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THE EFFECTS OF WIND ON PEOPLE IN THE VICINITY OF BUILDINGS

T V Lawson
Department of Aeronautical Engineering
University of Bristol United Kingdom
and
A D Penwarden
Environmental Design Division
Building Research Establishment United Kingdom

This paper deals with some aspects of the environmental wind studies performed in the Department of Aeronautical Engineering of the University of Bristol and in the Building Aerodynamics Section at the Building Research Station, Garston, Herts. Each establishment handles a large number of enquiries concerned with pedestrian comfort and safety among groups of buildings, and each has developed its own techniques for helping clients. These techniques are to a large extent complementary, and it is the purpose of this paper to describe them and to show how they are applied. A number of other wind-dependent factors which must be considered during the design of buildings are also included.

1. INTRODUCTION

In the body of the paper the authors consider the two major effects that wind has upon man in a built environment - namely, the mechanical and thermal effects. In Section 2 these are considered separately and it is concluded that, within certain limitations, the criteria of acceptability for thermal comfort will automatically be satisfied, providing the criteria for mechanical effects are met. Consequently, the bulk of the paper considers the mechanical effects and how best to write criteria of acceptability.

At the inception of a design project, the question of whether a problem will arise from the mechanical effects of the wind on people should be considered. At an early stage when the design is only half-conceived, the assessment will be crude and based upon past experience alone. As the design hardens, the quality of the assessment needs to improve until the stage is reached when sufficient is known about the detail design for a model to be built. At this stage, a decision has to be taken as to whether a sufficient problem exists to justify the cost and time involved in conducting a wind tunnel investigation. To make full use of a wind tunnel investigation, all parties to the study (the planning officers, the architect, the consulting engineer, the client and the wind tunnel specialist) should meet to determine the objectives of the investigation and to evaluate the subjective terms used to define the wind environment.

A range of assessment procedures is thus required, starting with those based on experience and intuition only, developing into quantitative studies based upon experience and thence to the full wind tunnel investigation. It is to be hoped that the first two stages will form part of all studies, but that the wind tunnel investigation will only be made if it is concluded in an earlier stage that there could be a problem of sufficient magnitude to warrant the time and cost involved.

This paper considers two kinds of investigation, the quantitative study without a wind tunnel investigation, Section 3, and the full wind tunnel investigation, Section 4. In Section 3 the assumptions made to allow a generalised solution prescribe the form of the criteria of acceptability so that the values of the criteria to be used are discussed in that Section. In Section 4 describing the full wind tunnel investigation, more latitude is available in the writing of criteria so that different criteria are used; these are explained following a discussion of the philosophy of criteria of acceptability in general.

An illustrative example of each type of investigation is presented in its respective Section.

A discussion of other related topics which must be borne in mind by the designer is given in Appendix 1, while Appendix 2 gives some background information on wind and rain.

2. EFFECTS OF WIND ON MAN

2.1 Mechanical Effects

The most serious direct effect the wind can have upon man is to blow him over. This can cause injury and sometimes death: For example two old ladies died in 1972 after being blown over by wind close to tall buildings. These are extreme occurrences and careful design and layout of buildings should ensure that they do not happen.

Of lesser severity is the imposition of a wind load against which man has to work as he moves from point to point, when the wind can create annoyances such as turning his umbrella inside out or removing his hat.

Less seriously, the wind can make standing and chatting to friends an uncomfortable experience; it can make the opening of a newspaper difficult and the subsequent reading laborious due to the watering or blinking of the eyes, and there are other minor effects.

A list of these and other effects is given in Table 1, based on references 1 and 2.

It is to prevent hazardous or unpleasant wind conditions in man-made environments that criteria of acceptability have to be written and agreed between planning authority, client, architect and consultant engineer. The exact form in which they are crouched depends upon the sophistication of the investigation envisaged, but in general they will demand that a given wind speed is exceeded for less than a stated duration. Suggested values for the criteria are given for each of the two types of investigation described in Sections 3 and 4.

Table 1 - Effects of wind on people

	Beaufort Number	Description	Windspeed m/s	Effect
	0	Calm	0-0.2	
	1	Light air	0.3-1.5	No noticeable wind
COMFORT	2	Light breeze	1.6-3.3	Wind felt on face
	3	Gentle breeze	3.4-5.4	Hair disturbed clothing flaps, newspaper difficult to read
	4	Moderate breeze	5.5-7.9	Raises dust and loose paper, hair disarranged
DISCOMFORT	5	Fresh breeze	8.0-10.7	Force of wind felt on body, danger of stumbling when entering a windy zone.
INCREASING	6	Strong breeze	10.8-13.8	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forwards walking force, wind noise on ears unpleasant
	7	Near gale	13.9-17.1	Inconvenience felt when walking
	8	Gale	17.2-20.7	Generally impedes progress, great difficulty with balance in gusts
DANGER	9	Strong gale	20.8-24.4	People blown over

2.2 Thermal Effects

An attempt to assess the effects of wind upon the thermal environment of man becomes extremely complex because of the interrelation of so many different phenomena. The property which characterises man's subjective description of this condition is his skin temperature. This is controlled firstly by his metabolic rate and his work load. It is then modified by his clothing which acts as an insulation between himself and his environment. Unfortunately, its insulation depends, among other quantities, upon the moisture content of the clothing (supplied either from within as sweat or without as rain) and on the extent to which it is penetrated by the wind. Heat is also removed from the external surface of the clothing by wind, and heat is added by radiation from the sun or any other source of heat. A state of equilibrium can eventually be established in which all surfaces attain temperatures for which the heat flow throughout is consistent with the thermal properties of the various parts.

Wind appears three times in this system: firstly as a work load against which man has to walk, secondly by removing heat from the outer surface of the clothing, and thirdly in penetrating the clothing and removing heat directly.

In the first effect, the energy needed to progress against the wind load can be equated to that involved in walking up a hill (Reference 1). For example, walking against a 13 m/s wind is roughly equivalent to walking at the same speed up a slope of 1 in 10 with no wind. In each case the walker has to work harder to maintain his speed, and the extra heat produced by his body can cause sweating and discomfort.

The second effect has been examined by several experimenters for a range of clothing impervious to wind and rain, both in sunshine and shade. Using a relationship derived by Humphreys (Ref. 3) and modified to include the effects of solar radiation, and inserting subjective comfort descriptions also defined by Humphreys, it is possible to show the combination of outside air temperature and wind speed for different clothing which conform to the subjective descriptions of man's warmth. Examples are reproduced from Ref. 1 in Fig. 1.

The third effect is difficult to assess because all the experiments which have so far been conducted have concerned specialised clothing (military, mountaineering, polar, etc), which is impervious to wind and rain. However, it is possible to postulate that taking account of wind penetration would produce a curve similar to the dashed curve in Fig. 1(b). The philosophy behind this curve is that the porosity of the clothing would progressively reduce its insulation value as the wind speed increased. The dashed curve represents clothing with excessive porosity to wind.

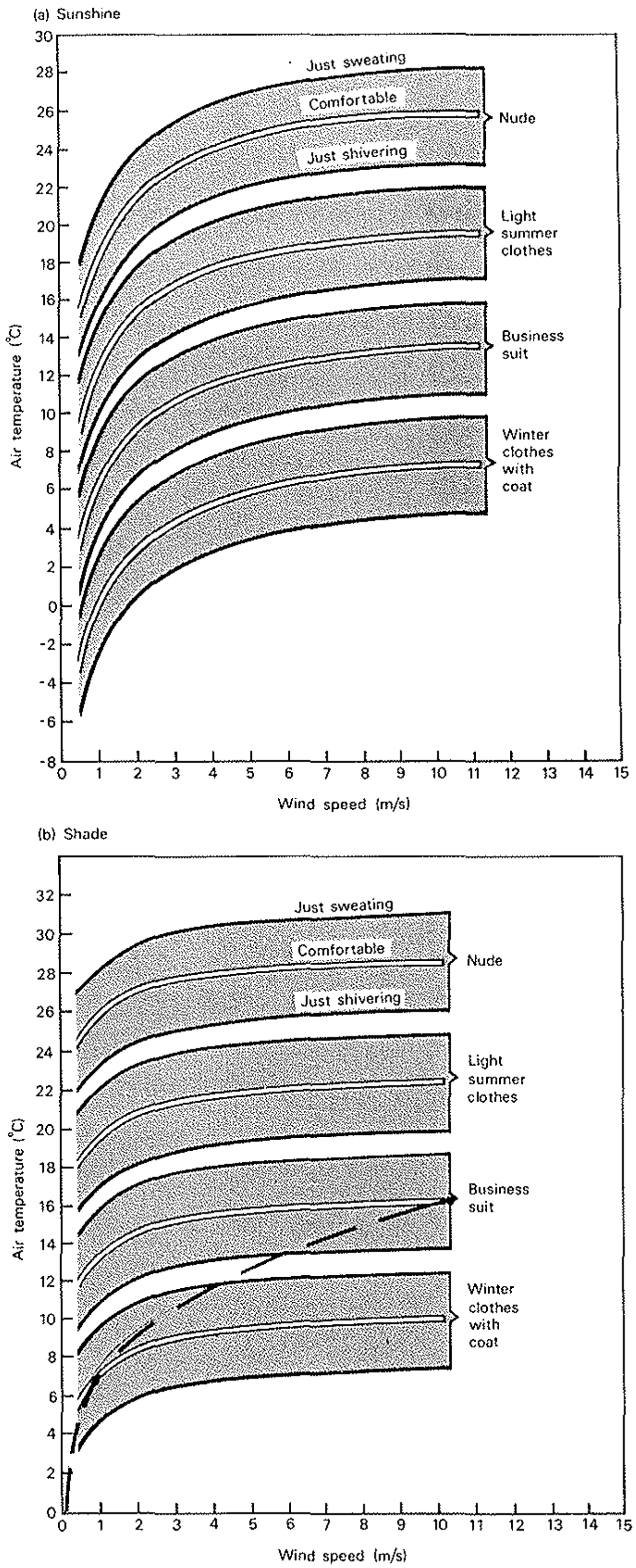

Fig. 1 - Examples of thermal comfort conditions for strolling

In an investigation in which subjects were exposed to various wind and temperature conditions for short periods, Hunt (Ref. 2) showed that the subjective assessment of warmth tended towards the colder description as the wind speed increased. As this tendency is the same as that described in Fig. 1 when the exposure has been long enough for an equilibrium heat flow system to be established, it is reasonable to accept these curves.

