwelling may take place through paths other than the cracks around windows and doors.

4) A comparison of pressurisation and tracer gas measurements indicates that the possibility exists for using the simple pressurisation leakage test as an indicator of the ventilation performance of a dwelling. Further research and theoretical analysis is, however, required.

ACKNOWLEDGEMENTS

The authors wish to thank their colleagues who contributed to the measurements described in this paper, in particular to Mrs L Parkins who was responsible for the component tests and much of the analysis of the results.

The work described 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 Director.

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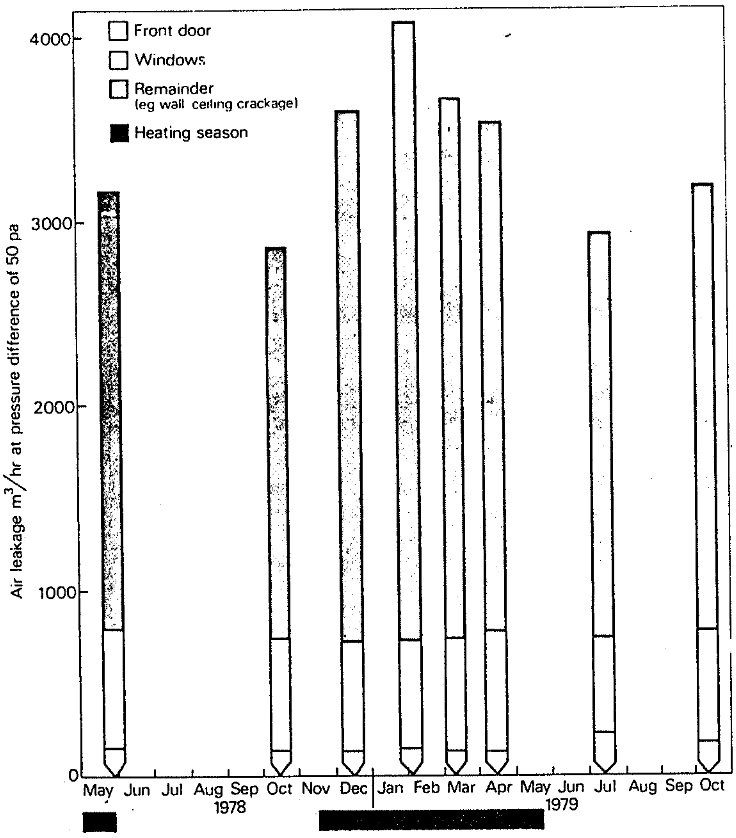

Figure 1. Seasonal Variation of Whole House Air Leakage at 50 Pa (House 11)

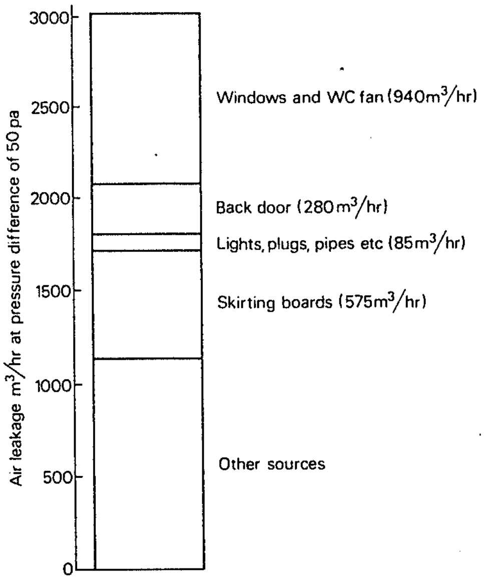

Figure 2. Distribution of Whole House Air Leakage between Components at 50 Pa (House 18)

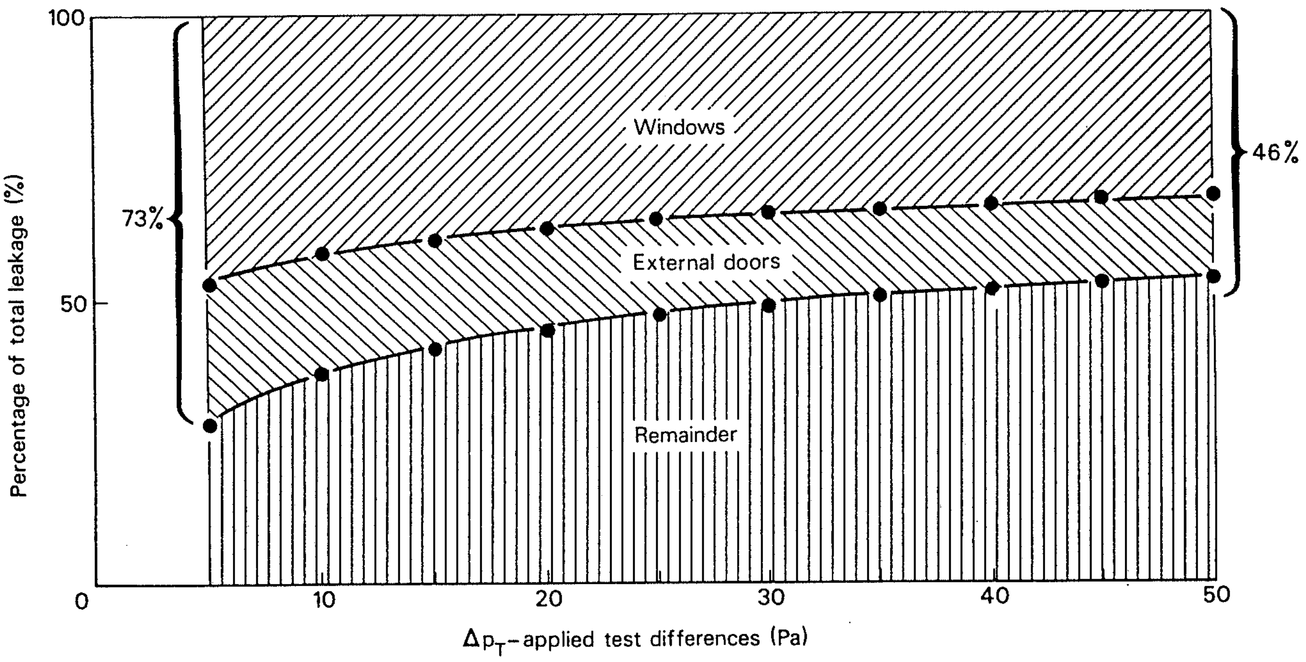

Figure 3. Variation of the Proportion of Whole House Air Leakage Attributable to Various Components with Applied Test Pressure (House 17)

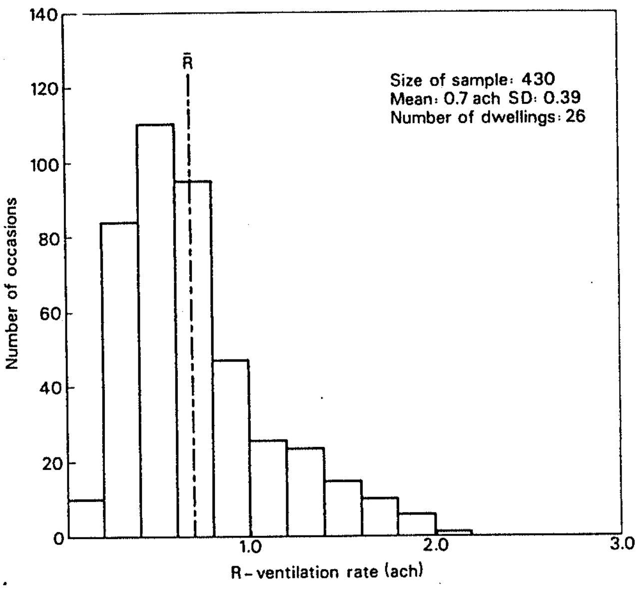

Figure 4a. Distribution of Whole House Ventilation Rates

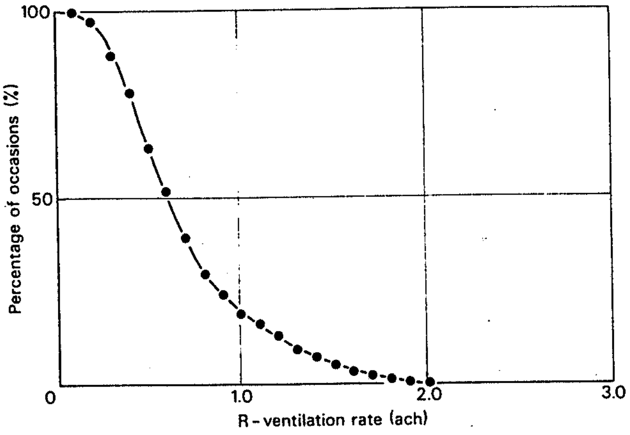

Figure 4b. Cumulative Frequency Diagram for Whole House Ventilation Rates

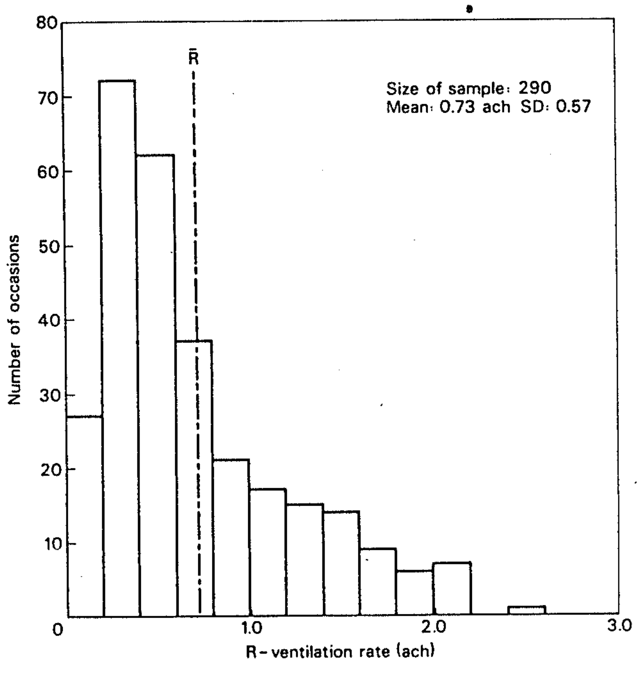

Figure 5a. Distribution of Ventilation Rates - Large Bedrooms

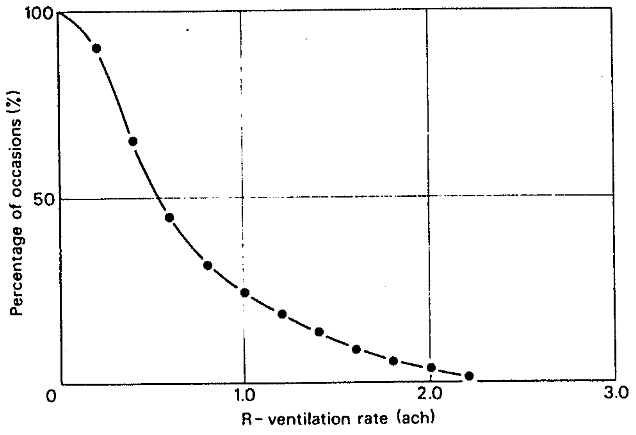

Figure 5b. Cumulative Frequency Diagram for Ventilation Rates in Large Bedrooms

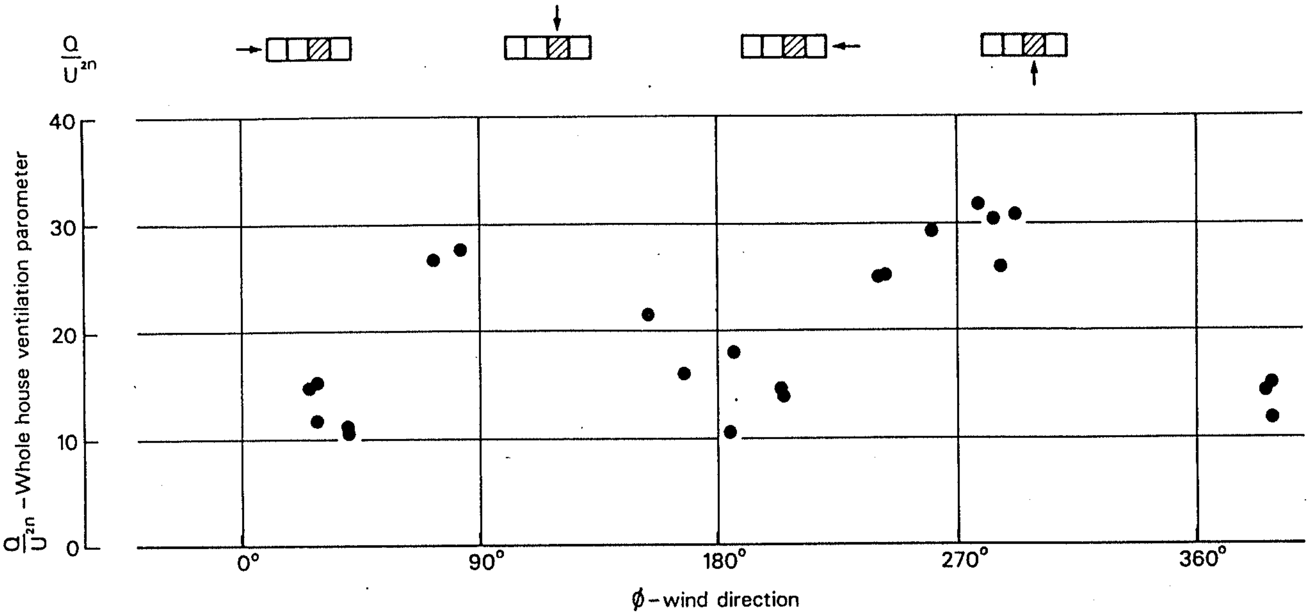

Figure 6. The Effect of Wind Direction on Whole House Ventilation Rate (House 6)

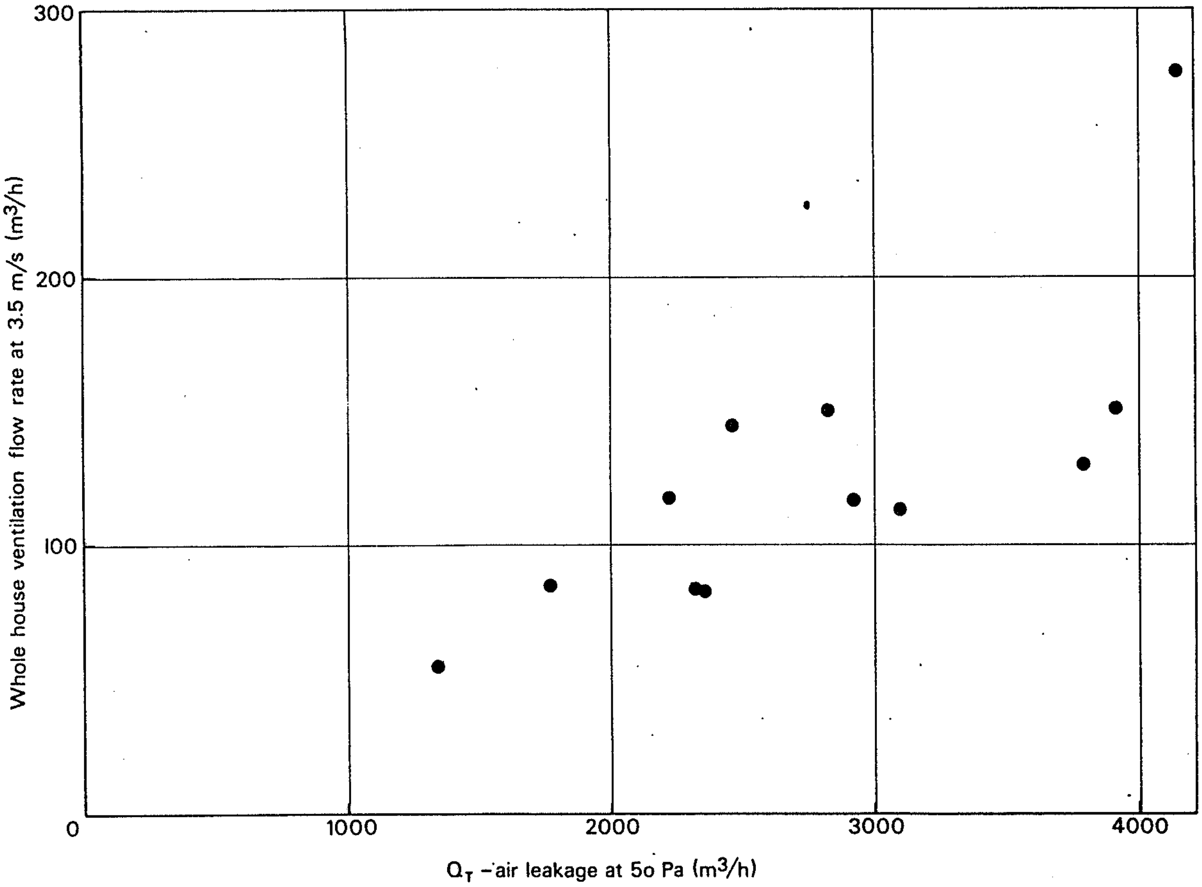

Figure 7. Variation of Whole House Ventilation Rate at a Wind Speed of 3.5 m/s with Air Leakage at 50 Pa

PROBLEMS IN COMMERCIAL AND INDUSTRIAL VENTILATION

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The paper starts with a brief review of the factors to be taken into account in considering natural ventilation in such installations - the factors are, inter alia, its location and surrounding buildings, the activity within the building and the results required of the installation.

