CLIMATIC FACTORS IN PLANNING AND ENVIRONMENTAL DESIGN

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Summary

The major aim of this thesis is to describe the requirements and methods for assessing climate in the planning and design process. Since the first step in an assessment is determining the basic relationships between climate and design problem, two specific design problems (termed 'activities') have been selected for detailed investigation. The activities are: pedestrian comfort in a cold environment, and average building heat loss. These activities represent two basically different types of climate-activity relationship which are assessed differently and which use different forms of data. Tentative climate-activity relationships are proposed for each. From these, a general theory of the analytic discovery of climate-activity relationships is derived. The climatic data required for such relationships is discussed, and the pathways for its use developed. The methods of estimating and predicting site climate are summarized, and a general procedure of assessing climate in the design process is proposed.

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The investigations into the climate relationships of pedestrian comfort and building heat loss are derived almost entirely from existing literature and theory. Design values are proposed, particularly for pedestrian discomfort due to thermal cooling and the physical, or mechanical, effects of wind.

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I. Introduction: climatic information in planning and design decisions.

1. Need for evaluating climatic aspects of environment.

Considerable interest has arisen over the quality of the environment. This is reflected in current research into the physical influences and economic costs of pollution, noise, visual amenity, and wilderness preservation or development. The need for quantifying such often intangible qualities is leading cost-benefit analysts into new, often indirect, scales of costing (Jones, 1971). The results of such work now appear in 'environmental impact statements' which must accompany many major proposals to alter the environment.

The influence of climate on most of the activities which are of concern to planners and designers has received far less attention, and the value of climatic quality for these activities has not been established. The major exceptions are climate's relationship to air pollution, extreme wind loading on engineering structures, and the Meteorological Office's traditional concerns with air travel, flood control, and agriculture. The influence of climate on many other important activities (used here in the general sense to signify 'design problem') is only imperfectly understood, hardly ever costed, and rarely included in the planning or design process. However, there is increasing concern about the effect of climate on the cost and quality of many aspects of building and planning. Page (1971), speaking of outdoor comfort, notes a "steadily deteriorating urban climate", and states that land scarcity is causing development on sites often unfavourable climatically for the purpose required. Reidat (1970) reviews international conferences on climate and the built environment in recent years.

Lacy (1972) has assembled a list of activities important in town planning, architectural design, the outdoor construction process, and maintenance and running costs. His survey makes a start at describing the relationships between climate and the activities by identifying which climatic elements are important for each. Another list (Section IV.1.1.) gives climate-influenced activities which concern land and town planners. It is instructive to investigate the relationships between climate and some activities, and to develop the procedures required to assess them. From noting what features are common among them, certain principles about climatic design can be deduced.

2. Requirements for assessing climatic information in the planning and design process.

A sequence of steps is required to accurately assess climatic influence on an activity:

A. The influence of climate on each activity must be determined. This involves:

  a. determining the measurable aspect, or assessment criteria, of the activity (termed the 'activity parameter').
  b. identifying which climatic elements affect the activity parameter.
  c. determining the relationships between the elements and the activity parameter.

B. Climatic data must be obtained in a form that can be used in the climate-activity relationship to predict the climatic effect. The pathway through which available climatic information is organized and simplified for use in the relationship must be understood.

C. Since there will be no climatic records for local sites or for future (unbuilt) sites, modifications of a general nature must be applied to the available regional data to estimate the specific site climate. These modifications must apply to the proper size scale of the site.

D. There must be a method for considering climatic effects in the design process. This involves:

  a. identifying the climatic effects relevant at each stage of the design process. This follows a decreasing scale, from the geographer's choice of region suitable for an activity, through land planning, town and building location, landscaping and building layout, to architectural details (Page, 1970).

b. applying the proper scale climatic data to the proper climate-activity relationship, in order to determine the magnitude of climatic influence.

c. costing the climatic influence in some way in order to make it comparable to other considerations at that stage in the design process.

3. Object of the thesis.

It was decided to investigate and formulate relationships between the climate and two specific activities in some detail. The activities are: pedestrian comfort in a cold environment (Chapter II), and average building heat loss (III). These activities represent two basically distinct types of climate-activity relationship which are assessed differently and which use different forms of climatic data. Comfort is a 'failure function', where the rate of heat loss above a limit results in discomfort. The discomfort is then assessed and costed in terms of the time that it occurs. Average building heat loss is an 'accumulative function', where the accumulated heat loss over time can be directly related to running cost.

As a result of the relationships developed in Chapters II and III, tentative design values are proposed for pedestrian thermal comfort and discomfort in the cold, pedestrian physical discomfort due to mechanical effects of wind, and for building heat loss. The relative effect of each climatic element on the activity is assessed, and the likely variation between sites described.

From the development of the relationships in Chapters II and III, a general theory of the analytic discovery of climatic functions is derived (Chapter IV.1.) This can be expressed in a sequence of operations, which are shown schematically for six activities in the appended Chart A 1. The operations involve analysing the activity itself, determining the relationship between each climatic element and the activity, and then summing the influences of the climatic elements into a function for the combined climate. Such functions, for each activity, are displayed graphically in the form of three dimensional arrays.

In Section IV.2., the climatic data required for each type of function is discussed. The pathway that such information must take in the application of the function is summarized; for comfort in Figure IV 4, and for building heat loss in Figure IV 6. The overall information pathway for evaluating the climate of a site is given in Figure IV 7.

In Section IV.3. the estimation of local and future site climate from available climatic data is discussed. This is done by means of general climatological and microclimatological information, and site and model testing. The procedure involves a sequence of modifications to the regional climate data which bring it increasingly close to the climate of the site. Such a sequence should go from large to small scale. A basic summary of site climate modifiers is given in Figure IV 8.

Section IV.4. puts the analysis of pedestrian comfort and climate in the framework of a design theory. An example is given of a model test of an urban complex with a pedestrian precinct. The climatic and comfort effects are mapped, giving a method for the designer to judge the suitability of his project early in the design process.

No attempt is made to cost the effects of comfort or heat loss, and consequently there is no attempt to suggest how to weigh climatic considerations against other planning considerations. It became clear during the preparation of this thesis that there is very little information to be found on the costs of climate. This is very possibly because climate cannot be effectively costed until reasonably precise functions between climate and activity are available. Following the functions developed in Chapters II and III, possible methods of costing are proposed.

In drawing together work from many disciplines, some rationalization of the many unit and symbol systems was required. The SI unit system has been used throughout, and the symbols decided on are listed in Appendix I 1.

CHAPTER II

II The effect of climatic factors on pedestrians out of doors.

1. Introduction.

1.1. Ways in which climate affects pedestrian behaviour.

The comfort of a pedestrian depends on the climate of the place he is in. The climatic elements act on him to make him comfortable or uncomfortable. Since he is likely to adjust his activity in order to remain comfortable, the climate influences his path and the length of time he remains outdoors. As a result, the popular success of public places and marketing areas can be heavily dependent on the climate within them. It is well known that merchants sales fluctuate with the weather (Zeisel 1960, 1963), and that store rents vary with the climatic quality of the store's location. The sunny side of the street, and the areas sheltered from wind and rain, bring higher rents. Observation of parks and public squares will show the sensitivity with which the mass of people select the climatically comfortable spots for the various forms of recreation (Paul, 1971), (Penrose and Lawson, 1971).

Page (1971) describes three levels of acceptability for the influence of climate on humans. In climatic terms, there are comfort zones, optimum performance zones, and tolerance limit zones. The first two zones are not identical, and the climatic 'bandwidth' of tolerance is greater than that of comfort. The nature of the place or activity being designed for will give an indication of which level of acceptability is required. In this chapter it is attempted to define the limit between comfort and discomfort at the cold end of the comfort zone.

1.2. The elements of climate involved.

The elements of climate which affect comfort are temperature, humidity, longwave radiation, solar radiation (sun or shade), precipitation, and wind. Their relative importance varies with the geographical location and the characteristics of the local climate. There are methods of controlling any of them, but in a cool outdoor environment the only factors which can be substantially manipulated are the degree of exposure to precipitation, radiation, and wind. Exposure to precipitation is lessened only by building direct overhead shelters over the routes or areas to be protected. Solar radiation and wind are more difficult to evaluate and control, and are discussed at length in this Chapter. The small influences of humidity and longwave radiation are described in Appendix 1.

_a_. Solar radiation. The sun or shadow times around buildings can be computed for any time of day and year using calculators such as that published by the Building Research Station, or by modelling techniques. The desirability of a given amount of radiation or shading is harder to determine quantitatively. In the British

Isles it is generally quite safely assumed that the more radiation the better, but the magnitude of the effect of radiation on comfort, should be known so that economically based decisions can be made about the cost of obtaining it.

b. The element wind is more complicated. It is very difficult to predict the actual windflow in any local space because of the complex relationships between the air flow and the obstructions on the ground. It is also difficult to assess the effect of wind on a person. Because of this difficulty very few attempts have been made to find design standards for wind control as yet. The following aspects of wind can be seen to affect people directly:

1. Wind and its effect on body heat loss and thermal comfort.
2. Wind-driven particles and rain.
3. Wind pressure and buffeting of body or carried objects.
4. Wind noise and interruption of audible communications.

Less directly it could affect them by dispersing pollutants or drifting snow. In this chapter, 1, 2, and 3 are considered. 2 and 3 are considered 'physical effects' of wind.

1.3. Proposed order of consideration.

A designer should have a tool or method for taking all the above effects into account to determine whether the windspeed will be acceptable for a projected outdoor environment. In this chapter, the effect of wind on thermal comfort is considered first. This is done by developing a function for wind and temperature versus comfort of individuals wearing various amounts of clothing and engaged in different levels and types of outdoor activities. Solar radiative heat gain is treated as a modifier to the more complex temperature-wind relationship. After this the physical effects, wind-driven particles and wind pressure, are described to determine limits for windspeed on comfort.

1.4. Difficulties in describing thermal comfort in temperate outdoor wind and temperature ranges.

a. Information available in the literature.

Difficulties in making a study of this type are considerable. The majority of available information is from investigations in the two extremes of indoor and Arctic climates. There is a large body of information on building heating and ventilating, the effects of draughts, and on the influence of temperature, humidity, and air movement over nude subjects. The range of temperature and wind speeds covered in these fields is necessarily small and close to an optimum temperature and nearly still air. Clothing, if present at all, is of the indoor variety. This narrow climatic range renders the various comfort indices (reviewed by Bruce 1960) useless for outdoor conditions.

The other extreme is found in tests done by Arctic explorers and the military in determining man's endurance in conditions of great cold and body cooling. In these there is rarely any consideration of comfort, the usual object being the determination of maximum times possible before physical injury occurs. The middle ground between these two extremes has been studied relatively little, and hardly ever in a form which is immediately applicable to civilians in normal outdoor exposure. This is due to a variety of factors described next.

b. The clothing worn under everyday conditions in non-extreme climates varies widely in the insulation it provides, and in how much and what parts of the body it covers.

c. The insulation of body tissue varies by more than 50% between optimum and cold air temperature. Also, insulation differs between individuals, sexes, and by acclimatization.

d. The range of temperatures in a 'temperate' climate extends from -15 to 38°C, and all have to be covered.

e. The outdoor environment changes so that the pedestrian rarely achieves thermal equilibrium with it. For urban pedestrians, this would be due in large part to the relatively short times spent out of doors, a high proportion of which would be spent adjusting from the indoor equilibrium held previously; and also due to such more rapid changes as occur in walking from a sheltered place to a windy place, or are caused by the natural turbulence of the wind. Experiments have for simplicity's sake always been made in as steady state conditions as possible: smooth windflow and uniform temperature. Measurements have been made of the rate of the body's reaction in being moved from one steady state condition to another, but it is hard to draw conclusions from these about the rate of change of thermal balance in normal outdoor conditions.

f. The problem of how body thermal equilibrium is related to comfort, and how comfort can be assessed, is a complex one that has not been tested extensively in cool outdoor conditions. Specifically, it is unknown whether the effect of severe local chilling is comparable to a mild overall cooling which might remove the same amount of calories from the body as a whole. There are a few physiological observations showing how the body will react to local as opposed to general chill, but these are not tied in with comfort observations.

g. Psychologically, imagined comfort might be more important than reality. Dunbar (1966) shows that, in one study at least, "climate is as much a set of expectations as a set of physical relations." The psychology of comfort perception in the outdoors is an unexplored field.

1.5. Assumptions about comfort: shortcomings of chapter.

As a result of the difficulties outlined above, a great number of assumptions about comfort, physiology, and clothing are made in developing the climate-comfort relationships in the following sections. Each assumption is explained in turn, but because they are based on lack of knowledge, they represent the shortcomings of the climate-comfort relationships. Briefly, the major assumptions are that:

a. The diverse experiments in the literature have sufficient common ground that their conclusions can be combined.

b. The relationships available for basically indoor or arctic conditions can be stretched toward the range of the temperate outdoors.

c. Comfort can be realistically expressed in terms of a steady state relationship based on deep body thermal equilibrium.

d. Single values of insulation for both tissue and clothing can be used to represent the variable coverage of a pedestrian in reality.

e. Local chilling of parts of the body does not affect comfort during thermal equilibrium.

f. Differences between sexes, individuals, time of day or season can be averaged out.

g. Psychological effects can be ignored.

h. For the physical influences of wind, a limiting velocity can divide 'acceptable' from 'unacceptable'.

1.6. Relevance of Chapter.

Against these shortcomings is the large need for outdoor climate-comfort relationships, and the paucity of applicable experimental data. The thermal comfort relationship function is built up in a stepwise manner, so that improvement of any of the assumptions or formulae within it can be made without disrupting the whole structure. The assumptions used allow for simple calculation of any level and coverage of clothing, level of metabolic activity, or of solar gain.

The magnitude of the assumptions _e_. and _f_. above can be assessed from the information presented in:

Appendix 2: Skin temperature and comfort.
Appendix 3: Sexual, diurnal, and seasonal differences.

These studies do not have sufficient experimental similarity to allow their conclusions to be combined with the proposed thermal comfort function.

At the end, desirable presentations of further, as yet unavailable, comfort information are proposed. Suggestions for research are also included.

Part A: Thermal comfort.

2. Physiological bases.

2.1. Dermal sensing and equilibrium of deep body temperature.

The concept 'comfort' has two physiological bases:

1.) Dermal sensing, the sensation of temperature (warmth and cold) in the skin.

2.) Neutral equilibrium of the deep body temperature, which the body tries to maintain at 37°C.

Comfort always involves a combination of the two. Most of the literature, however, puts the emphasis on deep body temperature as the controlling factor (Chatonnet and Cabanac, 1965; Benzinger, 1963). The state of deep body temperature controls:

<u>a</u>. The degree of sensitivity of the skin: at body temperature below neutral, the sensations of cold are accentuated even if the degree is not sufficient to cause 'discomfort'.

<u>b</u>. The onset of vasoconstriction, which occurs much sooner in a cold body than in a neutral body, (Hardy, 1953). Discomfort results from the drop in skin temperature due to vasoconstriction.

<u>c</u>. The onset of metabolic temperature regulation, which always entails discomfort even if it does raise the subjective sensation of warmth.

Dermal sensing is more important for comfort during transient thermal conditions, particularly during warming periods, when the sensations of warmth and comfort together increase faster than the body temperature. (See Section 2.3.). During cooling, a distinction must be drawn between 'cold' and 'uncomfortable'. Temperature sensations are more rapid than the body temperature linked comfort sensations, and the subject will sense 'cold' before becoming uncomfortable.

Dermal sensing is also important in describing the effects of local cooling, and the varying sensitivity of different areas of skin. There is very little data available for these, however. Gaydos and Dusek (1958) report that the strong cooling of a single part, such as a hand, will induce general peripheral constriction unless the body temperature is very warm. From this it might be inferred that general discomfort can result even with the body in neutral thermal equilibrium. However, the cooling in this experiment is by submergence in a cold water bath. It can probably be assumed that the pedestrian will not permit this degree of exposure. In contrast, if the deep body temperature is low (a deficit of $1^{\circ}C$), the warming of the hands alone will not cause them to vasodilate.

Gaydos and Dusek state that the hands are more sensitive to constriction than other exposed areas. Bruce (1960) quotes that the head and neck are the portions of the body surface most sensitive to thermal stimuli, with the backs of the hands next. If these areas are exposed, further stimulus from the rest of the body surface is said to be unlikely to change the subject's impression of the environment.

In conclusion, one can say that, except for warming transients, neutral body temperature is required for comfort, although it does not actually ensure it. Discomfort may exist together with neutral body temperature in cases of local chilling, but there is no conclusive data for this. Thus the assumption in this thesis that comfort is represented by deep body temperature is continued.

2.2. Temperature regulation.

2.2.1. Body insulation: vasoconstriction.

The body regulates its heat loss in two stages, vasoconstriction and metabolic response. For a description of the physiology of the temperature mechanism, consult Bader and Mead (1949).

The initial reaction to thermal imbalance in the case of body cooling is vascular constriction. Vasoconstriction is the muscular constriction of blood vessels close to the surface, and it impedes circulation of blood from the heated inner body to the cold periphery. This increases the insulation of the periphery, and it conserves the temperature of the inner body at the expense of the peripheral tissues.

Burton and Edholm (1955) describe the concept of an outer shell of tissue capable of changing insulation and of fluctuating temperature, surrounding an inner core of tissue which remains thermally constant. The two shells are thermally discontinuous. The depth of the outer shell varies between parts of the body, but has been estimated as between 2 and 5 cm (Winslow, Herrington, and Gagge, 1949; Adolph and Molnar, 1949). The temperature of the inner shell is 37°C at equilibrium. The temperature at the surface averages 33° in comfortable conditions, but can be as low as 20° during exposure to cold air (Aschoff, 1956; Gagge, Winslow, and Herrington, 1938). There is considerable literature on the thermal gradient in the outer shell.

Mean Body Temperature, MBT, is commonly used as an average temperature for the whole body. It is determined by the hypothalamus and skin temperatures, weighted 9 : 1. Equilibrium MBT equals 36.5°C, with hypothalamus at 36.9 and skin at 33°C. The variation of MBT is over a range of 2.5°.

Burton and Edholm state that very little energy is wasted in keeping the outer shell warm in cold conditions, but since over half the human body mass is in the outer 2.6 cm of the periphery, the loss to the air of the body heat stored in that mass can be substantial when vasoconstriction occurs.

In steady state, the value of heat transferred through the entire body surface of a nude at an air temperature of 28°C is an average of 11.6 W m^{-2} $^{o}C^{-1}$. At 12°C, the conductance is reduced by vasoconstriction to half, 5.5 W m^{-2} $^{o}C^{-1}$, holding the deep body temperature 1.5 to 2.0°C lower than at air temperature 28°C. This conductance is equal to that of a light sweater.
For a comparison, nudes at air temperature 48°C have a skin conductance of 46 W m^{-2} $^{o}C^{-1}$, four times that of 28° and eight times that of the vasoconstricted 12°.
The 'shell' concept is not fully accurate since large temperature gradients develop down the length of arms and legs when exposed to extended chilling, and the temperatures of the deep tissues towards the extremities approach those of the peripheral tissues (Barcroft and Edholm,1943). They suggest that there is a mechanism for constricting the flow in the deep tissues of the limbs, and that this mechanism is as or more important in conserving body heat than the insulation of the peripheral surface.

2.2.2. Body heat production: metabolic temperature regulation.

If vasoconstriction fails to maintain thermal equilibrium, the body will lose stored heat until the metabolic rate rises to produce the extra heat needed. In normal conditions, the metabolic rate begins to increase before the mean body temperature has fallen 1°C. The normal resting metabolic rate is 46 W m^{-2} body area at skin temperature 33°C (equivalent to 84 Watts for the 1.8 m^2 man). This rate rises to 58 W m^{-2} at skin temperature 31°, 64 W m^{-2} at skin temperature 29°, and to 70 W m^{-2} at skin temperature 27°C (Liddell, 1963).

The additional metabolic heat is generated in the muscles, first by involuntary tensing and then by shivering. Women seem to produce a metabolic increase earlier than men while showing no evidence of muscular tension (Hardy and Dubois, 1940). Shivering can quadruple the body's resting heat production, but its efficiency in warming the body is only 11% (Horvath, 1956) due to the increased circulation to the acting muscles. According to Edholm, it is unlikely that shivering can be maintained at over twice basal metabolism for more than a period of 20 minutes.

In the pedestrian situation, the metabolic rate is also increased by voluntary action, such as by walking faster. The subject of metabolic rates due to work is dealt with in Section 3, together with the thermal equilibrium calculations.

2.3. Thermal transients.

2.3.1. a. Temperature sensing and comfort.

The pedestrian is continually exposed to a changing thermal environment as he goes in out of doors, is affected by wind gusts and changing radiation. His reactions in sensations and comfort take place at different rates.

Stolwijk and Hardy (1966) have done research into the relation of temperature sensation to comfort and discomfort during temperature changes. In a cooling environment, cold sensation precedes discomfort, which has been found to correlate well to falling body temperature. The threshold for cold sensation is a rate of fall in skin temperature of 0.004°C per second (Bedford and Lewis, 1948), or 0.005 to 0.006°C sec^{-1} (Hardy and Hendler, 1959; Hensel, 1953). The detectable changes in ambient air temperature are ± 0.25°C for fast changes (time scale in seconds as in going from one room to another), and 1.7°C for slow changes over minutes (Bazett in Newburgh, 1949).

In a warming environment, the dermal sensation of warmth (threshold 0.001 - 0.002°C sec^{-1}) is accompanied by an immediate rise in comfort, and they precede the rise in body temperature. This creates a hysteresis effect for comfort - discomfort in a fluctuating environment: basically, the body will feel comfortable more often during such fluctuations than a monitoring of the air, skin, or MBT alone would indicate. The difference between the relatively immediate temperature sensation and the MBT lag extends to as much as 5 minutes, depending on the thermal difference. This applies to both cycles. Thus in turbulent winds comfort might be expected more of the time than the average wind would indicate.

2.3.2. b. Comfort and thermoregulation response time.

The response time of the vasomotor regulatory mechanism is roughly on the order of a minute (R. Passmore, personal communication). This means that higher frequencies of heat loss fluctuations would be followed with a lag or would not be responded to at all. The implication of this is that a designer could expect the significant physical response of vasoconstriction in cold spaces which take more than a minute to traverse.

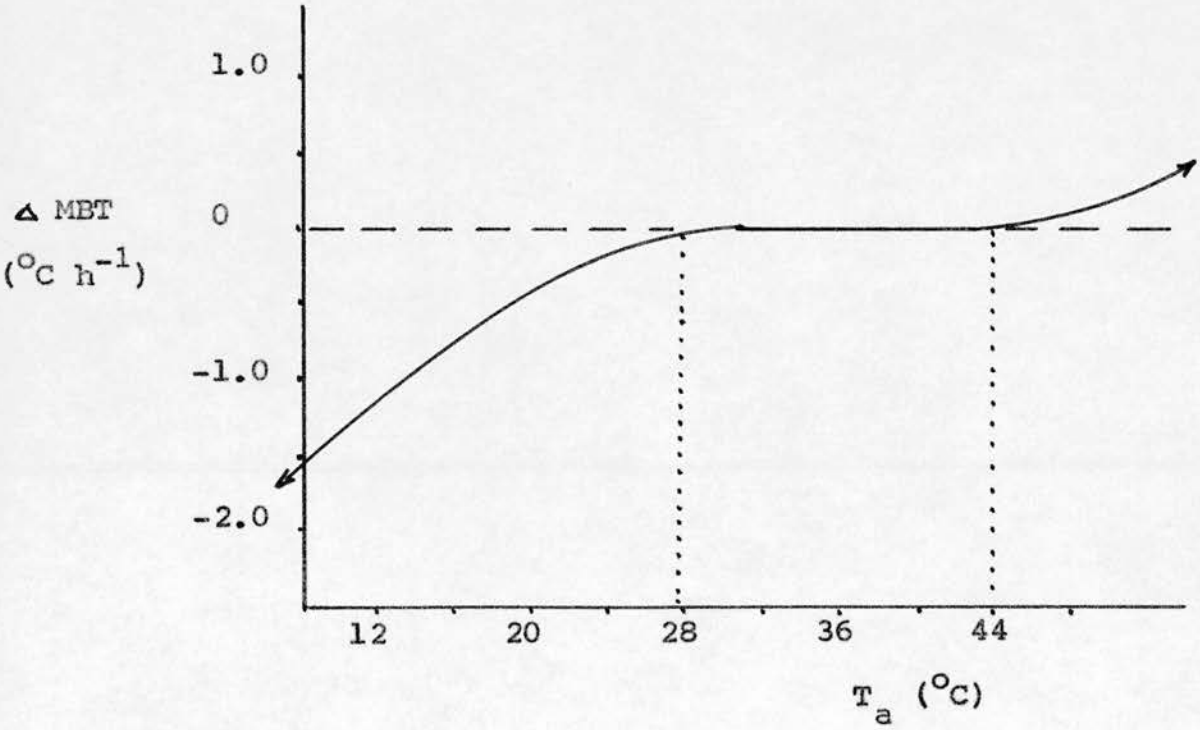
The rapidity of onset of shivering and metabolic temperature regulation depends on the level of MBT, which depends on the rate of cooling over a considerably longer time than one minute. The storage (rate of change of a body's heat content) is important for the early part of the body's response to cold. It is calculated from (Gagge, Stolwijk, and Hardy, 1967):

$$S' = M - (E' + 7.0(T_s - T_a)) \qquad (1)$$

Where S' is the storage, M is the metabolic rate, E' is the evaporative heat loss (all in $W\ m^{-2}$), and T_s and T_a are the skin and air (ambient) temperatures, respectively. The heat transfer coefficient here, 7.0, represents gain or loss of heat by radiation, convection, and conduction in $W\ m^{-2}\ {}^{o}C^{-1}$. Tissue conductance ranges from 11.6 (normal) to 5.5 (vasoconstricted) $W\ m^{-2}\ {}^{o}C^{-1}$, as described above.