The interesting fact from these curves is the small variation due to the wind if a person is wearing the correct clothes which are impervious to wind and rain. It would appear therefore that, assuming a tall building complex provides shelter from direct solar radiation, a person who is comfortably warm in a windspeed at the top of Beaufort Force 2 will not experience an unacceptable change of warmth if the speed increases to the top of Beaufort Force 6. It follows that if a person has dressed in impervious clothing and correctly for the weather (taking into account both wind speed and temperature) in shade at home, then his thermal comfort will not be greatly changed when walking in a building complex in which the wind speeds conform with the criteria based upon consideration of the mechanical effects.

In the rest of this paper therefore criteria for and descriptions of man's environment will be developed entirely in terms of mechanical effects.

3. A QUANTITATIVE STUDY WITHOUT A WIND TUNNEL INVESTIGATION (Designing for comfort in pedestrian areas)

3.1 Introduction

This aspect of environmental studies is one which has received much attention in the UK. The reason for this is the considerable number of developments, particularly shopping centres, where wind has proved to be a big problem. The BRE approach, described in detail in Ref. 4, for the case of a tall building standing in a suburban area of low buildings, involves a combination of human comfort considerations, meteorological wind data, and building aerodynamics. A mean hourly wind speed of 5 m/s is taken as the maximum for comfort, and the frequency with which this is exceeded in pedestrian areas is used as a comfort criterion. The procedure involves knowing the height H and width W of the tall building, the average height h of surrounding low buildings, the average hourly wind speed for the locality, and the relevant region of increased speed due to the tall building - usually corner-steams or through-flow, as described below.

3.2 High speed regions

A description of the basic pattern of wind flow around a single tall building with a low building to windward is helpful to designers. Fig. 2, based on wind tunnel tests, shows that as the wind approaches a tall building it gradually diverges until, at the windward wall, upward and downward flow can be seen. Some of the air deflected downwards rolls up to form a vortex in front of the tall building. The vortex stretches out sideways and wraps around the building in a typical horseshoe shape. The flow close to the windward wall radiates from a central region at about three-quarters of the building height, and a considerable quantity of air flows downwards and outwards to be concentrated near ground level at the windward corners. These accelerated airstreams pass around the corners as two jets of air which penetrate downwind for a distance similar to the height of the building. If the building is raised above ground on columns, or is pierced by an arcade or passageway, wind flows at high speed through the opening.

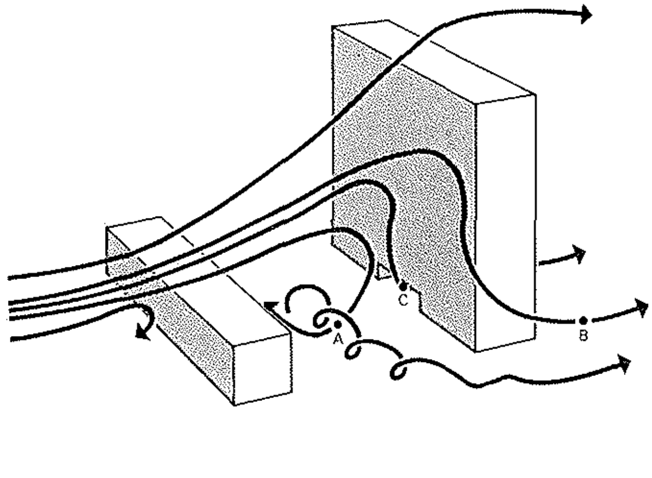

Fig. 2 - Basic pattern of wind flow around a tall building

This flow pattern results in three main regions in which increased speeds are experienced by pedestrians. These vortex-flow, corner-streams, and through-flow regions respectively produce maximum speeds V_A at A, V_B at B, and V_C at C, see Fig. 2, which vary with the building dimensions and with the height of surrounding buildings. Fig. 3 shows some typical relationships for corner-streams and through-flow found in tests at the BRE, with speeds expressed as ratios R_H to the free wind speed V_H at building height H. Representative values for a wide building, four or more times the height of surrounding buildings, are $V_A/V_H = 0.5$, $V_B/V_H = 0.95$, and $V_C/V_H = 1.2$, all speeds representing mean hourly values at full-scale.

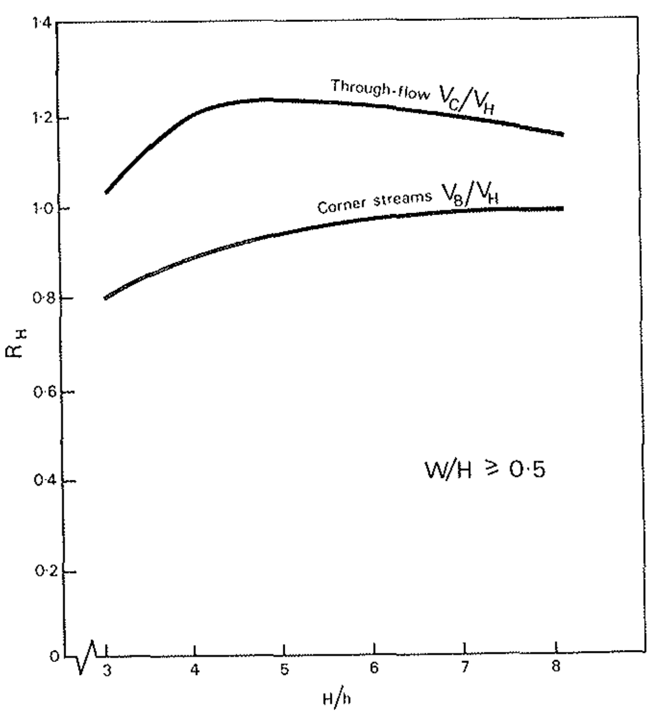

Fig. 3 - Typical ratios R_H. Width of tall building W, height of surrounding low buildings h.

These values are for wind perpendicular to the wide face of a tall building. Other wind angles produce different speeds in the vortex region, but maximum speeds in the corner-streams and in through-flow are not sensitive to direction over a wide range of wind angles. In particular, maximum speeds V_B in corner-streams vary very little with wind angle (typically ± 15% during rotation through 360 degrees), although the position at which the maximum occurs does change. Fig. 4 sketches the area around a single tall building where conditions for pedestrians are likely to be adversely affected by corner-streams.

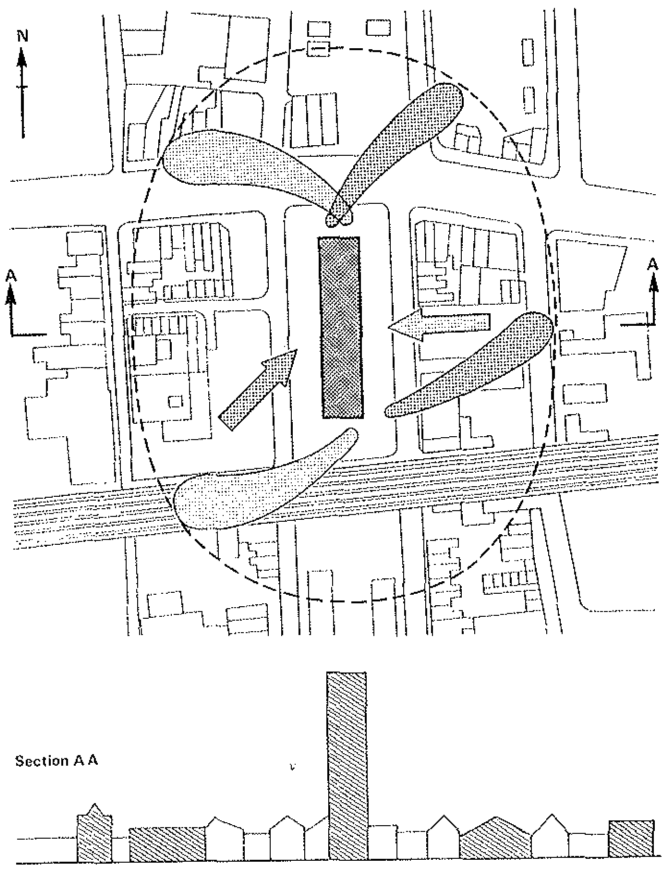

Fig. 4 - The area around a tall building affected by corner-streams

3.3 Wind Frequencies

The relative constancy of the ratio $R_H = V_B/V_H$ allows a simple calculation of the frequency with which a mean hourly speed of 5 m/s is exceeded in corner-streams. V_B will be equal to 5 m/s when V_H is $5/R_H$ m/s; that is, when the meteorological-site speed V_{10} is $5/R_HS$. Here S is a factor V_H/V_{10} based on predicting the effect on the open-site speed at 10m in passing over urban terrain; values are given in Table 2. S could also be modified to take account of local hill and valley configurations. The frequency of speeds greater than V_{10} at the meteorological site can be found in Table 3 from the ratio $V_{10}/\bar{V}_{10}$, where $\bar{V}_{10}$ is the long-term average hourly windspeed at the meteorological site, available from a wind map of the UK (Ref. 4). Thus it is necessary to find the frequency equivalent to a ratio $5/R_H S\bar{V}_{10}$.

Table 2 - Variation of S ($= V_H/V_{10}$) with tall building height H

H metres	10	20	30	40	50	60	70	80	90	100
S	0.60	0.73	0.82	0.89	0.94	0.99	1.04	1.08	1.11	1.14

Table 3 - Variation of cumulative frequency with $V_{10}/\bar{V}_{10}$

$V_{10}/\bar{V}_{10}$	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Frequency, %	100	95	89	84	78	73	68	62	57	51
$V_{10}/\bar{V}_{10}$	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
Frequency, %	46	40	35	30	24	20	16.0	12.7	10.0	7.8
$V_{10}/\bar{V}_{10}$	2.0	2.1	2.2	2.3	2.4	2.5				
Frequency, %	5.9	4.5	3.3	2.4	1.7	1.2				

As an example, consider a building 50 m tall among suburban houses 10 m tall, in an area where $\bar{V}_{10}$ is 3.9 m/s. From table 2 S = 0.94 for H = 50 m, and from Fig. 3 $R_H = V_B/V_H$ = 0.95 for H/h = 5.0. Then $5/R_H S\bar{V}_{10}$ = 5/0.95 x 0.94 x 3.9 = 1.44. The corresponding frequency obtained from Table 3 is 22%, and this is the frequency of speeds greater than 5 m/s in the corner-streams region around the tall building.