It continues with some notes about the problems and possible advantages of combining natural and fan powered systems and concludes with some examples in various installations, such as power stations, shopping malls, production areas etc.

INTRODUCTION

It is trite but nevertheless true to say that the days of cheap energy are gone and it behoves us all therefore to seek ways of reducing energy consumption.

This has meant a return to earlier forms of energy generation and we are looking again at water power, solar power, wind power and rediscovering or advancing their potential.

And so it is with ventilation. Natural ventilation of buildings has been practised for more years than mechanical ventilation and so it is in keeping to turn to this also.

However, in the past many natural ventilation systems have been uncontrolled and if the system has provided too much ventilation for comfort in the winter it was easily made up by additional heating. This paper deals with buildings where a need does exist for ventilation for some, if not all, of the time.

VENTILATION

Ventilation is the flow of air through a building, and to have fluid flow requires pressure difference - where there is no pressure difference - there is no air flow. These pressure differences are caused by :

1. The effect of the wind blowing over the building in question.

2. The effects of the wind on neighbouring buildings.

3. The effect of difference of temperature between the inside and outside of the building.

4. Any pressures, positive or negative, brought about by mechanical ventilation systems.

Because the flow depends upon the square root of the pressure difference, doubling the pressure difference does not double the flow, but gives only a 40% increase.

Thus when two or more forces are acting simultaneously, the individual pressures can be added to arrive at the combined flow, and not, as sometimes is done, add the individual flow rates to arrive at the combined flow.

THE EFFECTS OF WIND

Considering items 1 and 2 on the aforementioned list (the effect of wind), if a ventilation system is designed, reliant upon the wind effect, then the ventilation result should be judged over the period of time from which the average design wind speed is taken. Thus, if the average wind speed over a year in some location is 9m/s., and this is taken as the design wind speed, the result of any calculation using this figure should not be judged in m^3/s or even air changes per hour, but in air changes per year.

The point to make is that in commercial or industrial premises ventilating is for a purpose, usually connected with an industrial process.

When ventilating say, a glassworks, where the main problem is overheating, which will obviously be worse in June/July etc., it is not good thinking to design assuming the assistance of average annual winds which includes, apart from the summer calms, the February gales.

We must design taking into consideration the worst conditions, which is no wind, in the same way that the structural engineer must design allowing for the February gales and not the average wind speeds.

The source of data for wind speeds is worth examining. Data is often supplied from the local airport and, whilst this may be useful in assessing the highest wind speeds likely in the area, it may not be of much use in assessing the lowest wind speed in a city centre in the height of summer.

The effect of wind on buildings has been studied by various researchers (Baturin (1), Morgan and Marchant (2)). The location of ventilators, particularly their location in the roof, is important.

Obviously it is desirable to avoid putting exhaust vents in high pressure areas and inlet vents in low pressure areas. The former can be more difficult to achieve.

Often useful research information is reported on solid block models. In fact, however, actual buildings are permeable and it is the pressure difference across the skin of the building that we are concerned with. The internal pressure within a building is usually slightly below atmospheric, which means suction effects are perhaps not as great as results from research on block models would suggest.

Even more important is the location of very large openings. Very large openings on the leeward side can cause increased suction within the building and those on the windward side of the building can cause enhanced pressure.

The increased suction effect was brought home to the writer many years ago following a complaint that, when the wind was in a certain direction, natural ventilators installed over an open bath intermittently down draughted.

Investigations were made at site and the multibay building with barrel vault roofs (Fig. 1) had ventilators mounted on the roof of the end bay and these worked effectively for the majority of the time. After many site visits it was found that the only occasion when the ventilators failed to exhaust was when :

1. The wind was roughly at right angles to the line of the barrel vaults.

2. The large loading bay doors (at B in Fig. 1) were fully open.

The opening of these doors caused a suction within the building which was greater than the normal suction over the roof. The pressure inside the building was thus lower than the outside causing air flow into the building through the roof ventilators.

To sum up, therefore, wind has an effect on ventilation. It is, however, a very uncertain ally. To be sure of his results the designer would be advised to ignore its favourable effects, which then come as an agreeable bonus and concentrate his design effort to ensure that the effect of wind is not adverse.

If a scheme has been designed assuming the assistance of the effects of wind and this does not materialise, then the scheme may have been under-designed.

There could well be occasions when the bonus referred to above is an embarrassment, but all properly designed ventilation systems, natural or otherwise, should have a proper control system so that the ventilation can be reduced or eliminated as required. In this respect it is interesting to see the progress made over the past few years in sealing closed ventilators against unwanted air leakage. (Fig. 2).

Such sealing is, of course, vital in any building which must be heated in winter.

THE EFFECT OF TEMPERATURE DIFFERENCE

The effect of temperature difference between the inside and outside of the building is the main factor in design of natural ventilation systems for industrial and commercial buildings, and the designer's endeavours are usually to limit this to an acceptable level.

When calculating performance of natural ventilation standard formulae can be used for ventilator performance, relating height and temperature. There are several of these formulae of varying degrees of elaboration (ASHRAE (3), Hansen (4), Thomas et al (5), Hemeon (6)). The use of these formulae involves knowing the aerodynamic free area defined as follows :

"The rate of flow of gases through an orifice such as a vent is less than would be expected from energy considerations and the orifice behaves as though its area was less than that actually measured. This reduced area is known as the aerodynamic free area". (Thomas and Hinkley (7)).

This can be established by wind tunnel tests. Using equations for ventilator performance and conservation of heat, it is possible to calculate the ventilation requirements for various temperatures and the position of neutral layer.

As mentioned earlier, pressure difference causes flow at inlets, the pressure outside the building is higher than the pressure inside, thus there is a flow of air into the building.

At the exhausts, the pressure inside is greater than the pressure outside, thus there is flow out from the building. Somewhere between the pressures inside and outside will be equal. This is the level of the neutral layer. This is important particularly in schemes which involve both natural and mechanical ventilators.

POWERED VENTILATION

This is the fourth of those factors affecting the natural ventilation of a building: the pressures brought about by any mechanical ventilation system. These pressures can be relatively high and so in some locations difficulties may be found in opening doors, whilst rain can be drawn in through sheet laps because there is excessive exhaust and no provision for inlet with the result that air is drawn in through any opening at very high velocity.

In industrial and commercial buildings ventilation is provided for a purpose - usually to improve the working environment because otherwise it would be too hot or because there are excessive emissions of fume or noxious gases causing, to say the least, irritation and if consideration of fire is included, life hazard.

In many such applications results can be achieved by judicious application of some powered ventilation. One obvious case is overheating, where the additional air movement by fans can contribute additional cooling. Others could be where process extraction exhausts air from the building. Probably the most extreme case here is the boiler house in a power station where the air exhausted for the boilers is at the level of .46 kg/s per MW, and stations of 2000 MW capacity are not unknown.

In such buildings the level of neutral layer is important whether the ventilation is powered, natural or a combination of both.

Thus in a laundry, for example, with excessive moisture emission the level of the neutral layer must be above the top of the doorways to adjoining sections, otherwise moist and steamy air will flow out from one section to give condensation in another section. This can happen if there is larger installed inlet capacity than exhaust capacity.

Similar cases can occur in, say, a welding shop where the working level may be clear, but welding fume in the roof space above working level can spread into, say, adjacent fabrication shops through high level openings.

The reverse situation can of course occur. In the same laundry an excess of exhaust capacity such that the neutral layer was towards the top of the building could mean high level windows would allow cool air to meet warm, very humid air giving local fog, condensation, or perhaps even rain.

The same situation can occur in emergency heat and smoke exhaust systems when an excess of exhaust capacity over inlet capacity could mean openings in the building above the smoke layer acting as inlets, blowing smoke down to breathing zone. This could, of course, defeat the object of the exercise.

Having said something about the more basic considerations, it might be appropriate to consider some particular advantages of natural ventilation.

A natural ventilation system 1) uses no power

2) is silent in operation

3) gives results which (if the heat to be dissipated is under estimated) are closer to the design temperature difference than that achieved by a totally mechanical ventilation system

4) can impose less stress upon the building structure

5) can provide psychological relief to occupants

Advantages 1) and 2) are self evident, but advantage 3) needs enlargement by means of the following example :

Basic data; estimated heat load = 1 MW, ambient air temperature 293°K, and temperature of air leaving the building of 303°K, thus the ventilation rate must be 85.32 m^3/s.

This can be provided by powered ventilation with fans capable of handling this capacity or by natural ventilators with an aerodynamic free area of 46.6 m^2 (assuming a stack height of 10m). However, it may be that the estimated and actual heat loads differ. Fig. 3 shows the results achieved if the estimate of the heat was too low. Applying a 1.5 MW heat load to the graph we see the temperature rise with natural ventilation would be 13.2°C and with a mechanical system it would be 15.4°C. If the heat output is doubled the respective figures are 20.9°C for the mechanical system and 16.1°C for natural ventilation.

The facility of flexibility is, of course, extremely useful if heat loads cannot accurately be determined, or if they are known to vary with process - and, of course, in fire situations.

The example shows only temperature differences liable to be encountered in ventilation of industrial properties. If the fire situation is considered, this facility needs to be even more carefully considered. Data for the heat output from a fire is not likely to be exact and most mechanical units do have an operating temperature limit. If this is exceeded the unit will stop running. A powered ventilation unit failing in a day to day ventilation system can be regarded as inconvenient, in a fire situation it could be regarded as catastrophic.

A natural ventilator will not be subject to this same operating temperature limit. Referring to Fig. 3 for example, doubling the heat load increases the temperature difference in a natural ventilation scheme by about 60% and in a mechanical scheme by 110%. Thus, designing for conditions where the heat load is likely to vary, generous safety factors are needed when using powered exhaust. There is too, a "domino" effect - if one powered exhaust fails there will be a reduction in volume, which will automatically raise the temperature causing quicker failure of the remaining units.

The fourth advantage is stress on the building. This is mainly a question of roof loading. Natural ventilators have been used to render a roof permeable and thus reduce the wind pressure effects. Natural ventilators, by virtue of their relatively light weight, can also impose less stress on a roof than powered ventilators of similar capacity.

Referring to the data given in the example for advantage 3), the rate of 85.32 m^3/s could be provided by 14 individual powered exhaust units with an individual weight of about 110 kg spread over 1 m^2 giving a total weight of about 1500 kg.

The 46.6 m^2 of aerodynamic free area could be provided by 27 louvred natural vents with individual weight of about 40 kg, spread over an area of about 1.1m x 3m giving a total weight of about 1100 kg.

Psychological relief is illustrated by Figs. 4, 5 and 6, which show just how much natural daylighting and a clear view of the outside enhance the working environment.

CONCLUSIONS

To sum up, therefore, systems for ventilation of commercial or industrial buildings can be designed using natural ventilation and incorporating powered ventilation as appropriate.

Close control of both systems is possible.

Energy can be saved by reduction of running power and that same close control.

The system can reduce the loss in fire situations.

Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 15 show some applications.