As an example, if a subject walks at 2 mph from a warm environment ($T_s = 33^{o}C$) to a cold environment ($T_a = 3^{o}C$) the heat loss will be $S = 120 - (12 + (7 \times 30)) = -102\ W\ m^{-2}$ until the skin temperature drops or the metabolic rate rises. For an average man, a gain or loss of 47 $W\ m^{-2}$ over the entire body would be equal to a change of $1^{o}C\ hr^{-1}$ in MBT, the threshold used for initiation of metabolic response. This loss would occur in 47/102 hrs or 27 minutes for the subject described above, if he were completely exposed and continued to lose heat at $-102\ W\ m^{-2}$. In reality this rate of loss would soon decline due to falling skin T. Figure 1 is a representation of cooling rate for resting nude subjects in different ambient temperatures as calculated from equation 1.

Figure 1



The area between the dotted lines is the zone of thermal equilibrium, which is maintained by insensible vasomotor control below 33° and by mild perspiration up to 42°. It can be seen that changes in MBT of 1°C require on the order of 2/3 of an hour for nude subjects down to 12°C; with clothing this time would be longer. Corresponding temperature down to 0°C with outdoor clothing normally worn probably require a time the order of an hour to lower the MBT 1°C, providing no wind is blowing. However, vasoconstriction and discomfort will almost certainly precede this. If the MBT is low to begin with, as with variations described later, the time required for thermal chill is substantially reduced. S is also measured by weighting deep body temperature change (rectal) 0.6 and skin temperature 0.4 (Bazett and McGlone, 1927) but this has been disputed by Hardy (1953), giving $T_b = 0.8$ and $T_s = 0.2$ weighting. Further references are Hardy and Stolwijk (1966), and Stolwijk and Hardy (1966).

2.4. Conclusions.

Neutral body temperature in equilibrium conditions is judged to be an adequate representation for comfort, because of the paucity of other information on comfort.

The times and temperature drops required for dermal sensing, and for changes in body temperature, are to some extent known. However, the connections between these and comfort are not sufficiently known to make a transient temperature comfort model possible. This is particularly so in view of the lack of information on the influence of localized chilling on comfort.

Basing comfort on deep body temperature will tend to underestimate comfort in fluctuating heat loss conditions, such as turbulent wind. However, if moderate local chilling of exposed parts can induce discomfort in a warm body, then comfort might be overestimated.

3. Body temperature equilibrium: heat loss.

3.1. Variety of surface exposure found in outdoor conditions with normal clothing.

In cold weather, clothing normally covers between 85 and 90% of the body surface of men, and between 70 and 90% of the body surface of women. The exposed parts are the head (primarily the face, ears, and neck), hands, and as much as stockings fail to protect, women's legs. The insulative value for hair and stockings has not been estimated, but it is clear that they appreciably increase the insulation over that of bare skin. There are also areas of lesser exposure, such as areas within trouser legs, skirts, and to a lesser extent sleeves where air at environmental temperature circulates by a bellows type of action. Areas on the trunk and around the lower neck are normally quite well protected from circulating cold air. From this it should be possible to define areas on a clothed person's skin which would be fully exposed to the environment, partially sheltered areas, and the areas insulated by the full value of the clothing. The range of protection of different body parts by clothing arrangements could be determined also. But the difficulties in assigning average values of clothing for a whole population is obvious.
In this section, heat loss will be considered for two body surfaces: nude (exposed) skin and clothed skin. Three levels of clothing insulation will be considered, but only

one level at a time. The body is assumed either exposed, or uniformly clothed.

3.2. Heat loss from nude skin.

3.2.1. Means of heat transfer.

The body loses its heat by convection, evaporation from the skin and lungs, radiation, and conduction to cold objects. When there is no air movement and the temperature is below 28°C, insensible evaporation causes 25% of the heat loss of a resting nude man (12 $W m^{-2}$ surface), with radiation and convection accounting for the remainder (Newburgh 1949). The value of conduction is usually assumed to be negligible. In fact, this is probably a very significant factor in relation to comfort of the feet, as suggested by the marked vasoconstriction and thermal gradients down the legs in cold conditions. However, the experiments in the literature insulate the test subjects against conductive heat loss.

In decreasing temperatures, the amount of heat loss by evaporation remains constant. The percentages of radiation and convection loss vary with the ambient air temperature and with the velocity of air flow. Figure 2 shows the relative effect of convection, radiation, and evaporation on heat loss (from data in Burton and Edholm, 1955; and Bedford, 1948).

II FIG. 2: RELATIVE EFFECT OF EVAPORATION, RADIATION AND CONVECTION ON HEAT LOSS.
DERIVED FROM: BEDFORD 1948, AND BURTON & EDHOLM 1955.

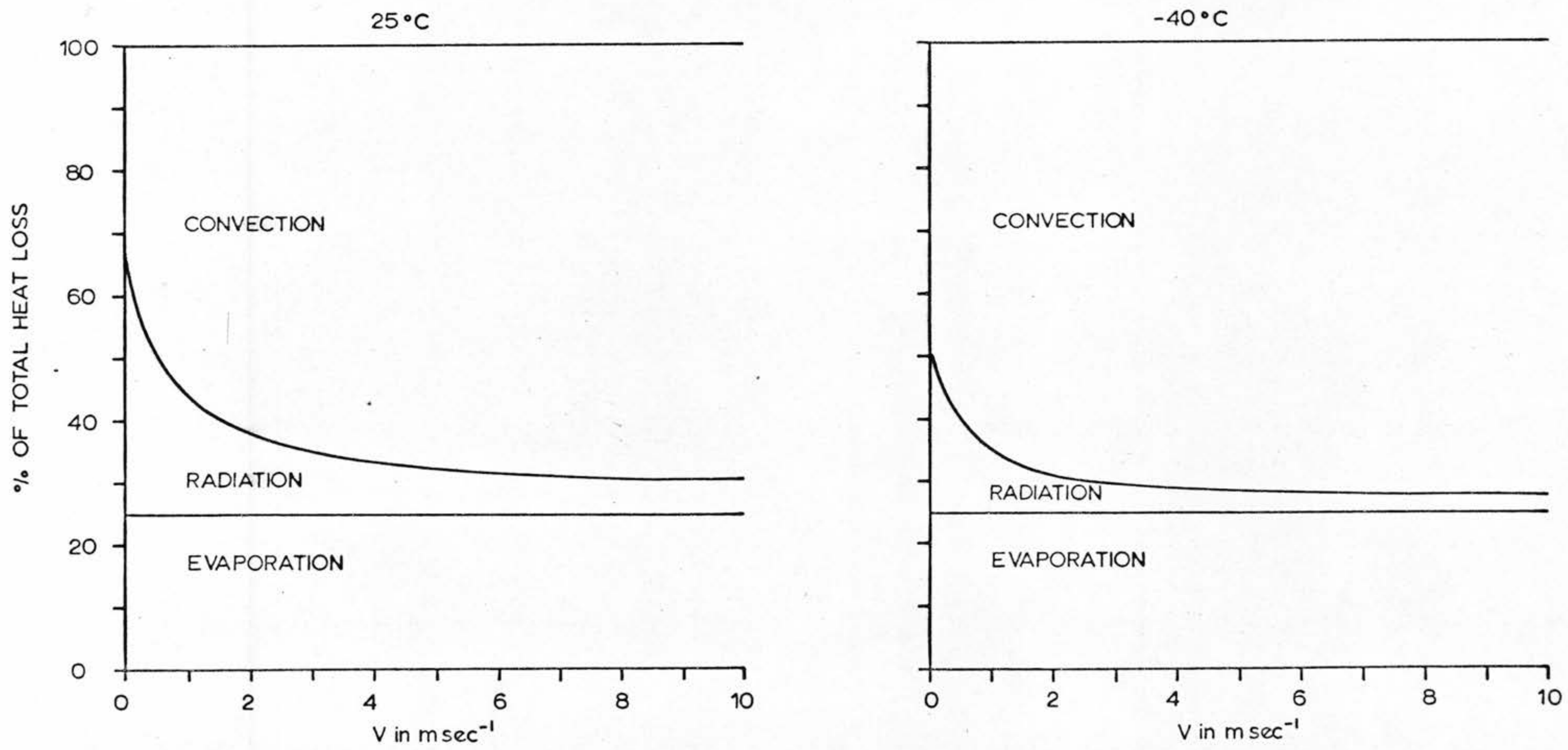


Table 1 gives the radiant heat loss Q_r and the radiative surface coefficient h_r for skin at 33°C in various ambient temperatures. Emissivity is assumed to equal 0.9. The calculations involved are described in Chapter III.

Table 1

Radiant heat loss from skin

T_a	Q_r $(W\ m^{-2})$	hr $(W\ m^{-2}\ {}^{o}C^{-1})$
20	76	5.8
10	125	5.4
0	165	5.0
-10	200	4.7
-20	242	4.5

It is clear from Figure 2 that increasing body movement or outer air speed markedly increases the role of convection while relatively decreasing the effect of radiation. Convective heat loss becomes the key factor to consider when determining the total heat loss of people in a cooling wind. Since the radiation loss does not change for different wind velocities, the shape of the wind effect curves is entirely based on the physics of convective heat transfer.

3.2.2. Surface areas of body parts.

The quantity of heat loss is proportional to the surface area of the skin. This is determined by the Du Bois formula (1937):

$$A = W^{0.425} \times H^{0.725} \times 71.84 \qquad (2)$$

where A is the area in cm^2, W is the body weight without clothing in kg, and H is the body height in cm. Figure 3 is a graphical representation of this (Houghton et al, 1929; Gagge, Herrington, and Winslow, 1937). Posture can reduce these total values by up to 10%. The proportion for the parts of the body are figured by the approximate 'rule of nines': 9% head, 18% arms, 36% legs, 36% trunk. The exposed areas described in Section 3.1. above are calculated from this rule.

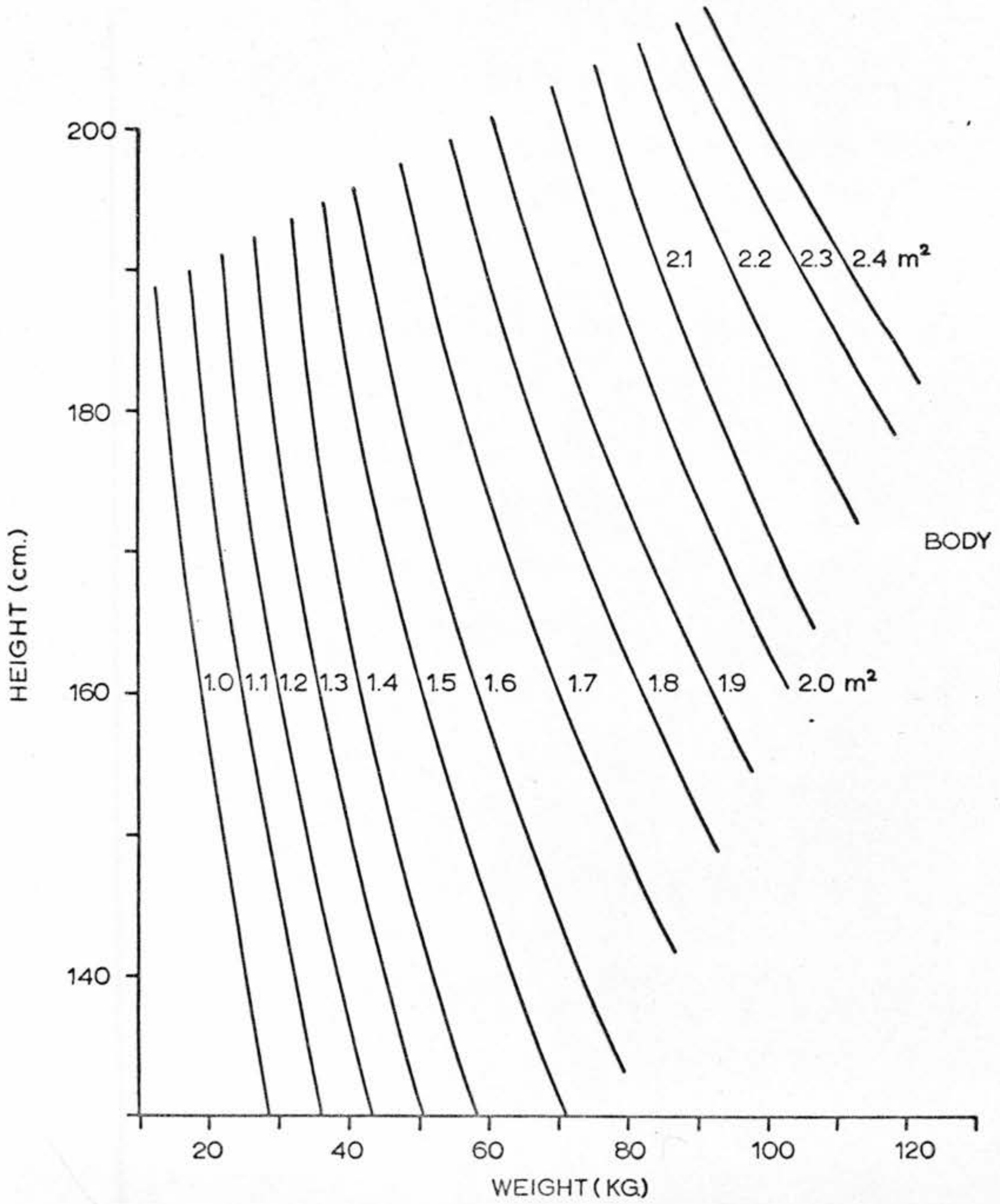
3.2.3. Review of formulae for the convective cooling of nude skin.

a. Formulae without a still air constant.

The rate of heat loss due to convection has been expressed in several formulae which give somewhat inconsistent results. The most common format is:

$$Q_c = AK\, v^{0.5}\, (T_s - T_a) \qquad (3)$$

(Winslow and Herrington, 1949) where Q_c is the heat loss by convection in Watts, A is the Du Bois surface area modified to apply to a seated subject (m^2), K is a convection constant, v is the velocity in m s^{-1}, and $T_s - T_a$ is the difference between skin and air temperatures, in°C. The average value of K for a nude man in a semi



II FIG. 3: BODY SURFACE AREA IN RELATION TO HEIGHT AND WEIGHT.

TRANSPOSED TO METRIC UNITS FROM HOUGHTEN et.al., 1929 reclining position was found to be 10.7 (units here transposed). This formula was used by the authors for windspeeds between 0.07 and 0.55 m sec^{-1}, but they state that the relationship should hold to 36 m sec^{-1}. Figure 4 gives the plot of this equation, along with the others that follow.

Fanger (1967) quotes Winslow, Herrington, and Gagge (1939) giving K = 12.0 for velocities less than 2.6 m s^{-1}.

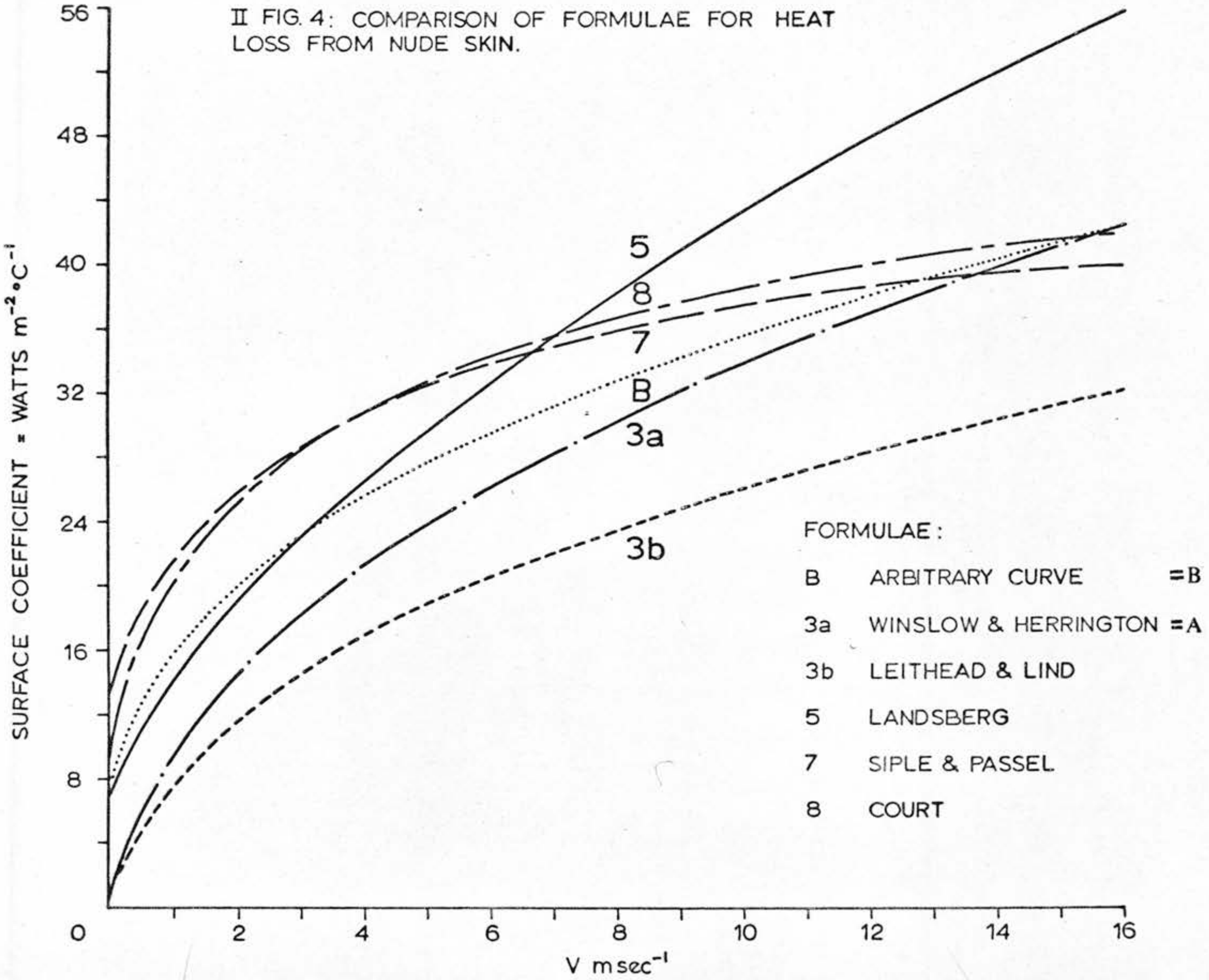
Leithead and Lind (1964) give K = 8.1 for their formula, which is intended for warmer conditions. Since wind cooling is accentuated by surface evaporation, this value would make the above two values seem high.

Buettner (1951) gives K = 4.9 for the same relationship, but this value seems exceedingly low.

b. Formulae with a still air constant.

Still air thermal convection (free convection) has been estimated by Hardy and Du Bois (1940) as between 5 and 7 W m^{-2} $^{o}C^{-1}$ in natural conditions. This is reflected in the following formulae.

Landsberg (1958) gives a formula for convectional and radiative heat loss. The values are higher than those of the Winslow and Herrington equation. The velocity exponent of 0.62 is suggested to be more accurate



II FIG. 4: COMPARISON OF FORMULAE FOR HEAT LOSS FROM NUDE SKIN.

than 0.5 above 2 m s^{-1}.

$$Q = (a + bv^{0.62}) (T_b - T_a) \qquad (4)$$

where Q is in Watts, v is in m s^{-1}, T_b is the body temperature which is usually 4° higher than skin temperature, and a is the free convection constant. The equation with recommended constants (transposed) is:

$$Q = (5.9 + 8.9 v^{0.62}) (4 + T_s - T_a) \qquad (5)$$

Values are given for the cooling of a wet body, where T_a' becomes the wet bulb temperature, and a = 8.9 and b = 11.4.

Hill (1923) gave a similar format, with almost the same free convection constant (10 W $^{\circ}C^{-1}$) but with a velocity factor that gives exceedingly high results. They are not plotted.

$$Q_c = (10 + 35 v^{0.5}) (T_b - T_a) \qquad (6)$$

The high results might be due to the use of a katathermometer as a cooling model to represent human skin.

Another equation can be extrapolated from the Wind Effect Index chart in the Handbook of Geophysics (1961). It is based on Siple and Passel's wind chill formula for the cooling of water in a cylinder in freezing air (1945):

$$Q_c = 1.16\ (10\ v^{0.5} + 10.45 - v)\ (T_s - T_a) \quad (7)$$

with the units the same as before. T_s is taken as 33°C. Radiative loss is included here. The plot of this curve is similar to that of Winslow and Herrington's but at low wind velocities Q is greater, and tapers off at higher windspeeds. This is due to the influence of radiation and free convection.

Court (1948) reviewed Siple's data and suggested the following constants of the same formula:

$$Q_c = 1.16\ (10.9\ v^{0.5} + 9.0 - v)\ (T_s - T_a) \quad (8)$$

These constants give a greater response of Q_c to wind velocity and a lower heat loss at low velocities. The curve more closely follows Winslow and Herrington's than Siple's original curve.

Another development of this is given by Plummer (1944, 1945) (in Horvath, 1960) who worked with the convective cooling of a cylinder 7 cm in diameter. A transformation of his results is:

$$Q = 0.32 + 9.7\ v^{0.5} + 2.2v \quad (9)$$

where the units are the same as above. The graph of this equation shows little similarity to Siple's, and the results are not plotted on Figure 4.

3.2.4. Conclusions.

The heat loss curves presented in Figure 4 show considerable variation. This is due primarily to two causes:

_a_. Some of the formulae represent the cooling of forced convection only, while the others include the effects of free convection and radiation.

_b_. Most of the formulae are extrapolated beyond their experimental range. This applies to wind velocity, temperature difference, and type of object modelled.

None of the curves can be said to represent the thermal characteristics of nude skin in an outdoor cool environment. The necessary empirical data is lacking. There is enough agreement among them, however, to give a rough estimate of the magnitude of heat loss expected. Their results can be checked against wind chill curves which have had empirical testing, but in which nude skin cannot be isolated from the types of clothing assemblies worn. These will be discussed later, after determining the heat loss through clothing and nude skin combined.

For the purposes of the calculations which follow, two nude skin formulae are used.

_a_. The first is formula (3) with the constants of Winslow and Herrington, as used by Fauger (1967). This has no terms for free convection or radiation loss, and Q becomes zero in still air conditions. Thus very low heat loss will be predicted in still air conditions. The radiation term is omitted, which means the radiation balance can intentionally be manipulated.

b. The second formula is an arbitrary one which adds a radiation and still air convection term to formula (3) in the low velocity range, but which flattens out somewhat in the higher velocities similar to formula (7) and the wind chill curves described later. It is plotted on Figure 4. It resembles formula (5), or an average of formulae (3) and (7), up to 5 m s^{-1}. Above this velocity it becomes roughly equal to formulae (3) and (7). The radiation coefficient is roughly 5 W m^{-2} $^{o}C^{-1}$, and the free convection coefficient roughly 4 in still air.

The influence of evaporation is not considered in these curves. It is added in later, in the combination of heat loss avenues.

3.3. Heat loss from clothed surfaces.

3.3.1. Insulation: the clo value and typical values.

Numerous workers have made use of an arbitrary insulation, or resistance, unit called the clo, and have presented their information using this unit.

$$1 \text{ clo} = 0.16^{o}C \; m^{2} \; W^{-1}$$ (Gagge, Burton, Bazett, 1941).

In the physiological literature it is symbolized by I, but here the resistance symbol R is used.

It is useful because it is easy to imagine practically. A clo is the insulation that keeps a resting subject with a basic metabolism rate of 58.1 W m^{-2} comfortable with a mean skin temperature of 33°C when seated in an atmosphere of dry bulb temperature 22°C.

a. Air.

The theoretical value of insulation of absolutely still air has been estimated as 7 clo per inch of thickness at 18°C. The clo protection of the film of air around the clothing or skin varies from 1.0 clo (still air) to 0.19 clo at high velocity (above 10 m s^{-1} at least). The still air clo value is lower at low temperatures when thermal convection is high.

b. Skin.

The clo value of the insulation of the peripheral tissues ranges from 0.8 to 0.15 depending on the level of vasoconstriction (Burton, 1946). Gagge, Stolwijk, and Hardy (1967) report an extreme value of 1.1 clo in vasoconstricted nudes at 12° ambient temperature.

c. Clothing.

The ordinary business suit for men has a value of approximately one clo. A light jersey has approximately the same. The best military arctic clothing has in practice a value of about 4 clo to the inch of thickness, and this value is the usual total maximum for cold weather clothing. Pugh (1967) asserts that down-filled clothing approaches 7 clo in value.

Measurements of the insulative value of clothing have usually been made on heated man-sized dummies (W & H 1949) or on small cylindrical models wrapped in the appropriate thickness of material. Formulas for computing the results of these tests are found in Burton and Edholm (1955). The tests that have been carried out are all of military cold weather assemblages (Lee and Lemons, 1949).

There is decreasing insulative value for each additional layer of clothing. This is largely because of the additional surface area that each of such layers imposes. Thermal heat loss equations for clothing require a parameter for the increased surface area which the clothing adds. Correlations have been made relating clothing weight to its surface area. A value of 0.127 m^2/kg (0.622 ft^2/lb) over the nude surface area (found above, Figure 3) has been accepted as a good average (Herrington, 1947).

It is difficult to apply the information above to the usual design of clothing found in civilian life. The only reference found on the insulation of normal civilian clothing is Newburgh's (1949) hypothesis that a man with overcoat, galoshes, scarf, thin gloves and hat might be lucky to have 0.5 clo on his hands, 1 clo on his feet, and 2 clo on his arms and torso. A comparison of men's and women's clothing is found only in a comparison of the weight of the clothing that they would wear at equivalent temperatures: indoor clothing for 19°C (66°F) weighed 1½ lb for women against

6½ lb for men, and for 12°C (55°F) 6 lb against 14.5 lb for men (Newburgh). It is easy to imagine that design considerations make these weight differences even more extreme, but it is impossible to say how much. It is clear that this data is insufficient for anything but a feel of what the clothing insulations are. Dummy tests are required of a variety of clothing types to determine their overall and local clo values; and these tests need to be amplified with subjective tests of live subjects in the same conditions. Until this is done, approximations of clothed areas will have to be made uniformly in one clo intervals.