Simple though this calculation is, the process can be made even easier by using the nomogram of Fig. 5. Lines showing the calculation in the paragraph above are superimposed on the nomogram.

The calculation has been applied to a number of sites which have been brought to the attention of the BRE as being unpleasantly windy. These sites are plotted in Fig. 6, which is a graph of $R_H S$ against $\bar{V}_{10}$, with lines of equal frequency included. In all cases, complaints had been made about wind

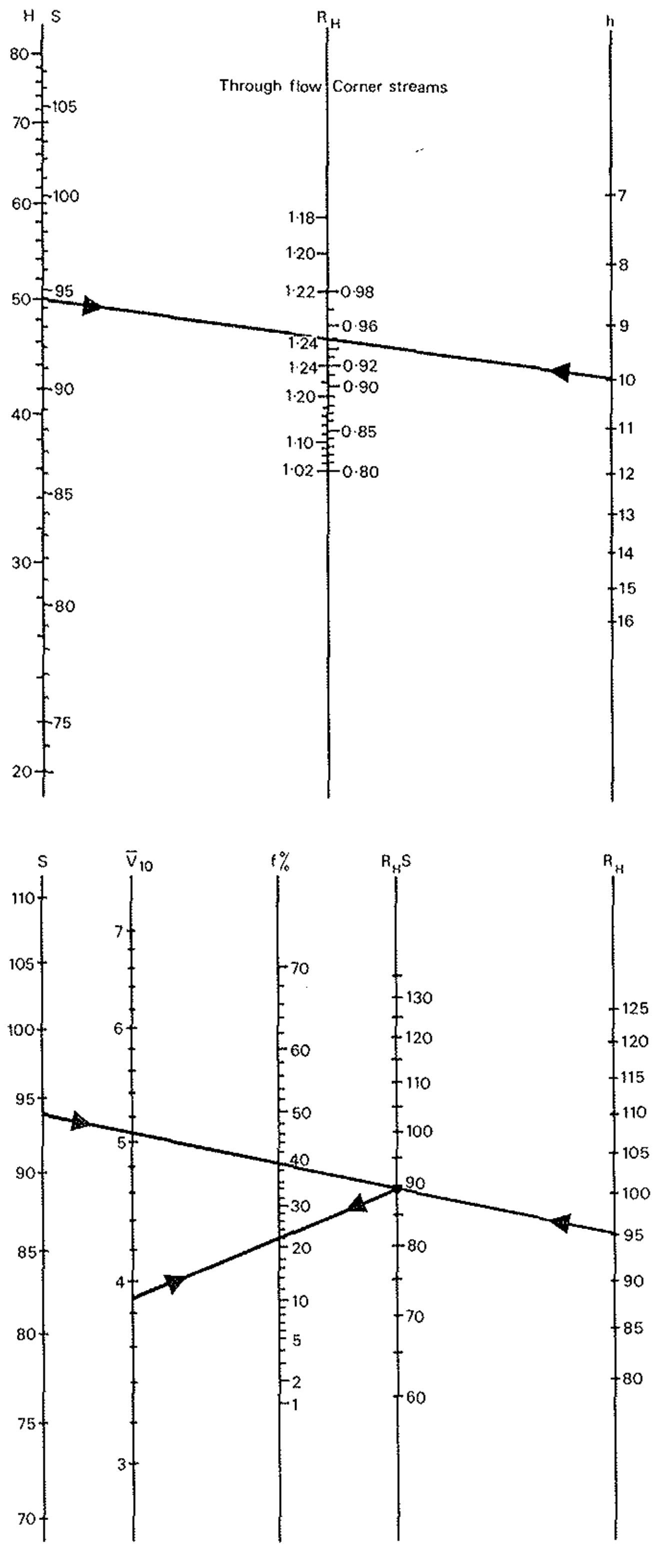

Fig. 5 - Nomogram for calculating the frequency of speeds greater than 5 m/s.

conditions, and in some cases protective measures were taken after consultation with BRE. The points shown as open circles refer to those sites where roofs or screens have been installed to improve conditions. The black circles concern centres which were investigated following complaints, but where no action was taken. The crosses represent sites where action is contemplated, but has not yet been taken. It can be seen that action was taken only in cases where the frequency was estimated to exceed 20%.

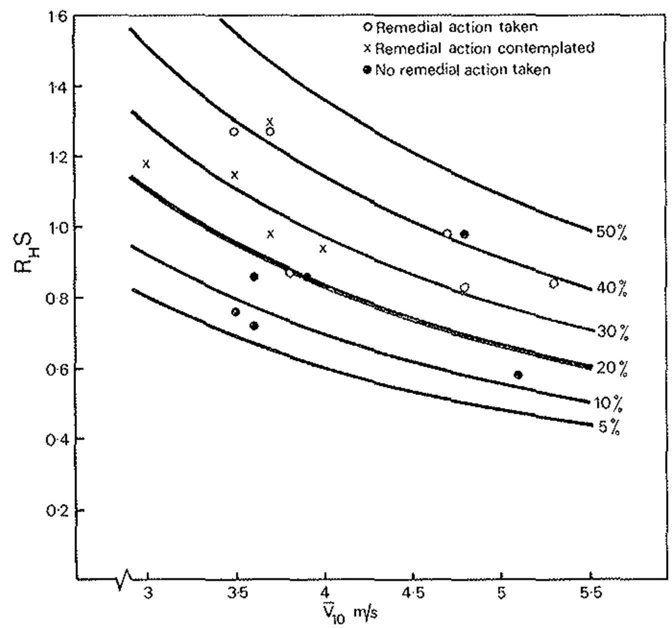

Fig. 6 - Estimated frequencies of speeds greater than 5 m/s on windy sites.

It is concluded from this work that the frequency of mean hourly speeds greater than 5 m/s is a useful, practical criterion based on User Satisfaction. When this frequency, calculated by the method above, exceeds 20%, protective measures are likely to be needed. Between 10 and 20% complaint is likely but may be insufficient to provoke action. Below 10% conditions are likely to be satisfactory.

The procedure outlined above is used in handling many of the environmental wind enquiries which come to the Building Research Establishment. Over the past 10 years some 300 such enquiries have been received from architects, consulting engineers and planners. Several of these problems, particularly in the early days of this work, have entailed wind tunnel tests, but most cases involving tall buildings can now be adequately dealt with by using the simple procedure above. In some cases the resulting appraisal has led to radical changes in design which have eliminated wind problems at a very early stage.

3.4 Remedial Action

Having had the wind problems diagnosed, the designer needs advice on what action he can take to improve conditons. Various ways of reducing windspeeds in pedestrian areas around tall buildings can be suggested:

At the design stage:

(1) Avoid tall buildings - an obvious remedy which is sometimes possible. In general it is buildings more than twice the height of their neighbours which give trouble.

(2) Keep pedestrian areas away from tall buildings - avoid the need for people to walk close to the corners of tall buildings, and particularly avoid routes beneath tall buildings.

(3) Stand the building on a podium - provided that the podium is large enough, the winds which will inevitably de deflected downwards by the building will be kept above street level.

At the design stage or later:

(4) Build a roof over pedestrian areas - this is a measure which has been used in many of the cases indicated with black circles in Fig. 6 (see Ref. 4 for details). The extra cost may run into hundreds of thousands of pounds, but a complete cure is possible.

(5) Install screens - floor-to-ceiling screens, offset to form a simple labyrinth, can reduce the flow of wind beneath a building, while maintaining access for pedestrians. Alternatively, solid screens with doors can be used.

(6) Build canopies - model tests suggest that a canopy at first-floor level, extending some 6 to 8 metres out from the faces of a tall building, and having a parapet wall 1 to 2 metres high around its periphery, will reduce speeds beneath the building to about one-third of their unobstructed speed. It may also be necessary to build screen walls at strategic points beneath the canopy.

(7) Provide handrails - this represents

the minimum which can be done to assist people, but may be valuable to old people walking up and down steps in a windy region.

(8) Use aerodynamic attachments - this is a largely unexplored field, but it is possible that fins, vanes, or deflectors, as used to control airflow over aircraft and in ducted air systems, could be adapted for use on buildings.

4. A FULL WIND TUNNEL INVESTIGATION

4.1 Preamble

In the situation when the building complex consists of separate buildings of varying heights, or when accurate measurements of wind speed at locations in the complex are required, a full wind tunnel investigation must be conducted.

4.2 Subjective Acceptability Criteria

It is recommended that four subjective terms be used to define the suitability of an area. They are:-

(1) UNACCEPTABLE, when, as its name implies, the conditions will not be allowed under normal circumstances.

(2) TOLERABLE, when conditions would cause annoyance and a search should be made for a remedy. The possible cures should then be examined in regard to aesthetics, economies or inconvenience, and a decision taken either to proceed with a cure which is compatible with the basic design philosophy, or to accept the original conditions with perhaps a slight change or restriction to the use of the area.

(3) OPEN, when conditions would be the same as those in an imaginary situation with the building complex razed to the ground, leaving an open area of limited extent. The purpose of this criterion is to establish those situations for which the building or complex provides no shelter, but neither does it aggravate the conditions.

(4) SHELTERED, when the building or complex provides positive shelter.

4.3 Suggested Numerical Values for the Acceptability Criteria

The purpose of separating the subjective criteria from the numerical criteria is to allow a range of numerical values to be applied to each subjective criterion at various parts of the site which have different uses. This is attempted in Table 4.

Firstly, a subjective term is chosen; for instance, UNACCEPTABLE. A series of accidents or incidents are listed and the minimum value of wind speed which could cause each occurrence is assumed. The major difficulty now arises in attempting to determine the frequency of occurrence of the incident which conforms with the subjective description.