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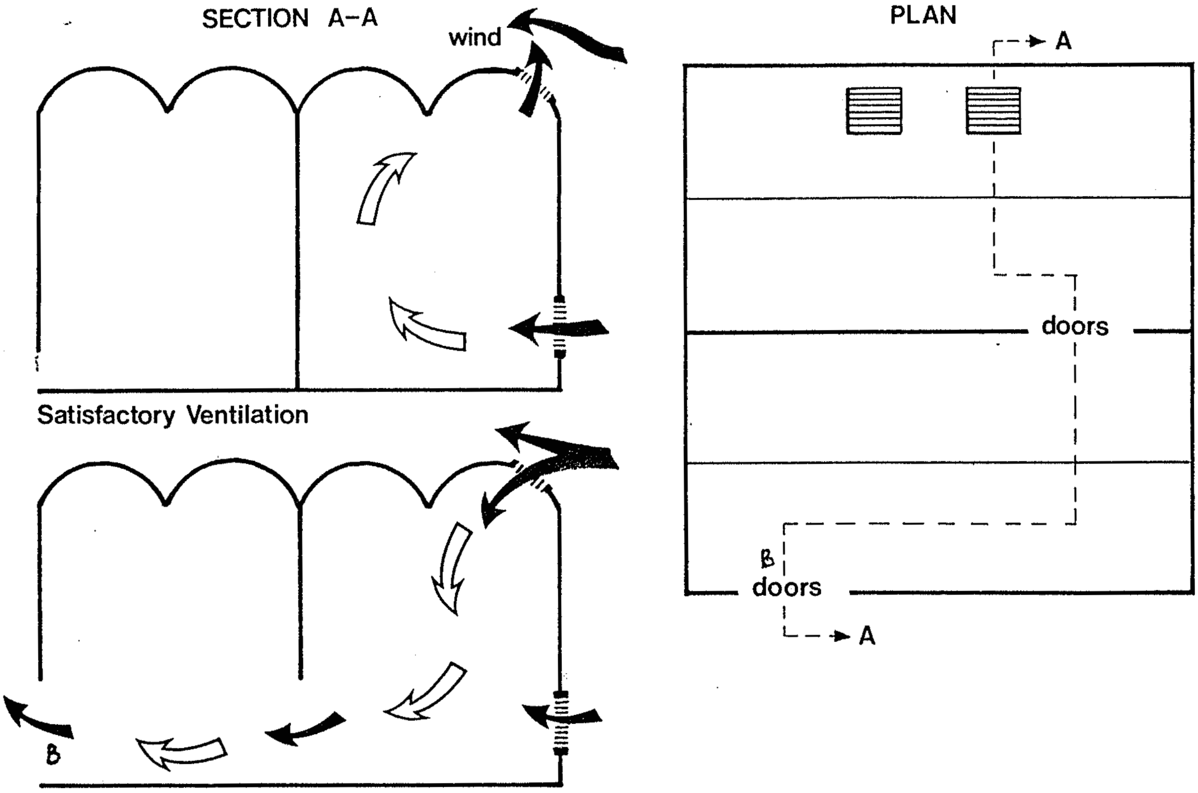

Satisfactory Ventilation

Opening very large doors on outer leeward wall & dividing wall cause downdraughting

FIG.1 HOW DOWNDRAUGHTING MAY OCCUR

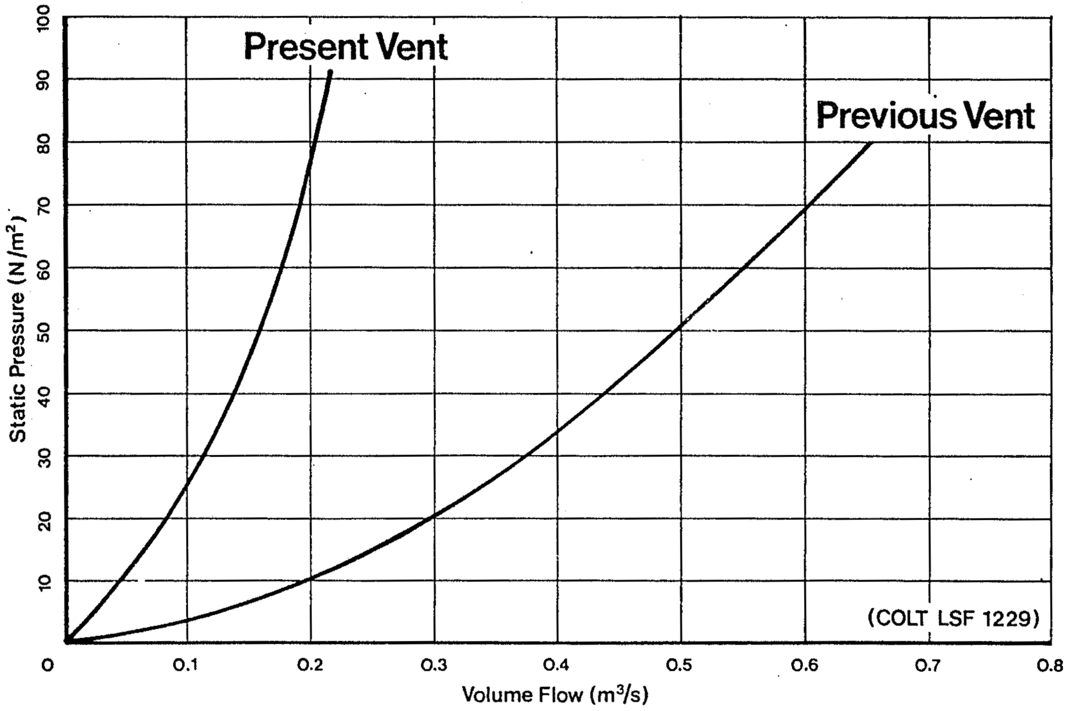

FIG. 2 VOLUME FLOW THROUGH CLOSED VENTILATORS AT VARIOUS PRESSURES

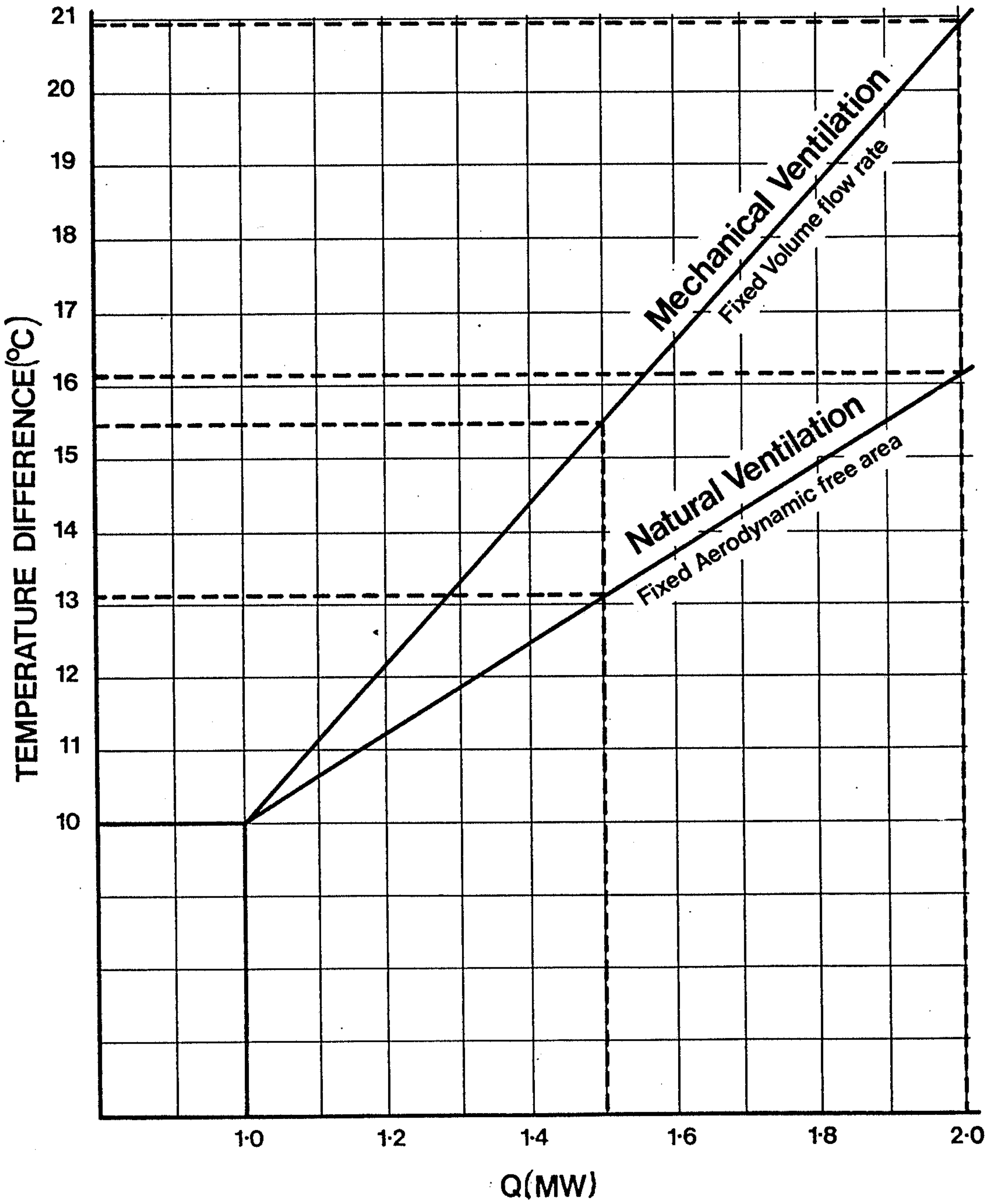

FIG. 3 SHOWING THE RESPECTIVE INCREASES IN TEMPERATURE WITH NATURAL & POWERED VENTILATION. IF DESIGN HEAT LOAD IS EXCEEDED.