3.3.2. Formulae for heat loss through clothing.

The total insulation around a body is the sum of the three insulations, air, clothing and skin. The expression for total heat transfer is given as:

$$Q = \frac{T_b - T_s}{R_s} + \frac{T_s - T_{cl}}{R_{cl}} + \frac{T_{cl} - T_a}{R_a} = \frac{T_b - T_a}{R_s + R_{cl} + R_a} \qquad (10)$$

where Q is in Watts m^{-2}; skin, clothing and air temperatures are in ^{o}C, and insulation R is in $^{o}C\ m^2\ W^{-1}$.

Winslow and Herrington (1949) give a value of K for lightly clothed subjects to be fitted into their wind cooling equation for nudes. This is 1.6 $W\ m^{-2}\ ^{o}C^{-1}\ (m\ s^{-1})^{-\frac{1}{2}}$. It is larger than the value of K for the nude man.

Furthermore the surface area of a clothed man is larger than that of a nude, as mentioned above. But for this formula the surface temperature is the temperature of the clothing, not the skin, with the result that the value $(T_{cl} - T_a)$ is less than $(T_s - T_a)$. The resultant value of Q is smaller for the clothed man. The usefulness of this equation is severely limited in that there is no useful correlation between comfort and clothing temperature as there is with skin temperature. It could be helpful in field testing however.

Burton and Edholm (1955), and Carlson and Hsieh (1965) give the formulae which are used for the conclusions developed in this paper. They are the same formula, with a difference in that the effect of the wind is conceived as a still air temperature decrement related to wind speed in the Burton and Edholm formula, and is given as an insulation decrement related to wind in the Carlson and Hsieh formula. These formulae are probably limited to steady state conditions below 21°C.

If Q = heat loss in Watts m^{-2}
T_s average skin temperature, °C
T_a air temperature, °C
R_a insulating value of air, clo or $m^2\ {}^oC\ W^{-1}$
R_{cl} insulating value of clothing, clo or $m^2\ {}^oC\ W^{-1}$
R_{sa} insulation of still air, clo or $m^2\ {}^oC\ W^{-1}$,

$$Q = \frac{K(T_s - T_a)}{R_{cl} + R_a - W} \qquad (11)$$

where W = wind insulation decrement, in clo or $m^2\ {}^oC\ W^{-1}$, and K = 0.0026 when R is in clo and K = 0.0162 when R is in $m^2\ {}^oC\ W^{-1}$.

Carlson and Hsieh give the relationship:

$$W = \frac{R_{sa} \quad R_a\ B\ \left(\frac{v}{vo}\right)^{\frac{1}{2}}}{1 + R_a\ B\ \left(\frac{v}{vo}\right)^{\frac{1}{2}}} \qquad (12)$$

where v is in $m\ sec^{-1}$

vo equals $1\ m\ sec^{-1}$

B is a heat loss coefficient, given as $14\ W\ m^{-2}\ {}^oC^{-1}$

$R_{sa} = 0.125\ {}^oC\ m^2\ W^{-1}$, or 0.78 clo

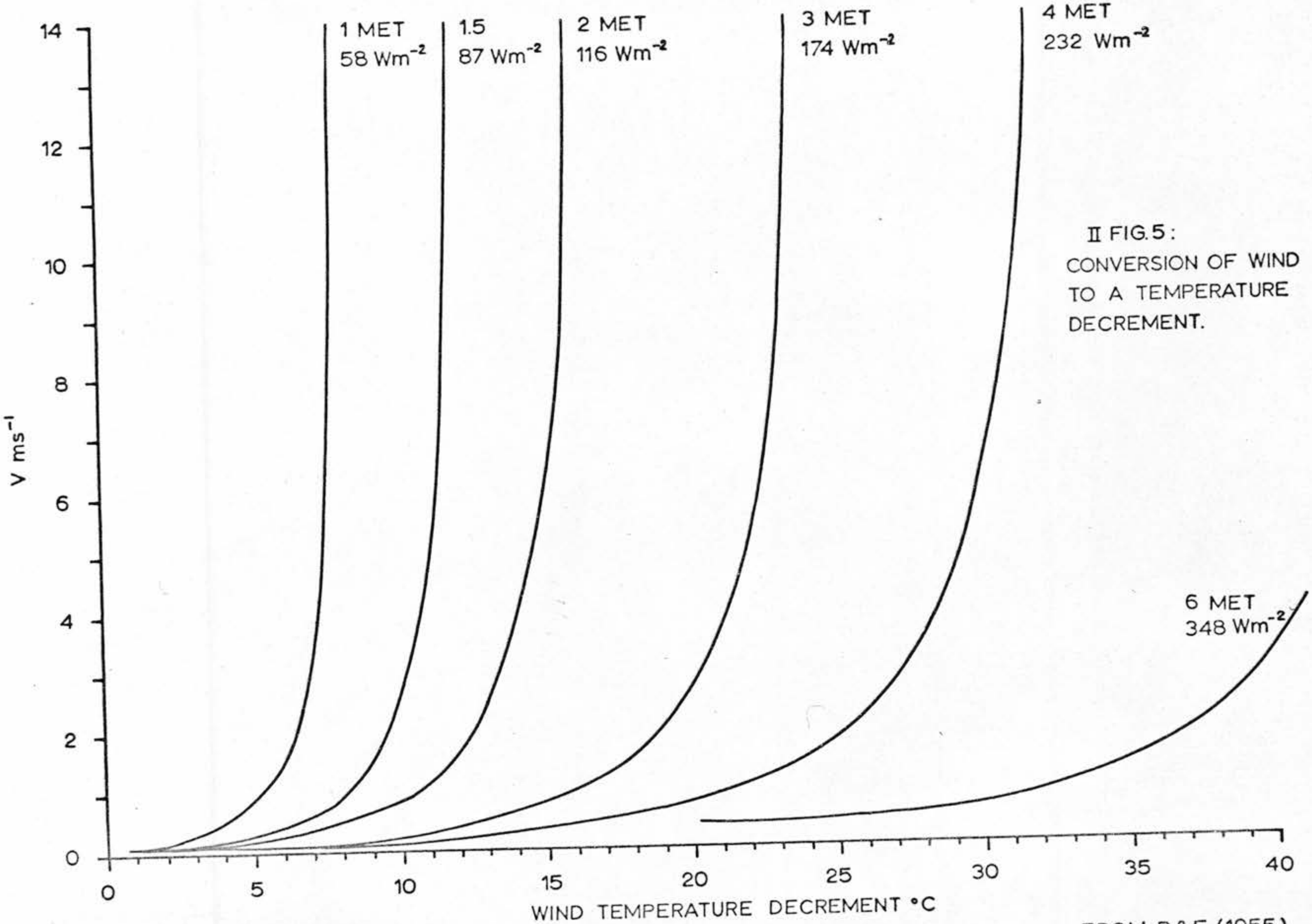
Values for W are computed in the literature.

The Burton and Edholm version is:

$$Q = K \left[\frac{T_s - (T_a - \frac{Q \cdot W}{K})}{R_{cl} + R_{sa}} \right] \qquad (13)$$

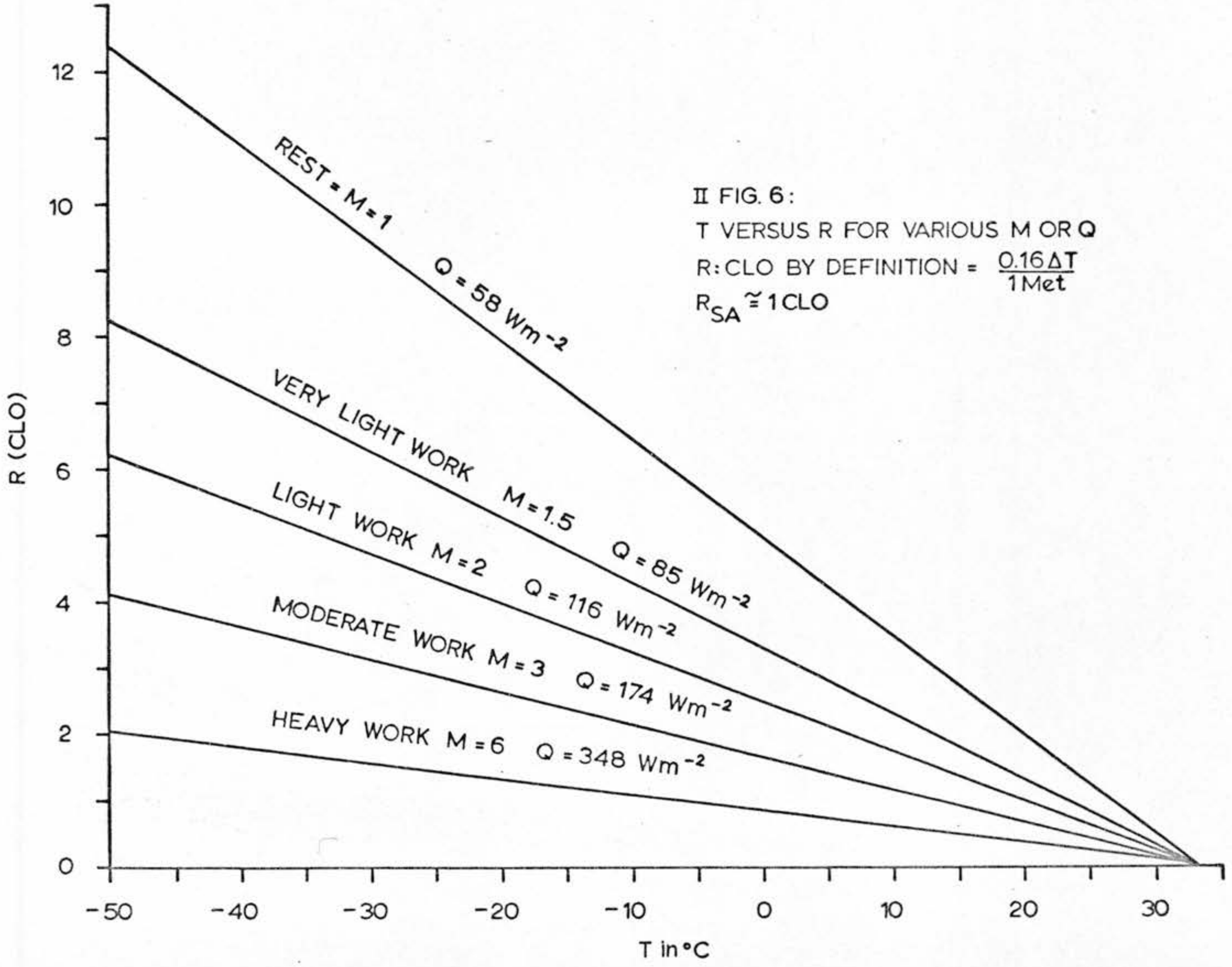
where K = 0.0026 when R is in clo units. R_{sa} is assumed to be 1 clo, as opposed to 0.78 clo in the Carlson and Hsieh formula. $\frac{Q \cdot W}{0.0026}$ in ^oC, is a 'still air temperature decrement', called the "thermal wind decrement" by the authors. Its relationship to actual wind speeds has been determined experimentally.

A list of values is given in the reference. A graphical representation of the wind decrement is given in Figure 5.



II FIG. 5: CONVERSION OF WIND TO A TEMPERATURE DECREMENT.

FROM B&E (1955)



II FIG. 6:
T VERSUS R FOR VARIOUS M OR Q
R: CLO BY DEFINITION = $\frac{0.16 \Delta T}{1 \text{Met}}$
$R_{SA} \cong 1$ CLO

It is used in conjunction with a temperature versus insulation graph at different heat losses (Figure 6) to determine heat loss or insulation requirements at any wind speed.

As R_a becomes large, the significance of the wind decrement decreases. With one clo clothing insulation, the wind can reduce total insulation by 45%; with 4 clo the change in insulation would not exceed 16%. Similarly at one clo the rise in heat loss between 0 and 5 m sec^{-1} is 110%, at 2 clo is 55%, at 3 clo 30%, and at 4 clo is about 20%.

As the rate of heat loss increases, the temperature decrement caused by the wind increases proportionately. For any given heat loss however, the temperature decrement due to wind will be the same regardless of the actual air temperature. This is understandable, since to maintain a given heat loss in progressively colder temperatures requires proportionately higher R values which reduce the temperature decrement.

3.3.3. Comparisons of formulae: conclusions.

The curves resulting from these formulae must be treated with some caution. Numerous field experiments have yielded data often substantially different from that developed here. For the example of the insulation decrement given above, tests by the RCAF give a rise of heat loss of 50% for people with 1 clo between still air and 5.3 m sec^{-1}. At 4 clo the rise was 15%. The discrepancy between this data and the formula at 1 clo is over 100%.

There are numerous other inconsistencies with other data. Unfortunately the conditions of experiment are never sufficiently controlled or stated to disprove the above approach, and no other relationships have been developed which can satisfactorily replace them. This is clearly an important area for field investigation.

These equations give the heat loss from a surface uniformly covered with insulation. They do not take into account convection within the clothing, wind penetration of permeable insulation, and the fact that no clothing assembly gives complete coverage or uniform insulation. Nor do they consider evaporative heat transfer. Approximations for these discrepancies are described next.

3.4. Combination of nude and clothed heat loss values.

3.4.1. Insulation coverage.

For a theoretical calculation of the effect of wind on a normally dressed subject a number of approximations need to be made. The first is about the amounts of insulation obtained from different levels of clothing. In the absence of descriptive values, it was deemed advisable to calculate the equations in 1 clo increments, and to roughly indicate the amount of clothing that each clo number represents. That is, 1 clo is the equivalent of a light jersey or a men's three piece suit, 2 clo would be the suit with a light overcoat and hat on, 3 clo would be with a heavy overcoat, boots, earmuffs and mittens, and 4 clo would be a heavy assemblage such as military cold weather uniforms and arctic clothing. 3 clo is the maximum that one would expect civilians to wear, and parts of their bodies would never be insulated by more than 2 clo, such as the legs, and hands.

The next approximation is of the relative insulations to be assigned to the various areas. It is thought that the various insulations found in a particular clothing type could be approximated by a single clo value for the total covered part and by the equation for nude skin heat loss for the exposed parts. This is necessarily rough, for the precise percentage of exposed area cannot be used because of varying degrees of insulation across the body. Two coverages were decided on for 1 and 2 clo: the exposed areas decrease as the level of clothing increases. The values decided on were, for a man: 1.85 m^2 total area; with 1 clo: 1.65 m^2 clothed, 0.20 m^2 nude; with 2 clo: 1.70 m^2 clothed, 0.15 m^2 nude; with 3 clo: 1.70 m^2 clothed, 0.15 m^2 nude. For a woman: 1.75 m^2 total area; with 1 clo: 1.35 m^2 clothed, 0.40 m^2 nude; with 2 clo: 1.45 m^2 clothed, 0.30 m^2 nude; with 3 clo: 1.52 m^2 clothed, 0.13 m^2 nude.

At the higher R values the nude proportion decreases. 4% of the body area is facial; this is the only area exposed in the tests of arctic and military cold weather clothing. Since civilian clothing is less efficient, 8% nude is retained as the smallest nude value.

The results of the two heat losses are added together in each case to form a composite heat loss curve. Figures 12 - 20, described later, are such curves.

3.4.2. Skin temperature.

Certain factors have undetermined importance in affecting heat loss, and their effect has been roughly weighed and assumed to average out in this paper. These are: areas that are assumed nude but are actually covered with hair, stockings, or are perhaps in pockets; conversely the areas that are assumed clothed but are open to bellows-type convection, where the air temperature inside is close to that outside. Possibly such effects cancel out. Their influence is presumed to be included in the averaging of the two whole clo values. Also, the skin temperatures of areas that are considered nude are often lower than the assumed 33°, the difference markedly lowering the $(T_s - T_a)$ factor. Winslow and Herrington (1949) give their estimate as:

$$T_s = \frac{T_a + 36^\circ C}{2} \qquad (14)$$

the mean of deep body temperature and outside air temperature. 33°C has been retained here as the fixed comfortable skin temperature, with the recognition that it might result in excessive heat loss curves. Conversely, Edholm and Bachamach (1965) state that 3°C must be added to $(T_s - T_a)$ to account for the 24% respiration loss. Such evaporative effect might cancel the difference between actual skin temperature and 33°C.

3.4.3. Evaporation.

The influence of evaporation, including respiration, has been described as approximately 25% of total heat loss (Figure 2). Under this definition evaporative loss increases with activity rate and, in thermal equilibrium, with heat loss. It is constant with $T_s - T_a$, however. Thus evaporation can be added to the combined heat loss functions to give total heat loss. This is done in Figures 8 through 20, described below, by the addition of a separate scale to the heat loss axis. Whether the respirative loss actually increases proportionately with metabolic rate as stated by Bedford (1948) and others is open to some question.

3.4.4. Experimental evidence on heat loss.

Herrington (1947) gives values for the parallel heat losses from the face alone. His subjects wore cold weather military clothing with only the face exposed. Its area averaged 0.07 m^2, or 4% of the total body surface. These values combine radiative and convective loss, and the evaporative loss from the face and lungs are included separately. The air is still, and the subjects are assumed resting.

Table 2

Heat loss in still air from the exposed face.

T_{air} °C	$T_{skin\ face}$ °C	Face loss R + C. Watts	Evap. skin	Resp. loss	Total
15	25.5	11.0	7.7	14.3	33.0
0	18.0	18.5	7.7	20.2	46.4
-5	15.5	21.0	7.7	22.0	50.7
-15	10.5	26.0	7.7	25.0	58.7
-25	5.5	31.0	7.7	27.0	65.7
-35	-0.5	37.0	7.7	29.0	73.7
-45	-4.5	42.0	7.7	31.5	81.2

These results show a somewhat larger loss from the nude face in still air than would be predicted by the nude skin function proposed above. Herrington's experiment most closely resembles the heavily clothed example given in Figure 16 below. Herrington's results have been included in this figure by substituting his facial results for the nude skin component in the figure. They are shown as two additional curves, for still air and 0.5 m s^{-1}. The fit seems encouragingly good, though it might well be fortuitous. One result from Table 2 is an indication that evaporative heat loss does not increase proportionately with total body loss.

4. Body temperature equilibrium: heat gain.

4.1. Metabolic rates for different activities.

The heat production of an active person is almost entirely determined by the level of muscular activity, which produces 85 to 90% of the total heat of the body. At rest the muscles supply 20% and the brain supplies 18%. The remainder is supplied by the basic metabolism of organs. Table 3 and Figure 7 show the metabolic rates for various activities in Watts m^{-2}. References on metabolic production for different activities are Passmore and Durnin (1955), Leithead and Lind (1964), and MacDonald (1961).

Most outdoor activities (as walking) produce twice the heat that indoor ones do. The basal metabolism is figured to be 46 Watts m^{-2} and the resting metabolism 52 to 58 W m^{-2}. 58 W m^{-2} is equivalent to a unit called the Met, frequently used in the physiological literature. Like the clo unit, it has no intrinsic connection to any measuring system. Since it is the same as resting metabolism it is possible to express other activities in terms of multiples of resting metabolism. The effort that can be expended over a full day is 4.5 met, or 6 times the basal (sleeping) metabolism (about 270 W m^{-2}). The maximum possible effort is 8 to 20 met (470 to 1200 W m^{-2}). The effort to climb stairs, and the consequent heat generated, should be noted. 50 to 60% of such energy is liberated in the limbs.

Table 3

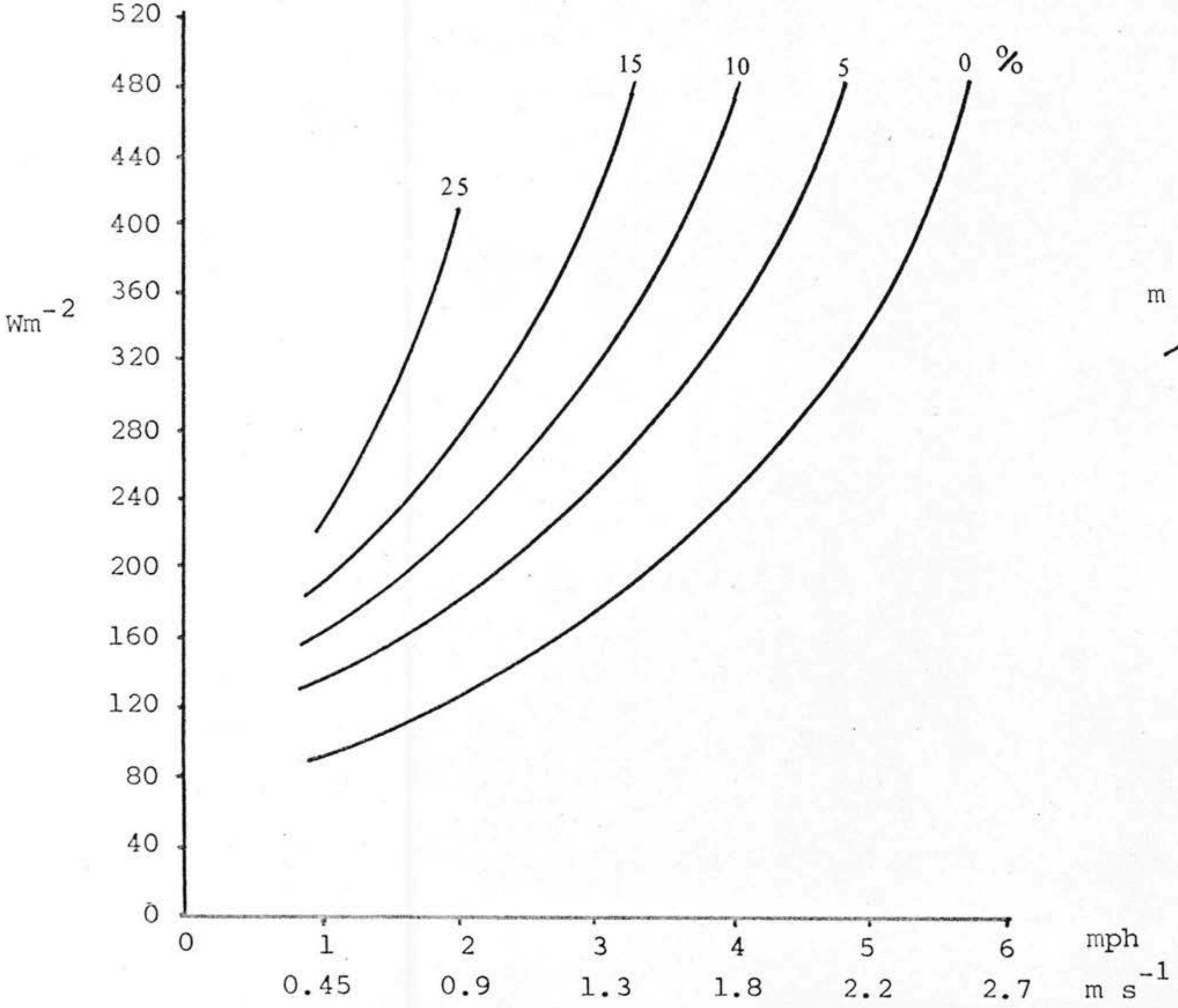
Relation between metabolic rate and activity

Activity	Watts m^{-2}
Basal	46
Seated at rest	63
Reading aloud (seated)	69
Standing at rest	70
Hand sewing (seated)	71
Dressing and undressing	76
Office worker moderately active	80
Light work standing	89
Typewriting rapidly	90
Clerk moderately active standing	97
Sweeping floor 38 strokes per minute	109
Pool player	110
Walking 2 mph, light dancing	123
Painter of furniture (at bench)	143
Carpenter	155
Restaurant serving	162
Walking 3 mph	171
Walking 4 mph, active dancing, skating	226
Walking down stairs	238
Stone mason	242
Bowling	244
Man sawing wood	292
Swimming	324
Running 5.3 mph	370
Walking 5 mph	380
Walking very fast 5.3 mph	420
Walking upstairs	710
Maximum exertion different people	450 - 770

Adapted from Heating, Ventilating and Air Conditioning Guide 1944, Chapter 2.

II FIGURE 7

Energy generated by walking various speeds and slopes.



Walking speed (from Leithead and Lind 1964)

Relation between energy, speed of walking, and body weight: (in W)

Walking speed m sec^{-1} / mph	Weight (kg) 36	45	54	65	72	81	90
0.9 / 2.0	133	154	182	202	224	244	264
1.1 / 2.5	160	188	216	244	264	295	314
1.3 / 3	188	216	250	280	310	334	390
1.6 / 3.5	216	250	290	320	350	396	425
1.8 / 4	244	284	328	368	400	450	490

From Passmore and Durnin 1955

Women show a 10% smaller expenditure while walking (for equal weight).

Macdonald 1961

It is a significant fact that production of heat in the brain, when the body is at rest, represents a sizeable part of total heat production (18%). Since this is an area unprotected by clothing or significant fat, and has been found not to vary its insulation with temperature (Edholm and Bacharach, 1965), the head is a major avenue of heat loss. At -4°C an inactive person loses half his total heat production from the head. As his activity increases this proportion decreases rapidly.

The use of the table of metabolic energy in conjunction with the curves for convectional heat loss should enable designers to determine what climatic conditions are suitable for thermal balance in areas where a level of activity can be estimated.