At this point, four different probabilities will be defined:

P_i - the probability of the particular person being at the chosen location at the correct time.

P_{ii} - the probability of the stated wind speed being exceeded for a given value of the reference wind in a sample of stationary length.

P_{iii} - the percentage of the time when the stated value of velocity at the location will be allowed.

P - the frequency of occurrence of the incident (the joint probability).

As the separate probabilities can be isolated, the joint probability is the product of the other three, so that values have to be ascribed to P, P_i and P_{ii} in order that P_{iii}, the quantity required in the wind tunnel investigation, can be evaluated.

The value of P_{ii} is the easiest to choose. Assuming that the length of the sample at every location for every wind direction is greater than the 'stationary length', it is possible to draw a unique probability density curve for the readings covering the central 98% of the readings. From a series of samples each of stationary length, the actual value of the readings in the largest 1% and smallest 1% differs from sample to sample. It is therefore impossible to determine a value of velocity which will be exceeded for less than 1% of the time from a single sample of stationary length. Procedures to obtain less frequent values are long and are described in Ref. 5. For our application, we can ignore the complication and accept P_{ii} as 10^{-2} in all instances.

Values for P_i can be obtained by guesswork. For example, in the case of the old lady riding a bicycle, the value of 10^{-8} was determined thus: the chance of anyone being at such a location is less than 1 in 10^2. If we consider 4 in 10^2 of the population are old ladies, of whom 2.5 in 10^3 ride bicycles and of them only 1 in 10^2 would go out in high wind conditions, we obtain a value of 1 in 10^8 as the value for P_i.

The value of the joint probability is harder to determine, but it is suggested that the values in Table 4 are reasonable.

Having determined P, P_i and P_{ii}, the values of P_{iii} are obtained for each situation. These represent the limiting value of the duration in which the wind speed exceeds the value in the critical velocity column.

Table 4 - Suggested values of acceptability criteria

Occurrence	Critical Velocity in ranges of the Beaufort scale	Joint Probability P	Separate Probabilities P_i	P_{ii}	P_{iii}
Unacceptable					
Old lady blown off bicycle	> 5	10^{-11}	10^{-8}	10^{-2}	10^{-1}
Old lady blown over while walking	> 6	10^{-10}	10^{-6}	10^{-2}	10^{-2}
Child blown over while walking	> 6	10^{-11}	10^{-7}	10^{-2}	10^{-2}
Adult blown over while walking	> 7	10^{-9}	10^{-5}	10^{-2}	10^{-2}
Adult walking around building	> 6	2×10^{-8}	10^{-4}	10^{-2}	2×10^{-2}
Pedestrian precint-walk through areas	> 5	2×10^{-8}	10^{-4}	10^{-2}	2×10^{-2}
- standing areas, doors	> 4	4×10^{-7}	10^{-3}	10^{-2}	4×10^{-2}
Tolerable					
Adult walking around buildings	> 4	4×10^{-8}	10^{-4}	10^{-2}	4×10^{-2}
Pedestrian precint-walk through areas	> 4	4×10^{-8}	10^{-4}	10^{-2}	4×10^{-2}
- standing areas, doors	> 3	4×10^{-7}	10^{-3}	10^{-2}	4×10^{-2}
- covered areas	> 2	4×10^{-7}	10^{-3}	10^{-2}	4×10^{-2}
Open - Appropriate values must be taken for the specific locality					
Cities in South East	> 2	2×10^{-4}	1	10^{-2}	2×10^{-2}
in North West	> 3	2×10^{-4}	1	10^{-2}	2×10^{-2}
Urban in South East	> 3	2×10^{-4}	1	10^{-2}	2×10^{-2}
in North West	> 3	4×10^{-4}	1	10^{-2}	4×10^{-2}
Rural in South East	> 3	6×10^{-4}	1	10^{-2}	6×10^{-2}
in North West	> 4	5×10^{-4}	1	10^{-2}	5×10^{-2}

If the values of Table 4 can be accepted, it is then possible to define UNACCEPTABLE, TOLERABLE for each location on the site, and the OPEN criterion for the site as a whole.

4.4 The Beaufort Scale

In 1805 Admiral Beaufort encountered the difficulty of obtaining accurate estimates of wind velocity from his unskilled sailors. He divided wind speed into ranges, each of which affected the sea or the ship in a different way, so that the sailors could look at sea or ship and evaluate the wind speed in terms of Beaufort Forces. The description used would be meaningless to landlubbers, so we have produced in Table 1 a Land Beaufort Scale in which the descriptions refer to occurrences readily experienced by laymen. We propose to use this as our measure of wind speed, because the division of wind speeds which occur in building complexes into 10 ranges produces a scale coarse enough to yield a sensible number of categories and yet fine enough for each range to have a different meaning.

The values of wind speed used to define the ranges of the Beaufort Scale in Table 1 are values averaged over one hour. Assuming that the trace of wind speed against time in Fig. 7 represents the boundary between two ranges of the Beaufort Scale, it is obvious that the numerical value of the boundary differs with the averaging time of the measurement. A study of the variation of wind speed with averaging time in Ref. 6 suggests that it is a function of the intensity of turbulence only, and as this value differs from location to location in a complex, it is impossible to derive a unique relationship. At Bristol the boundaries of the Beaufort Scale are defined by constant velocities for any averaging time between one hour and ten minutes, and for shorter averaging times by the logarithmic variation suggested in Ref. 6 for an intensity of turbulence of 28%. These boundaries are plotted in Fig. 7 on which the values of wind speed at the boundaries are quoted for averaging times of 3 seconds and 15 minutes.

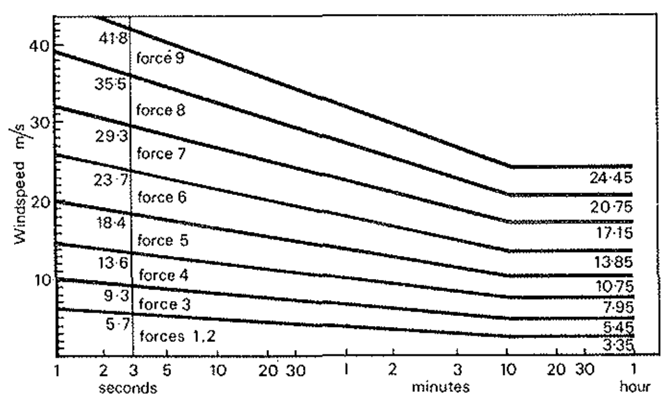

Fig. 7 - Variation of windspeed with averaging time.

4.5 The Wind Tunnel Investigation

The first choice to be made in a wind tunnel investigation is the scale of the model and, because of the size of most wind tunnels engaged in this work, this should be between 1/150 and 1/500. Within these scales, it is possible for the whole or lower part only of the atmosphere to be correctly simulated in the wind tunnel with respect to the velocity gradient, the turbulence gradient and the energy spectrum of the wind. This is essential to the accuracy of the results and it is recommended that all clients for a wind tunnel investigation require both a trace of the variation of wind speed with time (Fig. 8) and the energy spectrum of the reference wind (with the atmospheric curve from

Ref. 7 superimposed upon it), (Fig. 9) to be included in every report on the investigation. It is not suggested that the client should examine these in detail; their presence will demonstrate that the aerodynamicist has given the simulation of the atmosphere sufficient attention.

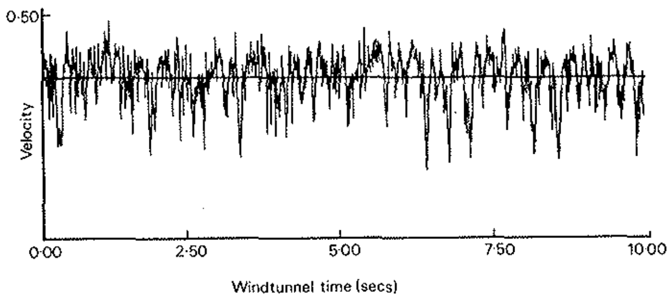

Fig. 8 - Variation of reference windspeed with time.

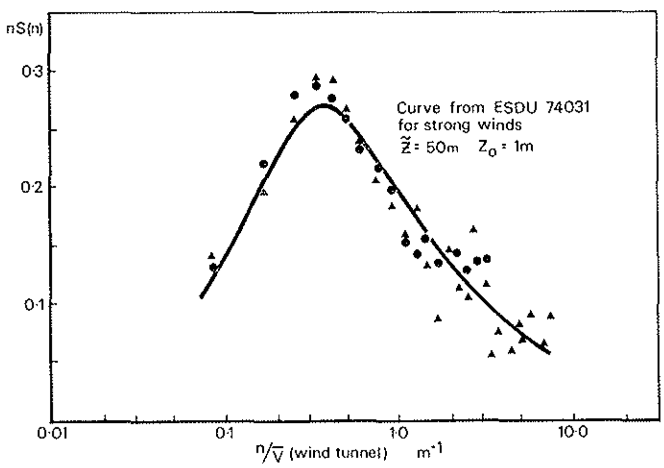

Fig. 9 - Comparison of turbulence spectra.

In the light of his experience, the aerodynamicist will choose a number of locations on the model at which high wind speeds could occur. Included in the list of locations studied should be any of particular interest or importance to the client. At Bristol it is customary to fix a small numbered disk at each location chosen to facilitate the exact positioning of measurements for all wind directions. A Xerox copy of a photograph of the model can be used to identify locations in the report; it is also useful to include the direction of the 'North Wind' on this photograph (see Fig. 10).

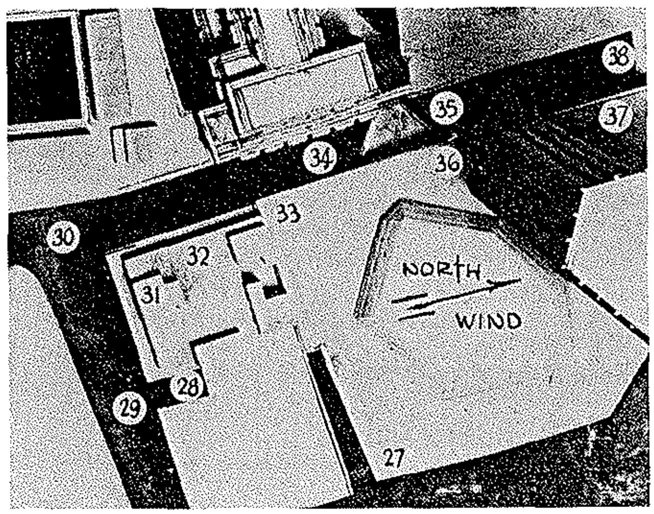

Fig. 10 - Measuring points on a model.