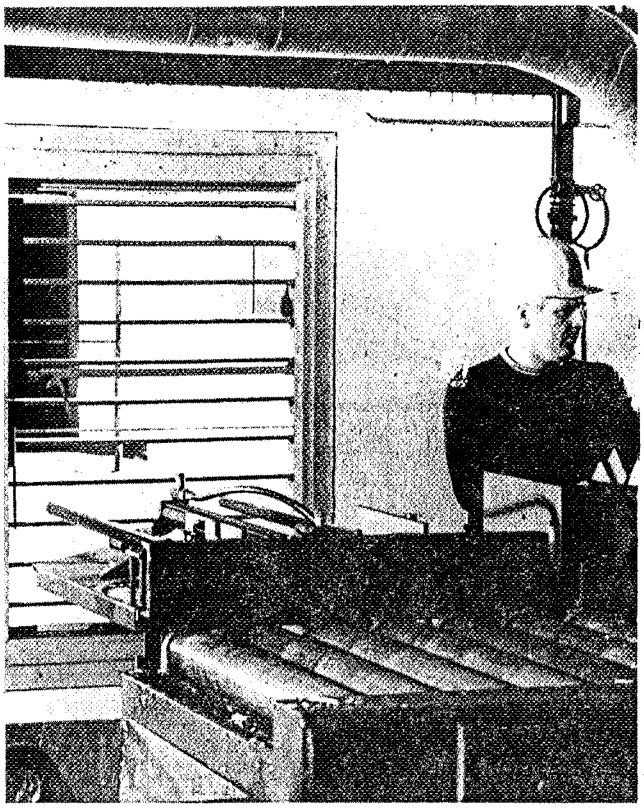

Fig. 4 - Aluminium Extruding Plant

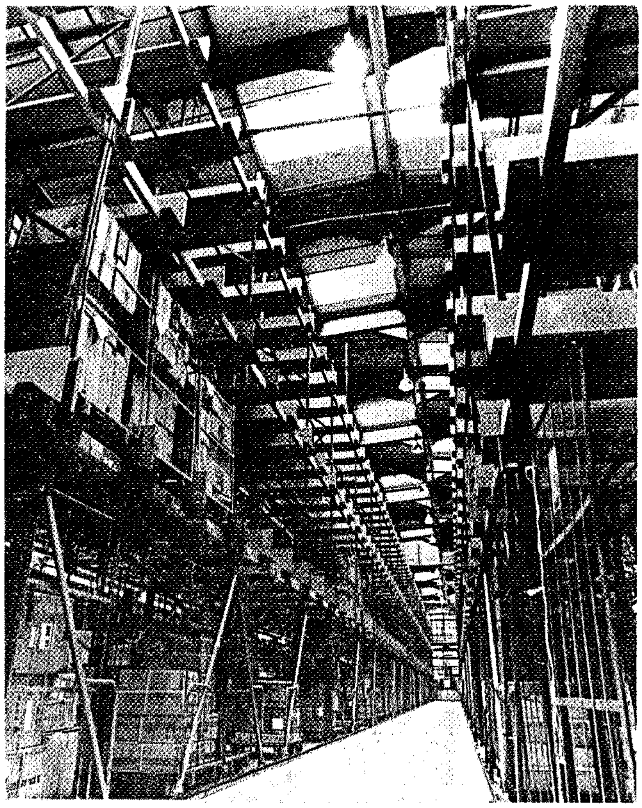

Fig. 5 - High Bay Warehouse

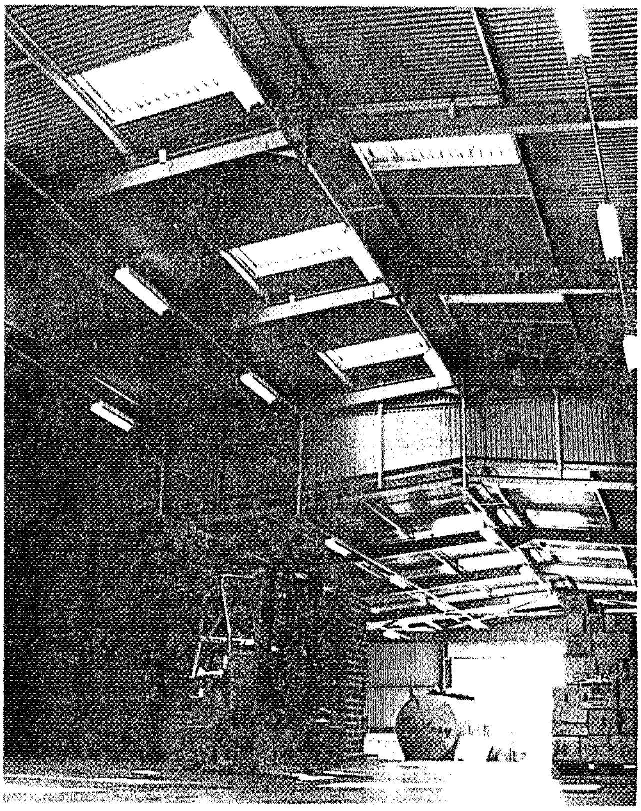

Fig. 6 - Food Warehouse Despatch Bay

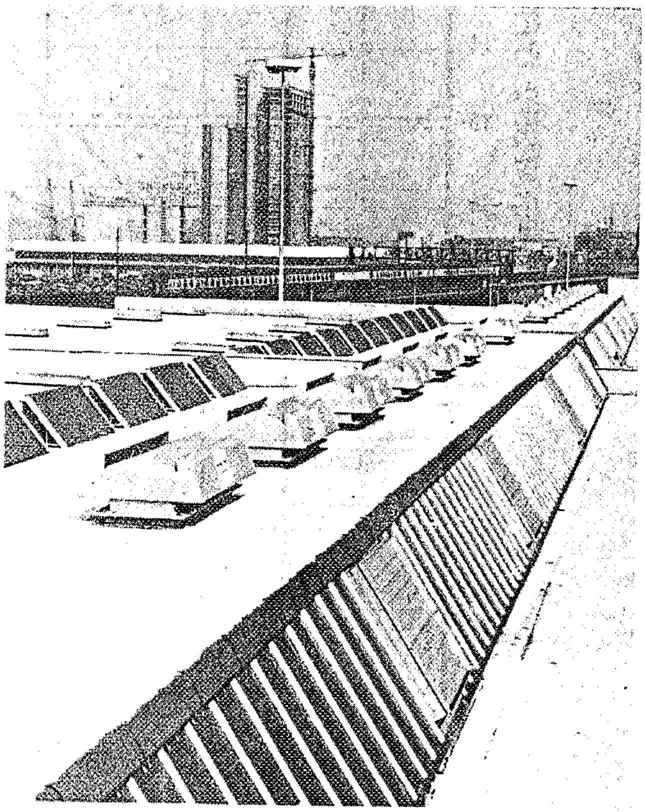

Fig. 7 - Fruit & Vegetable Market

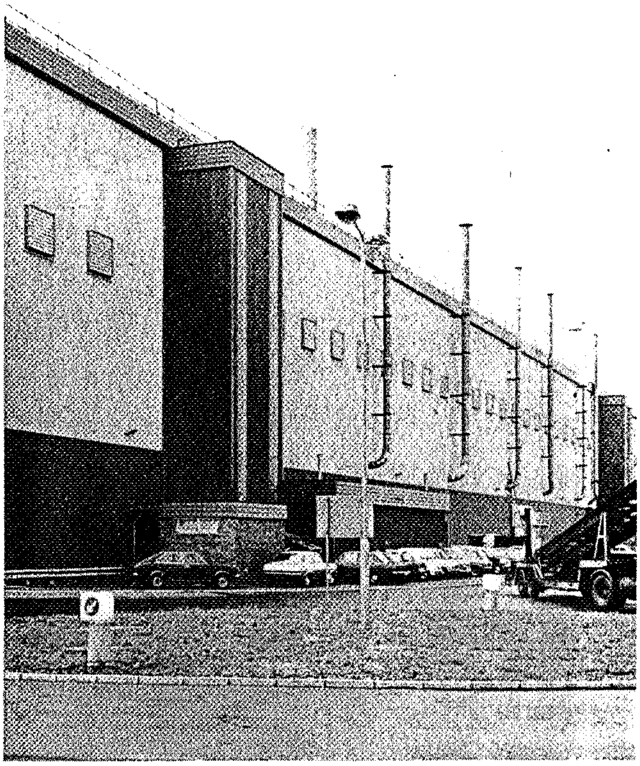

Fig. 8 - Manufacturing Plant

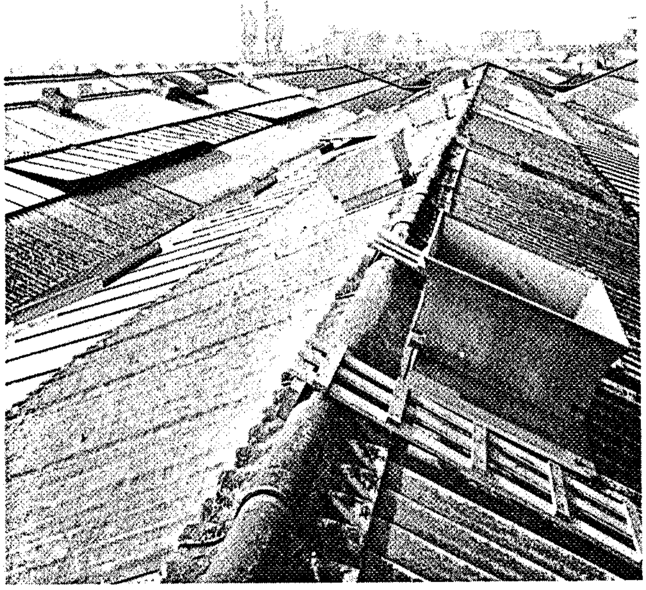

Fig. 9 - Improvement to older factory

Fig. 10 - Sports Stadium

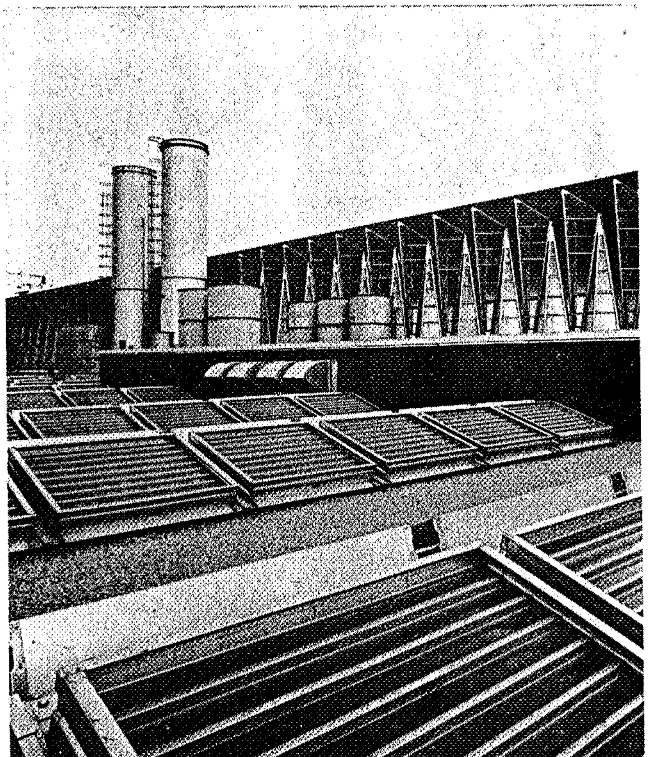

Fig. 11 - Power Station

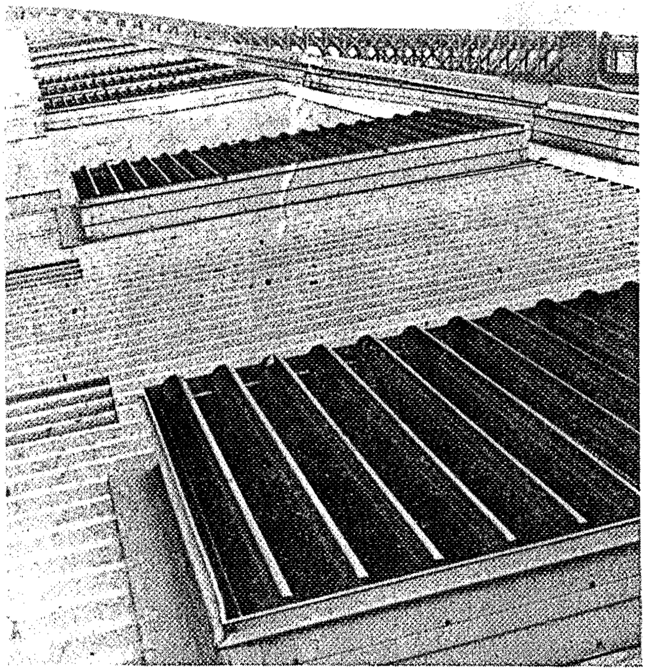

Fig. 12 - Shipbuilders

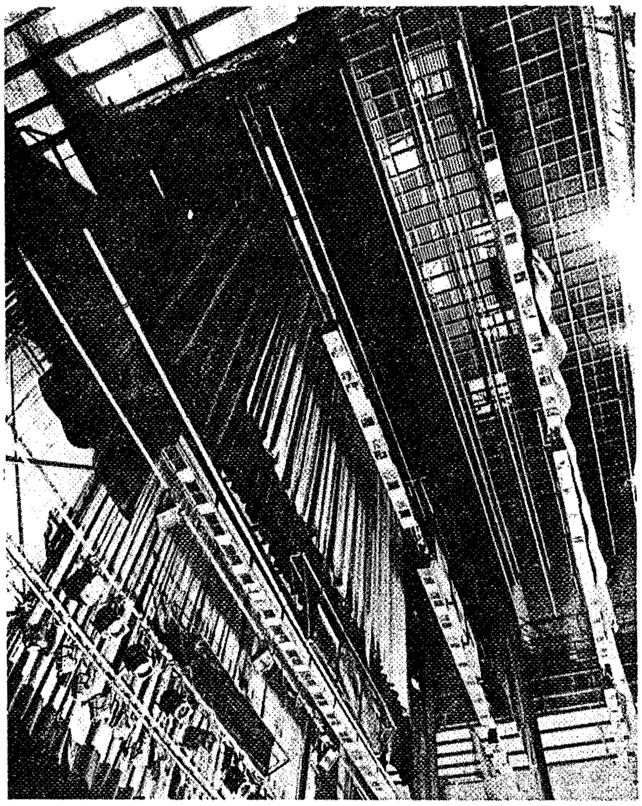

Fig. 13 - Theatre stage area

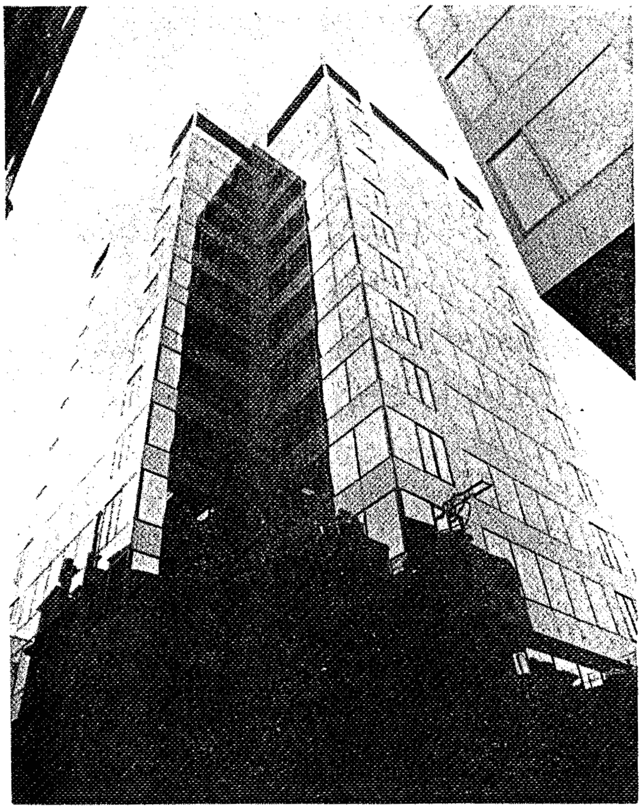

Fig. 14 - Rooftop Plant Room

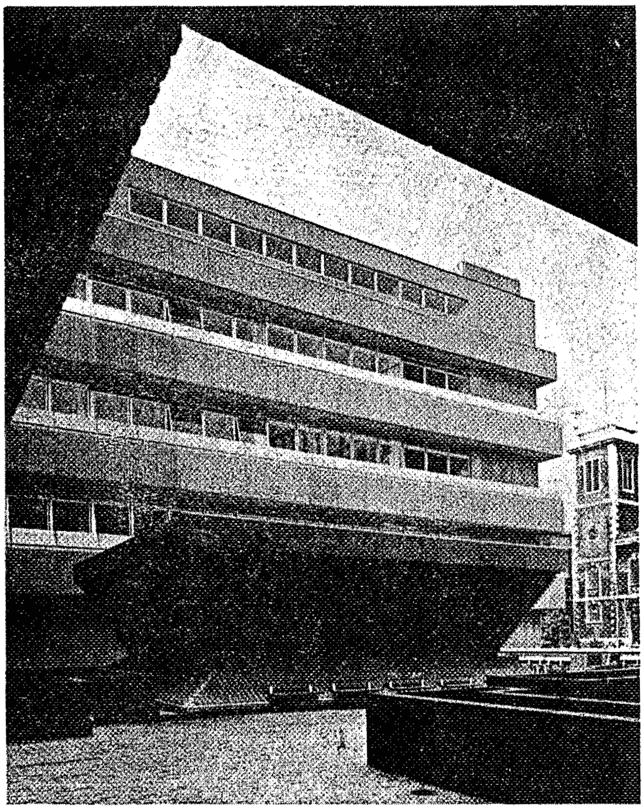

Fig. 15 - Underground Car Park

NATURAL VENTILATION IN THE MODERN HOSPITAL

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This paper asseses the role of natural ventilation in a modern hospital within the limits of current knowledge. It considers optimum standards of air change rates for winter and summer conditions and reviews factors within the hospital context that are likely to affect the realisation of natural ventilation. Reference is made to actual measurements in a new hospital and to other theoretical work. There is also some comment on future trends and the influence of energy consumption on the use of natural ventilation.

INTRODUCTION

"The very first rule of nursing is to keep the air the patient breathes as pure as the external air without chilling him. The question is often asked - when ought windows to be opened? The answer is - when ought they to be shut?" These extracts from "Notes on Nursing" 1859 are attributed to Florence Nightingale and express her sentiments on the therapeutic effects of fresh air and by inference natural ventilation.[1] Today this concept still holds good for hospitals in the United Kingdom albeit to a lesser degree. Whereas the general level of pollution has increased during the intervening years various Acts of Parliament have safeguarded the purity of the atmosphere and limited contamination. Ambient air is still suitable, with few exceptions, to naturally ventilate large areas of the modern hospital although the conditions under which it is now used have also changed significantly due to advances in medicine.

Over the past few years there has been some rethinking on the likely size and functional content of the District General Hospital (DGH) most appropriate for tomorrow's needs. This reassessment has come about by an awareness of the disadvantages of large size and changes in administering health care. A greater emphasis is now placed on the role of the primary health care team and the practice of preventive medicine. This is leading to an increase in provision for Out Patient and Day Care treatment facilities and a reduction in the overall number of beds provided. A future DGH is likely to cater for a population of some 200 000 with approximately 600 beds of in-patient accommodation comprising acute, geriatric, maternity, mental illness and children's nursing units. At current prices capital costs for the buildings and equipment will be about £35 million.

In past years the National Health Service has had problems with the construction of large hospitals. Practical experience gained from those already built has indicated that a large scale development should be avoided. There is also, quite understandably, a reluctance to commit limited resources to one specific project built in a single phase. Consequently there is a tendency for the hospital to be built in two or more phases with the first phase limited to about 300 beds. A typical first phase hospital is shown in Figure 1. It is in fact an example of a potential DGH based on the "Nucleus" designs developed by the Department of Health and Social Security (DHSS). This particular type of hospital is likely to constitute about 40% of all new projects planned for the next decade. The design relies on most perimeter areas being naturally ventilated throughout the year.

APPLICATION

Patients' wounds can become infected with micro organisms emanating either from the patient himself, or by cross infection from other patients and staff. Where cross infection occurs aerial-bourne contamination is often the first cause considered although there may be other contributing factors such as the techniques employed for aseptic procedures. The use of centralised shared treatment facilities as compared with ward based treatment rooms has been claimed as one method of controlling cross infection.[2] In areas other than those needing special aseptic conditions natural ventilation may be acceptable if it can provide a suitable environment.

There are of course many areas (which are listed in DHSS departmental Building Notes[3]) that must have mechanical ventilation for functional and clinical reasons. It will also be provided to other parts of the hospital to satisfy specific operational policies or to maximise use of accommodation. Usually these special requirements are identified in conjunction with the Client Group at the project briefing stage. Mechanical ventilation and/or air conditioning is used in these spaces to maintain aseptic conditions - operating theatres; to maintain fixed temperature and relative humidity conditions - special care baby unit; to deal with processes - sterilizing and disinfecting; to cope with special needs such as acoustic isolation of an audiology room; to provide suitable environmental conditions within deep-planned rooms.

The remainder of the hospital generally relies on natural ventilation whenever and wherever the quality of the ambient air is suitable. This is usually acceptable although there will be times when air change rates are adversely affected by high wind speeds, low outside temperatures and other factors.

In the exemplar hospital 50% of the total area of $14112m^2$ is naturally ventilated. Extract ventilation or assisted passive ventilation is provided to 30%. These areas usually include ablution zones as well as the internal corridors and circulation spaces through which they are ventilated. The remaining 20% is provided with conditioned air - 18% as of right for clinical or other needs and 2% due to internal planning. When the hospital is fully developed into a DGH these percentages may not change very much as more ward accommodation will be added in subsequent phases. It is more likely that a greater area will be naturally ventilated as less than a third of the area in a ward template is mechanically ventilated - supply or extract or both.

AIR CHANGE RATES

The minimum air change rate needed for various types of accommodation will be of different magnitude depending on the functional use of the space and these values will also vary throughout the year. The amount needed for life support and maintenance of a low level of CO_2 concentration[4] will readily be achieved without much attention - for example 0.3 air changes per hour will suffice within a 6-bed geriatric ward. Optimum rates will therefore vary from minimum required in winter for the dilution of body odours and background smells to a maximum in summer; the higher summer rate will reduce internal temperatures which would otherwise be intolerable.

In the early 1970's DHSS sponsored research on odours within an air conditioned hospital. The results indicated that source rooms with acute odours needed air change rates greater than 6 per hour.[5] Some confirmation of this particular work is witnessed at the totally air conditioned Greenwich DGH, one of the Department's early development projects. Here odour within the Geriatric ward is effectively suppressed by an air change rate of approximately 8 per hour. Such a rate would have to be maintained throughout the 24 hour period but it could not be sustained naturally and would cause draughts and other problems. It is therefore unlikely that within the present limits of existing technology natural ventilation can effectively cope with acute odours. Further research is continuing in this field and will include examination and field trials of other techniques of odour control. If they are successful and acute odours can be reduced to an acceptable level of tolerance for patients, staff and visitors then it will be possible to rely on natural ventilation in the affected spaces.