4.2. Solar gain

4.2.1. Efficiency of radiation.

The formula for solar gain is, as added to the formula for heat loss described before:

$$Q = \frac{T_s - T_{cl}}{R_{cl}} \qquad (15)$$

$$Q + (1-\alpha)I = \frac{T_{cl} - T_a}{R_a} \qquad (16)$$

where I equals radiant influx, insolation, and α is the reflectivity of the surface. $(1-\alpha)I$ equals I_s, the solar heat added at the clothing surface. It is opposite in sign from Q. Since the radiant energy is added to the outside of the clothing where it is susceptible to removal by convection, it is not as effective as an equal amount of metabolic energy generated internally. The equation for the effect of added radiation shows this:

$$Q = T_s - \frac{(T_a + IR_a)}{R_{cl} + R_a} \qquad (17)$$

Thus as R_{cl} increases, the effect of I decreases. This effect is called the efficiency of solar radiation: the greater the insulation within the point of absorption, the less effect of total radiation there will be. The formula is:

$$E_r = \frac{\text{R outside the point of absorption}}{\text{Total insulation}} \qquad (18)$$

E_I = Efficiency of radiation

Thus the effectiveness of radiation on exposed parts of the body is much greater than on the clothed parts of the body.

This condition obtains also to the insulation of the air next to the surface which is reduced by wind (from 0.16 m^2 ^oC W^{-1} still air to 0.016 m^2 ^oC W^{-1} at 10 m s^{-1}). Air movement reduces the insulation outside of the point of absorption while whereas that within stays the same, as a result lowering the effectiveness of the radiation received. During wind, the effect of solar gain is extremely reduced. This effect does not apply to nude surfaces however, where R_a = R total.

4.2.2. Surface areas exposed.

Even with the radiation efficiency and wind effect determined, the total heat gain remains a complex problem. The surface area exposed to the sun varies with posture and time of day. The absorptivity varies for different colour fabrics and skins. The radiation flux varies throughout the day and the year. Last, the sunlight itself is present only during periods of clear sky, so the meteorological probabilities of cloudiness become important in planning for average conditions.

Clearly some simplification is necessary. The surface area exposed to radiation exchange with the environment has been studied by Winslow, Gagge, and Herrington (1938) and by Guibert (1952). Winslow et al. give the radiation area as 75% of the Dubois area, as determined by heat balance methods. Guibert, in a very thorough assessment, gives the radiation area of the body as 70% Dubois seated, 77% standing, 72% semi-erect, and 65% crouched. Since these percentages apply to omnidirectional (global) radiation, irradiation from a point source will cover a smaller area. This has been done theoretically and experimentally by Rapp and Gagge (1967), who describe a method of very precise area determination for a complete range of irradiation points.

For the purpose of outdoor usage, the simplifications suggested by Blum (1945) seem the most useable.

a. Direct radiation. A standing man with the sun at the zenith has 7% of his Dubois surface exposed to direct radiation, I_o: 0.12 m^2 for a 1.7 m^2 man. Lying prone, the area exposed is 30% total body area, or 0.51 m^2 for the 1.7 m^2 man. This is the maximum exposure. As the sun moves from the zenith to the horizon, the exposed area on a standing man will increase from 7 to 30%.

b. Diffuse radiation. On the average, scattered radiation from the clear sky comprises 15% of the total radiation. The proportion of the body exposed to the sky vault, which radiates essentially uniformly, is roughly 50%

c. The third radiation source is the ground, which reflects roughly 20 to 25% of incoming sun and sky radiation. The proportion of the body exposed to this is roughly half. With these approximations, the amount of radiation impinging on the body during sunlight can be estimated.

During overcast conditions in daytime, the diffuse radiation from the sky vault averages 35% of clear sky direct radiation, (see Chapter III, Appendices 2 and 3). 50% of the body surface is exposed to this, and 50% to the ground reflected component, 7% of I_o.

The skin and clothing reflect a significant proportion of the radiation falling on them. The reflectivity ~~of~~ (1 - absorptivity) of white clothing = 0.80, for khaki 0.43, for black 0.12. White skin has a reflectivity of 0.43, brown skin 0.35, black skin 0.16 (Blum 1945).

4.2.3. Insolation values.

The amount of radiation from the sun and sky varies considerably with time of day, year, and with atmospheric clarity. An average for very bright sunshine with clear skies is 840 Wm^{-2}, which is equivalent to 60% solar constant. This value is distributed as 910 $W\ m^{-2}$ for the sun in the zenith, to 770 $W\ m^{-2}$ for the sun at a zenith angle of 60^o. This average overestimates sunlight in areas of high atmospheric turbidity, or in high latitude areas where the atmospheric path is long. For weak sunshine, the amount of direct irradiation is half to one third of these values. However it was decided to use this value for bright sunlight to illustrate the effect of sun.

Using these values the solar heat load from the various sources can be computed. The following table, derived from Blum's data, uses a nude/reflectivity 0.43. For surfaces with different reflectivity, multiply these results by $\frac{\alpha}{43}$.

TABLE 4

Solar heat load (Watts) (I_o = 840 Wm^{-2})

	Zenith angle	Direct	Sky	Albedo	Total
Erect	0	63	79	130	272
	60	186	32	52	270
Prone	0	267	79	54	400
	60	106	32	22	160

The average of the total values if 280 Watts (per unit body area, 165 W m^{-2}) and represents the figure used for overall surface for nudes in a clear atmosphere. This energy is equivalent to that of walking at 3 miles per hour, an average pace.

The solar gain is reduced, as was noted before, by any insulation between the skin and the point of absorption. With 0.5 clo, the thermal effect on the skin (still air, reflectivity = 0.43) is 186 W. With 1 clo, the value is 140 W, 1½:112 W, 2:93 W, 2½:80 W, 3:70 W, 3½:62 W, 4:56 W. With wind, these smaller values are further reduced. The following table gives the data in W m^{-2} to make it comparable to metabolic energy.

Table 5

Solar heat load through clothing (Wm^{-2})

Reflectivity = 0.43 I_o = 840 Wm^{-2}

R (clo)	V (m s^{-1})					
	Still air	05	1	2	5	10
0	165	165	165	165	165	165
½	110	88	82	78	71	64
1	82	59	54	50	46	40
1½	66	45	71	37	33	29
2	55	36	33	30	26	23
2½	47	31	27	25	22	19
3	41	27	24	21	19	17
3½	36	23	21	18	16	14
4	33	20	18	16	14	12

The combined effect of wind and body insulation must account for the judgment of Adolph and Molnar (1946) that strong direct solar radiation (970 Wm^{-2}) would only replace 105 W of the body metabolism of nude subjects being subjected to extreme cold. The vasoconstriction in this experiment would bring the insulation of the other tissues to approximately 1 clo. This relatively unheated tissue must become the equivalent of a layer of clothing, for the energy system is measured not at skin-air interface (as with comfortable people) but at the deep body-outer shell interface. Since the subjects mentioned are also subject to an unspecified wind, it is consistent that the useful heat from the sun should approximate 105 W.

Diffuse radiation from an overcast sky averages 21% I_o over the entire body, or 93 W m^{-2} nude. These values of heat gain in bright sunlight are presented in graph form on the combined heat loss charts, Figures 8 through 20 below.

Meteorological data on sunshine is taken into simplified account by the equation:

$$I = (1 - 0.9C) \; 165 \text{ W m}^{-2} \qquad (19)$$

where C equals average cloudiness in tenths.

Another means of sunshine reporting is the used sunshine hours. These can be used directly for some purposes. For an overall average of radiation received, the percentage of sunshine hours over possible sunshine hours (determined from latitude and time of year) can be multiplied against the average radiation per hour of sunshine.

Terjung (1965), in an assessment of bioclimatic regions, used this method. His figure for radiation gain was inordinately high, however, for he used 230 W m^{-2} of body surface as an average radiation addition to metabolic energy regardless of clothing worn or wind insulation decrement. Even as a nude in very bright sunshine it is difficult to see how such a high value is obtained.

Theoretical assessments of the effect of solar radiation are given in Buettner (1951) and Lowry (1970). Lee and Vaughan (1964) give an empirical temperature equivalent to solar radiation, but the hot desert conditions make the values inapplicable here.

5. Body temperature equilibrium: balance of fluxes.

5.1. Heat loss and heat gain.

The thermal balance of a person is computed by the addition of the heat loss and heat gain components described above. The results may be expressed in a variety of ways. The significant factors in a thermal balance equation are:

T = temperature ^{o}C
V = wind velocity m sec^{-1}
Q = heat loss Watts (usually W m^{-2})
Q_I = radiant heat gain "
M = metabolic heat production "
R = insulation value m^{2} Watts^{-1}
or in clo (0.16 ^{o}C W m^{-2})

It is possible to equate the M for an activity to Q because in steady state equilibrium heat loss must equal heat gain. For transient cases where M is low and Q high, the body will cool at rate Q until vasoconstriction and falling body temperature lowers heat loss towards Q. Then M will equal Q, but they will be at a lower value and the body will be uncomfortable. For comfort, the subject would have to raise his metabolic rate to where it equalled Q without vasoconstriction or shivering, such as by walking to "warm up". This action produces a metabolic rate which will fit the comfort formulae, and would be a requirement for comfort in those particular thermal conditions.

Temperature comes in at least three forms:

T_a = air temperature

T_{s-a} = (skin temperature)-(air temperature): The thermal decrement used in the heat loss equations for nude and clothed bodies.

T_{sa} = still air temperature: often used in conjunction with a known heat loss and a thermal wind decrement in expressing the influence of wind in lowering the effective cooling temperature of air.

Most expressions of thermal balance, the effect of insulation, the effect of metabolic level, and of wind chill fix two or more of the above factors to make the relationship clear. Figure series 8 - 20 below is discussed in these terms.

5.2. Graphical presentation of calculations.

a. T:R

Figure 6 gives T against R required for a group of selected M rates. Still air is assumed. This chart shows the linear relationship between Q (and M), R and T. The only non linear function in the parameters affecting comfort is the relation of velocity to the other parameters. The wind parameter is related to Figure 6 by a separate set of curves (Figure 5), which are read first and which convert wind to a temperature parameter (the temperature decrement described above). Temperature decrements can be expressed on a graph of T:R such as Figure 6 as lines parallel to and above the line for a given Q. They would indicate the increase in insulation required by each wind velocity. Since it is more direct to think of the heat loss cost of wind, these curves are not presented here.

b. T:Q

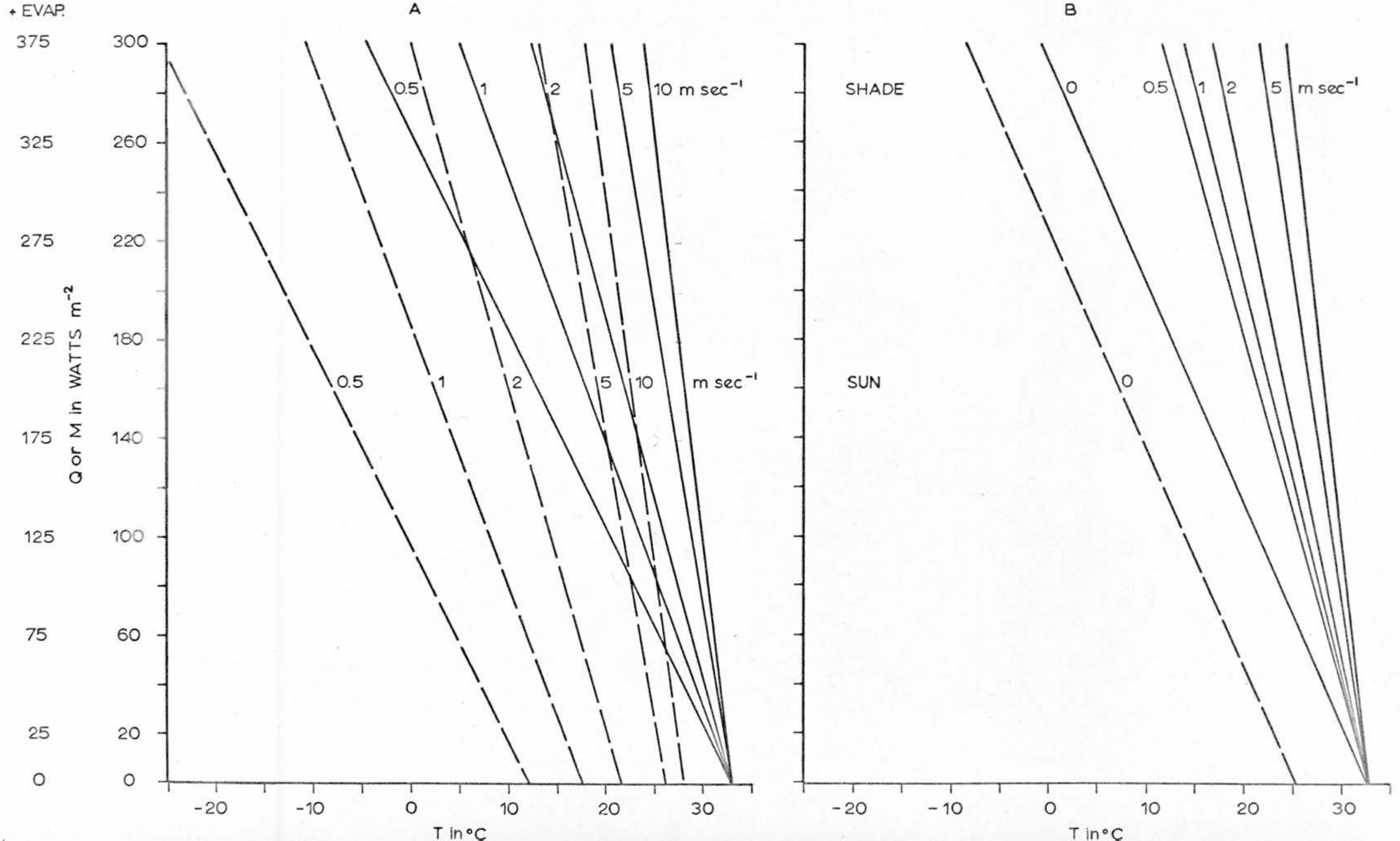
In Figures 8 - 16, temperature is put opposite Q (or M) on the graph. Then, using selected insulations and wind speeds, lines are drawn which give the effect of temperature and wind on thermal balance. The differing slopes for the different wind speeds indicated shows the increased effect of wind at high metabolic levels and high heat losses.

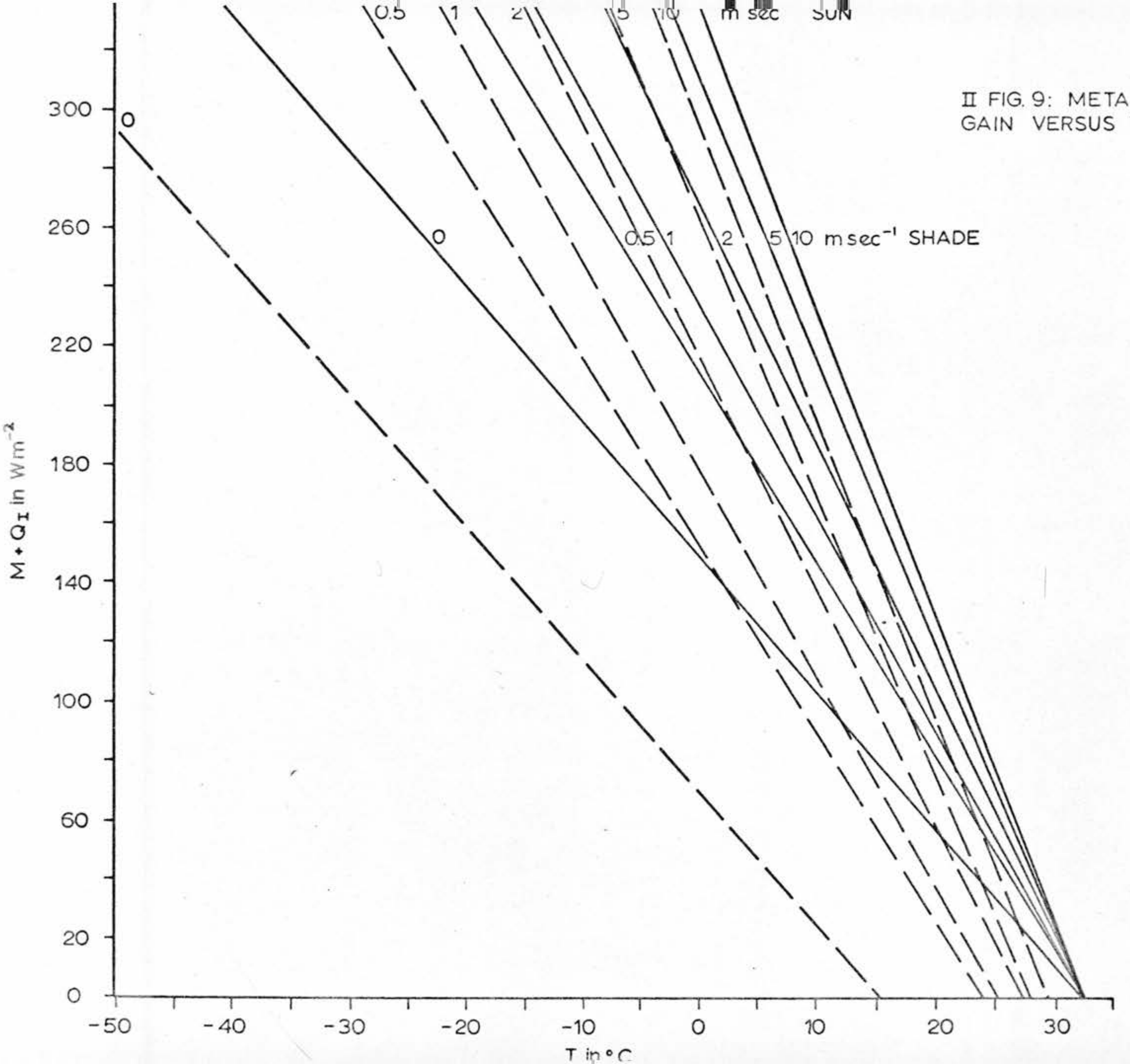
Figures 8 through 11 give thermal equilibrium lines for nude and uniformly insulated surfaces. Figure 8 includes the two functions for nude heat loss described in 3.2.4. and graphed on Figure 4. They are labelled here A and B.

Combinations of heat loss lines for different R values can be made by addition. Figures 12 through 16 show combined heat loss for various assumed percentages of nude and clothed surfaces. The clo values vary from 1 to 3, and the nude areas are represented by the two formulae.

Evaporative heat loss is included by adding a scale ($Q + 0.25\ Q$) alongside the scale for Q or M, as described in Section 3.4.3. Since there is some question of whether E actually increases proportionately with M, the scale is maintained separate.

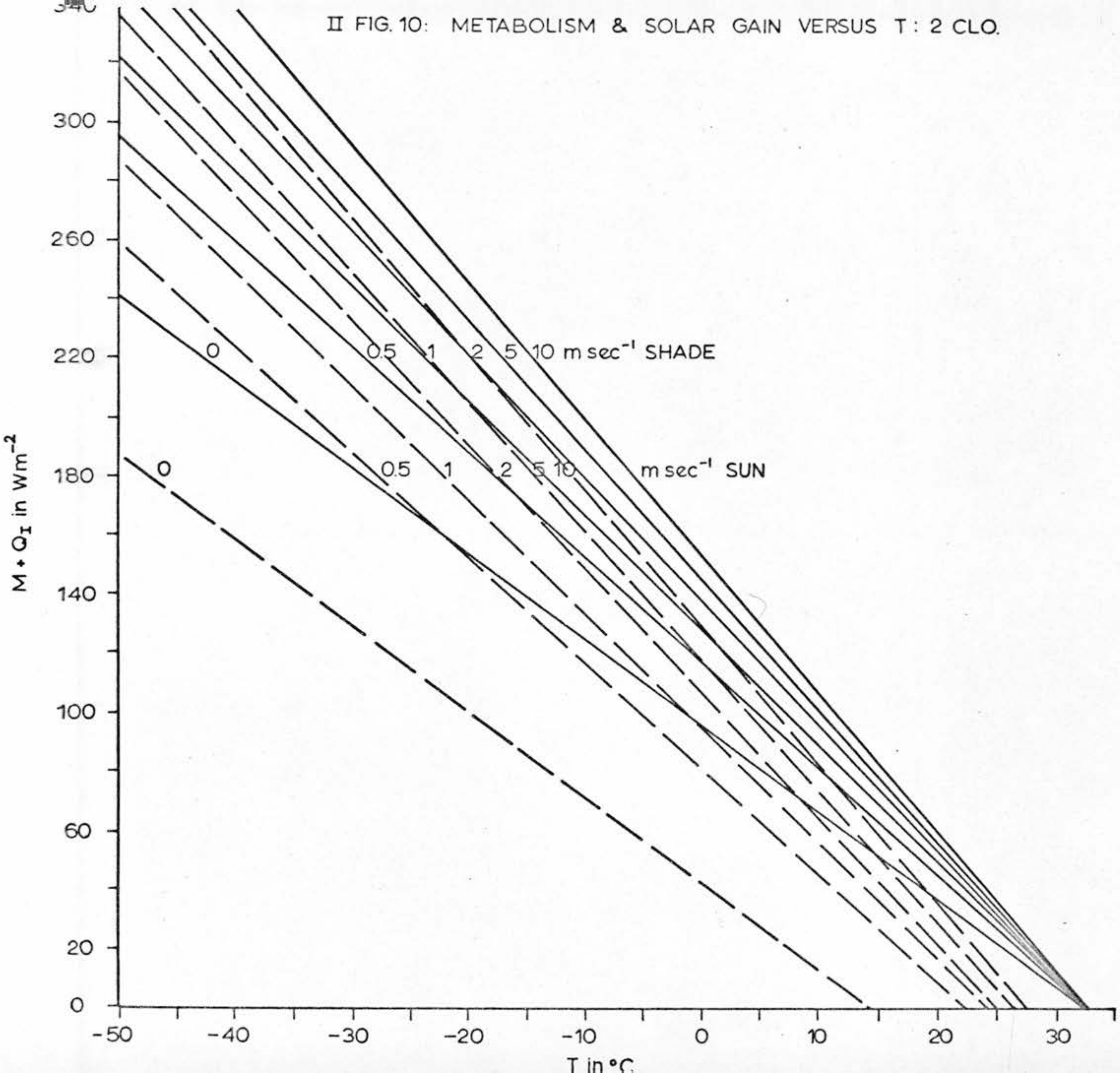
II FIG. 8: O CLO HEAT LOSS.



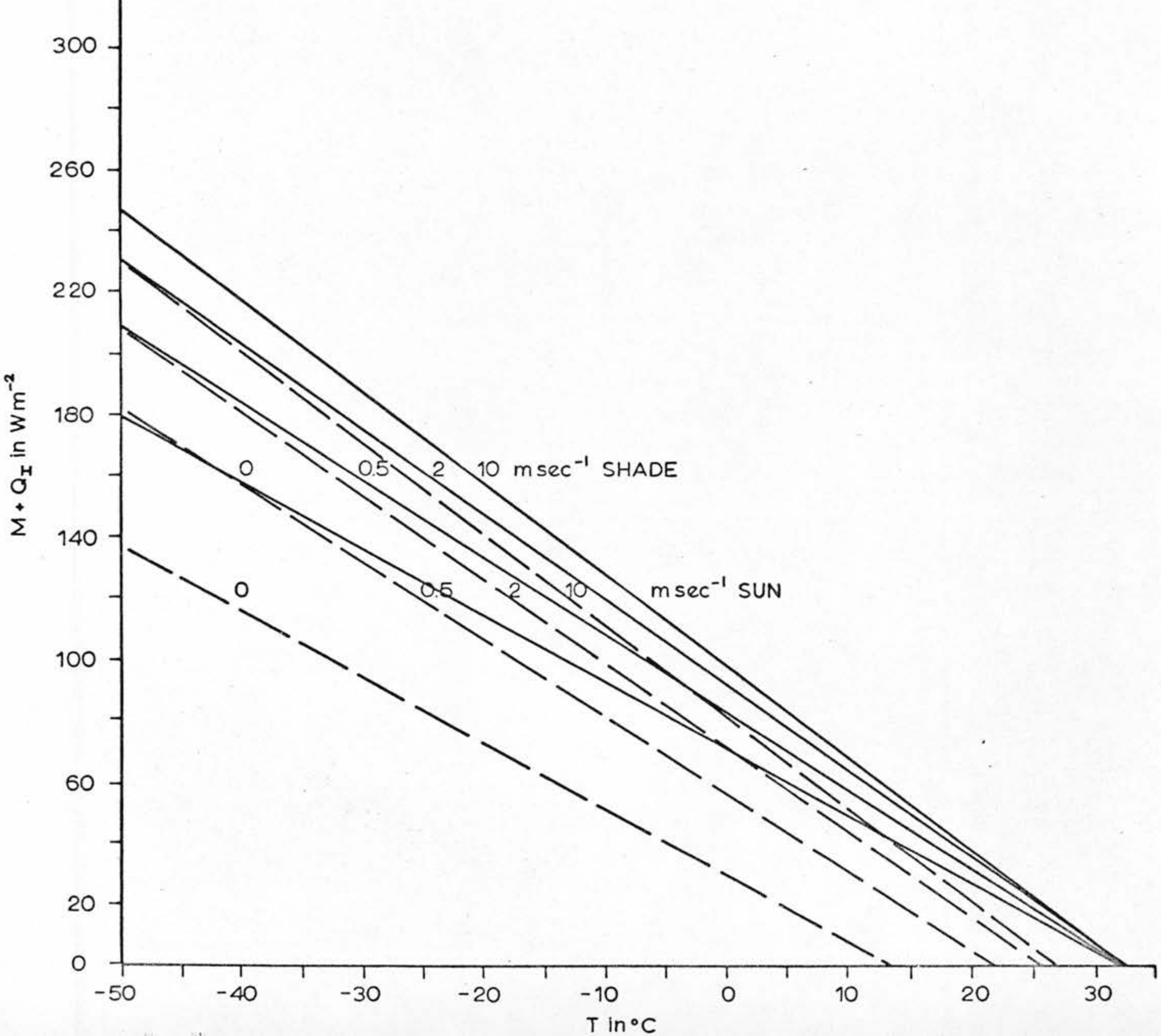


II FIG. 9: METABOLISM & SOLAR GAIN VERSUS T : 1 CLO.