Twelve wind directions at 30° intervals are normally used. The justification for this is twofold; firstly, that 'frequency of wind speed and direction' Tables (an excerpt is shown as Fig. 11) produced by the Meteorological Office, Ref. 8, are used as the source of data on the wind, and these split the wind directions into 30° sectors. Secondly, this is considered justified because, with the correct simulation of the atmosphere, the wind direction is outside $\pm 15^{\circ}$ of the nominal direction for some 30% of the time. The choice of 12 wind directions is therefore a compromise which is both practical in using data from other sources and economically viable in time and cost.

Most of the occurrences, which have been used to determine the values of our acceptability criteria, are produced by short term gusts and not by steady winds blowing for long periods. In Section 4.4, describing the Beaufort Scale, values of wind speed averaged over 3 seconds were added to the usual boundaries of the Beaufort Scale. The difficulty in that instance was that the relationship between wind speed and averaging time depends upon the intensity of turbulence. The same difficulty arises in every instance when this 'correction' is performed. The conclusion is therefore that gust velocities (using short averaging times) must be measured in a wind tunnel investigation, in addition to values averaged over long time intervals.

In the literature concerning wind tunnel investigations, as well as most loading codes (for example, Refs. 9 and 10) the reference wind speed is usually either the hourly average or the 3 second average value measured at the height of the building. The meteorological data is usually referred to what is called 'meteorological standard conditions' which mean values averaged over one hour measured 10 m above open flat level country in the vicinity of the site. The relating of the wind speed at building height in the town or city to the value at meteorological standard conditions is still an art and ought not to be left to the layman. Consequently, all velocities in reports ought to be referred to 'meteorological standard conditions'.

TABLE X – PERCENTAGE FREQUENCIES OF WINDS AT SELECTED STATIONS

BIRMINGHAM (EDGBASTON) *(contd)*

Mean wind speed knots	m.p.h.	350°–010°	020°–040°	050°–070°	080°–100°	110°–130°	140°–160°	170°–190°	200°–220°	230°–250°	260°–280°	290°–310°	320°–340°	All directions Total
								YEAR						
Calm														0.8
1-3	1-3													9.1
4-6	4-7	1.7	1.7	1.7	1.8	1.8	2.2	2.6	3.5	3.4	2.5	2.2	2.4	27.5
7-10	8-12	1.7	2.1	2.6	2.0	1.4	1.8	3.2	5.1	5.8	4.0	3.1	3.2	36.0
11-16	13-18	1.0	1.0	1.6	1.0	0.5	0.8	2.2	3.1	3.1	2.9	2.0	2.4	21.6
17-21	19-24	0.2	0.1	0.2	0.1	0.1	0.1	0.4	0.6	0.6	0.7	0.5	0.5	4.1
22-27	25-31	0+	0+	0+	0+	0+	0+	0.1	0.1	0.1	0.1	0.1	0.1	0.6
28-33	32-38		0+	0+					0+	0+	0+	0+	0+	0+
34-40	39-46								0+			0+	0+	0+
41-47	47-54													
48-55	55-63													
56-63	64-72													
>63	>72													
TOTAL		4.6	4.9	6.1	4.9	3.8	4.9	8.5	12.4	13.0	10.2	7.9	8.6	99.7
													Percentage number of hours missed	0.1

Fig. 11 – Percentage frequencies of winds.

Measurements in the wind tunnel investigation ought to be values at every location of wind speed averaged over both 3 seconds and 15 minutes (say) expressed as percentages of the meteorological standard wind speed for each of 12 wind directions. In the case of the 3 second average values, the wind speeds quoted ought to be the values which are exceeded for 1% of the sample which must exceed the stationary length. Fig. 12 illustrates such a form of presentation.

4.6 The Reduction of Results

From the meteorological data in the form of frequency of wind speed and direction Tables (typically illustrated in Fig. 11) and the wind tunnel results (Fig.12), the duration of time when the wind speed at every location, averaged over 3 seconds and 15 minutes, is in each range of the Beaufort Scale can be computed and presented as 'Hours of Wind' Tables, as in Fig. 13.

AVER'NG TIME MIN.SEC	LOC.	WIND DIRECTION 0	30	60	90	120	150	180	210	240	270	300	330
3	1	66	55	48	81	68	78	93	73	33	48	60	29
15	1	21	20	14	23	18	18	37	32	10	13	24	8
3	2	89	95	80	113	88	79	85	64	49	82	94	73
15	2	32	39	28	38	36	32	32	19	12	28	36	27
3	3	80	68	71	53	75	71	73	65	38	61	60	70
15	3	28	27	24	20	31	23	39	27	12	24	17	23
3	4	132	132	98	70	98	101	117	97	44	62	71	125
15	4	81	71	41	30	54	54	60	37	9	21	32	64
3	5	108	86	60	71	77	80	101	66	53	82	83	79
15	5	35	30	19	28	41	41	44	31	13	28	30	24
3	6	99	97	66	86	109	103	80	53	54	66	96	88
15	6	39	32	20	40	59	47	39	12	12	27	38	35
3	7	100	75	81	70	74	78	61	52	47	81	78	66
15	7	28	23	18	33	31	31	21	18	11	27	25	18
3	8	108	103	73	94	85	50	86	93	62	67	56	64
15	8	40	42	26	40	36	17	22	41	16	21	22	20
3	9	72	67	41	85	82	76	97	77	41	58	57	48
15	9	26	21	15	28	30	29	44	44	14	27	24	13
3	10	35	66	97	89	58	58	76	94	43	49	46	25
15	10	14	26	33	27	17	18	35	49	16	19	14	7
3	11	45	73	66	103	79	38	67	77	52	61	73	34
15	11	11	18	22	39	28	10	17	25	11	26	21	7
3	12	36	56	37	63	61	56	79	86	48	58	55	29
15	12	13	18	15	24	24	15	32	38	18	22	17	8
3	13	87	105	71	68	101	78	64	75	36	49	48	81
15	13	33	33	28	31	47	37	25	26	10	16	21	30
3	14	84	80	60	89	74	70	53	32	56	71	80	72
15	14	34	29	18	31	31	22	16	8	16	21	27	29
3	15	49	49	85	92	81	93	127	109	49	36	38	36
15	15	16	15	25	39	24	22	40	48	11	8	9	9
3	16	50	71	100	104	90	74	109	119	82	60	43	43
15	16	15	23	40	41	34	24	32	45	31	15	13	11
3	17	118	67	69	112	95	88	92	102	75	51	70	51
15	17	55	26	25	50	32	28	31	35	29	17	20	13
3	18	117	66	50	56	62	58	57	72	96	125	147	97
15	18	50	26	19	20	23	26	18	17	47	66	64	39
3	19	57	68	96	119	117	82	89	85	75	86	48	46
15	19	14	26	41	55	38	26	25	32	26	26	14	15
3	20	72	78	46	39	49	54	99	97	64	68	62	54
15	20	27	18	11	12	17	22	31	27	16	20	18	18
3	21	42	64	49	45	52	52	47	54	61	60	49	45
15	21	17	28	20	22	23	19	15	23	22	24	15	16
3	22	64	81	40	31	40	51	45	44	63	60	50	39
15	22	22	36	8	8	11	14	13	16	16	19	16	10
3	23	40	53	64	76	49	39	38	34	35	38	25	29
15	23	13	19	15	22	17	11	12	10	7	6	4	6
3	24	38	39	57	83	71	64	61	95	59	58	67	38
15	24	8	11	22	31	18	25	29	34	16	18	16	11

Fig. 12 – Velocities as percentages of the reference velocity.