The early studies also demonstrated that within general surgical wards and similar accommodation 3 air changes per hour would dilute intermittent background odours to an acceptable level of tolerance. Today improved nursing techniques, the adoption of Central Treatment Suites and better standards of mechanical ventilation where it is needed have all contributed towards better conditions. Against this background it seems likely that natural ventilation with less than 3 air changes per hour can provide an acceptable environment within nursing units and other like areas.

The higher rate needed in summer will be influenced by several factors but the underlying requirement is to ensure that internal temperatures do not rise to unacceptable levels. There are many authoritative publications on summer-time temperatures and the CIBS Guide[6] is as good a reference point. It recommends that 27°C should not be exceeded often in non-air conditioned buildings. Some patients will undoubtedly be less able to cope with high space temperatures because of their weakened physical state. However the wearing of light clothing within the hospital environment will help to alleviate the level of discomfort.[7] In practice peak conditions do not happen often and do not last very long. They normally occur when wind speed is low and this coincides with high external temperatures. During these times natural ventilation can only materialise through temperature differences between inside and outside and the air change rate is likely to be lower than that produced by the wind. The last hot summer of 1976 was indeed an exception and weather data for Kew 1967 is regarded as being more typical of ambient conditions. In that year there were only 6 days when an external temperature of 25°C was exceeded and for a total time of 24 hours.

Figure 2 gives an indication of internal air temperatures that are likely to prevail within the shaded top floor 6-bed ward in Figure 1. It is based on computer simulations of the space for July 16 using the Kew '67 weather data. The room has two roof lights each 900mm square and 23% of the south facing external wall is glazed and provided with internal venetian blinds. Air change rates are assumed to be constant throughout the 24 hour period. These graphs show the marginal reduction in room temperature when the air change rate is increased beyond 6 per hour. In fact an increase from 6 to 10 lowers the temperature by only 0.5°C. Similar patterns were noted for 17 July when the external temperature rose to 28°C for 2½ hours. The results demonstrate that between 5-6 air changes per hour would provide tolerable temperatures within this particular room during peak conditions. Since this space is not unrepresentative of other naturally ventilated parts of the hospital the data can be applied elsewhere with some degree of confidence. In a live project it may be judicious to categorise the accommodation into various space types and simulate each type for a more accurate assessment.

Recent tests to which reference is made later on have indicated that a wind speed of 2m/s would generate an air change rate of 6 per hour in the case of the exemplar ward. It would therefore have achieved adequate ventilation as wind speed recorded in the Kew 1967 file averaged 2.2 m/s and exceeded 4 m/s most of the afternoon. However the same room in a closed courtyard location, without the effect of wind, would not have fared as well. If the space temperature must not exceed 27°C when the ambient is at 25°C then the driving force for natural ventilation is limited to that caused by a temperature difference of 2°C. Such situations would need special attention particularly with regard to the type and size of windows that minimise solar gain and readily support natural ventilation by this method.

PLANNING

Quite apart from external influences, several characteristics of the hospital itself will help to determine the manner in which and the degree of natural ventilation that will be achieved. The building shape and form for example will influence the extent of naturally ventilated accommodation. In normal situations the hospital is not likely to be more than 4 storeys and as windows can be opened at this height any accommodation on the perimeter is a potential candidate for natural ventilation.

Since an element of deep planning can seldom be avoided it makes sense to locate within the core, whenever possible, those rooms that must be mechanically ventilated for functional reasons. This position will also suit rooms which have a transient occupancy.

The introduction of internal and external courtyards will open up greater areas to natural lighting and ventilation albeit at a higher capital building cost. The wall to floor ratio will increase as will the winter heating load. Nevertheless, there will be a significant reduction in overall energy usage for environmental services. Current studies into the design of a low energy hospital sponsored by DHSS have indicated that the annual energy consumption for core rooms is about five times that for perimeter spaces. The performance of closed courtyards as ventilators is outside the scope of this paper, but it is obvious that internal dimensions will have to be sufficient to permit continuous air exchange with the outside and avoid stagnation at ground level.

Subdivisions within the hospital play a major role in determining the ease with which air can migrate throughout the accommodation. Individual departments tend to operate within closed compartments for a variety of reasons. This effectively reduces the contribution made by crossflow and prevents the realisation of any driving force due to "stack effect" between floors. It is likely too that the effectiveness of cross ventilation which was very much a feature of Nightingale Wards will also be seriously reduced by internal partitioning. In recent times health care practices have necessitated direct supervision of a larger number of more acutely ill patients as well as greater flexibility in the use of accommodation to nurse mixed sexes. In order to achieve these and other aims nursing units have become compartmentalised into single and multi-bed wards which suppress cross ventilation. Open doorways do help but this cannot always be tolerated in operational terms.

The quality and extent of internal barriers, above and below any false ceilings, that are needed to satisfy modern standards of fire separation and smoke stopping are other negative factors. Their effect could be lessened by the installation of louvres that close on initiation of some automatic sensing device. However such systems can have only limited application since any failure will undoubtedly compromise the integrity of the barrier and the compartment. Internal partitions within the exemplar 56 bed acute nursing unit are shown in Figure 3. Sub-compartments are formed within the overall 1 hour fire resistant compartment to assist staged horizontal evacuation in the event of a fire.

WINDOWS

Windows make a major contribution towards enhancement of the internal environment. They benefit the well being of both patients and staff in maintaining their visual and aural contact with the outside world. They are also the means by which perimeter accommodation is naturally ventilated and lit and benefit from solar gain in winter. Yet notwithstanding its many virtues the window is often cast in the role of villain; a role that has been acquired over the past few years through the indiscriminate use of glass as a cladding material. This has caused draughts in winter, glare and high internal temperatures in summer and even spring and autumn. Now, there is a better appreciation of such factors and an awareness of the need to optimise glazing ratios throughout the hospital and especially in continuously occupied spaces. In the exemplar hospital the recommended overall glazing ratio has been fixed at 26% although this would be varied to suit particular needs within each room. If rooms are to be naturally ventilated the types of windows forming these smaller glazed areas must not restrict or prevent this process.

Historically bottom openings of windows have usually been limited to 100mm (although a few recently built hospitals have opted for 225mm) but this restriction does not seem to have been applied to the top as well. Past practice can no longer remain sacrosanct and in the current climate more effort will be directed to the search for other means of obtaining maximum openings consistent with acceptable standards of patient safety and security.

Louvre windows that are air tight when shut may be acceptable. An alternative could be the vertical sliding window which can provide 50% opening with maximum separation between top and bottom; a profile most likely to promote natural ventilation. Window shading will also need special consideration. Such devices must not impede air flow neither must frequent adjustment, be necessary or a burden to nursing staff.

In exceptional cases openable roof lights could be used at top floor level to increase day lighting and natural ventilation. However, their installation needs to be evaluated against such factors as cost, control, ease of maintenance and the like.

SITE MEASUREMENTS

During summer 1978 tests on natural ventilation were carried out at Southlands Hospital, Shoreham-by-Sea while it was being fitted out. They were conducted by personnel from West Midlands Regional Health Authority under the aegis of the DHSS. This hospital, see Figure 4, is similar in profile to the Nucleus shape and has four storeys of ward accommodation totalling 294 beds. The average glazing ratio is 55%, part of which is fixed. Openable areas have vertical sliding windows 1.5m high x 1m wide with restrictions which limit top and bottom movement to 225mm. This represents 7% of the room elevation at maximum opening. Internal blinds are installed throughout the wards and consist of individual vertical blades which can be drawn across the glazing and set at any angle.

Natural ventilation rates using the tracer gas Krypton were measured in a courtyard facing 5m deep 3 bed ward on the ground floor, 7.5m deep 5 bed wards with external elevation on the ground and 4th floors and a specially formed courtyard facing room 7.5m deep within the catering department on the 2nd floor. In all but 2 of the tests these rooms were sealed with polythene sheet to simulate conditions for single sided ventilation.

The range of wind speeds recorded was between 0.5 m/s to 10 m/s with a maximum of about 6 m/s occurring more often and from a south westerly direction. In the courtyard facing the catering room air movement was turbulent and air speeds in excess of 4 m/s were logged. Recordings were also taken of wind speeds at window openings and these confirmed that whenever wind causes ventilation air can flow through both top and bottom openings simultaneously. During the test programme the temperature within the catering room remained fairly constant at 21°C whilst the external ambient varied cyclically between 14.5°C and 20°C. An inside peak of 23°C was charted at the weekend when the building was closed and the outside a maximum of 19°C.

Measurements from this pilot study on natural ventilation were not sufficiently exhaustive to advance positive conclusions. Yet the results did yield valuable data which can influence building design. The realisation of single sided ventilation was confirmed as was its effectiveness in deep planned courtyard facing rooms. Five air changes per hour were measured at back of the catering room when the inside/outside temperature difference was 2.6°C and wind speed 9 m/s. The same temperature difference produced a rate of just under 4 with a wind speed of 4 m/s. It was to be expected that identical window openings in the 3 bed ward would foster greater air change rates. Indeed a rate of 11 per hour prevailed when the wind speed was 9 m/s and the temperature difference 2°C. Within the 5 bed ward a gentle breeze (4 m/s) caused 11.5 air changes per hour.

Computed air change rates based on a theoretical formula for air transferred by temperature difference[8] were partially supported by field results for courtyard facing rooms. Measured values were marginally greater except for the 3 bed ward where they were three times as much. These indicate the likelihood of wind having a greater affect on natural ventilation in these areas then temperature differences. In the 5 bed ward the enhancement from cross ventilation was found to be less than one air change per hour.

The work also provided crude yardsticks on the characteristics of internal blinds. Roller types reduce natural ventilation by 80% when fully closed. The performance of venetian blinds is better with 20% to 40% reduction depending on blade angle. Vertical blinds with individual slats do not impede air flow providing blades are less than 50% closed. Beyond this setting the reduction varies from 35% to 60% depending on the rate of air exchange with the outside.

SUMMARY

Present health care practices acknowledge that a significant part of the modern hospital can be naturally ventilated throughout the year by the introduction of untreated fresh air. The ventilation rate needed varies and is usually adjusted by manually opening windows. There are no specific winter design parameters although 1.5 air changes per hour is usually assumed for heat loss calculations and the avoidance of draughts is an obvious pre-requisite. Undoubtedly there are instances when an enhanced rate of 3 per hour for short periods would be beneficial but this should not influence the design of the heating system. In peak summer conditions a minimum rate of 6 air changes per hour is needed to off set heat gain.

Cross ventilation is unlikely to be achieved and designs should be based on single sided ventilation. Although wind will be the driving force for both courtyard and perimeter locations, the force created by temperature difference will predominate in light air conditions. Windows play a vital role and before a selection is made their performance as ventilators should also be evaluated. The choice should be for a type that permits maximum opening without endangering patients' safety and security. Computer simulation techniques are powerful tools that can be used to help this design process.

FUTURE TRENDS

Natural ventilation has many virtues not least of which are its availability and free cost. However there are drawbacks which although not particularly important in past years will cause greater concern in the future.

It is not uncommon for optimum ventilation rates needed to vary during the course of the day. Yet the rate that actually occurs defies instantaneous measurement. Effective control over air flow is also elusive as contributing forces change over short periods. This effect is more pronounced because of variations in wind direction and speed; the latter over a range of zero to in excess of 11 m/s. In practice higher air change rates than those actually needed are often realised. During summer this can benefit the internal environment without incurring cost; not so in winter when consumption of fuel used for space heating is increased.

Extra revenue cost is incurred by wasteful heat loss from an overprovision of ventilation in winter. This is only a small proportion of the total fuel bills and is moderated by the temperate climate in the United Kingdom. In the exemplar hospital for example, the annual revenue cost of fuel to provide one air change per hour in the Clinical Block is £1,500. However, as fuel prices rise in real terms individual elements of overall fuel consumption will become more significant and will be identified as such. This is likely to establish the need for better management of ventilation during winter. Installations which satisfy this objective will also have added advantages of guaranteeing specific air change rates throughout the day and at nights and relieving nursing and other staff of any control function. Perhaps central air handling and heat reclaim plant providing 3 air changes per hour for both space heating and ventilation would be economically worthwhile.

The building would need to be sealed in winter but windows could be used in summer to enhance ventilation. These benefits will have to be balanced against an inevitable increase in capital costs and the response of manufacturing industry in meeting the need for better equipment. The DHSS low energy hospital studies are paying particular attention to these and other issues.

ACKNOWLEDGEMENTS:

The author wishes to thank the Department of Health and Social Security for its support in the drafting of this paper. His views are not necessarily those of the DHSS.