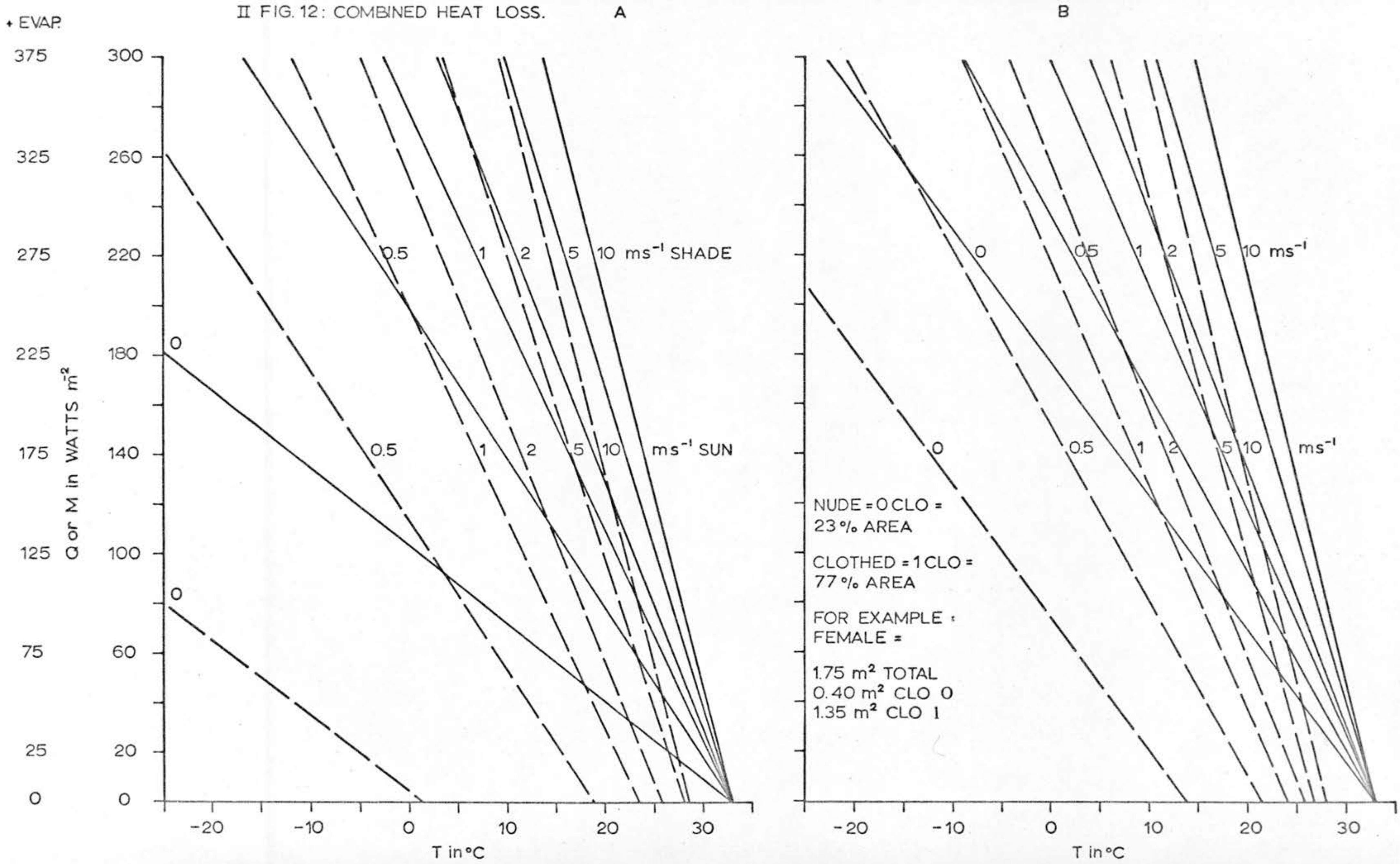
II FIG. 10: METABOLISM & SOLAR GAIN VERSUS T : 2 CLO.



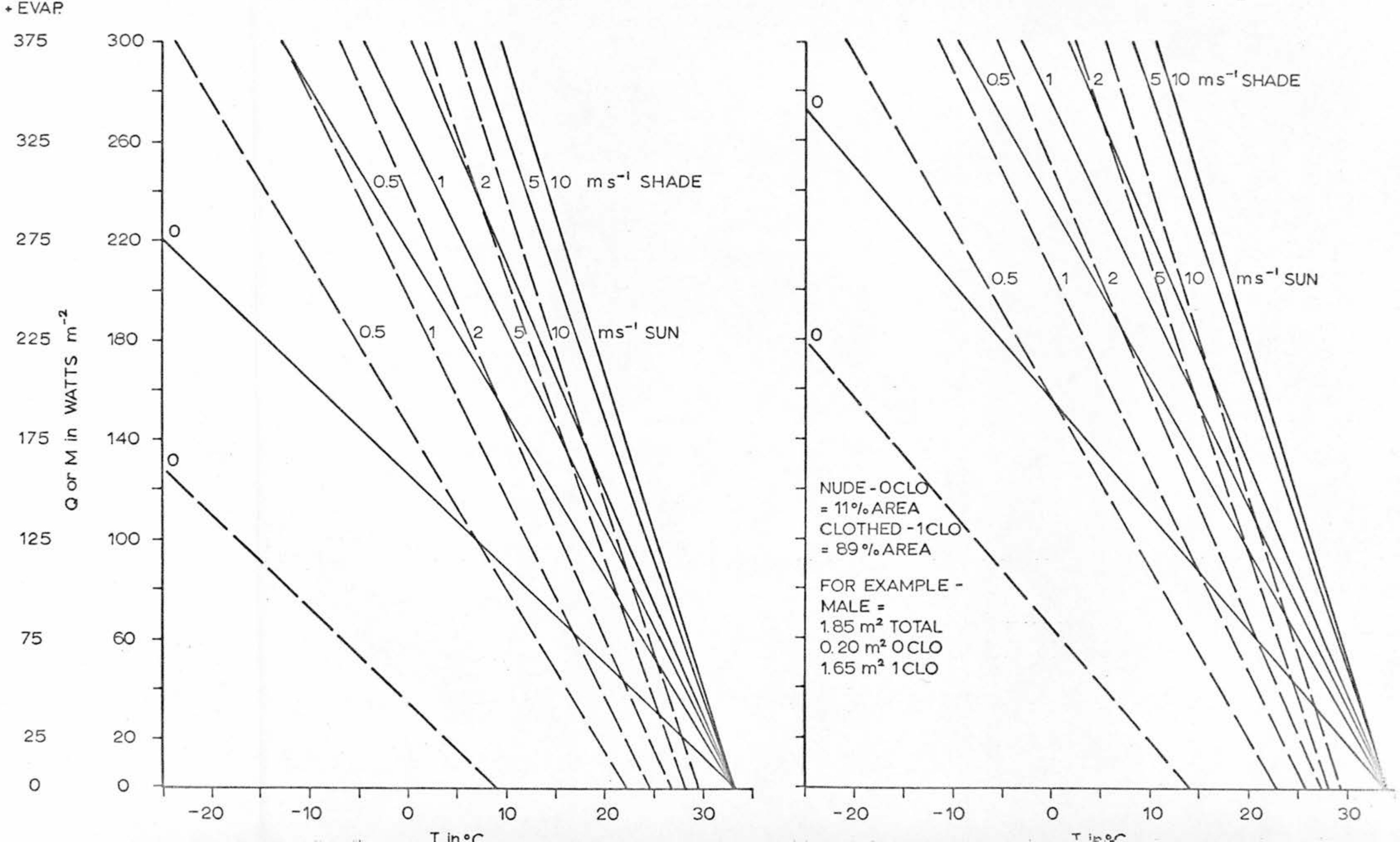
II FIG. 11 : METABOLIC RATE + SOLAR GAIN VERSUS T : 3 CLO = IR



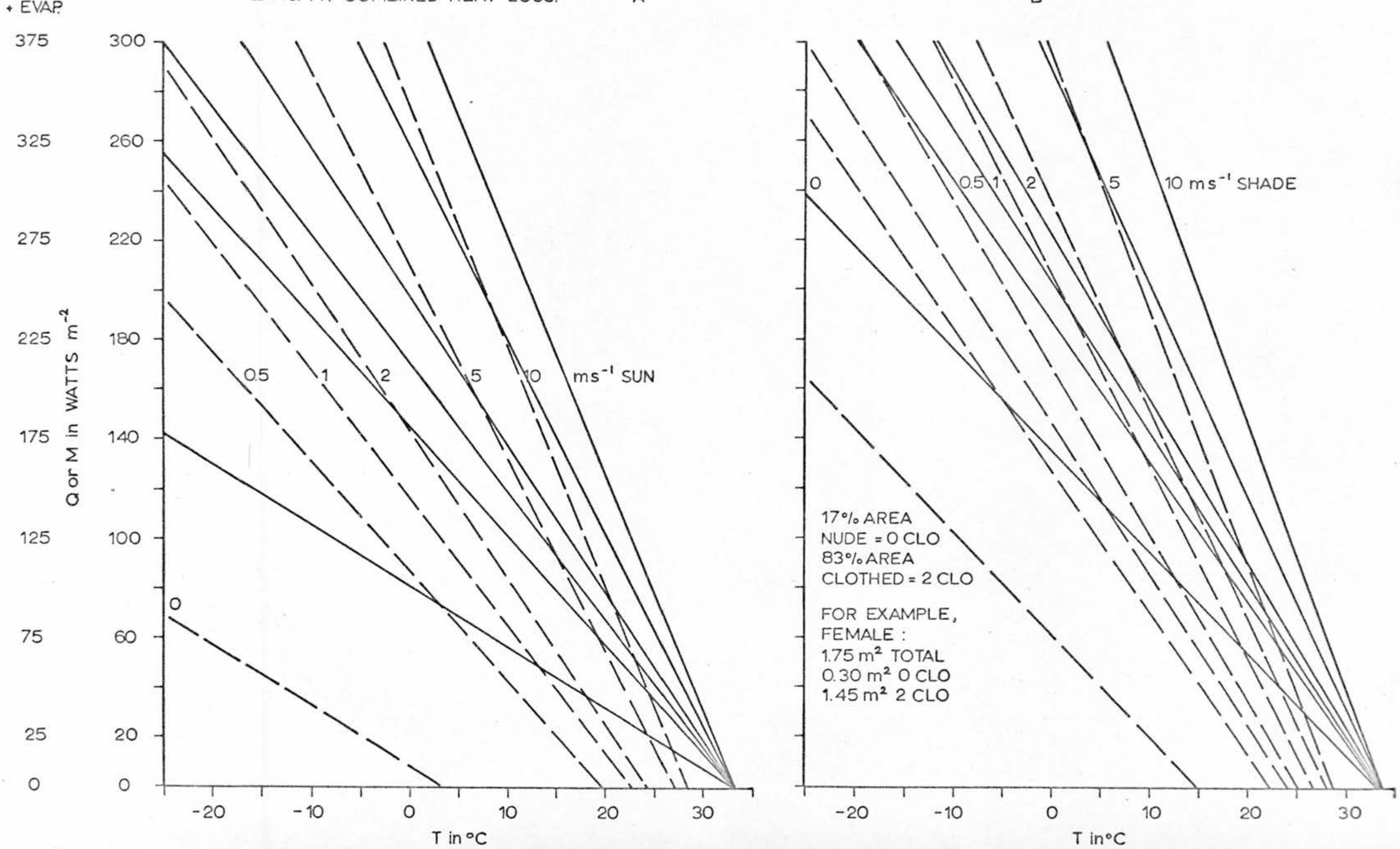
II FIG. 12: COMBINED HEAT LOSS.



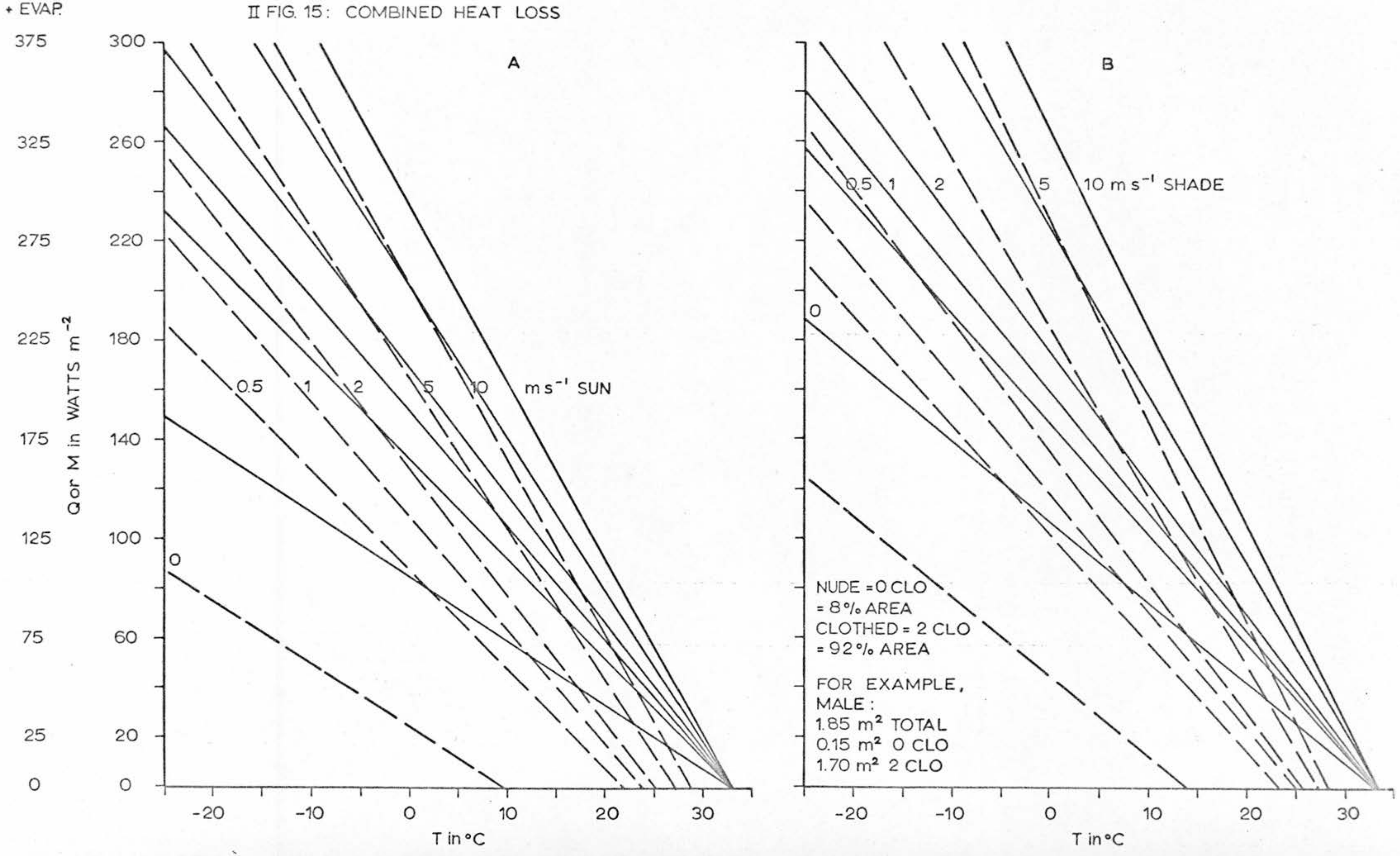
II FIG. 13: COMBINED HEAT LOSS.



II FIG. 14: COMBINED HEAT LOSS.



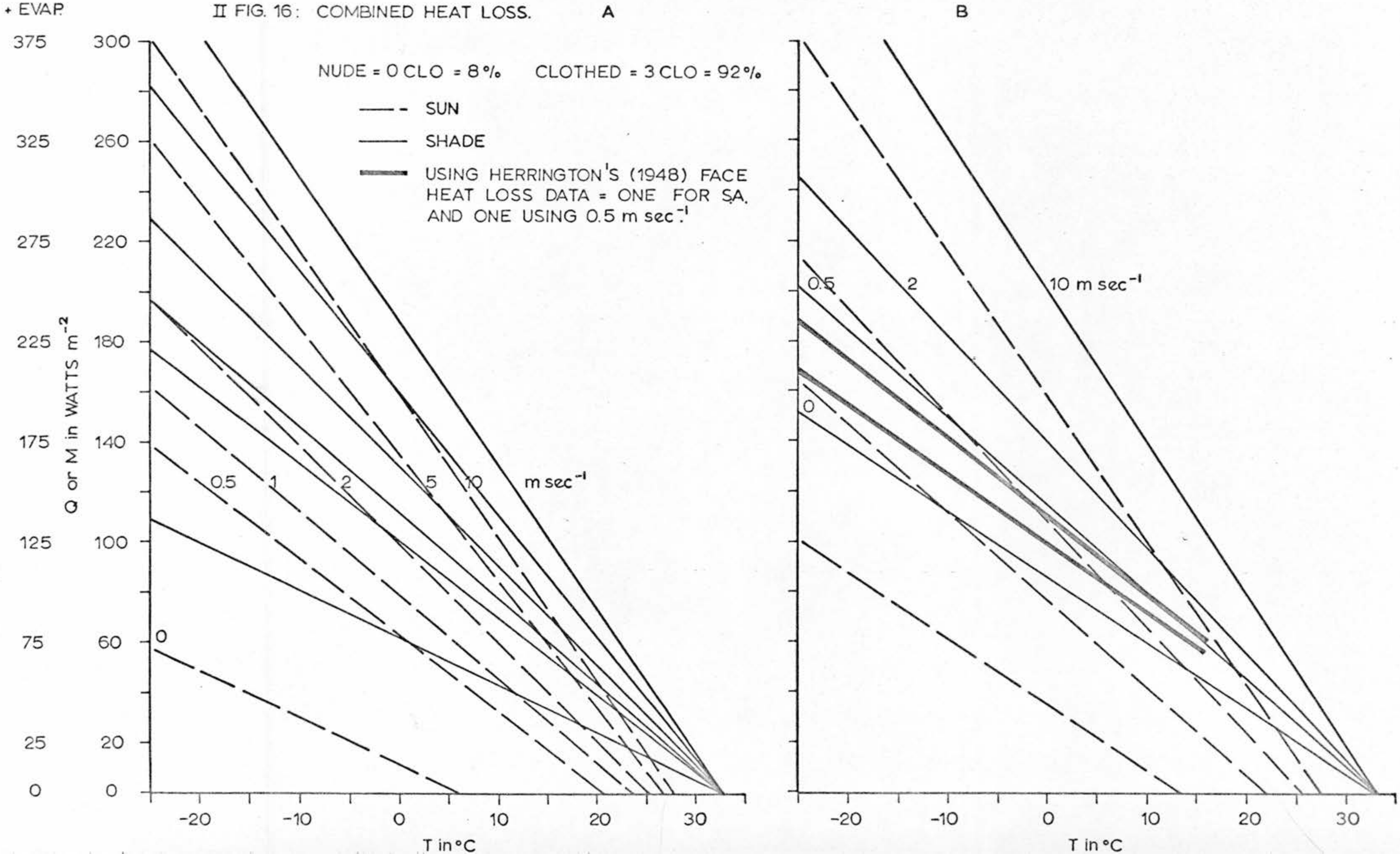
II FIG. 15: COMBINED HEAT LOSS



NUDE = 0 CLO
= 8% AREA
CLOTHED = 2 CLO
= 92% AREA

FOR EXAMPLE,
MALE :
1.85 m^2 TOTAL
0.15 m^2 0 CLO
1.70 m^2 2 CLO

II FIG. 16: COMBINED HEAT LOSS.



The influence of bright sunlight is shown for each curve in hatched lines. The assumed still air heat gain over the entire nude body is 165 W m^{-2}, as described in Section 4.2. For sunlight values less than this, extrapolation must be used.

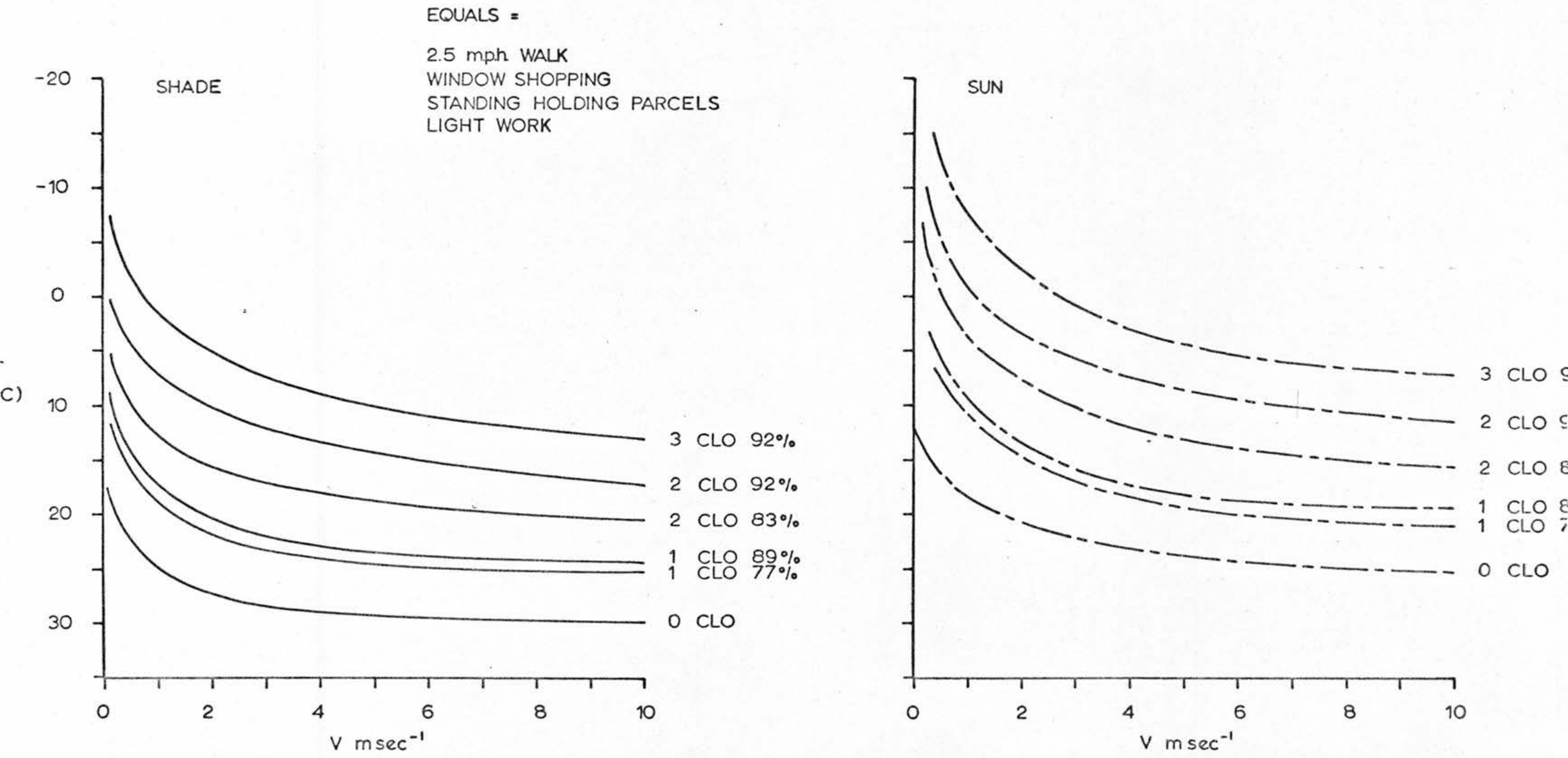
c. T:V

The most common graphical representation of thermal equilibrium in a cool environment is the plot of air temperature versus wind velocity, with a series of curves representing thermal equilibrium for different R and M. For any chosen metabolic level, which can be related to a common activity, a curve can be drawn which shows its range of thermal balance and approximates the lower comfort limit for that activity. Additional curves can be added for differing R coverages, and to account for solar gain. These are presented in Figures 17 - 20 for two activity levels, and for the two nude heat loss functions used before: (A and B).