MONTH 10

LOC.	B2	B3	B4	B5	B6	B7	B8	B9	B10
29	320.3	148.8	43.8	9.0	1.6	.0	.0	.0	.0
29	340.4	132.0	41.6	8.1	1.3	.0	.0	.0	.0
30	263.3	159.9	82.1	15.2	2.9	.1	.0	.0	.0
30	291.3	133.8	69.0	23.4	5.0	.9	.0	.0	.0
31	244.0	163.9	76.1	28.0	9.6	1.8	.1	.0	.0
31	268.1	111.7	74.0	40.9	19.2	7.1	2.2	.2	.0
32	355.6	133.6	29.6	4.5	.1	.0	.0	.0	.0
32	429.4	66.5	23.1	4.2	.3	.0	.0	.0	.0
33	468.3	48.6	6.5	.0	.0	.0	.0	.0	.0
33	487.0	12.9	.4	.0	.0	.0	.0	.0	.0
34	253.0	161.3	77.1	23.9	6.8	1.2	.1	.0	.0
34	282.8	111.2	77.2	36.7	12.2	2.5	.8	.1	.0
35	410.7	99.4	12.8	.5	.0	.0	.0	.0	.0
35	480.5	36.1	6.8	.0	.0	.0	.0	.0	.0
36	255.5	139.5	97.2	24.6	5.7	.9	.1	.0	.0
36	269.9	96.0	88.6	48.9	14.9	3.7	1.3	.1	.0
37	353.0	97.6	53.8	14.9	3.8	.3	.0	.0	.0
37	368.4	74.5	53.7	19.7	6.1	1.0	.0	.0	.0
38	268.0	153.1	83.7	15.9	2.3	.5	.0	.0	.0
38	289.3	110.7	80.8	33.2	7.7	1.3	.4	.0	.0
39	279.1	143.4	80.2	16.8	3.5	.4	.0	.0	.0
39	321.6	103.6	68.7	21.4	6.3	1.5	.2	.0	.0
40	282.8	153.0	66.3	17.2	3.9	.3	.0	.0	.0
40	334.4	94.6	65.8	21.4	6.5	.8	.0	.0	.0
41	297.5	140.8	69.3	13.1	2.4	.3	.0	.0	.0
41	330.5	103.2	72.1	12.9	3.5	1.0	.3	.0	.0
42	247.7	164.3	83.6	21.9	5.2	.7	.0	.0	.0
42	269.9	119.0	80.2	38.8	12.7	2.6	.1	.0	.0
43	204.8	154.9	110.1	38.6	11.9	2.9	.3	.0	.0
43	186.7	126.4	106.5	68.5	25.3	7.1	2.5	.4	.1
44	288.0	131.4	64.1	32.4	6.4	.7	.4	.1	.0
44	327.0	101.4	49.4	32.9	9.8	2.3	.5	.2	.0
45	300.9	142.9	69.9	8.7	1.1	.0	.0	.0	.0
45	354.0	125.9	39.2	3.7	.6	.0	.0	.0	.0
46	224.3	159.2	108.5	25.3	5.6	.6	.0	.0	.0
46	235.4	152.2	106.2	24.0	5.1	.6	.0	.0	.0
47	293.8	165.9	52.7	9.7	1.4	.0	.0	.0	.0
47	354.1	113.5	44.4	9.3	2.2	.0	.0	.0	.0
48	224.2	148.5	108.0	32.3	9.0	1.2	.1	.0	.0
48	223.4	127.2	112.4	43.6	13.3	2.8	.7	.1	.0
49	303.0	146.1	55.6	14.4	3.9	.4	.0	.0	.0
49	367.3	94.3	43.4	13.5	4.2	.8	.0	.0	.0
50	282.9	146.3	71.2	18.8	3.7	.6	.0	.0	.0
50	321.3	125.9	55.7	16.6	3.2	.8	.0	.0	.0
51	210.0	158.2	106.9	35.2	10.5	2.5	.2	.0	.0
51	220.0	140.8	86.6	48.7	18.7	6.2	2.2	.2	.0
52	393.0	97.6	27.6	4.8	.5	.0	.0	.0	.0
52	442.3	62.8	16.0	2.3	.2	.0	.0	.0	.0
53	475.6	43.8	4.0	.0	.0	.0	.0	.0	.0
53	490.6	6.4	.0	.0	.0	.0	.0	.0	.0
54	223.4	159.9	105.7	27.8	5.7	.9	.0	.0	.0
54	258.5	144.8	76.6	32.9	8.2	1.9	.5	.0	.0
55	445.3	68.0	9.9	.2	.0	.0	.0	.0	.0
55	478.0	17.8	1.2	.0	.0	.0	.0	.0	.0
56	254.8	141.1	98.8	22.1	5.6	.9	.1	.0	.0
56	278.1	109.9	94.1	29.5	8.8	2.5	.5	.0	.0

Fig. 13 - Hours of Wind.

Although this is the basic data on which decisions ought to be made, it has become too bulky for easy digestion. Some form of predigestion is required, although the basic Tables (such as Fig. 12) ought to be presented in full in every report.

The predigestion takes the form of examining each location in turn, discovering the use to which it will be put and, using Table 4, allocating to each location a percentage of time when a given wind speed can be exceeded corresponding to the first two subjective assessment criteria. The uses will normally fall into four or five groups; for instance, car parks, pavements, pedestrian areas through which people walk, pedestrian areas for loitering and general access areas.

At Bristol a programme has been developed in which two symbols have been allocated to each range of the Beaufort Scale for velocities exceeding Force 6 (E and e) to Force 2 (A and a). Any percentage value can be allocated to each symbol, so that the UNACCEPTABLE and TOLERABLE criteria for a pedestrian stand-about area become (C, b) where 'C' represents a situation when the wind speed is greater than Beaufort Force 4 for more than 4% of the time, and 'b' a situation in which the wind speed is greater than Beaufort Force 3 for more than 4% of the time.

In a column at the left-hand side of the sheet next to the location number is listed the critical letters and a quick scan across the line will show in which month, if at all, the conditions at that location exceed the criteria for either gusts of long duration winds. A typical sheet is shown in Fig. 14.

CRIT	LOC	YEAR 3s15	MONTHS: JAN 3s15	FEB 3s15	MAR 3s15	APR 3s15	MAY 3s15	JUNE 3s15	JULY 3s15	AUG 3s15	SEPT 3s15	OCT 3s15	NOV 3s15	DEC 3s15
ECc	1	b A	B A	B A	B A	A A	A A	A A	A A	A A	A A	A A	b A	B A
ECc	2	A	A	A a	A	A	A	A	A	A	A	A	A	A
ECc	3		a	A	A	A	a							
dCc	4	B A	B A	B A	B A	B A	B A	A A	B A	B A	B A	B A	B A	B A
dCc	5	A	b	b	b	A	A	A	A	A	A	A	b	b
dCc	6	c B	c B	C c	c B	c B	c B	B b	B B	c B	c B	c B	c B	C B
dCc	7	A	A a	A a	A A	A a	A a	A				a	A	A
ECc	8	c A	C b	C B	C B	C B	c A	b A	A A	b A	b A	B A	c A	B A
Cbc	9	A A	B A	A A	A A	A A	A A	A a	A A	A a	A A	A A	A A	A A
ECc	10	A A	A A	A A	A A	A A	A A	A	A A	A	A A	A a	A A	A A
ECc	11	B A	B A	B A	B A	B A	B A	A A	A A	A A	B A	b A	B A	B A
Cbc	12	B b	c B	c B	c B	B b	B A	b A	B b	B A	B b	B A	B A	c B
Cbc	13	c B	C B	C B	c B	c B	B b	B A	B B	B b	c B	c B	c B	C B
dCc	14	B A	B A	B A	B A	b A	b A	A A	A A	b A	b A	B A	B A	B A
CBc	15	B A	B A	B A	B A	b A	b A	A A	B A	B A	B A	b A	b A	B A
dCc	16													
dCc	17	B A	C B	c A	c A	B A	B A	B A	B A	B A	B A	B A	B A	c A
Cbc	18	A	A	A	A	A	A	A	A	A	A	A	A	A
Cbc	19	A A	B A	b A	B A	b A	A A	A a	A	A	A	A	A A	b A
Cbc	20	B A	c b	B A	c b	B A	B A	b A	B A	B A	B A	B A	B A	c A
dCc	21	B B	c B	c B	c B	B B	B B	B b	B B	B B	B B	B B	B B	B B
Cbc	22	A	A	A	A	A	A	A	A	A	A	A	A	A
Cbc	23	A A	B A	b A	B A	A A	A A	A a	A a	A	A a	A	A A	b A
Cbc	24		A	A	a									A
dCc	25	B A	c b	c b	B A	B A	B A	b A	B A	B A	B A	B A	B A	c b
Cbc	26	A a	B A	A A	A a	A A	A	A	A	A	A a	A	A a	A a
Cbc	27	B A	c A	B A	B b	B A	A A	A a	A A	A a	b A	A a	b A	B A
dCc	28													
Cbc	29	A	A	A	A	A	A	A	A	A	A	A	A	A
Cbc	30	A	A	A	A	A	A	A	A	A	A	A	A	A
CBc	31		a	a										a
dCc	32													
dCc	33	B A	c A	c A	c A	B A	B A	B A	B A	B A	B A	B A	B A	c A
dCc	34	A	A	A	A	A	a		A	A	A	A	A	A
dCc	35	B a	c A	c A	b	B a	A	A	b	A	B a	b	B a	c A
dCc	36	B A	B A	B A	B A	A A	b A	A	b A	b A	B A	b A	b A	B A
ACc	37	B A	B A	B A	B A	B A	B A	A A	B A	b A	B A	b A	B A	B A
Cbc	38	B A	c A	B A	c A	B a	b	A	B A	B A	B A	B a	B A	c A
Cbc	39	A	A	A	A	A	A	A	A	A	A	A	A	A
Cbc	40	B a	B A	B A	B A	b a	b	A	B	b	B a	b	B	B A
Cbc	41	A	A	A	A	A	A	a	A	A	A	A	A	A
Cbc	42			a	A									
Cbc	43	A	A	A	A a	A	A	A	A	A	A	A	A	A
Cbc	44													

SHEET 1 of 1 TABLE OF ACCEPTABILITY CRITERIA USING VALUES:-

2.0%	1.0%	10.0%	5.0%	4.0%	2.0%	5.0%	4.0%	5.0%	4.0%
E	e	D	d	C	c	B	b	A	a
BEAUFORT ←6→		BEAUFORT ←5→		BEAUFORT ←4→		BEAUFORT ←3→		BEAUFORT ←2→	

(No symbol denotes ACCEPTABLE conditions)

Fig. 14 - Table of acceptability criteria.

It now becomes a simple matter to see whether conditions at each location satisfy the acceptability criteria or not. Those which satisfy the criteria can be forgotten without further comment. For those locations at which the conditions do not meet the criteria, the first question is to see by how much they exceed the criteria. This can immediately be seen from the 'Hours of Wind' Figure (Fig. 13). If the criteria required 5% (36 hours in the month) and the hours of wind showed that the given wind speed was exceeded for 36.5 hours, then the condition could be accepted as marginal. If, however, the exceedence is of considerable duration, then either the area can be down-graded to a different use requiring less strict conditions, or some remedial action is required. This is discussed in the next Section.

If the planning authorities, the client, the architect and consultant engineer can be involved in writing the criteria in the first instance before the investigation, the subsequent dialogue is easier because each has declared his interest and position.

4.7 Cures for Problem Areas

At each location with a problem the same procedure to suggest cures is applied. From Fig. 12 are determined those wind directions responsible for the high wind speeds (usually only one or two in number). The relationship between the offending location and the surrounding buildings is quickly seen in Fig. 10 when the troublesome wind direction is marked. It is almost always possible now to explain the cause of the high wind speed at the location and to suggest modifications to the buildings which would reduce its value. All problem locations are considered in succession.

In referring to cures, one general remark should be made: the use of solid screens or other such devices merely deflects the wind from one location to another. Care must be taken not to exchange one trouble spot for another and unknown one. If deflectors are used, the wind tunnel investigation of the surrounding areas ought to be repeated to ensure that no new areas of high velocity wind have been created.

5. CONCLUSIONS

The authors have tried to show that techniques are available to assist the architect to realise a design which will only be adversely affected by the wind to an acceptable extent. Although it might not appear obvious from the foregoing paper, they do appreciate that wind is only one of the constraints within which the design has to grow.