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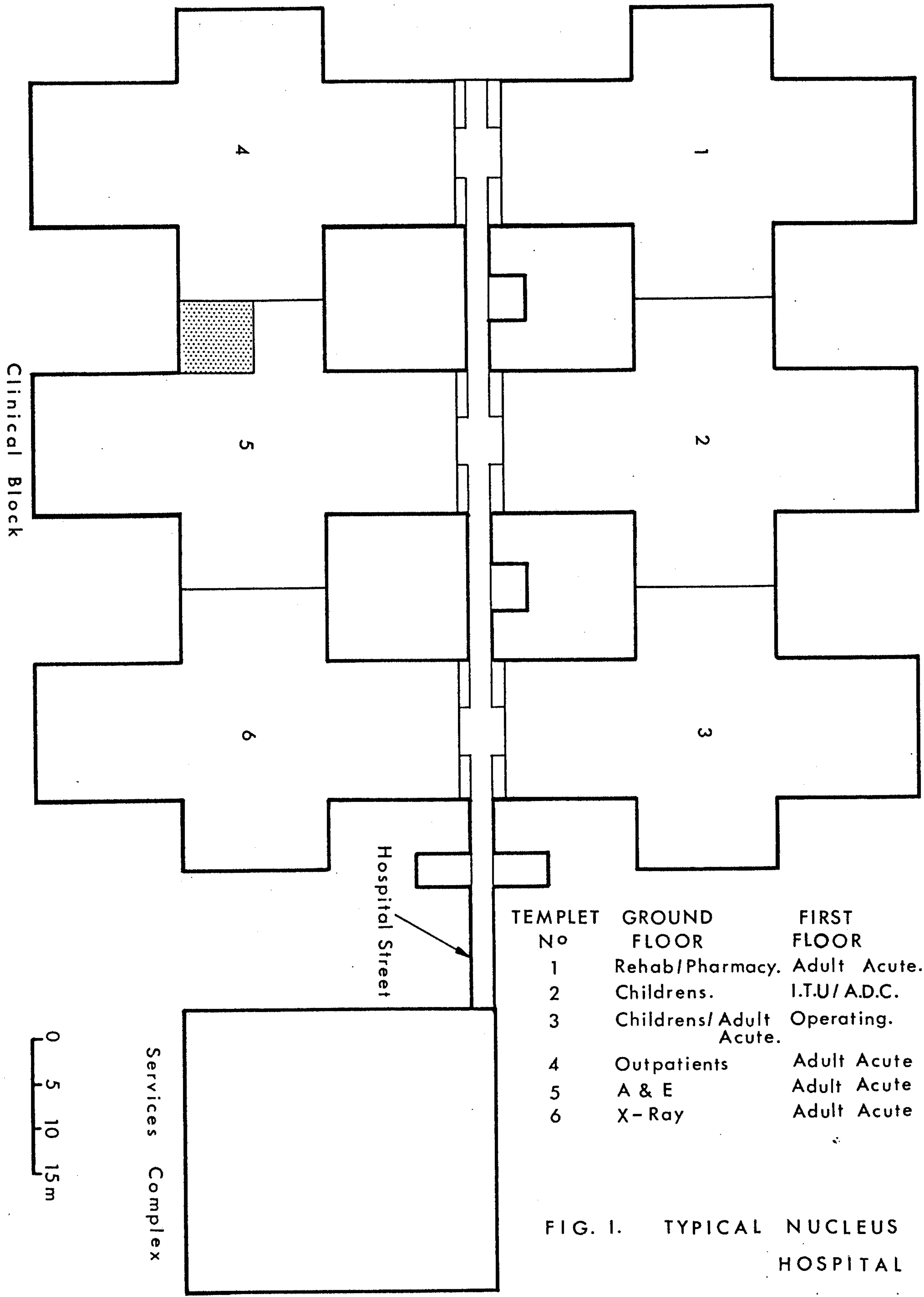
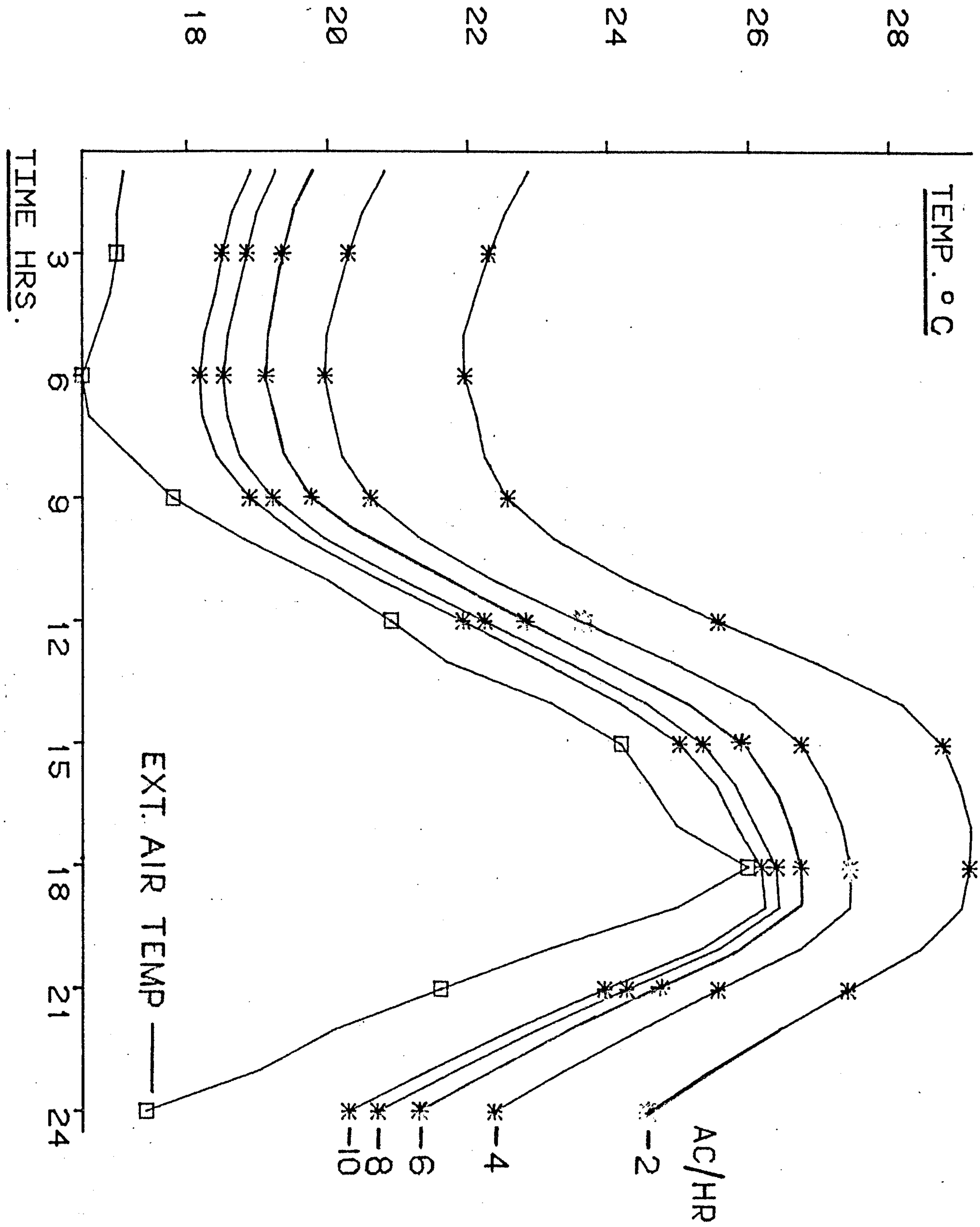


TEMPLET Nº	GROUND FLOOR	FIRST FLOOR
1	Rehab/Pharmacy.	Adult Acute.
2	Childrens.	I.T.U/A.D.C.
3	Childrens/Adult Acute.	Operating.
4	Outpatients	Adult Acute
5	A & E	Adult Acute
6	X-Ray	Adult Acute

FIG. 1. TYPICAL NUCLEUS HOSPITAL



SIMULATION NO. 1 OUTPUT PERIOD FROM 16, 7, 1 TO
16, 7,24

FIG.2 SIX BED WARD INTERNAL AIR TEMPERATURE

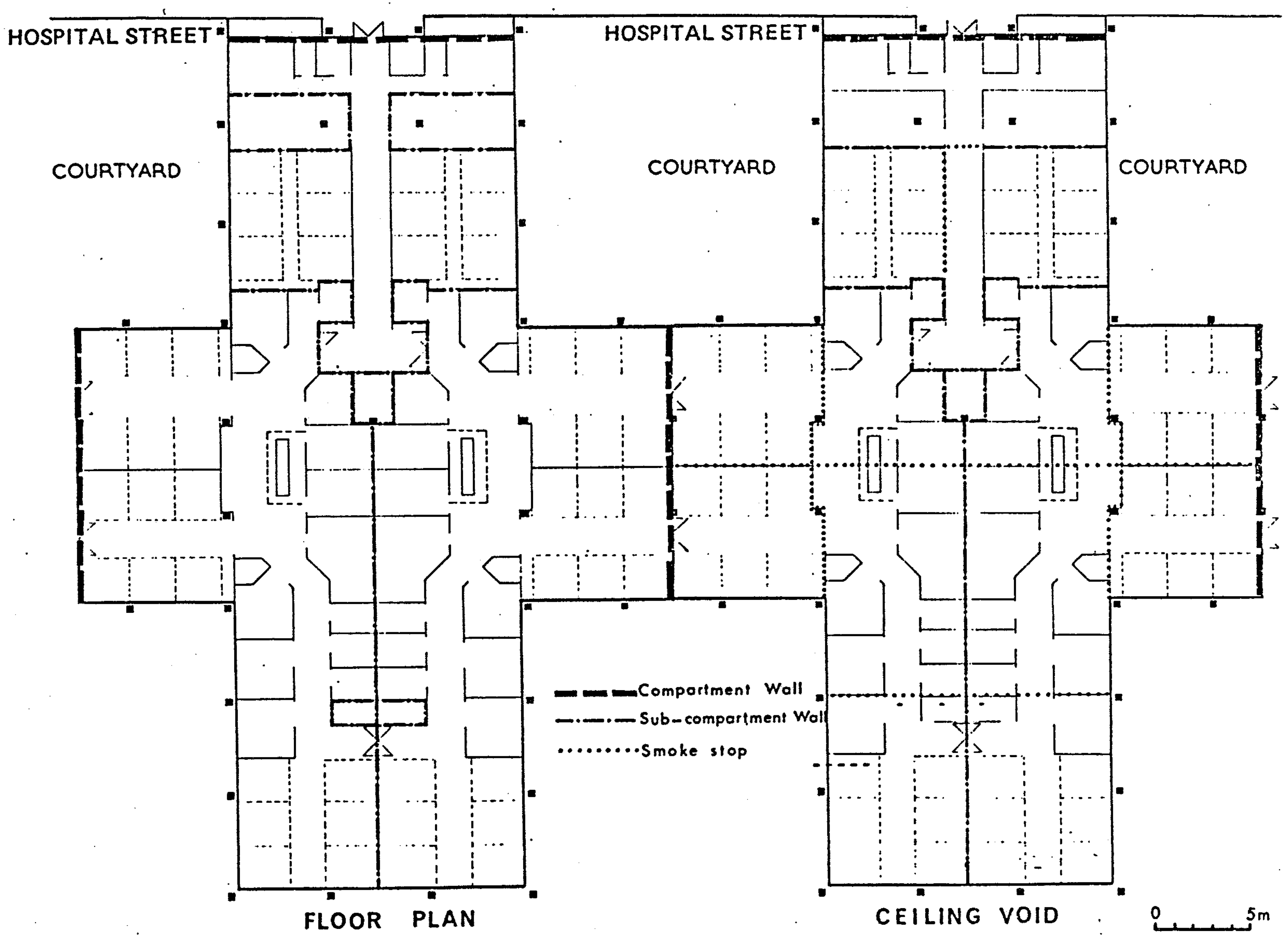
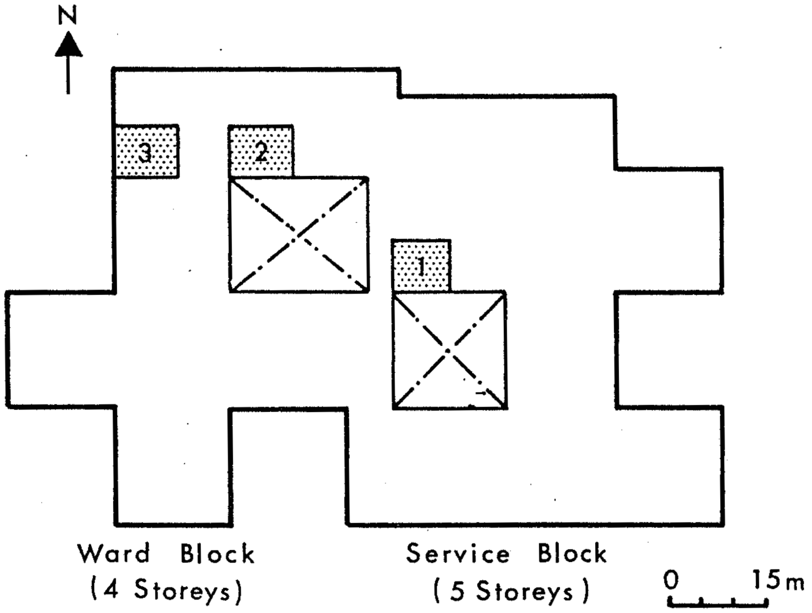


FIG.3 FIRE/SMOKE BARRIERS- ADULT ACUTE WARD



Key

1. Catering. 2. 3 Bed Ward. 3. 5 Bed Ward.

FIG.4 SOUTHLANDS HOSPITAL

NATURAL VENTILATION AND THE PSA ESTATE

B.A.TAYLOR
Property Services Agency

The wide variety of buildings that constitutes the Central Government estate pose many differing ventilation problems. Most buildings are naturally ventilated and the rates achieved in practice are unknown but in many instances are thought to be excessive and as such responsible for considerable energy waste.

The paper sets out recent PSA experience and findings in an attempt to obtain a better appreciation of the interacting problems associated with natural ventilation.

INTRODUCTION

Escalating fuel costs over the last decade, a trend likely to continue into the foreseeable future, has focussed attention on the use of energy, particularly that used for heating buildings. For new buildings this has resulted in improved thermal insulation standards and greater attention to energy requirements during the conceptual design stage. While, for existing buildings, it has resulted in improved plant operation and maintenance and the upgrading of building services and the thermal envelope. More recently attention is being directed towards natural ventilation in both new and existing buildings because of its increasing significance on energy requirements.

The Property Services Agency (PSA) forms part of the Department of the Environment (DOE) and provides, maintains and operates a wide range of accommodation and fixed installations for UK Government Departments. This wide range of accommodation poses many differing ventilation problems but it is not intended in this paper to examine these in detail but to relate recent PSA experience and findings to the endeavour of a better appreciation of the interacting problems associated with natural ventilation.

ENERGY USE

The energy conservation programme undertaken by PSA over the past seven years has primarily concentrated on existing buildings. This has resulted, through the selective application of highly cost effective measures such as the up-grading of heating controls, improved plant management and additional thermal insulation, in an annual energy saving for heating fuels in excess of 35% to date. However, while a significant reduction in overall consumption has been achieved and the mean consumption per unit floor area for heating reduced, it was of concern to find that the variation in consumption per unit floor area has remained relatively constant at about 4 to 1. Table 1 shows the results for the period 1972 to 1979 of a sample of buildings located in the Midlands.

TABLE 1 - Energy Consumption (GJ) per m^2 (Nett Floor Area) For Heating and Domestic Hot Water

YEAR	MEAN VALUE	95% POPULATION CONFIDENCE LIMITS LOWER	UPPER	RATIO OF LIMITS
1972/73	1.47	0.697	3.093	1:4.4
1975/76	1.21	0.635	2.33	1:3.66
1978/79	1.11	0.57	2.168	1:3.8

Figure A shows the typical frequency distribution of the energy consumption per square metre of floor area for a representative year. It is evident that there is a bias in the sample which indicates that there exists some lower limit, below which few existing buildings can operate and maintain comfort, while there appears to be less constraint on the maximum amount of energy consumed. In practice the installed capacity of the heating plant, which has been found to vary between 115 W/m^2 and 375 W/m^2, will limit energy consumption. Generally buildings with a high energy use per unit floor area were found to have a high installed plant capacity per unit floor area.

Plotting the annual energy consumption for each building over a period of five years confirmed, as expected, that some buildings remained consistently either above or below the average for all buildings. The average consumption line for all buildings was determined as the best fit line through the points for each year. Not all the points have been plotted in the interest of clarity but most buildings whether greater or less than the average had a reducing consumption. It seems not to have been possible to make extra large savings in most of the original relatively heavy energy users.

Clearly there was a need to survey the buildings, but as the high and low energy users were of prime interest, it was decided to survey those above or close to the upper 95% confidence limit and similarly those below or close to the lower 95% confidence limit.

It was not possible to measure the ventilation rates for the buildings but a common feature of buildings with a high energy consumption was that they were generally cold and draughty which suggests that ventilation rates were higher than need be. Similarly for the same group of buildings, the standard of plant operation and maintenance was not always what it should have been. The reasons for this are perhaps many, but it is suspected that often maintenance staff are driven to despair, through numerous complaints from the building occupants about low temperatures and draughts, consequently heating controls are overriden or incorrectly adjusted in an attempt to satisfy client requirements.

The relative significance of these problem areas could not be determined from the results of the surveys. The surveys did however suggest that buildings of an apparent high energy design did not necessarily demand excessive consumption in practice.

PREDICTED VARIATION

A common feature of the PSA energy conservation programme of work has been to compare empirical findings with theoretical predictions. This has generally led to a better understanding of problems.

In view of the large variation in consumption per unit floor area found in existing buildings and the limited findings of the surveys, a simple assessment of the theoretically predicted spread in consumption was undertaken. There were problems however.