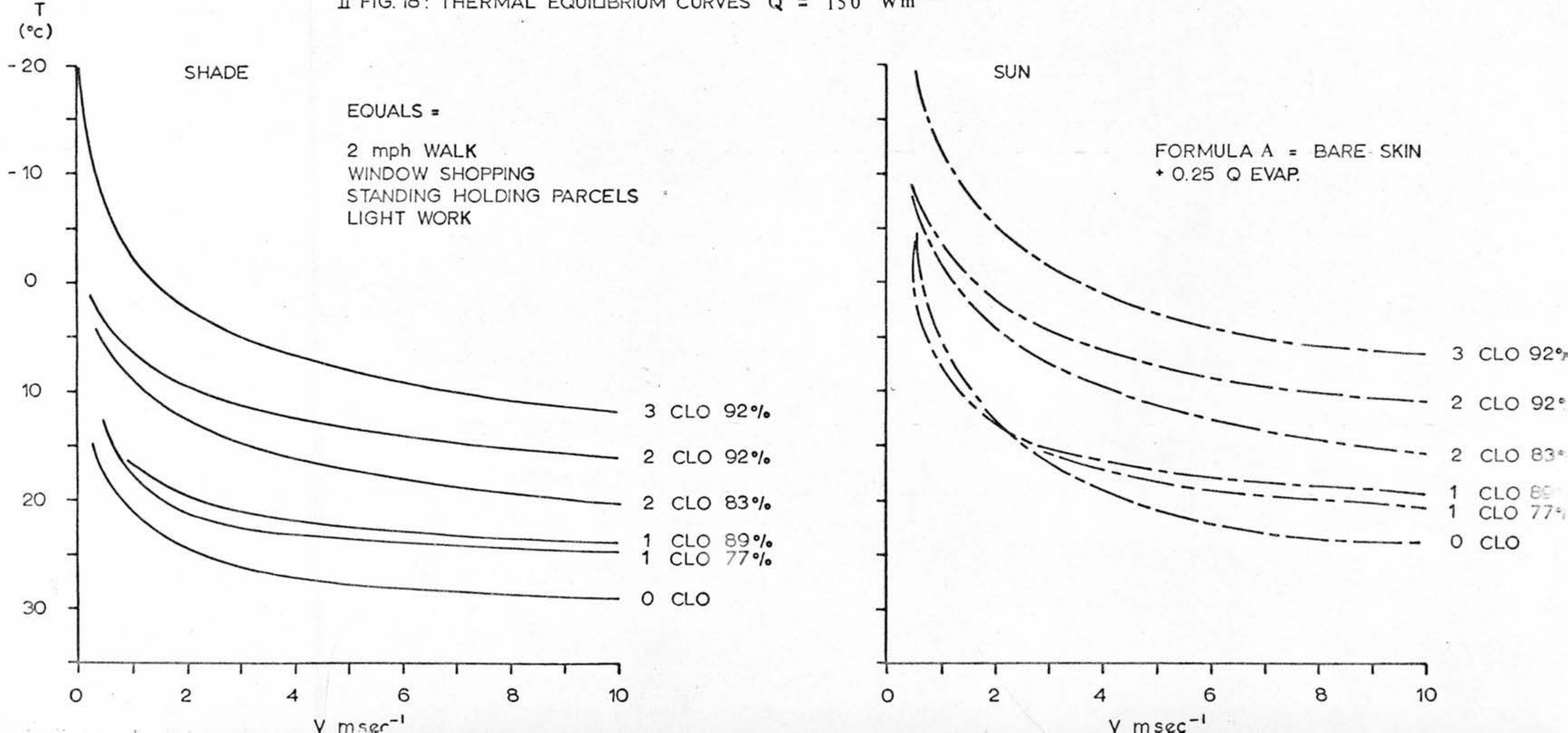
The non evaporative heat transfer levels chosen are 120 and 230 W m^{-2}. The first is equivalent to light work, walking slowly (2 mph), standing with a moderate load (parcels), or doing stationary work (traffic warden). The second is equivalent to moderate work, walking 4 mph, or descending steps.

With the assumed 25% evaporative heat loss added, the total loss for these curves is 150 and 288 W m^{-2}, the metabolic

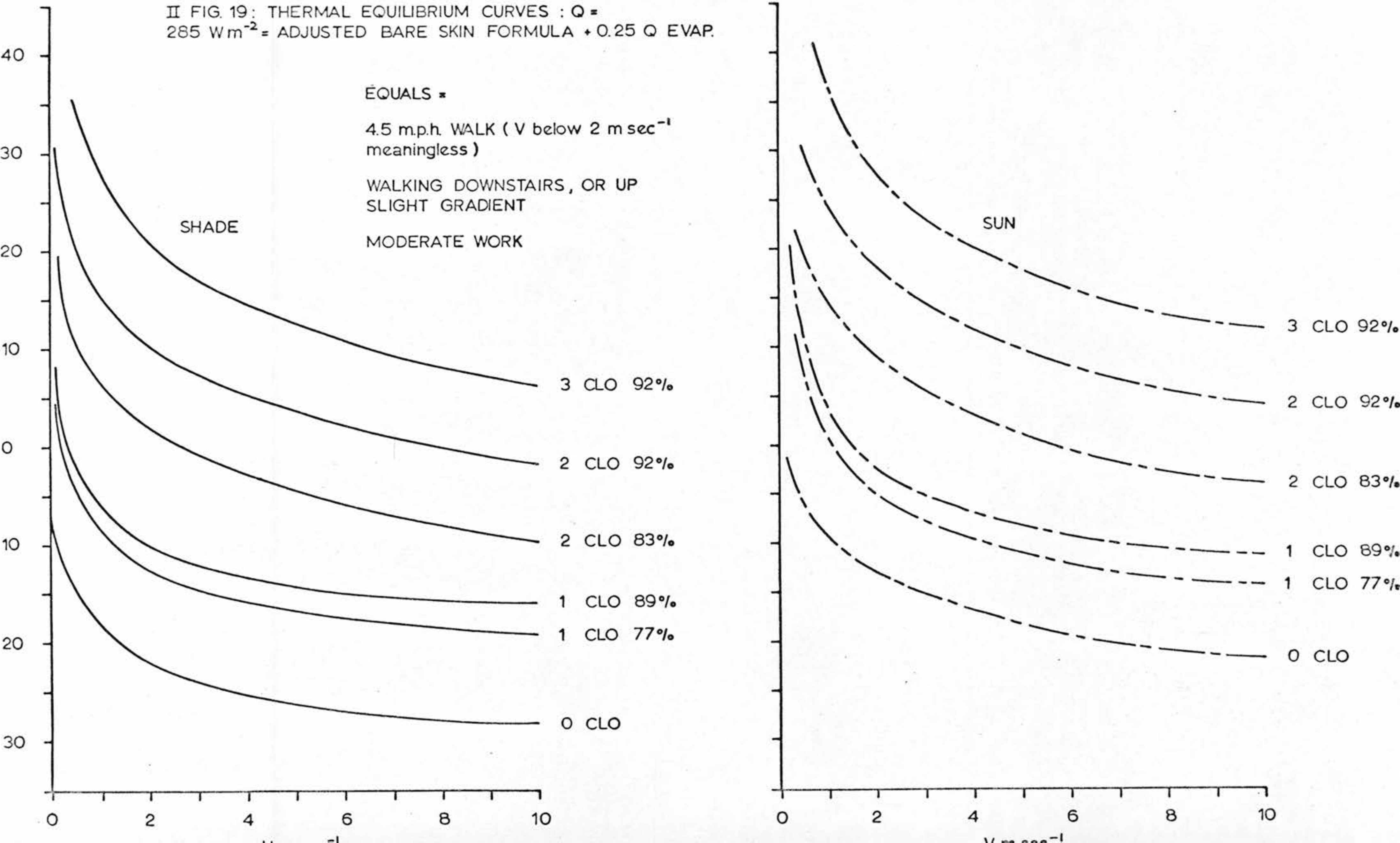
II FIG. 17: THERMAL EQUILIBRIUM CURVES : 150 W m^{-2} = ADJUSTED BARE SKIN FORMULA + 0.25 Q EVAP.



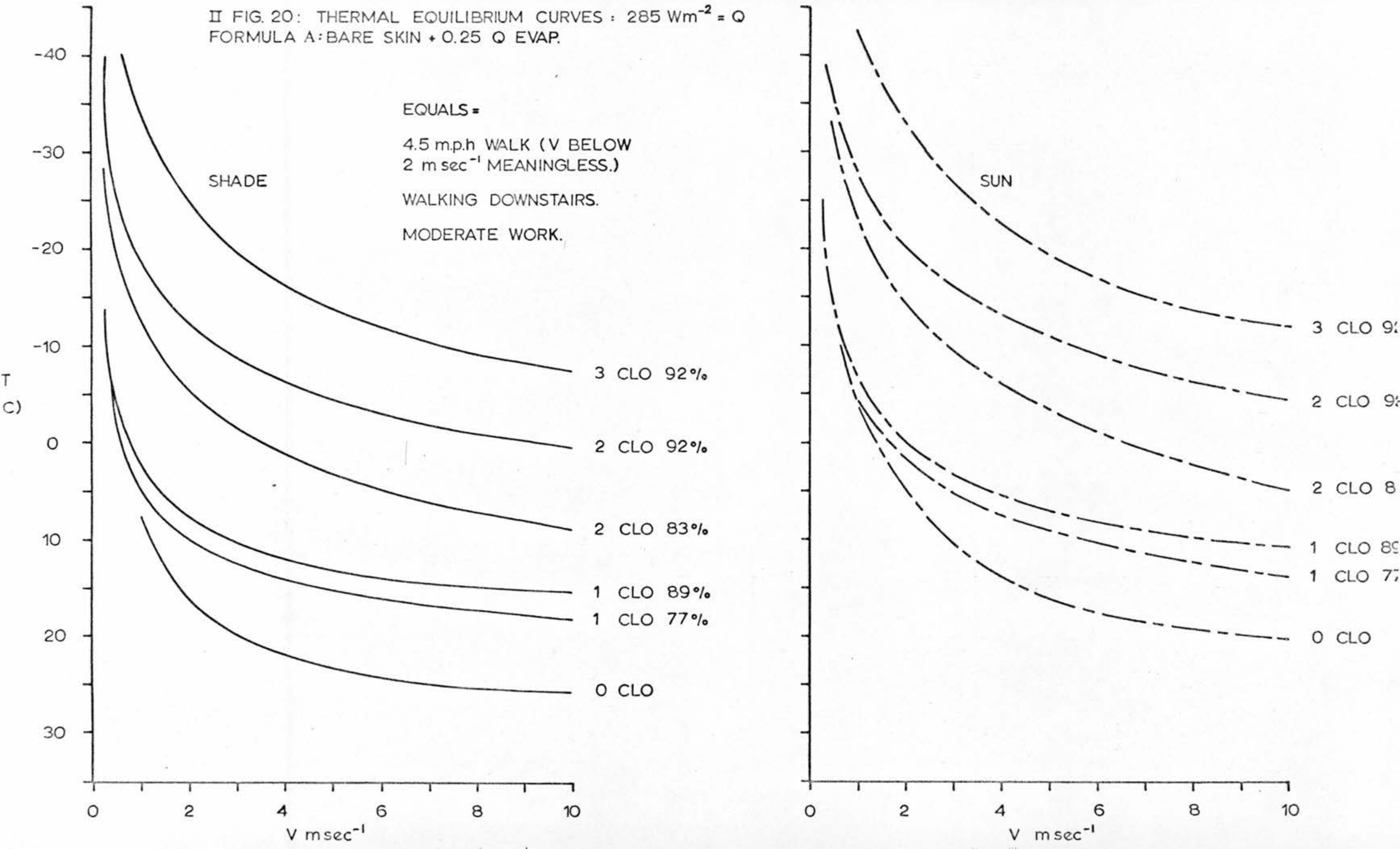
II FIG. 18: THERMAL EQUILIBRIUM CURVES $Q = 150 \ Wm^{-2}$



II FIG. 19: THERMAL EQUILIBRIUM CURVES : Q = 285 W m^{-2} = ADJUSTED BARE SKIN FORMULA + 0.25 Q EVAP.



II FIG. 20: THERMAL EQUILIBRIUM CURVES : 285 Wm^{-2} = Q
FORMULA A: BARE SKIN + 0.25 Q EVAP.



equivalents of walking 2.5 mph and 4.5 mph, or of walking more slowly up slight gradients.

During daytime with overcast conditions, the addition of diffuse radiation in British latitude could be expected to move the equilibrium curve 20 to 35% of the difference between the solar and shade curves as given in Figures 17 - 20.

In conclusion, heat balance curves have been made for assumed levels of M, R, and I. Provision for modifying the curves to account for evaporative heat loss and differing levels of insolation are included.

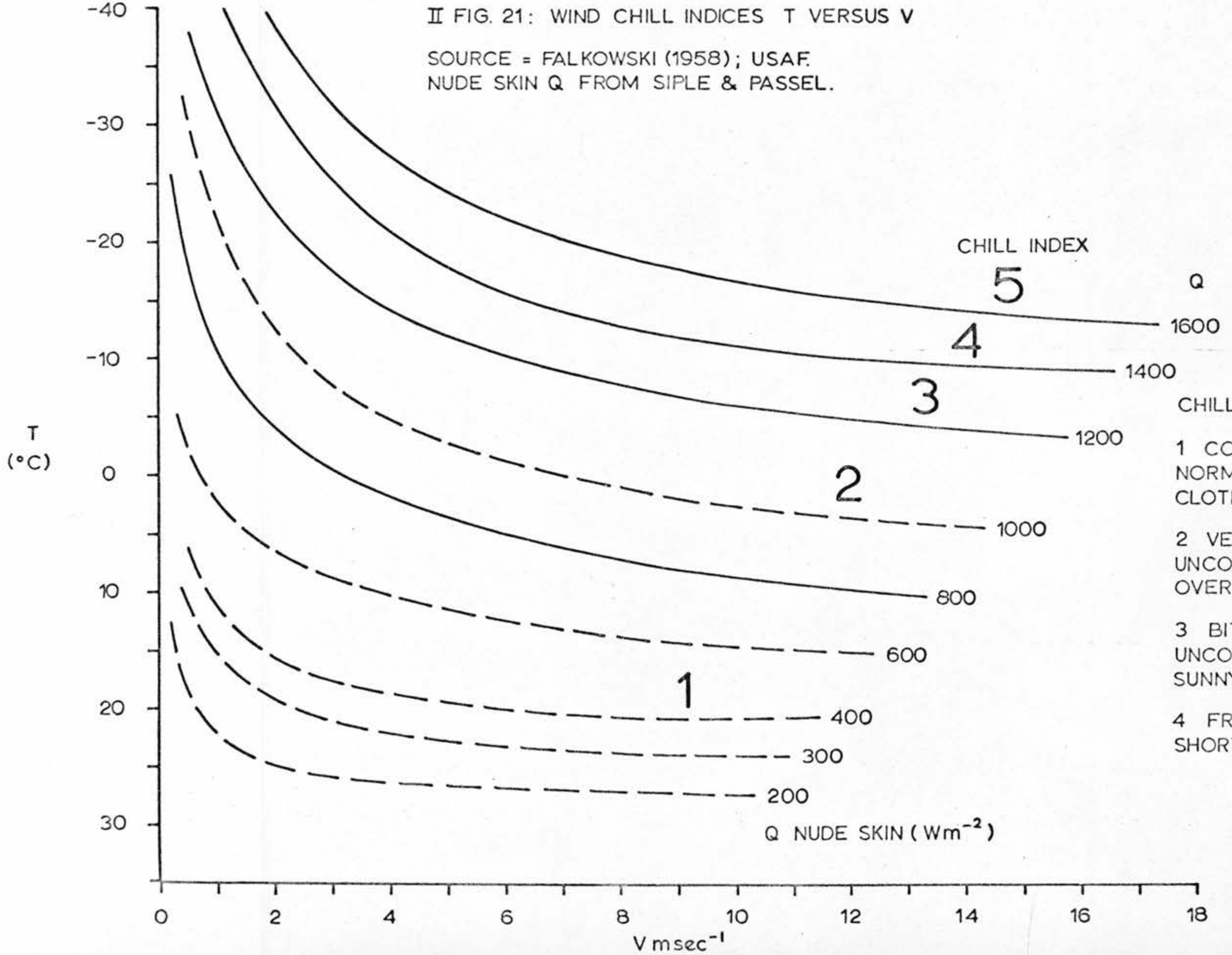
5.3. Wind chill charts.

The format of Figures 17 - 20 is the same as is used for classic wind-chill charts. These have been derived from empirically obtained data, usually in the arctic (Court, 1948; Falkowski, 1958; Thomas and Boyd, 1957). They employ arbitrary and sometimes unspecified 'chill index' categories which combine the variables R, M, Q, and I. M and Q are not necessarily at equilibrium. An example is Figure 21. The chill indices are listed on the graph. The 'normal winter clothing' is a military skiing assemblage, and is probably comparable to good winter clothes in the urban environment. The value of these charts is that they are empirically tested in the outdoors, unlike practically all of the other studies which were done either with models or in the laboratory. The limitation of wind-chill is that they are a combination of at least three variables, a final thermal-demand statement to which changes, as in insulation level, cannot be systematically made. According to Burton and Edholm (1955), it is only the limiting factor of exposed faces, nude skin, which determines their shape. The clothing is irrelevant. Falkowski includes bare skin Q on his wind-chill chart; these are reproduced on Figure 21.

Comparison of Figure 21 with Figures 17 - 20 shows considerable similarity between the curve shapes, especially the curves with higher clo values. The curve using the adjusted nude heat loss function shows a shape giving higher heat loss at lower windspeed, but the difference is not great.

II FIG. 21: WIND CHILL INDICES T VERSUS V

SOURCE = FALKOWSKI (1958); USAF.
NUDE SKIN Q FROM SIPLE & PASSEL.



CHILL INDEX :

1 COMFORTABLE WITH NORMAL MILITARY WINTER CLOTHING.

2 VERY COLD = TRAVEL UNCOMFORTABLE ON OVERCAST DAYS.

3 BITTERLY COLD = TRAVEL UNCOMFORTABLE ON SUNNY DAYS.

4 FREEZING FLESH BEGINS = SHORT TRIPS DISAGREEABLE.

6. Conclusions about climate and thermal comfort.

6.1. Tentative values of climatic factors for thermal equilibrium.

The calculations and assumptions in the thermal equilibrium curves have been described and summarized in the appropriate sections above. Below are given some of the results of these curves.

a. Wind is the most controllable climatic element in the thermal equilibrium functions. Maximum windspeeds suitable for comfort at selected temperatures are given in Tables 6 and 7, as taken from Figures 17 - 20. The clothing assumed at each temperature level is that which experience suggests to be most likely. Different levels are often assumed for men and women. It is clear from these tables that metabolic rate, solar gain, and insulation value each make a critical difference to the amount of wind velocity acceptable at any one temperature. Knowledge of these, or assumptions about them, are required in the initial stage of comfort assessment. Then the probability of sunshine is used to determine in which proportions the sun and shade curves should be used.

We take for example a subject with what we suppose to be relatively light winter clothing - 83% 2 clo coverage, 17% bare skin exposed. This is the clothing assumed above for females. She is in a standing or waiting

TABLE 6

Maximum permissible wind m sec^{-1}

				SHADE				SUN			
		Percent I		120 w m^{-2}		230 w m^{-2}		120 w m^{-2}		230 w m^{-2}	
T ^{o}C	I clo	male	fem.	m	f	m	f	m	f	m	f
-10	3	92	92	0+	0+	7	7	0.5	0.5	10+	10+
- 5	3	92	92	0.5	0.5	10+	10+	1.5	1.5	A	A
	2	92	83	0+	0	4	1	0.5	0.5	9	3
0	3	92	92	0.5	0.5	A	A	3	3	A	A
	2	92	83	0+	0	8	2.5	1	0.5	A	6
5	2	92	83	0.5	0+	A	5	3	1	A	10+
	1	89	77	0+	0	1	0.5	0.5	0.5	3	2
10	2	92	83	2	0.5	A	10	7	3	A	A
	1	89	77	0.5-	0+	2	1.5	1	0.5	7	4.5
15	1	89	77	0.5	0.5	6	3	2.5	2	A	10+
20	1	89	77	2	1	A	A	10	6	A	A

using adjusted 0 clo data: β.

I clo values are the likely clothing levels for each temperature.

A denotes V above 10 m s^{-1}

TABLE 7

Maximum permissable wind m sec^{-1}

				SHADE				SUN			
		Percent I		120 w m^{-2}		230 w m^{-2}		120 w m^{-2}		230 w m^{-2}	
T °C	I clo	male	fem.	m	f	m	f	m	f	m	f
-10	3	92	92	0.5	0.5	7	7	1.5	1.5	10+	10+
- 5	3	92	92	0.5	0.5	A	A	2.0	2.0	A	A
	2	92	92	0	0	2	2	0.5	0.5	9	9
0	3	92	92	1.5	1.5	A	A	3.5	3.5	A	A
	2	92	83	0.5	0	9	3.5	1.5	1.0	A	6.5
5	2	92	83	0.5	0.5	A	6	3.5	2.0	A	10
10	2	92	83	2.0	1.0	A	10+	7.5	4	A	A
	1	89	77	0.5	0	2.5	2	1.5	1.0	9	5
15	1	89	77	0.5	0.5	8	5	3	2.5	A	10+
20	1	89	77	2.0	1.5	A	A	10	8	A	A

using W & H 0 clo data: A.

activity such as waiting for a bus (150 $W m^{-2}$). Conditions are cloudy or it is night or in the shade. At $5^{o}C$, the windspeed should not exceed approximately 0.2 m sec^{-1} (½ mph) before discomfort sets in. At the same temperature, a briskly walking woman (at 285 $W m^{-2}$) can tolerate a 5.5 m sec^{-1} breeze. It is probable that an 'average' M for urban pedestrians and shoppers would be in the vicinity of 175 $W m^{-2}$ (walking 3 mph). For the example of $5^{o}C$, the wind comfortable at 175 $W m^{-2}$ is 1 m s^{-1}. These velocities are definitely in the vicinity of those found tolerable in common experience.

$0^{o}C$ is the best approximation to a practical minimum temperature in Edinburgh. In January T falls below $0^{o}C$ 25% of total hours, in February 22%, and in December 13%. The rest of the year lower temperatures are negligible. The coldest temperature at Turnhouse has been $-15^{o}C$. Using the same clothing as before, we see that at $0^{o}C$ the woman with M of 150 $W m^{-2}$ will be uncomfortable in any breeze, at 220 $W m^{-2}$ she will be in balance at 0.3 m s^{-1}, and at 285 $W m^{-2}$ she will be in balance at 2.6 m s^{-1}. With a man's warmer clothing value of 92% 2 clo, the windspeeds tolerable are still air for 120 $W m^{-2}$, 0.5 m s^{-1} for 175 $W m^{-2}$, 2.4 m s^{-1} for 220 $W m^{-2}$, and 10 m s^{-1} for 285 $W m^{-2}$.

<u>b</u>. Relative importance of wind, radiation and temperature in their effect on comfort.

In Edinburgh, the range of temperature within any one season will seldom exceed 17°C, and the daily range will rarely exceed 7°C. The average wind in exposed places will range between 0 to 11 m s^{-1} during 90% of hours in the winter. Solar radiation will range from 0 to 670 W m^{-2} direct irradiation.

It is possible to compare the effect on comfort of each of these ranges by converting to a common temperature equivalent. At M = 285 W m^{-2}, with 2 clo 83% and 17% 0 clo, the effect of wind velocity 0 - 10 m s^{-1} is equivalent to over 20°C in the shade, and over 30°C in the sun. Half of this difference occurs between -0 and 0.75 m s^{-1} in shade, and between 0 and 0.5 m s^{-1} in sunlight. At M = 150 W m^{-2} with the same R, the temperature equivalent of 0 - 10 m s^{-1} wind velocity is 15°C in the shade and 20°C in the sun. The larger values in sunshine reflect the additional cooling effect of wind in removing surface-generated energy. These values are roughly equivalent to the temperature equivalents calculated by Green (1967) from Brunt's formula (1947).

These temperature equivalents exceed or equal the air temperature range for the entire season, indicating that wind has a greater effect than temperature variation when the clo values and/or metabolic values are high. At 0 clo, the wind induced equivalent temperature difference for $M = 285$ W m^{-2} is 17°C in the shade and 20°C in the sun. At $M = 150$ W m^{-2} it is 11°C in the shade and 13°C in the sun. Here the effect of normal wind variation is similar to normal seasonal temperature variation, but it still exceeds the effect of normal daily variation (7°C).

These values exceed those given by Penrose and Lawson (1971) after an empirical observation of park use. They give 5 m s^{-1} as having the equivalent effect of 3°C. These observations were made in March through May, under warmer conditions, and they do not actually represent comfort, but behaviour.

The relative importance of radiation is less than that of wind velocity and approaches that of daily variations in temperature. Taking the extremes of no sunshine and very bright sunshine, the equivalent temperature difference between them ranges from 4°C to 10°C for a subject clothed 83% with 2 clo. The larger value occurs at still air, and the smaller value at the maximum value of 10 m s^{-1}, for the reasons described before. This range holds for $M = 285$ as well as 150 W m^{-2}. At 0 clo, the temperature equivalents at both $M = 285$ W m^{-2} and 150 W m^{-2} range from 5 to 7°C. These values correspond to the average daily temperature fluctuation. They compare to Penrose and Lawson's 5°C difference between a bright sunny day and an overcast day.

In a climate like Edinburgh, where temperature fluctuations are moderate but wind velocity has a large range, the relative importance of wind, temperature and solar radiation is on the order of 2 : 1 :1 if one uses daily temperature variation, and roughly 2 : 2 : 1 if one uses the seasonal temperature range.

In areas where temperature range is far greater and probable wind fluctuation less,the relative importance will be altered. The importance is only measurable in terms of the variation of the climate in question.

6.2. Time for discomfort to develop.

The heat balance relationships described above have all assumed steady state equilibrium as necessary for comfort. It is likely, however, that short term heat loss and some vasoconstriction can be tolerated without appreciable discomfort. This would be implicit in the concept that deep body temperature has to be lowered a certain amount to cause discomfort. The rate of cooling of a body of given heat capacity can be calculated, as in Section 2.3.2., making it possible to determine the length of time during which thermal disequilibrium can exist. Gagge, Stolwijk and Hardy (1967) found that a heat loss of 47 $W m^{-2}$ causes a body to cool at $1^{o}C h^{-1}$ M.B.T., and Edholm estimates that a drop in M.B.T. of $1^{o}C$ will ensure a metabolic response in outdoor conditions. Using the onset of metabolic response (shivering) as the limit for comfort, a net heat loss of

$100\ W\ m^{-2}$ could be tolerated a maximum of 25 minutes before discomfort.