6. ACKNOWLEDGEMENTS

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The authors would like to place on record their thanks to Miss M E Gibbs who has typed many drafts of this paper. We are sure she is glad that this is the last!

APPENDIX 1

RELATED TOPICS OF IMPORTANCE

There follows a series of topics where man's relation with the problem of wind environment is at secondhand. The purpose of this Section is only to describe the problems for the sake of completeness, and not to go into them in any depth.

A1.1 Removal of Pollutants

The desire is always to ensure that the wind speed in the vicinity of buildings and building complexes is low: the impression is given that zero velocity would be ideal. But this is often not the case where pollutants have to be removed. The most obvious areas which require this ventilation are those used by motor cars, either for parking or for waiting to drop or pick up passengers. Other obvious point sources are outlets of ventilating systems, especially if servicing kitchens or certain food shops, and in these cases reingestion may also be a problem if the inlet and outlet of the system are located close together.

The conventional way of removing pollutants is to use chimneys. Tall ones can be designed so that they do not pollute the near field except in conditions of complete calm or when inversions occur. Low chimneys on low rise buildings can cause problems if unventilated areas are allowed to fill up with pollutants.

It is interesting to note the slight change in terminology: before, we were talking about gusts and windiness, now we are speaking of ventilation. In both instances, we mean the movement of air masses. The new reader of this subject is recommended to start with the light reading of Ref. 11.

A1.2 Fire Risk

An important aspect of this subject, and one which is particularly relevant to the present discussion, is that of smoke dispersal from covered shopping centres. This is a problem which must be considered when a roof is to be built to combat bad wind conditions in a previously open shopping centre. Vents must be provided in the roof for smoke removal in case of fire, but careful design is needed, and the possible adverse effect of wind must be considered.

Extensive tests carried out at the Fire Research Station on a full-scale mock-up of a covered precinct and in models (Fig. 15) have shown how the smoke spreads and what can be done to contain it.

Fig. 15 - Model test of smoke movement in a covered shopping precinct.

In the tests, a fuel typical of that which could be found in some of the shops and furniture stores of these shopping centres (wood, polyurethane foam, polystyrene pieces and foam rubber) is ignited in a compartment representing a shop. The shop rapidly becomes filled with black smoke, and toxic fumes billow out through the open shop front into the mall. In the mall the smoke forms a buoyant high-level layer which advances at a fast walking pace. This well-defined layer is usually destroyed when it reaches the end of the mall, with the smoke being brought down to a low level and returning towards the fire. Within about two minutes visibility is eliminated and virtual black-out conditions exist in the mall. These tests show that in a real mall there can be a serious escape problem and all the ingredients for panic, combined with conditions which make it difficult for the fire brigade to approach the fire and extinguish it. The problem is to prevent the smoke from travelling too far along the mall. The Fire Research Station have found that four remedial measures are necessary:

Smoke reservoirs must be created by the design of the mall or by installing screens under the ceiling.

Smoke must be extracted from the reservoirs as fast as it flows in, by mechanical or natural ventilation.

Air must be allowed to enter the mall at a low level to replace the gases flowing out.

Sprinklers must be installed in the shops to limit the size of the fire and the amount of smoke produced.

These remedial measures are illustrated in Fig. 16. All four must be used; none will work effectively on its own.

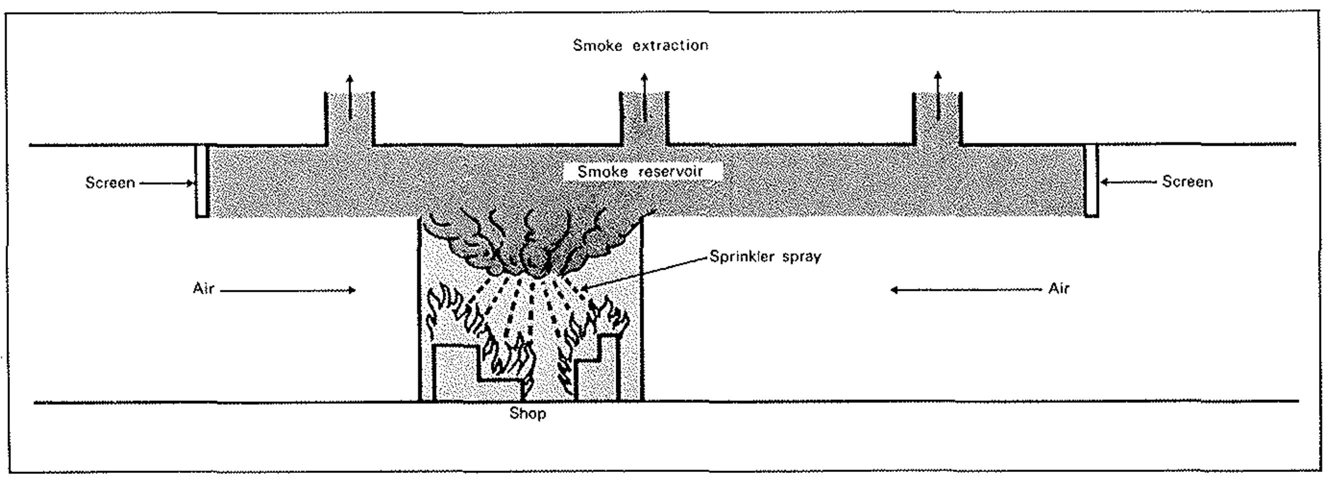

Fig. 16 - Measures needed to maintain access and escape routes.

Care has to be taken to prevent adverse wind pressures from destroying the smoke-clearing action of roof-vents. This could occur with a vent placed at the windward side of a tall building where wind entry could cause smoke-logging by mixing the previously stable layer of hot gases throughout the mall. In such cases, wind tunnel tests may be useful in establishing the optimum positions of roof vents.

It is important that the smoke control measures listed above should be considered at an early stage in the design of a building development as they may be difficult to incorporate as modifications later. As relaxations of the normal fire regulations will be needed whenever such covered shopping centres are built, advice should be sought at the design stage from the local authorities, the Building Regulations section of the Department of the Environment and the local fire authority. Some useful references (12, 13, 14) are given at the end of this paper.

A1.3 Wind Noise

Many elements of a building may become noise sources during windy conditions. Berhault and Davies (Ref. 15) have investigated many of these sources in a 14-storey apartment building in Southampton. They found that the wind noise spectrum inside a building could be conveniently divided into three spectral bands.

Infrasound - frequencies below 15 Hz. Measurements suggested that high noise levels could be expected in tall buildings during strong winds, the levels being comparable to those naturally occurring in the incident wind. Levels might be enhanced by eddy shedding from the building or by the wakes from neighbouring buildings.

Low Frequency Sound - 15 to 200 Hz. The acoustic behaviour in this band was found to be dominated by room resonance effects. Room resonance can be excited by natural wind turbulence or eddy shedding causing vibration of windows or wall panels, or by wind-driven cross-flows in lift shafts or ventilating ducts. Such resonances are common experience and include moaning in chimneys. Berhault and Davies were able to demonstrate clearly the strong coupling which can exist between window and room vibrations.

High Frequency Sound - 200 Hz to 10 kHz. The acoustic energy in the free wind in this band was found to be negligible compared with the levels observed in the building. In all cases such noise seemed to be related to some local mechanism excited by air flow through the building. Air flow through items such as partly-open windows, ventilator grilles, letter boxes and gaps around doors produced broad-band noise with a few strong discrete tones. The loud howling and whistling emanating from these sources was dependent on the detailed design of each component, and such details as the width of a window sill or frame were found to have a large bearing on whether a narrow window opening produced a significant noise level or remained inaudible. The details giving rise to each source appeared too complex for any general conclusions to be drawn about them beyond the fact that they were eliminated if the wind-generated internal flows were suppressed, which was hardly a practical procedure.

Berhault and Davies' results showed that the leeward side of the building was generally some 15 dBA quieter than the windward side. Their work is continuing with the study of the acoustic behaviour of letter boxes, door slits and natural ventilation grilles, the quantitative relationships between noise levels and wind strength not having been established yet.

A1.4 Rain Run-Off Effects

In the past, the texture of buildings was such that it could absorb a large quantity of rain during the heavy part of a storm. And as wind tends to remove water from the surfaces of the buildings in liquid form during a storm, as well as by evaporation, with gutters to collect and remove the rain impinging upon the roof, there was no problem from the rain impinging or being driven by the wind onto the walls.

The advent of walls constructed of impervious materials, coupled often with architectural features in the form of vertical projections, also often made of impervious materials and forming gullies to bring the water impinging upon the walls rapidly to ground level, has introduced a new problem due to the restricted possibility of removal of the rain by the wind.

In these latter extreme cases, the meaningful quantity must be the volume of rain impinging upon the face of the building/sec., divided by the length of the wall. Coincident values of wind speed and rainfall are outlined in Section A2.2, but the calculation of how much water impinges upon the vertical faces of tall buildings can only be estimated in the absence of surrounding tall building, using Ref. 16. Page (Ref. 17) quotes the results of some theoretical studies in which the static pattern of wind velocities averaged over long periods is assumed and shows impingement patterns on the building. Flower and Lawson (Ref. 18) describe a method whereby the rate of impingement could be measured in a wind tunnel experiment, allowing for the removal of rain from the wind by the surrounding buildings. This problem has arisen seldom in the past and work on remedies is scarce. However, it is possible that it could become more important in the future.

A1.5 Effect on Vegatation

This is a huge subject meriting whole papers to itself, ranging from the problem of windstorms on extensive plantations to the planting of a small hedge in a suburban garden. For the large problems, readers are referred to the Forestry Commission at Alice Holt Lodge, Wrecclesham, Farnham, Surrey, where professional advice can be obtained.

In windy areas, especially near the coast, we have all seen trees bowed over and stunted because of the continual battering from the prevailing wind, sometimes accompanied by salt-laden spray. Few species can survive at all, let alone prosper and look attractive in this extreme climate and careful choice of plant variety is essential. Even without the added salt spray, choice of species, their planting and subsequent cultivation, particularly in their early years, are matters which require careful attention. Beginners are referred to a simple publication by the Royal Horticultural Society (Ref. 19).