In order to undertake the assessment it was first necessary to decide over what range natural ventilation rates occur in existing buildings. It was generally felt that the average minimum rate was unlikely to be less than 0.5 air changes per hour but the maximum was more difficult to assess. One or two assessments of draughty buildings have indicated that the natural ventilation rate was about 3 air changes per hour. Another pointer to the likely maximum is that it is not uncommon practice for many Building Services Engineers to assume 2 air changes per hour in design calculations, as a result of adverse experience with lower values. Finally it was decided that 3 air changes per hour is likely to be representative of the maximum average value of natural ventilation found in existing buildings.

Using the air change values outlined a simple computer aided analysis was undertaken to establish the likely variation in annual energy demand for existing office buildings. The results are summarised in Figure C which indicates that the annual energy demand varies with a ratio of about 4 to 1. This correlates with that found in practice.

It is not possible to draw firm conclusions from the analysis but its correlation with empirical findings suggests there may be considerable energy savings through reducing excessive natural ventilation rates in existing buildings.

PERFORMANCE INDICATORS

To aid staff in the field, a simple method of assessing the energy performance of individual buildings has been developed which will enable bad performers to be quickly and easily identified. The method is based on a series of performance indicators deduced from the actual energy consumption characteristics of a random sample of existing office buildings, similar to those shown in the histogram in Figure A. It is not intended here to discuss the basis of the indicators, suffice to say that they are derived from established statistical techniques. The indicators are intended to be an approximate gauge against which to compare the energy performance of existing buildings. So far, indicators for naturally ventilated office buildings have been produced but it is intended to extend them to other types of Government buildings. The indicators for office buildings are shown in Table 2.

TABLE 2 - Performance Indicators for Existing Single Shift, Intermittently Operated, Naturally Ventilated Office Accommodation

RATING	PERFORMANCE INDICATOR
	Heating & Domestic Hot Water (GJ/m^2 (Gross Area)/annum)
GOOD	Up to 0.72
FAIR	0.72 - 0.84
POOR	0.84 - 1.16
VERY POOR	Over 1.16

The large variation in energy consumption per unit floor area for heating and domestic hot water services would seem to be inherent in the existing building stock due largely to variation in ventilation rates, though other factors do have an influence. This being so it follows that for buildings which compare poorly with performance indicators it is likely that their ventilation rates are excessive, subject to their heating systems being operated correctly. However more data and experience is required to fully validate this hypothesis but if it is verified the use of performance indicators will provide a valuable aid to the identification of buildings with excessive natural ventilation rates.

PRACTICAL CASE

To obtain an indication of the achievable savings through reducing the rate of natural ventilation in existing buildings, a field trial was recently undertaken on a London Office building.

The building chosen was located in an exposed position adjacent to the river Thames. It was erected post-war, and is constructed of 14" thick solid brick outside walls with metal windows on three sides, a flat roof, concrete ground floor, demountable internal partitions, and suspended ceilings. The metal frame casement windows give a glazing ratio on 3 faces of the building of about 50 percent, of which only half of the glazed area is openable. The building has 5 floors and a total gross floor area of 2230 square metres.

Over the years, the window frames have become twisted and no longer produce an effective seal, assuming they did in the first instance. A silicon rubber sealing mastic was applied to the frames so as to mate with the openable windows. This is a standard method of treating such windows and is widely employed. The cost of the work was about £2300 at 1980 prices and took about two months to complete. The initial reaction from the building occupants was favourable and comfort conditions were considered to be more acceptable.

Before proceeding further it is perhaps important to outline other reasons why this particular building was chosen for the trial. Firstly, as a result of previous trials for other purposes the fuel consumption and performance data for the building was well documented, secondly and perhaps more important, thermostatic radiator valves were fitted additional to the existing weather compensator control. The significance of these valves may not be obvious but without some form of internally sensed space temperature control, improvements to the envelope of a building in the form of better insulation or draught proofing, will rarely realize fuel savings without the readjustment of the controls which can be difficult and often is not carried out.

The preliminary results of the trial are summarised in Figure D which shows the performance of the heating system before and after sealing the windows. The annual fuel saving is estimated to be about 22 percent. The cost effectiveness of the measure based on the above fuel saving is as follows:-

Discount FACTOR	Life Span	5 years	10 years
4% TDR	IOP *	0.906	2.47
	PAYBACK PERIOD	2.4 Years	2.4 Years
7% TDR	IOP *	0.75	2.0
	PAYBACK PERIOD	2.7 Years	2.7 Years

*Index of Profitability

The remedial work was obviously cost effective and produced worthwhile savings. In addition a noticeable improvement in comfort was reported by the building occupants, though parts of the building are still draughty due to poor fitting window frames.

While it is possible to infer by calculation the ventilation rate prior to and after sealing the building, the inherent inaccuracies of such a calculation render the results unreliable. A simple method of measuring the ventilation rate would be a considerable aid to validating improvements.

INTERNAL TEMPERATURE CONTROLS

Most office buildings are controlled by means of a weather compensator; a device that senses external air temperature only and infers internal temperature conditions. The main disadvantages of such devices are that they do not take account of the dynamic condition that occurs within buildings due to occupancy, lighting, other beneficial gains, and variations in natural ventilation rates.

The distinct advantage that internal temperature controls offer over the more traditional weather compensated control in minimising the energy losses associated with natural ventilation is not widely recognised.

Work undertaken during theoretical verification of energy savings associated with the installation of Internal Temperature Controls over and above weather compensator control, revealed that considerable energy savings are possible when natural ventilation rates are high. Figure E shows computer predicted percentage energy saving for rectangular buildings. Buildings of other shapes also produced similar savings but they cannot be represented in a graphical form. No extensive attempt has been made to test these theoretical findings in practice, but one closely monitored trial revealed savings of about 17% for a building with a glazing ratio of about 40 percent. The average seasonal natural ventilation rate was not known, however the building is that referred to earlier which is believed to have a relatively low natural ventilation rate of about $1-1\frac{1}{2}$ air changes per hour.

Perhaps the most significant conclusion to be drawn from the theoretical analysis was that if the energy requirements for buildings are to be minimised, heating controls must be of a type that respond to beneficial heat gains and the dynamic changes that occur within a building, particularly in relation to a natural ventilation.

In addition it can be concluded that for existing buildings with a high natural ventilation rate, internal temperature controls are essential where it is not practical or economical to reduce the ventilation rates to more acceptable levels, if energy consumption is to be minimised.

CONTROL STRATEGY

The interaction of the many energy related variables is perhaps one of the most undervalued areas associated with building design. Much is assumed during the design process but more often not realised in practice.

For existing buildings, the situation is worse in that generally little attention has been afforded to obtaining a better understanding about their dynamic performance. Where there has, the tendency has been to treat particular problems in isolation with little regard to other interconnected variables and influences. As a consequence, optimum solutions are not necessarily evolved.

Reference has already been made to the close association of natural ventilation rates and internal temperature controls. The computer based analysis previously mentioned also revealed that as natural ventilation rates are reduced, the necessary running hours of heating plant is also reduced. The results are shown in Figure F. In practice, heating plant is generally running for well over 2000 hours for intermittently occupied buildings whereas theorectical predictions suggest that considerably less is required. To fully realise this additional benefit however requires a more comprehensive heating system control strategy than is generally applied to most buildings.

RETROFIT IMPROVEMENTS

Little work has been done to date by PSA to reduce excessive natural ventilation rates in buildings. This is not because it has been considered unimportant but because the limited effort available has been directed towards low risk proven measures. Work which has been undertaken however, generally falls into one of two categories; improvements to metal framed casement windows through the application of silicon rubber mastics, or alternatively, minimising the gaps around large sliding doors of hangars and workshops through the fitting of nylon brush seals.

Some of the first applications of silicon rubber mastics were undertaken four to five years ago, and have generally proven reliable in use, with the painter perhaps being its worst enemy. Most silicon rubber mastics are resistant to common gloss paints and will in fact repel them but it is not unknown for the painter to remove the mastic. For most practical purposes the life of the installation can be expected to be above five to ten years, which some suppliers will guarantee.

It has been a problem to maintain an acceptable working environment in buildings with large doors such as hangars and workshops and in one particular type of hangar it was found that infiltration gaps around the doors amounted to an equivalent area of about 158m^2 (170 sq ft), enough to drive a double-decker bus through. Nylon brush seals have proved to be an effective solution. Another but not disassociated problem was that the doors were often left open. To combat this problem, proximity switches were fitted to the hangar doors so as to turn off the heating system when they were opened. These adaptations were initially carried out on twelve such hangars and the effect on fuel consumption was as follows:-

Year	Condition	Actual Consumption (litres)	Consumption Degree day Corrected to a base year 77/78
1977/78	No Modification	481494	481494
1978/79	Modification fitted *	427545	390253
1979/80	Modification fitted *	246159	243269

*The modification involved the fitting of nylon brush seals to the hangar doors and proximity switches.

The first year, despite a very hard winter, produced fuel savings of about 19 percent but for 1979/80 the saving was about 50 percent. This large saving occurred because during 1979/80 the doors were left open due to the mild weather but the proximity switches rendered the heating system off. However during the severe winter of 1978/79 the hangar doors were kept closed as much as possible in order to maintain comfort conditions. This is a simple but effective solution to many door problems, which demonstrates that it may be more acceptable to tolerate high rates of natural ventilation, at times, providing the heating is turned off.

BUILDING FAULTS

So far reference has been made to the particular problems associated with casement windows and large hangar doors, but there are other problem areas that lead to excessive ventilation rates. These generally fall into three categories:

(i) those resulting from poor design
(ii) those due to the poor fit of building components
(iii) those attributable to poor construction

Solutions to these particular problem areas are largely unexplored but if the wide disparity in energy consumption per unit floor area is to be reduced and energy savings achieved, a full range of remedial options must be developed, supported by sound evidence of their cost effectiveness.

BUILDING DESIGN

New buildings are generally designed with ventilation rates as recommended by the CIBS Guide, however it is not uncommon practice for higher rates to be assumed particularly when the recommendation is for relatively low rates. This practice has evolved as a direct result of higher than expected ventilation rates occurring in practice, which has led to underheating.

Closer attention is being given to assessing the natural ventilation rates of design options. One approach being adopted is based on obtaining a fair knowledge of the microclimate of the particular site together with a detailed knowledge of the window that has been selected for the proposed building. This data is subsequently processed by methods recommended by the BRE and the CIBS to derive a ventilation rate. This approach is thought to be a shade more exact than that of taking figures direct from the CIBS Guide, though as yet there are no measured results to confirm this.

The benefits of closer attention to natural ventilation rates in the design process will not necessarily be realised unless the fit of building components and construction standards are improved. These faults alone are responsible for excessive ventilation rates in many existing buildings.

CONCLUSIONS

1. Theoretical predictions suggest that excessive ventilation rates are a major contributory cause to the large disparity in consumption per unit floor area found in existing buildings.

2. Initial results of trials suggest that significant energy savings are achievable through reducing natural ventilation rates to more acceptable levels but further validation is required before extensive upgrading of existing buildings can be undertaken.

3. A simple method of measuring natural ventilation rates and assessing average yearly values would enable potential savings to be quantified so that investment decisions can be soundly based.

4. A greater understanding of natural ventilation within buildings needs to be developed, together with its interaction with other energy related variables, if the energy demands of buildings are to be minimised.

5. A full range of cost effective options for reducing excessive natural ventilation in existing buildings needs to be developed.

6. A sound heating system control strategy needs to be developed to take full account of the dynamic changes that occur within buildings.

7. A proven method of validating the natural ventilation rates of building design proposals must be developed to aid designers.

8. Building components fits and construction standards must be improved if the benefits of better designs are to be realised.

ACKNOWLEDGMENT

The work described has been carried out as part of the energy conservation programme for Government buildings and the author wishes to thank the Property Services Agency for permission to publish this paper.