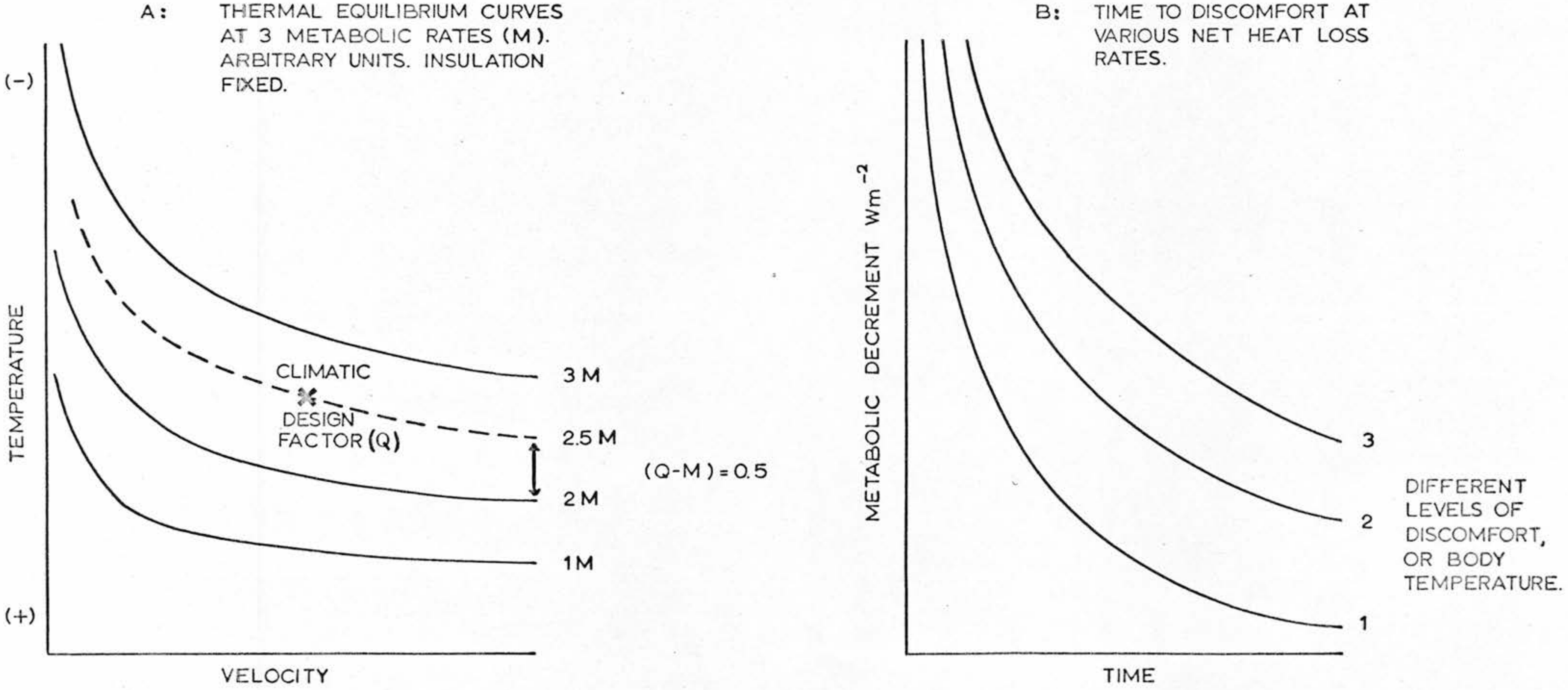
Discomfort developing over time requires further research before values can be speculated at. The means of presentation that would be most useful to designers is proposed in the following schematic figures.

Equilibrium curves T versus V are prepared with the metabolic rates as multiple lines and the R value fixed. Figure 22a demonstrates this for 2 clo. The climatic design value (perhaps the mean) is discovered, and the difference between the metabolic rate required by the climate (Q) and that produced by the activity expected (M) is the net heat loss, or a 'met decrement'. For an M of 2, the met decrement = 0.5 in arbitrary units.

Figure 22b represents heat loss over time, with the multiple curves representing different levels of discomfort. These levels would have to be defined and discovered empirically. They are probably best defined as levels of body or skin temperature. They will not be straight lines because of physiological regulation and conscious adjustment of clothing and behaviour caused by the rate of heat loss.

Figure 23 is the final form of discomfort graph. The axes of Figure 22b are transposed, giving discomfort versus time, and a family of net heat loss curves. The curves, for a

II FIG. 22: SCHEMATIC DISCOMFORT CURVES:



A: THERMAL EQUILIBRIUM CURVES AT 3 METABOLIC RATES (M). ARBITRARY UNITS. INSULATION FIXED.

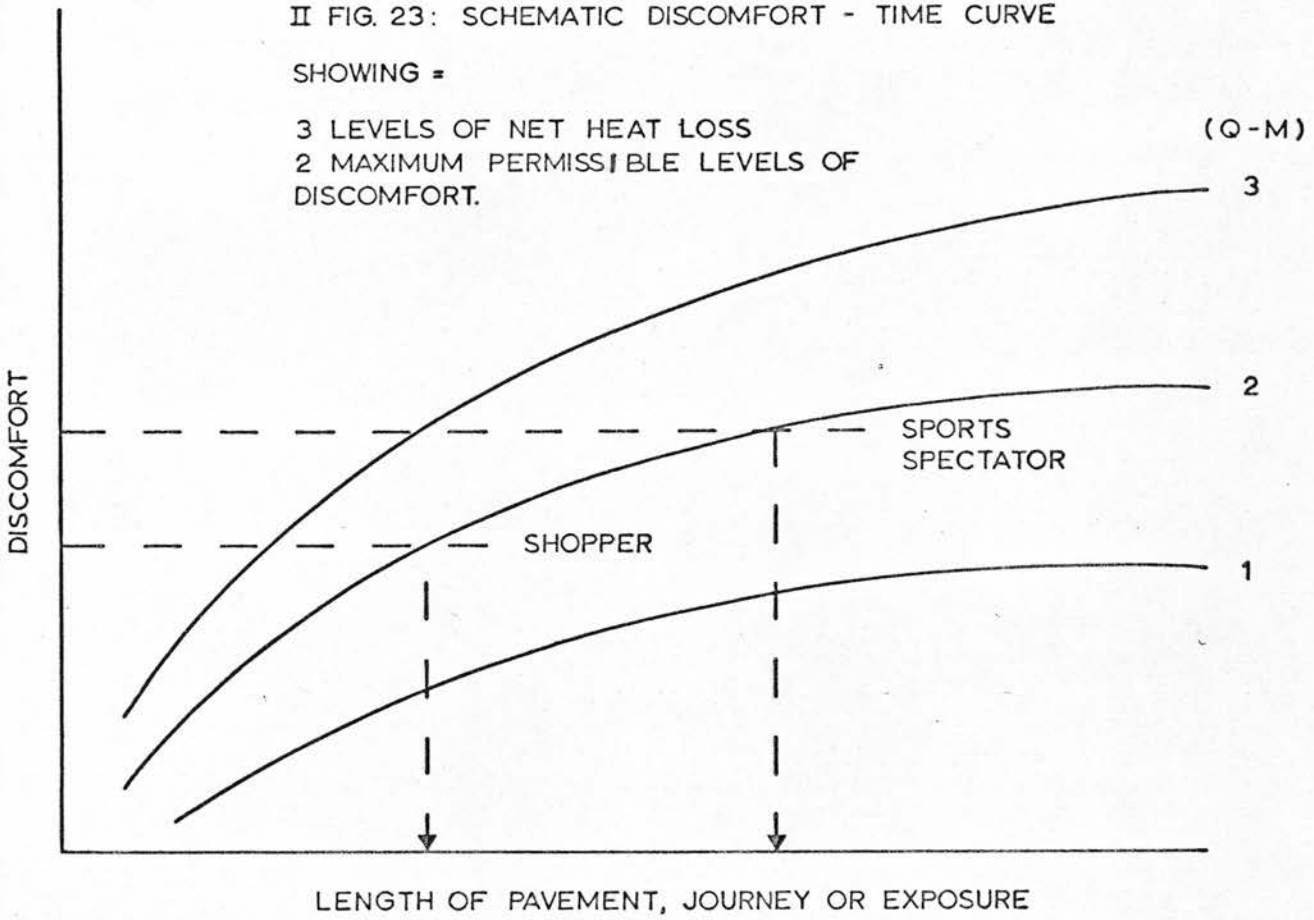
B: TIME TO DISCOMFORT AT VARIOUS NET HEAT LOSS RATES.

METABOLIC DECREMENT = NET HEAT LOSS (Q-M).

II FIG. 23: SCHEMATIC DISCOMFORT - TIME CURVE

SHOWING =

3 LEVELS OF NET HEAT LOSS
2 MAXIMUM PERMISSIBLE LEVELS OF DISCOMFORT.



given metabolic rate, are determined by the climatic conditions alone.

The time axis can also be expressed as a distance, if the rate of progress can be estimated. Thus this figure would be useful in city planning for the design of walking distances and interbuilding spaces.

Another concept shown on the figure is different levels of discomfort acceptable for different activities. The levels of discomfort acceptable on a ski lift and shopping precinct are quite different, and they affect the acceptable length of exposure.

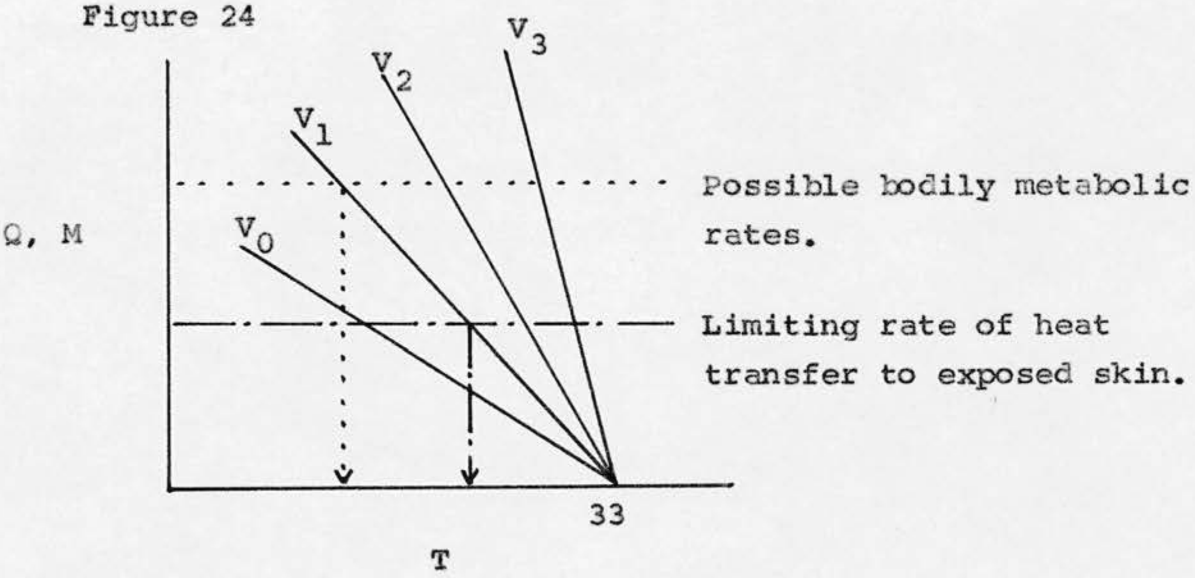
6.3. Areas requiring empirical testing.

The only variable that has been adequately researched is M, the heat production for various specified levels of activity. There is an immediate need for research into the integrated average R value of standard civilian clothing assemblies. This work should include assessment of the evaporative as well as conductive heat loss, and should be tested live in the open. Characteristic insulations for both males and females are necessary.

Empirical research into nude heat loss at wind velocities over 0.5 m s^{-1} and at temperatures to $-10^{\circ}C$ is required. Since the shape of the nude curve has such a dominant effect on the combined heat loss curve, this relationship should be reliably known. The formulae presently referred to in the literature have sizeable discrepancies.

Information is needed on whether there are limits to the amount of metabolic heat that can be transported to the exposed face and hands at the differing metabolic rates. This would give an 'exposed skin limit' which will be lower than the limits permitted by the combined thermal equilibrium curves Figures 12 through 20. On these figures it will resemble this:

Figure 24



The magnitude of the evaporative heat loss must be determined over a range of temperature. Assuming 25% Q (total) as above results in high heat loss at low temperature which is called into question by Herrington's (1947) experiment.

In the absence of required data on R values or on precise outdoor heat loss relationships, much immediately useable information could be obtained from limited practical tests on subjects. These would fix M at one value and use standard (though unquantified for R) clothing assemblies. After a length of exposure it will be detectable without sensory equipment whether the subject is cooling or warming up. Designers who have decided on the practical minimum temperature for their area can test for comfort at that temperature alone, thus minimising their measurements.

The time required for discomfort to develop is unexplored in outdoor conditions. A definition of different levels of discomfort is required. Empirical verification is needed for the relationship between rate of heat loss, the lowering of skin T and M.B.T. and the appearance of discomfort.

The relationship between steady wind velocity and gustiness or turbulence of differing scales requires empirical test. The outcome would indicate whether the practice of averaging wind speed over long periods gives adequate results, or whether a 'gustiness factor' should be applied to meteorological averages to increase or decrease their effect.

Part B: Physical effects of the wind.

7. Introduction.

7.1. Types of wind discomfort.

The wind influences human comfort in a direct mechanical way as well as via thermal comfort. This is termed the physical effect of wind. It occurs through pressure effects and through particle transport. In the former group are disturbance of clothing and hair, resistance to walking, and buffeting of the body and of objects like umbrellas. In the latter group are the lifting of dust and grit to eye level, and driving of rain sufficiently horizontally to bring it into the eyes or under clothing.

The wind velocities which cause these various discomforts differ considerably. Thus one form of discomfort will commence before another as the wind rises. Virtually no information was found in the literature which could indicate a scale of discomfort versus wind for any one of these effects. Consequently it is necessary to think of a limiting velocity above which discomfort usually results from each physical aspect of wind. It is attempted here to describe some increasing wind velocities at which the different discomforts begin to take place.

It is possible to think of cases where some of the different discomfort effects do not apply: athletes and hill walkers are not bothered by clothing disturbance, but by wind pressure. Dust and grit are not available to be lifted from moist or vegetated surfaces. Thus in order to find a general physical limit to wind for any particular situation, information is needed on each wind effect. It is not likely, however, that any distinction can be made between the severity of the various discomforts for the pedestrian situation. The lowest windspeed at which discomfort occurs would serve as the limit for physical wind discomfort.

7.2. General wind effects.

A general list of the physical effects of different wind velocities is given in the Beaufort Scale. This is a method of estimating wind velocity by observing its effects on the surroundings. The following representation of the Beaufort Scale (Watts, 1965; Lacy, 1972; and several basic meteorology handbooks) gives the effects in terms of common land observations.

TABLE 8

Beaufort wind scale for land.

Beaufort number	Description	Av. V ($m\ s^{-1}$)	Effects of wind on land
0	Calm	0.5	Smoke rises vertically
1	Light air	0.5-1.5	Direction shown by smoke
2	Light breeze	1.5-3.0	Wind felt on face; leaves rustle; wind vanes move
3	Gentle breeze	3.0-5	Leaves and twigs in constant motion; flag extended; hair disturbed
4	Moderate breeze	5 - 8	Raises dust and loose paper; clothing flaps; small branches are moved
5	Fresh breeze	8 - 11	Small trees in leaf sway; rain and sleet driven
6	Strong breeze	11 - 14	Large branches in motion; umbrellas hard to use
7	Moderate gale	14 - 17	Whole trees in motion; hard to walk against wind
8	Fresh gale	17 - 20	Breaks twigs off trees; generally impedes progress
9	Strong gale	20 - 24	Slight structural damage; slates and chimneypots blown off
10	Whole gale	24 - 28	Seldom experienced inland; trees uprooted, much structural damage.

This chart gives wind force 4 to 5 as initial limits for dust and rain propulsion, and wind force 6 to 7 for wind effects on umbrellas and walking. The values here can be compared to the more specific details which follow. It might be noted that the velocities given here for each Beaufort number are slightly higher than those presented in some overseas texts (Conrad and Pollak, 1950). The velocities given are the ones corresponding to the descriptions.

8. Wind pressure effects.

8.1. Experiment to obtain subjective response to wind.

Wind pressure has been assessed by various workers for the force it exerts on a human body and for the energy required to overcome this force. This will be described later. There has been no work on subjective appraisals of the discomfort caused by this pressure, and no statement of what aspect of the pressure might cause discomfort. An experiment was undertaken here to assess the relative magnitude of the various aspects of wind pressure acting on a human body. This was a very abbreviated experiment not intended to produce final results. It did produce the very pronounced fact that discomfort due to clothing disturbance initiated at a much lower velocity than that due to pressure acting on the body as a whole.

Five male and three female subjects were exposed in wind velocities ranging from 0 to 20 m s^{-1} in an ambient air temperature of 16°C. Subjective appraisals of physical discomfort due to wind pressure were taken independently from each subject in the fluctuating wind. Wind velocity was measured by a high response Schildknecht vane anemometer. The sky was overcast. Clothing worn ranged approximately from 1 to 1.5 clo. Men wore suits or trousers with light outdoor jackets; women wore dresses with short coats. The high temperature on the day of the experiment (Oct 21, 1971) served to isolate thermal loss discomfort from effects solely due to wind pressure. No subjects expressed any sensation of being chilled, though temporary cooling could be sensed as the peak gusts penetrated the clothing.

All subjects felt that wind effects became unpleasant as the velocity at 1.5 m height increased through 7 to 8 m s^{-1}. The primary source of irritation at this velocity was the disarrangement and flapping of clothing. General impedence to walking due to wind pressure and the unbalancing effect of buffeting was found beginning in gusts to 15 m s^{-1}. By 18 m s^{-1} all subjects found walking quite difficult. These velocity values agree with those given in the Beaufort Scale above. The effects occurred both if the gusts were of short duration or long. There was a tendency for the comfortable state to resume at a higher velocity when velocity is falling than is comfortable when velocity is rising. This is of no significance in the selection of physical limit. It was not possible to determine how much the suddenness (violence) of the gust would alter the limiting values, though sudden gusts were clearly more uncomfortable. Likewise, the possible influence of recurring gusts (frequency of velocity fluctuations) was not noted.

The experiment was done under walking conditions at a range of walking rates. It is evident that as the rate of activity increases, the sensitivity to wind pressure decreases. Under athletic exercise (climbing hills) velocities up to 10 m s^{-1} caused no irritation. This range of sensitivity was not quantified.

A further experiment was made to determine the 'nuisance limit' of wind on umbrellas, and newspapers. Depending on the orientation of the umbrella, difficulty commenced between 7 and 8.5 m s^{-1}. Sudden gusts caused the most inconvenience. Newspaper reading became unpleasant in a steady wind of 3 m s^{-1}, but gusts had a particularly disconcerting effect.

The forces required to cause disorientation of clothing or of objects like umbrellas are too variable to be analysed physically. From the close results of the above experiments it would seem that statistically significant thresholds for these effects can be found by a more intensive empirical experiment. For the purpose of this paper it is assumed that 7 to 8 m s^{-1} is the threshold value for discomfort in walking pedestrians due to clothing disturbance. The value for stationary pedestrians is probably less. The threshold for umbrellas is 8 m s^{-1}, and for newspaper reading is much lower, 2 to 3 m s^{-1}.

8.2. Wind pressure: forces involved.

Wind pressure on the human body has been studied by several workers using physical principles and modelling techniques. Their objectives were to show the forces on the human body and the physiological work required to overcome these forces. These experiments are summarized below.

The resistance of an object in a stream of air is proportional to its cross-sectional area and the square of the air velocity. An empirically determined coefficient of resistance, which takes into account the shape of the object and its surface roughness, is essential for each type of object.

Wind tunnel tests on models (DuBois-Reymond, 1925) give the following relationships for a man 167 cm high in a velocity of 5 m s^{-1}:

Nude	0.57 kg frontal resistance.
Covered in knitted wool:	0.63
Men's suit of clothing:	0.75

With the wind from the side, a standing nude offered only 0.23 kg resistance. A model in a bicycling position covered with wool material offered 0.29 kg. It is clear that the frontal position offers by far the largest resistance of any body position, and that clothing increases resistance significantly.

These values can be converted to any windspeed by multiplying by the square of the velocity ratio. At 10 m s^{-1} there is frontal resistance for a man in a suit of 3 kg. At 15 m s^{-1} resistance is 6.8 kg, and resistance equals average human body weight, 70 kg, at 50 m s^{-1}.

Closely corresponding results to these were found by Hill (1927). These workers give no indication at which velocity resistance makes forward progress difficult or unpleasant. However, comparison with the thresholds suggested by the experiment above gives an idea of the pressures associated with the onset of discomfort. The pressure on the entire body at the threshold of clothing disturbance, 7.5 m s^{-1}, is 1.7 kg. The pressure at 15 m s^{-1}, above which walking in a steady wind is difficult, is 6.8 kg. This corresponds to a forward lean of a 65 kg body at the centre of gravity (100 cm) of 10 cm, or a lean of 17 cm at head height.

8.3. Energy required to walk against wind.

Pugh (1970, 1971) measured the effect of headwind on the energy expenditure of runners and walkers. The energy measure used was expired oxygen, but it is possible to deduce from his data an 'equivalent gradient' which requires the same effort as walking against wind. The gradients corresponding to three windspeeds are summarized in the following table. The lifting work from Pugh's data is compared to the calculated work of walking against the pressure force given by DuBois-Reymond.

TABLE 9

Wind velocity versus work and equivalent gradient.

Wind velocity $(m\ s^{-1})$	Equivalent vertical work rate (Pugh) $(kg.m\ s^{-1})$	DuBois: horizontal work rate $(kg.\ m\ s^{-1})$	equivalent gradient (percent)	angle of slope (°)
8	2.5	2.4	2.5	1.5
14	8	7.3	8	5
18	13	12	14	8

Walking velocity is 1.25 $m\ s^{-1}$, with a subject weight of 75 kg. The work rates of Pugh and DuBois-Reymond correspond closely. Since the mechanical efficiency of vertical work on a gradient is 33% and of work against the wind is 44% (Pugh, 1971), the total energy expenditure of the pedestrian in the wind is slightly higher in the Pugh figures. The Pugh values of work rates and equivalent gradient are probably the more realistic, being based on recent extensive empirical tests on male subjects.

The concept of comparing wind resistance to gravity resistance on a slope might be useful in some planning contexts. It has been applied to athletic performances (Pugh). In the pedestrian context it can give a general idea of the effect required to walk in windy conditions.

8.4. Wind turbulence.

a. Effect on comfort.

The wind pressure on the pedestrian fluctuates rapidly in a turbulent wind with large eddies. The result, buffeting, causes the pedestrian to lose his balance. It also has the effect of disorganizing clothing which could act as shelter in a steady wind. Common experience tells us that a buffeting wind is more annoying and less comfortable than a steady one, but the extent is impossible to calculate. An indication of the unbalancing effect might be given by the example above that a wind of 15 m s^{-1} causes a body lean of 10 cm at the centre of gravity. Such a wind, suddenly halted or reversed, would cause the pedestrian to adjust at least 10 or 20 cm respectively, which would cause him to take at least one correctional step. The displeasure associated with such unbalancing would have to be subjectively determined.

Empirical tests behind turbulence generators of different scales would give the most straightforward and reliable information on this problem. These would be done with subjective assessment by the subjects, and objective study of body and clothing movement by cinema techniques. Turbulence was present in the experiment described above which indicated 15 m s^{-1} as a progress impeding wind.

Another test which would yield very useful information to the planner is one which would assess the remembered discomfort of being exposed to a single gust on a given journey. Many building plans have areas where concentrated gusts are likely to be generated, or where the pedestrian is exposed to atmospheric gusts. The meteorologist can give some idea of the return period (i.e. the expectation) of atmospheric gusts in such an area. Some information on the displeasures arising from gusts is needed before the following analysis of wind turbulence can be of any use.

b. Nature of the turbulence affecting pedestrian comfort.

A considerable literature exists dealing with turbulence as expected near the ground. None of it is intended for application to pedestrian problems. Most of it is at the scale of large engineering structures or at the small scale of crops on a uniform surface of unlimited extent. The pedestrian is in a transition zone, being affected by eddies of several scales, and generated by several processes.

Small scale eddies generated by the friction drag on the surface have average diameters roughly 40% the height of their centres above the ground, (Prandtl, 1949). They move with the wind and will cause a rapidly fluctuating wind pressure on a stationary pedestrian. Their average size is small at pedestrian height, so that they generally do not affect the whole body surface at once. However, the size variation is considerable. Webb (1965) in a discussion of turbulent transfer, considers only eddies whose size approximates the height above ground. The eddy internal velocity, and hence the fluctuation of the mean wind speed, is determined by the roughness of the surface.

Eddies or deflected wind generated by obstructions to the air flow such as buildings or topography are generally of a larger scale than the friction-induced eddies. These will approach the scale of the generating obstruction, and thus be larger than the pedestrian, affecting his whole body at once. Unlike friction eddies, the wind variations caused by buildings are shed from fixed locations for a given wind direction. Thus in a group of buildings, a wind from a given quarter will generally cause predictable eddy locations.

Larger scale eddies are due to cumulus convection (mesoscale) and due to thunderstorms and frontal passage (large scale). The first is caused by a combination of surface friction and thermal convection. The length of the eddy usually ranges between 1,300 and 2,600 m downwind, and the repeat time depends on the wind speed. At 10 m s^{-1} the gusts can be expected to repeat on 3 minute averages. Night time eddies are of smaller amplitude, and under the same conditions as above tend to repeat more often (1-2 minutes) (Watts, 1965). During high winds, the greatest gust activity has been found in the frequency of one minute (Van der Hoven, 1957). These gusts are ascribed to large frictional eddies. Their length is quite similar to the small cumulus convection eddies. Other eddies are found to be between 5 and 15 miles long, but these are associated with summer thunderstorm cells and the passage of fronts. The energy carried in the different eddy frequencies can be expressed in terms of a wind spectrum, commonly used in structural engineering (Harris, 1970). There is no present application of such information to pedestrian comfort.

c. Conclusion.

This brief description of turbulence is intended to show the time and length scales at which the wind turbulence affects a pedestrian. It is evident that the usefulness of such information in terms of planning for pedestrians depends on some quantification being made of its effect on comfort. If such information were known, the planner could account for turbulence both in terms of its limitations on comfort (all eddy scales), limitations to place (eddies in fixed relation to buildings), and limitations to various activities due to the climate of a place (return periods of middle and large scale eddies). Small scale turbulence is considered in more detail below in relation to its role in particle transport.