Certain pollutants, notably sulphur dioxide, tend to discolour or even kill certain species of trees and care should be taken not to mix the two. Concentrations of pollutants which are scarcely noticeable to the nose can still kill the trees, because of their continuous exposure to contamination. This aspect of occupation is referred to in a different context in Section 4.3.

A1.6 Aesthetics - Staining due to Wind-Rain Interactions

This may sound trivial, especially compared with talk of fire risks, but nevertheless it is relevant to the architect when he imagines the completed building. He has taken care in order that the building shall be visually pleasing to the viewer and in that care has been an appreciation of light and shade as well as mass. These effects can change during the lifetime of a building due to deposits on some areas and continual washing of others. Alkaline mortar may resist deposition longer than the stones it binds, producing a chequerboard effect not envisaged initially and unattractive to the viewer. The weathering of the newer materials in sun, wind and rain requires consideration, but guidelines in this general paper are impossible.

APPENDIX 2

BACKGROUND TO WIND DATA

A2.1 The Wind

A2.1.1 Generation of the Wind

Wind is created in the first instance by the differential solar heating of the earth's surface. Both cloud cover and the different reflectivities of the earth's surface produce a patchwork of atmospheric heating. Change of temperature affects the other two properties of state of the air, namely pressure and density. The changes in pressure in particular cause the air to move from regions of high pressure to regions of lower pressure and the movement of the air is called wind. Due to the rotation of the earth, equilibrium considerations for the air require that the velocity vector at heights well above the surface (of the order of 500 m) should lie close to the isobars or lines of constant pressure.

As with the flow of any gas over a surface, the mean velocity decreases towards the surface, until, at the surface, it is zero: the region in which this change occurs is called the boundary layer. This reduction in velocity is caused both by the frictional drag of the air over the surface and the drag of any bodies (such as trees, hedges, buildings, and mountains) protruding into the airflow. These retarding forces are transmitted through the layer by shear forces and by the exchange of momentum due to the vertical movement of the air. The co-ordinated movements in these layers of air break down into a random movement which is called 'turbulence'. If the surface is that of the earth, the region is called the atmospheric boundary layer: the main difference from boundary layers on any man made surface is due to the rotation of the earth. This causes the velocity vector to slew round with height from the ground, an effect called the Ekman spiral, but this has little relevance to the problems discussed in this paper and will be ignored.

The speed and direction of the wind vary with time in the way shown in Fig. 8; its mean value varies with height, type of surface, the averaging time and the geographical location. Other variations are of a smaller order.

A2.1.2 Quantification of the Wind

The mean value for the trace of wind speed in Fig. 8 is shown by the horizontal line. If wind speed is averaged over periods much shorter than the whole sample, say for example 3 seconds, then a range of values is obtained from the trace, the largest of which is always greater than the mean value of the whole trace. It becomes obvious that every measurement of wind speed must be accompanied by a statement of the averaging time or the measurement is meaningless.

In calculating wind loads for use in the structural analysis of a building, the averaging time is carefully chosen in the light of the component to be stressed and the shape and size of the building complex. Then another time quantity is added - the Return Period. This arises from the requirement that the component shall not fail during the lifetime of the building - say 100 years. The design wind speed defined as the maximum value of wind speed averaged over, say, 1 second, which will not be exceeded in 100 years is required to calculate the design loads. It is difficult to quote a value which will not be exceeded but, after recourse to extreme-value analysis, it is possible to determine a value which will be exceeded once in, say, 100 years, with a probability of P. Wind data in this form have been studied and are presented in extended form (with derivations) by the Engineering Sciences Data Unit in Ref. 6, or can be obtained in extract form in the relevant Code of Practice (the British Code is listed as Ref. 9).

But wind data in this form are of little use in solving the problems listed in the Introduction: much more frequent occurrences are important, for example the wind speed exceeded for more than 10% of the time. When more regular occurrences are introduced, a new parameter, the wind direction, must be added to the variables. It also becomes necessary to define groupings of wind speed and direction. Wind directions in the UK are usually divided by the Meteorological Office into 30-degree sectors, and wind speeds into the ranges of the Beaufort Scale. This format appears ideal for our needs, because it produces a managable number of divisions (10 in wind speed and 12 in wind direction): it is also convenient to devise procedures which require the wind data in this format, because the Meteorological Office is the main supplier of meteorological data in the UK. These data are available on a monthly as well as an annual basis (Ref. 8); a typical extract is shown in Fig. 11.

A word of warning is needed at this stage concerning the evulation of wind speed determining the limits of the ranges of the Beaufort Scale. The wind exemplified by the trace of Fig. 8 will represent a typical wind over an open site in one of the ranges of the Beaufort Scale. As mentioned before, this trace will be represented by different maximum velocities if different averaging times are used. Therefore, the velocities defining the ranges must declare their averaging time. The Table in Fig. 11, as most data from the UK Meteorological Office, defines the ranges with hourly average values. Ref. 6 shows that the ratio of maximum wind speeds for two different averaging times depends upon the intensity of turbulence, which is affected not only by the local type of environment (city centre, urban, etc.) and by the height above ground of the measurements, but also the detailed layout of the buildings locally. Consequently, no general relationship between the divisions of the Beaufort Scale and the averaging time is possible when considering wind amongst buildings.

A2.2 Rain

Rain in this context is not a problem in itself: we are interested in the interrelation of wind and rain. This aspect of the subject has been summarised by Lacy (Ref. 16), who defines a 'Driving Rain Index' which gives an indication of the risk that walls may be penetrated by rain. This index is calculated as the product of annual average rainfall and annual average windspeed, and a contour map in Ref. 16 shows the geographical variations within the United Kingdom. Lacy also shows that wind direction is important, and presents roses of the Driving Rain Index for 23 meteorological stations, based on simultaneous measurements of wind and rain. Further analysis shows that the higher the windspeed, the greater the percentage of that windspeed's time will it rain. This is illustrated in Table 5, with values for eastern and western meteorological stations separated. Readers requiring more information on this and other aspects of the inter-relation of climate and buildings are referred to Ref. 20.

Table 5 – Proportion of hours during which rain falls in different wind-speed classes. British stations, means for period 1957–66 (Ref. 20)

Wind-speed class (hourly averages) m/s	Eastern stations %	Western stations %
0.5 – 2.1	5 – 6	7 – 10
2.6 – 4.1	7 – 9	9 – 13
4.6 – 6.2	10	13 – 15
6.7 – 8.2	12 – 13	15 – 21
8.8 – 10.3	15 – 16	17 – 28
10.8 – 12.4	17 – 18	20 – 40
12.9 – 14.4	20 – 21	25 – 44
14.9 – 16.5		27 – 56
17.0 – 18.5		36 – 62
19.1 – 20.6		37 – 75

REFERENCES

1 PENWARDEN, A.D. 'Acceptable Wind Speeds in Towns' BRE Current Paper No. 1/74, January 1974, DoE.

2 HUNT J.C.R. Wind Tunnel Experiments on the Effects of Wind on People. Unpublished report to the Building Research Establishment. 1974.

3 HUMPHREYS M.A. 'A Simple Theoretical Derivation of Thermal Comfort Conditions' J Inst Heat and Vent Engrs. Vol 38, No. 95 (1970).

4 PENWARDEN A.D. and WISE A.F.E Wind Environment around Buildings. Building Research Establishment Report, London, HMSO 1975.

5 LAWSON T.V. 'The Measurement of Short Term Average Pressures in a Wind Tunnel Investigation'. Department of Aeronautical Engineering, University of Bristol Report No. TVL/7436, 1974.

6 ESDU 'Characteristics of Wind Speed in the Lower Layers of the Atmosphere near the Ground: Strong Winds (Neutral Atmosphere)' ESDU Data Item 72026, Dec 1972.

7 ESDU 'Characteristics of Atmospheric Turbulence near the Ground'. 'Part 1 – Definition and General Information'. ESDU Data Item 74030. 'Part 2 – Single Point Data for Strong Winds (Neutral Atmosphere)' ESDU Data Item 74031. (Both obtainable from Engineering Data Sales Ltd, 34 Haymarket London SW1Y 4HZ).

8 HMSO 'Tables of Surface Wind Speed and Direction over the UK' Met 0.792, 1968, HMSO.

9 BSI 'Code of Basic Data for the Design of Buildings'. Chapter V Loading, Part 2, Wind Loads. CP3 Ch V, Part 2, 1972, BSI.

10 NEWBERRY C.W. and EATON K.J. Wind Loading Handbook. Building Research Establishment Report. London, HMSO 1974.

11 SCORER R.S. 'Air Pollution' The Commonwealth and International Library of Science Technology Engineering and Liberal Studies. Pergamon Press 1972.

12 HINKLEY P.L. BUTCHER E.G. and PARNELL A. Fires in Shopping Malls. Architects Journal, 28 Nov. 1973 p. 1319.

13 HINKLEY P.L. Some Notes on the Control of Smoke in Enclosed Shopping Centres. Joint Fire Research Organisation Fire Research Note 875, 1971.

14 BUILDING RESEARCH ESTABLISHMENT Smoke Control in Single-storey Shopping Malls. Digest 173, 1975.

15 BERHAULT J.P.A. and DAVIES P.O.A.L. Wind Noise in Buildings. Symposium on Full Scale Measurement of Wind Effects on Tall Buildings and other Structures. University of Western Ontario, London, Ontario, Canada, June 1974.

16 LACY R.E. 'An Index of Exposure to Driving Rain' Building Research Station Digest No. 127, March 1971.

17 PAGE J.K. 'Five Meteorological Facets of the Design of Tall Buildings' International Association of Bridge and Structural Engineers and the Institution of Structural Engineers, Conference, Oxford. Sept. 1974.

18 FLOWER J.W. and LAWSON T.V. 'On the Laboratory Representation of Rain Impingement on Buildings' Atmospheric Environment, Vol. 6, pp 55-60, 1972.

19 SHEPHERD F.W. 'Hedges and Screens'. Wisley Handbook No. 17, The Royal Horticultural Society, 1974.

20 LACY R.E. Climate and Building. Building Research Establishment Report (to be published).