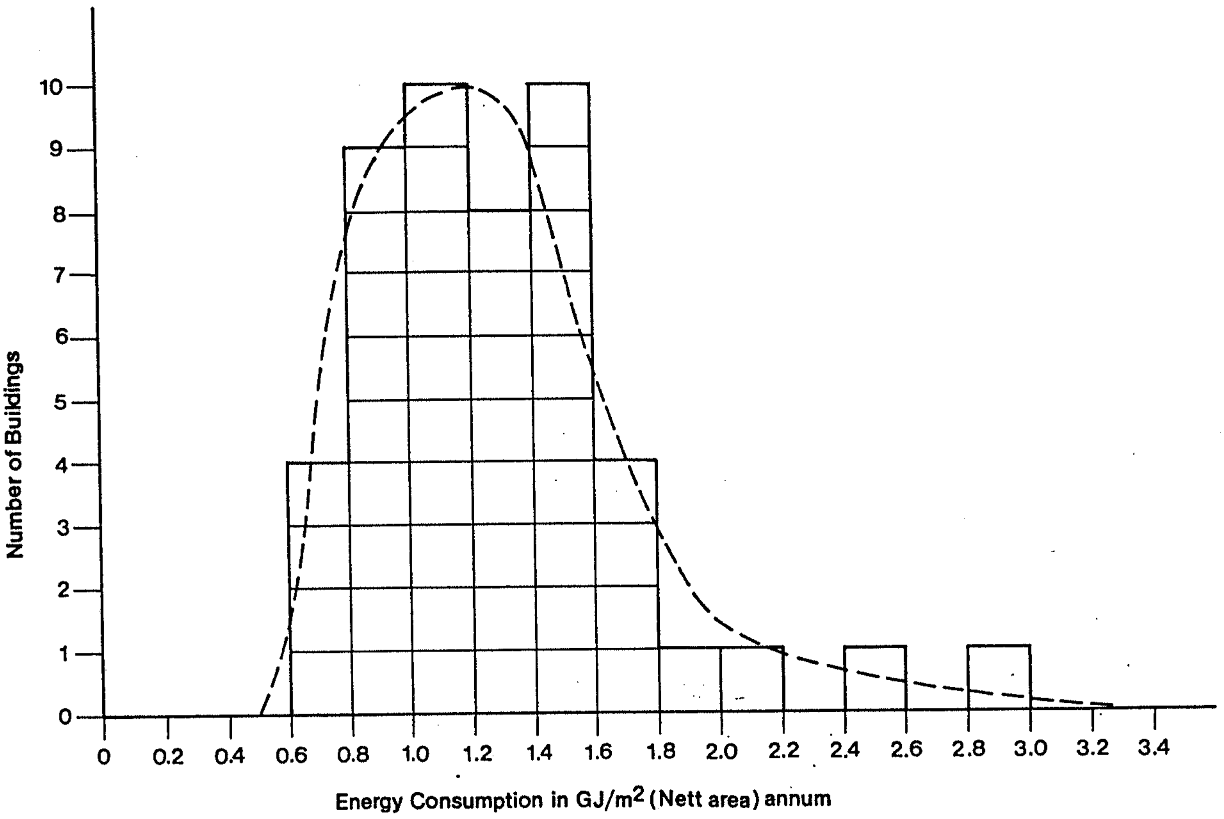


Figure A Histogram of Heating and Domestic Hot Water Consumption 1975/76

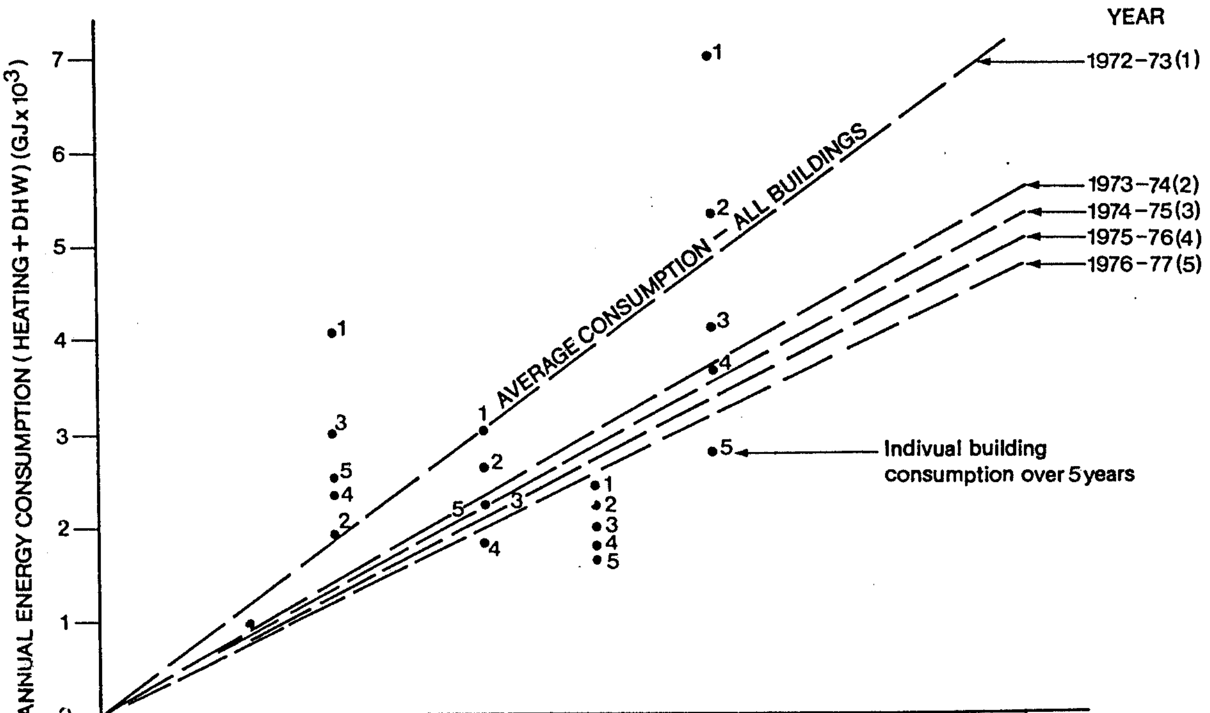


Figure B Assessment of Fuel consumed in 50 buildings

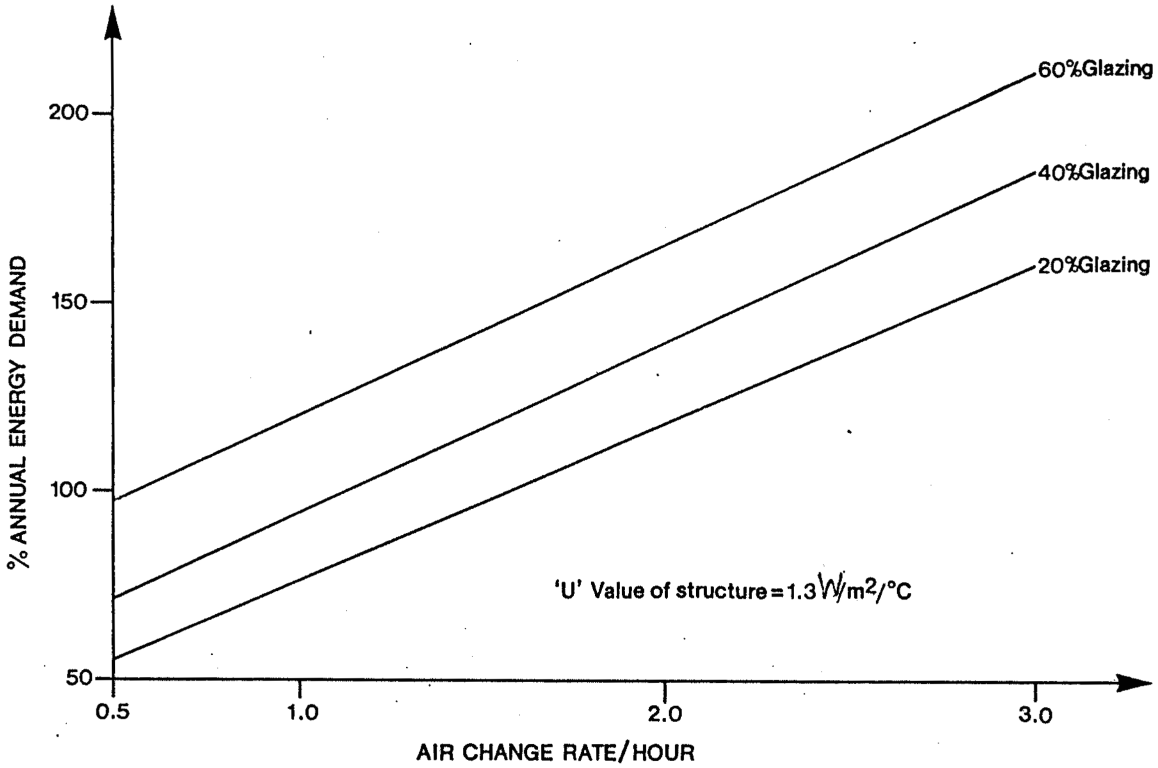


Figure C Annaul Energy Demand in relation to Glazing and Air Change Rates

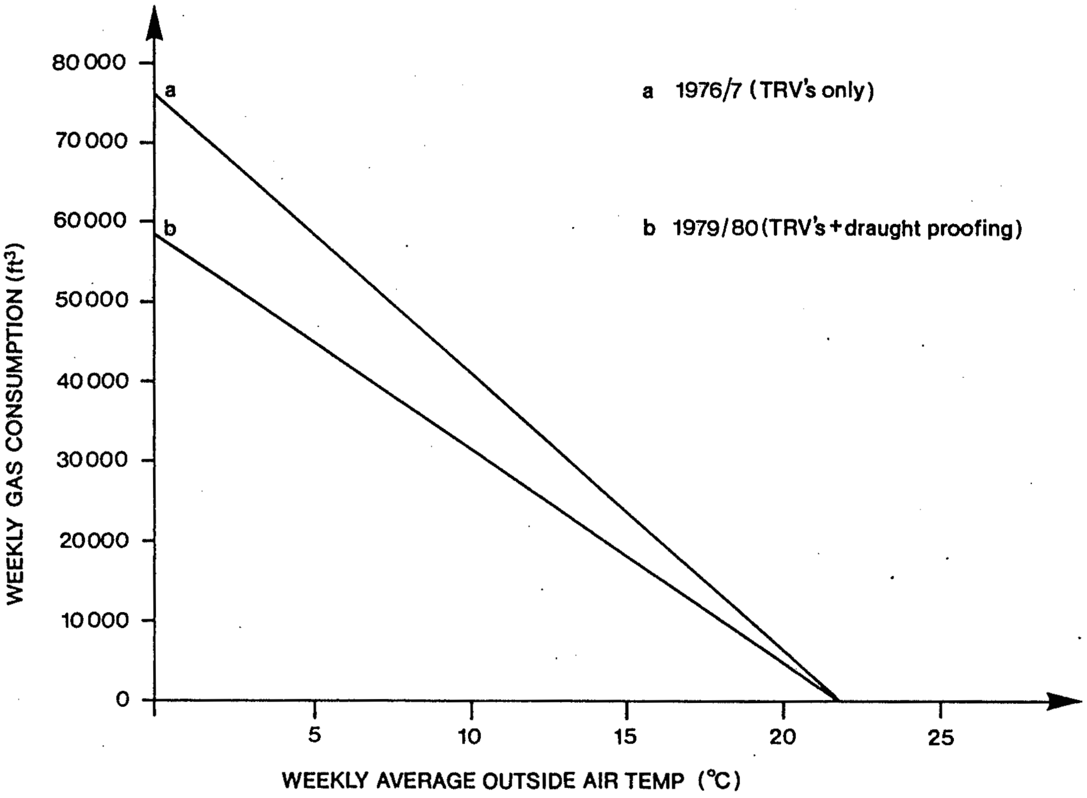


Figure D Heating System Performance

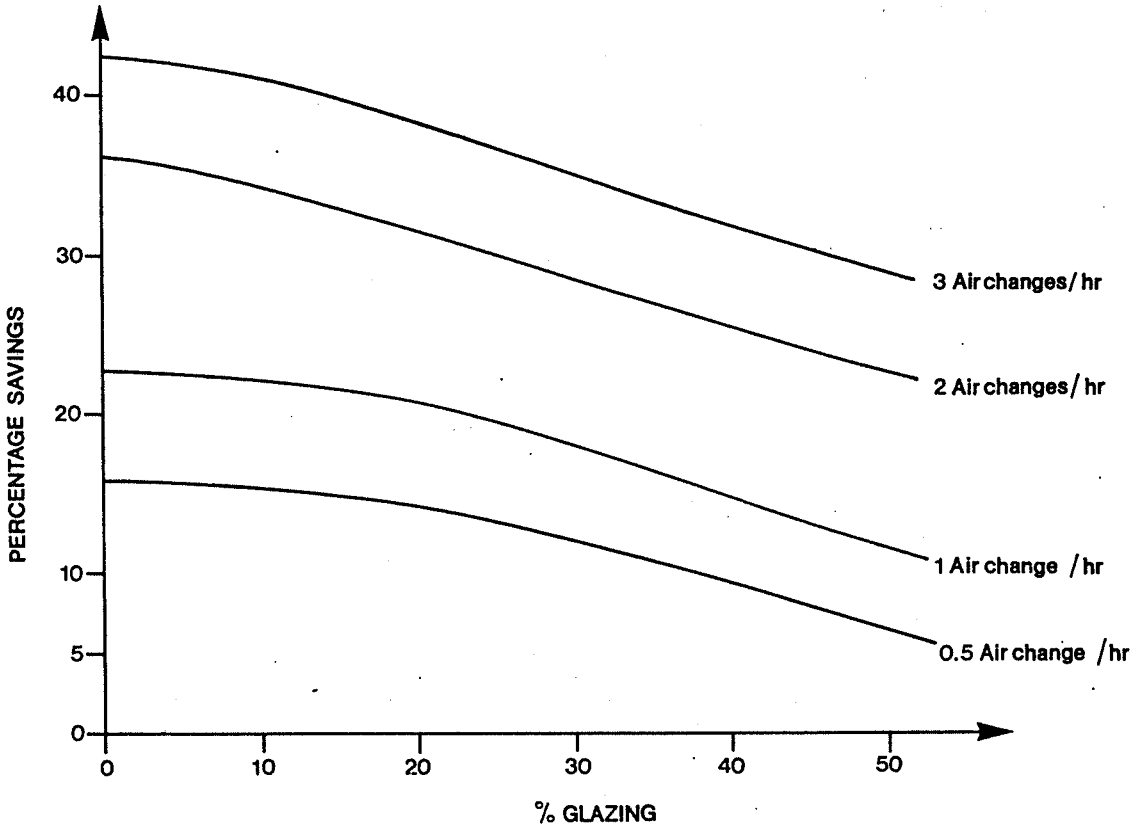


Figure E Potential Energy Savings due to internal Temperature Controls

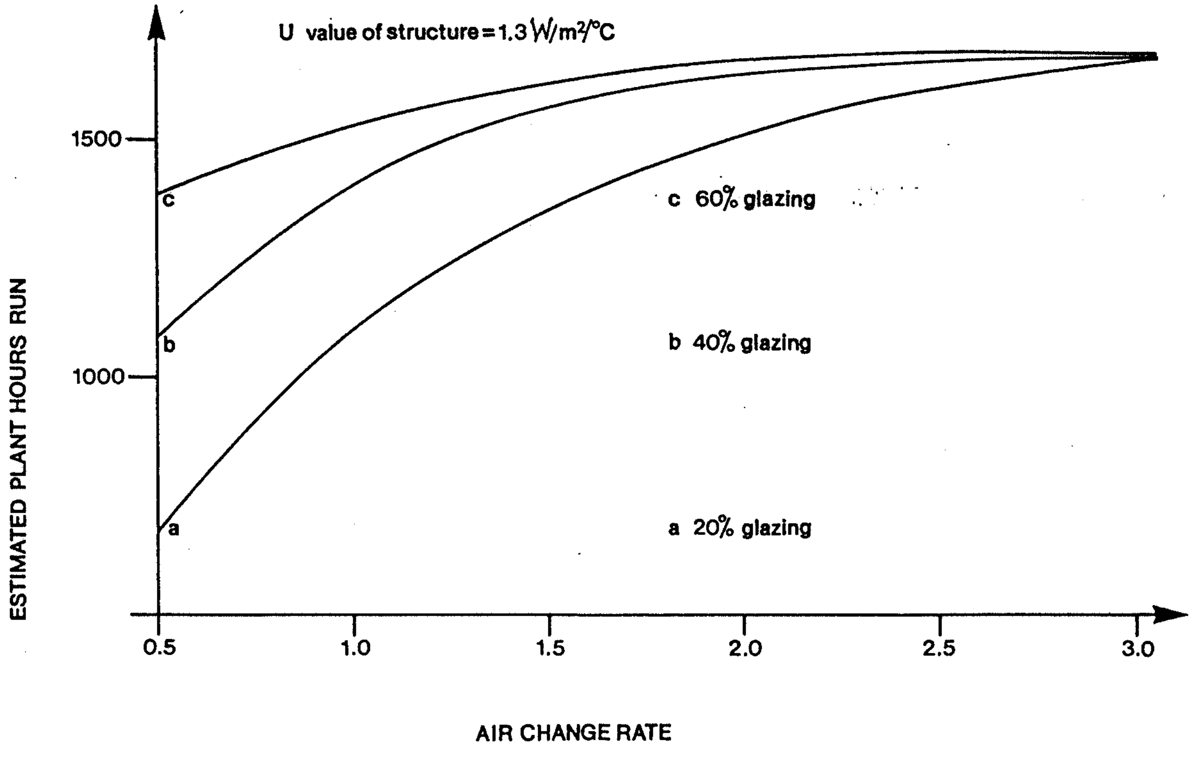


Figure F Estimated Plant running hours

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Section A6	**SOLAR DATA** Sun positions, radiation intensity and design data for the United Kingdom and overseas. Solar heat transmission through the building structure.
Section A7	**CASUAL GAINS** Heat produced by animal metabolism, electric lights, motors and other equipment.
Section A8	**SUMMERTIME TEMPERATURES IN BUILDINGS** Heat gains and peak indoor environmental temperatures without air conditioning.
Section A9	**ESTIMATION OF PLANT CAPACITY** Heating and refrigeration plant, summer and winter design temperatures and calculation of energy requirements and allowances which might affect the total plant capacity, e.g. height of space, intermittency, temperature swing, etc.
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Section C2 PROPERTIES OF WATER AND STEAM
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Section C3 HEAT TRANSFER
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CODE SERIES R	Refrigerating Systems
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PART 1 Guidance towards energy conserving design of buildings and services.

PART 3 Guidance towards energy conserving operation of buildings and services.

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NUMBER 2 Recommendations for the provision of combustion and ventilation air for boilers and other heat-producing appliances: Installations exceeding 45kW.

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