9. Wind-driven particles and rain.

9.1. Introduction.

The pedestrian's assessment of discomfort in wind is strongly influenced by the rain that might be blown in his face and the grit which, in dry periods, might be blown into his eyes. This latter experience is probably the most unpleasant single effect of the climate on a pedestrian, and is likely to be remembered for a long time.

The suspension of a solid or liquid particle requires an upward air velocity equal to the terminal velocity of the particle. A horizontal wind equal to or exceeding the terminal velocity of a particle will cause it to descend at an angle of 45° or less to the horizontal. Below is a list of the terminal velocities for small particles, the terminal velocities being roughly proportional to the square root of the diameter, or directly to the volume, of the particle.

TABLE 10

Terminal velocities of airborne particles.

V (m s^{-1})	Diameter (mm)	Character
10^{-2}	0.01	Dust
10^{-1}	0.03	Extremely fine sand, dry snow.
0.6	0.1	Fine sand.
1	0.2	Medium sand, snow, sleet, fine rain.
2.5	0.3	Average sand in the desert.
7	1	Large raindrops*
10	1+	Sand to pebbles, great rain, hail.

(Bagnold, 1941, *Reidat 1970)

The conditions under which blowing rain and blowing dust are unpleasant differ. For driven rain to be unpleasant the wind:rain combination causing an unacceptable condition must persist for some significant percentage of the time out of doors. This is because wetting by rain takes time. For blowing solid particles to become unacceptably unpleasant one needs only one particle of grit to be lifted to eye level by a single local eddy or a peak gust. Moreover, there is the difference that rain is in the air because it is falling from above, while virtually all the blowing grit requires lifting from the surface to become airborne. Wind flow at the surface depends on the nature of the surface and is not solely determined by the wind at 2 m. Thus the wind conditions significant for driven rain and grit are somewhat different and are described separately.

9.2. Rain.

From the table above it can be seen that a horizontal velocity of 7 m s^{-1} will cause large raindrops to descend at 45°. This value is used by building climatologists for driven rain data. It is clear that fine drizzle will be driven at 45° or less by velocities as low as 1 m s^{-1}. The parameters which are unknown are the size of h droplet and the angle of fall which individually and in combination are unpleasant. This can only be determined by some field testing. It is probable that flatter angles of descent are permissible for smaller droplet sizes. This would possibly permit one velocity to be a limit for a range of drop sizes.

a. Friction eddies

Vertical motions in the airstream tend to suspend the falling drop, making the descent angle much flatter. Following the discussion of turbulence above, the eddies of the scale induced by friction with the surface are only a metre large at pedestrian height, which means that raindrops falling into them will have only short contact with their upward components. The velocity of the upward components is not sufficient to make an appreciable difference in the angle of descent. As an example, a raindrop falling 5 m s^{-1} in a wind of mean velocity 5 m s^{-1} over a coarse pavement will encounter an upward velocity averaging 0.2 m s^{-1} over an average length of 1 m. This means the raindrop will take 0.21 sec to fall through the eddy, rather than 0.20 sec in horizontal wind. The additional horizontal transport due to the suspension in the eddy is 0.05 m, a lessening of the descent angle to the horizontal of less than 1.5°, which is an insignificant amount. Stronger upward components are required than are provided by friction-induced eddies over normal surfaces. Also, the lengths of the vertical airstreams must be sufficient to decelerate the droplet to a minimum velocity of fall. Lengths greater than one metre would be required for the larger raindrops.

b. Deflection eddies.

Obstructions to the windflow such as buildings cause various eddies where the vertical component can approach the mean wind speed, and where continuous upward air-streams are as long as the obstruction itself. In such locations, the suspension of raindrops can have a very strong effect on the angle of the driving rain. Horizontal and upward moving raindrops are quite possible in such eddies. The strongest upward currents are usually in fixed relation to certain shapes of building in the wind. This means that specific locations around a given building will be particularly susceptible to rain driving. The extent of the rain driving in any such location depends so much on the configuration of the specific buildings that it is impossible to reach conclusions on quantitative limits to mean wind speed becauoe of them. Recognition of these locations should enable the planner to make decisions about avoiding them or ameliorating them. Methods of testing specific urban locations in advance are described in Chapter IV.

c. Larger eddies.

Meso-scale and large eddies due to convection and friction combined cause large zones of lifting which may accompany showers. The height of the lifting zone may extend over 500 m. The velocity of the lift component can be considerable, perhaps approaching the magnitude of the velocity difference between the wind at the surface and at the top of the eddy. However, most of this lift velocity is found above the surface layer occupied by pedestrians. Analysis of these eddies (convection cells, Watts 1965), shows that, at the surface, the large areas of lifting are accompanied by strongly reduced horizontal speeds. The increased horizontal velocity attending the descending wind drives the rain more than the low velocity in the zones of lifting. Thus the lifting components of these and larger eddies can be neglected as an influence on driving rain.

d. Conclusions.

For the purposes here, the wind velocity threshold for driving rain will be taken as 7 m s^{-1} in a non-eddy condition. This equals a descent angle of 45° for large raindrops and is the threshold for driving rain quoted by Reidat (1970). This value is 2 m s^{-1} less than the velocity suggested by the Beaufort Scale as 'Driving rain'. Clearly the size of raindrops, or the angles of descent, differ. 7 m s^{-1} corresponds with the velocity suggested for the onset of discomfort due to clothing disorientation. The combination of driving rain with clothing disturbance has obvious consequences. In conditions where obstruction-induced eddies introduce large lifting components, the limiting velocity will be lower. But as discussed above, these large eddies are usually confined to specific places, and can be treated as exceptions.

9.3. Airborne grit.

9.3.1. Introduction.

It has been noted that grit in the eyes or in the face is the most disagreeable sensation that the wind can give a pedestrian. It is not easy, however, to draw general conclusions as to what nature of wind causes this effect. There are several unknown variables which have an overriding influence on the conditions in which grit is lifted and blown. At present, only the basic relationships can be pointed out,and solution of specific cases in the future might permit more comprehensive understanding and prediction ability.

Essentially, if the upward wind velocity w' exceeds the terminal velocity of a particle as in Table 10, the particle is capable of being lifted. Since virtually all grit particles affecting the eyes will originate on the surface, some mechanism is required to lift them off the surface to where an upward moving airstream exists. This mechanism is a lateral shifting of the particles due to the fluid drag on them, followed by bouncing from the surface. Once into an upward moving current, any current of air exceeding the terminal velocity which extends from near the surface to 2 m is capable of carrying a particle to the eye. The grit problem should ideally be considered in terms of extreme value probability of such currents occurring. The information required for this is not available, and for the present discussion the average w' for a given horizontal velocity is used as the threshold for lifting capacity.

9.3.2. Parameters required.

a. Particle size.

The unknown parameters make quantification of the process impossible at present. The first unknown is the minimum size particle causing irritation. The threshold size is between dust and fine sand, thus between 0.01 and 0.1 mm. The terminal velocities of particles within these limits can vary by as much as sixty times. Although it is possible that closer limits could be quickly found, say between 0.03 and 0.05 mm, the terminal velocities (and hence lifting velocities w') will still differ by 250%. Since w' varies directly with horizontal wind speed, this constitutes an extremely wide range of wind speeds meteorologically. For a limiting velocity to become useful, it would have to be defined much more closely, at least within a factor of 1.5. Moreover, the terminal velocities used here apply to quartz particles whose roughly rounded shapes permit them to be lifted by a wind approximately 0.75 times that required to lift perfect spheres. Many particles with a large dimension will be lifted by lower windspeed because of more irregular shape or lower density.

b. The second unknown is the appreciable effect of moisture in cementing particles together and to the surface. Data used below on the subject of sand blowing is largely derived from that of Bagnold (1941) in desert conditions. A test was made in Edinburgh to determine the effect of normal (82%) humidity on particle movement as compared to Bagnold. A tray of mixed grit from the surface was exposed to wind in an open field under roughness conditions comparable to those of the desert. The wind velocity exceeded 20 m s^{-1} at 2 m. The velocity at the surface exceeded Bagnold's sand shifting threshold velocity by a factor of two without any shifting being observed. The lack of particle movement was attributed to the moisture in the grit from the atmosphere and a rain two days previously. In the interim it had lain in a well drained site. On another occasion, grit blowing was repeatedly observed as gusts touched 10 m s^{-1}, even after rain that day. This was in an area of smooth paving and deflection eddies. Such observations indicate the level of uncertainty introduced by the addition of moisture.

Smaller particles are more capable of moisture absorption and retention than larger ones. This means that, for any given moisture content, there is a particle diameter below which particles are less susceptible to wind lifting. The terminal velocity of this particle diameter becomes the threshold w' if the particle is above the minimum size for irritation. It is likely that humidity levels normal in the British Isles suppress particles above the irritation level. In dry spells the surface dries enough for the finer particles to become independent. Dust blowing in Edinburgh is noted to take place mostly during the extended dry periods of spring and summer. The author has heard several comments that Glasgow, which is wetter than Edinburgh, especially at these times, is not as 'dusty'. Thus it would seem that the threshold w' depends both on the wind and humidity of the surface, with the lower limit to the size of irritating particles exerting an influence only in the dry periods. The meteorological parameters involved could perhaps be expressed, after experiment in the field, as a variant of the evapotranspiration formulas used in agriculture and hydrology.

c. The third unknown concerns the availability of particles to be lifted from the surface. Since particles are generally shifted in direct proportion to the wind speed over them, the fine particles will be preferentially removed to crevices or to screens like vegetation by an average wind velocity. The larger particles will accumulate waiting to accompany the extreme gust. Such evenly graded collections can be found on inspecting any pavement or street. In the desert, hardly any particles under 0.08 mm diameter are to be found, while the predominant grain size is 0.2 mm (Bagnold). Since the oceanic source of desert particles had vanished, the gradation of particles by windstrength became extremely uniform over time. The particles under 0.008 mm were all blown downwind from the desert area as loess, leaving a very uniformly sized sand on the dunes. A threshold windspeed for sand lifting would have to use this size grain rather than a finer grit. In the case of a city the availability of small particles will depend on a continuing source of the particles and means of replenishing the wind swept surface from this source. The source would be bare soil, slow breakdown of hard surfaces, and products of combustion settling from the air. In paved pedestrian precincts, the areas around buildings which have continual eddies rarely have any fine particles on the surface. In areas with motor traffic the redistribution of fine particles from calm areas into fixed eddies might be more rapid. Without this active transport, the most effective replenishment occurs during wind shifts, when the new direction erases or shifts the fixed eddies. When the original wind resumes, there is, temporarily, strong dust blowing. This phenomenon is common in arid regions (Bagnold). The meteorological information needed for this is an analysis of the periods of wind from each direction, expressing the frequency of changeover, and the velocity at the onset of the new period. The concept of wind steadiness S^* gives part of this information in an averaged form.

$$S^* = 100 \frac{R'_*}{R_*} \qquad (20)$$

where R_*' is the resultant run of the wind (sum of vectors) and R_* is the run of wind disregarding direction. S^*, combined with a frequency of significant shifts, and with the mean velocities after the shifts, would give some indication of the frequency of severe grit blowing periods. Again, quantification of the severity depends on experiment. An experiment on this phenomenon would have to test various environments, with different levels of particle source and different levels of particle sink (screens to trap particles: vegetation and water). The result of such an experiment would be to show that the limiting value of wind for expected grit lifting is dependent on the steadiness of the wind and on the nature of the site.

9.3.3. Physical principles involved in particle lifting.

In spite of the above unknowns, the basic relationships of wind and particles can be described, and empirical data from the desert conditions can be used as illustration. This divides into two subjects: the susceptibility of a particle to be rolled and then lifted by the drag force imposed by the wind, and the nature of wind and wind drag over the surface. The second subject divides, as in the discussion of pressure effects, into wind over homogeneous surfaces and over surfaces with vertical obstructions. In the case of the homogeneous surface, the drag and lifting velocity is dictated by friction with the surface. In the presence of obstructions, the wind drag and lifting are determined by eddies originating in the wind deflections caused by the eddies.

a. Particle rolling.

Bagnold and Chepil (1959, 1965) have investigated the physical principles of wind drag on particles nested in a surface of sand. They found, in dry conditions, that particles begin rolling at roughly one seventh the wind that is required to suspend them. Above this "shifting velocity" the particles move by bouncing, or saltation. Above the threshold value for suspension, they are capable of being lifted as high as the zone of wind shear above the surface. Over any natural surface inhabited by pedestrians this zone is at least 10 m thick, thus completely engulfing the pedestrian. The figure one seventh cannot necessarily be expected to apply to conditions in a humid climate, for the reasons of moisture coherence described above. Nevertheless, an average value for a city in a humid climate might not be much different because of the difference in surface between a desert and paving. Particles of sand on the desert are nested in other particles, with less area exposed to the wind than a particle resting on a paved surface. The effects of moisture adhesion might be compensated for by the probable increase in exposure. This exposed area could be proved relatively easily by an experiment similar to Bagnold's.

The above discussion brings out a basic fact usable in design. Since particle shifting on the surface begins at considerably lower windspeeds than particle lifting, particles can be expected to travel laterally a considerable distance before being lifted. The provision of screens like low thick vegetation, crevices or grates, or water surfaces can be expected to screen out any particles passing over them. Conversely, totally paved areas bounded by buildings can be expected to conserve all their particles until sufficient wind arises to lift them out.

_b_. The nature of wind over a homogeneous surface: vertical velocity via the concept of friction velocity.

The vertical component of wind w', caused by the friction of velocity over a surface, can be computed from knowledge of the mean horizontal windspeed at any level, and the roughness of the surface. The work, derived from Prandtl's method, is described in Sutton (1949). Briefly, the roughness of the surface causes eddies whose energy transfer and velocity of rotation vary with the logarithm of the roughness and directly with the mean velocity. Since the eddies are approximately circular, the eddy velocity U_* can be roughly equated to an instantaneous w' and is given by the following expression:

$$U_* = k\,U_z\left(\ln \frac{z}{z_o}\right)^{-1} \cong w' \qquad (21)$$

where U_z = mean velocity at height z (the symbol used in physics)

k = von Karman's constant: 0.4

z_o = height at which $U_z = 0$, and is known as the "roughness length".

The roughness length is a parameter which, for pedestrian surfaces, is proportional to the actual height of the topography of the surface.

Equating U_* and w' assumes the eddies to be isotropic, ie, circular. This is not quite true close to the surface. Scrase (1930) found that eddies had the following proportions (ie velocities) in three dimensions: $w' = 0.75\ u'$, and $v' = 1.16\ u'$ where u' is the fluctuation from the mean of the horizontal windspeed, and v' is the lateral velocity component. U has a value between u' and w'. These are assumed close enough to consider equal for these calculations. A practical way of visualizing this is that the vertical velocities in the air are roughly equal to the horizontal gustiness about the mean.

From this relationship we calculate U_* to approximate 1/20 to 1/25 U_z ($z = 1.5$ m) for a roughness equivalent to that of paved surfaces or a beach ($z_o = 0.05$ mm to 0.5 mm). The results are presented in the table below:

TABLE 11

Values of U_* for three surfaces

U_z	Smooth Pavement z_o = 0.05 mm	Coarse Pavement z_o = 0.5 mm	Desert Surface (rippled, = cobbles?) z_o = 7 mm
1	0.04	0.05	0.075
2	0.08	0.10	0.15
4	0.16	0.20	0.30
6	0.24	0.30	0.45
8	0.32	0.4	0.6
10	0.4	0.5	0.7
12	0.5	0.6	0.9
14	0.6	0.7	1.1
16	0.6	0.8	1.2

Values of U_* are given in Bagnold for the shifting of particles when z_o is of the same magnitude as the particle diameter. This corresponds to the smooth pavement for most sand particle sizes: the two rougher surfaces have values of z_o which engulf the particle. Accordingly, the values of U_* do not apply for shifting the grains on the surface, and particles need to be lifted above the roughness zone to become suspended. The actual wind force or drag within the roughness length is not defined, but Bagnold demonstrates it to effectively have a lower U_* than the zone above z_o. Thus, although rougher surfaces have higher eddy velocities and vertical wind speeds above them, the shelter afforded to particles within the zone of roughness is greater, and the velocity required to move particles from this shelter is greater than for a smoother surface. A detailed discussion of wind within the 'roughness length' is given by Thom (1971).

The threshold U_* values for a 0.1 mm particle are 0.15 m s^{-1} to shift it and 0.6 m s^{-1} to suspend it. The corresponding values for a 0.25 mm particle are 0.2 m s^{-1} and 1.5 m s^{-1}. On the smooth surface, these threshold eddy velocities for the smaller particle are reached at values of $U_{(z=1.5\ m)}$ of 4 and 14 m s^{-1} respectively. For the larger particle the $U_{(z=1.5\ m)}$ values are 5 m s^{-1} and considerably over 20 m s^{-1}. The suspension velocities are lower above the two coarser pavements (12 and 8 m s^{-1} for the 0.1 mm particle over the 0.5 mm and 7 mm roughness lengths). Shifting velocities are not available for these particles within the roughness length. If the surface particles were dry, saltation from surface shifting could be expected to lift particles through the roughness length by the time suspension U_* has been reached.

c. Conclusions on to wind and particles over homogeneous surfaces.

It is evident that the method of approaching eddy velocity and particle lifting via the friction caused by surface roughness gives results that are fully applicable only to beaches and large exposed paved or unvegetated surfaces. However, the method does begin to apply partially as soon as any wind runs across a surface. The eddy system generated by surface friction builds up to a height roughly 1/40 the fetch from the onset of the wind over the surface. For the small roughness lengths and eddy sizes needed to initially shift and lift particles, this fetch is not very long. The friction-induced eddies become a turbulence system within the larger turbulence system caused by surface obstructions in a city, and the characteristics of the smaller eddies dominate the conditions directly at the surface everywhere except immediately in the downwash or uplift of a gust or eddy.

It is clear that shifting velocities particularly will have to be empirically tested for humid conditions. The measurements undertaken suggest values above 10 m s^{-1}. If Bagnold's data may be applied, the threshold $U_{(z=1.5)}$ for picking grit (0.1 mm) off paved surfaces ranges between 14 and 8 m s^{-1}. This can be only loosely compared with the Beaufort standard of 5.5 to 8 m s^{-1} to 'lift dust and loose paper', since the size of the dust particles and nature of the surface are not specified in the Beaufort Scale.

d. Deflection eddies.

Wind conditions within an area of large impervious vertical obstructions are unlike those of the natural surface from the standpoint of grit lifting. A limited area of the total is covered by eddies and vortices which are either fixed in location or originating from a fixed location and then travelling downwind. These are considerably stronger, particularly in their vertical components, than the eddies from the natural surface. They extend down directly to the surface, effectively erasing the boundary layer. Since the lifting of grit is an extreme occurrence phenomenon (one occurrence causes lengthy discomfort) these vortices are more important than their small actual area on the ground would suggest. In this way grit lifting vortices differ from those driving rain in cities. They are the mechanism for lifting grit into the air, and once it is in the air it can be assumed to be intercepted by pedestrians. The major limitation is in the supply of particles to the base of the eddy, as described above.

On an urban street, vortices are continuously shed behind lampposts, pillar boxes, tree stems, and vehicles still and moving. Other larger eddies are found at building corners and large areas to windward and at the sides of taller buildings. In such roller eddies to windward of a tall slab, w' at 1.5 m has been measured inEdinburgh to equal the horizontal velocity at the same height. The lifting velocities at the surface have not been measured or calculated. They will lift grit at a lower ambient air speed than the friction induced eddies, but it is noted that ambient airspeeds are usually considerably lower within areas of vertical obstruction. This is mesometeorological information, outlined in Chapter IV.

9.4. Conclusions about driving particles.

Conclusions about threshold wind velocities for wind lifting of particles are thus hard to obtain. It is possible to pick the meteorological parameters which will control the phenomenon, but considerable experimental work will have to be done to specify the significant values of these parameters. It is possible that such work might be found useful, particularly by someone in an arid climate. The parameters that are influential are as follows:
_a_. For grit: wind velocity, wind steadiness, and frequency of direction change determine the lifting ability and particle replenishment when considered together with the nature of the surface and of obstructions. The length of dry periods together with atmospheric moisture content determine the availability of particles for lifting.
_b_. For rain: wind velocity correlated with presence of rain, and drop size. Both these sets of parameters should be limited to the time of day one is interested in.

Experimental work that will be needed before the problem can be analysed includes the following.
_a_. For grit: the size of particle causing discomfort, the role of moisture in suppressing fine particles, the effect of wind steadiness on particle availability, and the threshold velocities for particle shifting. Finally, a general testing in urban locations for airborne particles, culminating in a multiple regression of all the parameters.
_b_. For rain: the sizes of droplet correlated with angles of descent that are considered unpleasant.

10. Conclusions about 'physical effects of wind'.

The velocity $U_z = 7\ m\ s^{-1}$ at $z = 1.5\ m$ will be used as a cutoff for the thermal comfort relationships derived in the first part of the human comfort section. Below this cutoff the comfort of the pedestrian is assumed to be governed by thermal balance between his heat production and loss. Above the limit it is assumed that a pedestrian will be uncomfortable regardless of his heat balance.

It has been noted that some exception should be made for activities with unusually high metabolic and movement rates, such as some athletics, where physical wind effects are not as disagreeable as for pedestrians. Also, wind sensitive activities such as newspaper reading and handling large rigid objects have a nuisance threshold at a lower value, perhaps $3\ m\ s^{-1}$. For the average pedestrian, wind above $7\ m\ s^{-1}$ is assumed uncomfortable and disconcerting from both the pressure and rain particle viewpoints. It has not been possible to determine the discomfort threshold for grit, but over most natural surfaces it is definitely higher than $8\ m\ s^{-1}$, and in the presence of vertical obstructions it is probably in the vicinity of $7\ m\ s^{-1}$.

It is quite possible that field investigation with a large sample of subjects will show this assumed limit to be too high. Wise (1970), for example, uses $5\ m\ s^{-1}$ as the discomfort threshold under 'winter conditions'.

For the purposes of this thesis, however, it is safer to keep 'ceiling' type limits high and attempt to judge comfort (or degrees of discomfort) by the more quantifiable thermal criteria. 'Limits' and 'ceilings' do not permit the possibility of adaption by the pedestrian to bad conditions, and although no information on this is available to be used in this thesis, human flexibility in the outdoor climate must affect any of the criteria used here.

CHAPTER III

III. Relationship between climatic factors and building heat loss in a cold environment.

1. Introduction.

The thermal performance of buildings is affected by the same climatic elements as those influencing pedestrian comfort: temperature, wind, solar radiation, rain and humidity. These control, in varying degree, the heat loss and heat gain in a building.

There are several aspects of the thermal performance of buildings which are of interest to designers. The primary ones in a cold climate can be subdivided as follows. The first is the maximum heat loss rate that can occur before heat production is exceeded, interior temperatures fall, and 'thermal failure' occurs. This maximum heat loss is a function of the climatic conditions expected, the overall level of insulation of the building, and the heat producing capacity of the plant in the building. The designer is interested in the extreme heat loss expected in order to make decisions on the building's level of insulation, and on the size of the heating plant to install.

The second aspect of thermal performance is the behaviour of internal temperature during non-extreme external conditions, particularly through the diurnal cycle. This internal temperature is a function of the changing external climate and the internal heat production, as controlled by the influence of the building's thermal capacity and its unshaded windows. The designer is interested in the expected daily behaviour of the internal climate in order to make the interior space comfortable, and perhaps to economise on heating and cooling requirements.

The third aspect of thermal performance is the average heat loss anticipated over the heating season. This is a function of the external climate, level of internal temperature, and the level of insulation. The designer is interested in this because it represents the cost, in fuel, of building to a given insulation level. The planner is interested in it because it represents the cost, in terms of fuel or insulation, of building in a given climate.

The intent of this chapter is to draw the relationships between climate and the average heat loss from buildings. The purpose is to give the planner a tool for evaluating the cost of putting buildings in one site climate instead of another. This cost could be due to fuel cost over the life of the project, cost of insulation installed to lessen fuel cost, or the cost of site climate modification by landscaping or layout to lessen heat loss. In each case, the planner has a cost which he can add to the other costs involved in planning, and which will influence his decisions on site choice and site planning.

The planner will also be influenced to some extent by the maximum heat loss rate expected for a climate, since it influences the size and cost of heating plant which must be installed. However, it is chosen not to discuss this here since it is primarily important to the designer of the building itself, involving decisions on what are acceptable probabilities of thermal failure. The development of relationships between this aspect of a building's thermal properties and climate is discussed schematically in Section IV.1.

This chapter presents a method of developing a building: climate relationship. The effects of the different climatic elements on heat loss have to be established separately, and then combined. Likewise, the effect of climate on the different major components of a building (i.e. walls, roofs, windows) are determined separately for unitary areas of each, and then assembled in the appropriate proportions to simulate the effect of climate on the complete building. The combination of the different components is presented graphically.

The type of building which is discussed is as generalized as possible, but since some of the empirical data used comes from a study of domestic houses, the final results should strictly apply to houses only. This is not considered a disadvantage of the method proposed, for if data on other building types should become available it can be easily substituted for the data that is presently used. The individual components of heat loss are isolatable in the methods, and are open to independent alteration.

A qualification at the outset is that any such relationship must take the actions of the occupants into account. Human action is included in this design method, based on the most complete empirical data available, that of Dick (1950). Human behaviour may well have changed in the interim, as well as the characteristics of houses. Dick's occupants were average house dwellers of the time, who supplied their own fuel. In a different situation, occupant behaviour can cause a completely different climate:heat loss relationship, in fact can cause no relationship to exist at all. An example of this (B. Davidson, quoted in Munn 1970), is in New York, where apartment dwellers with free central heating leave their thermostats turned up and adjust interior temperature in warm weather by opening windows. The result is constant fuel consumption regardless of the climate. This chapter depends on the assumption that there will be at least some relationship between climate and building heat loss.

2. Heat transfer from buildings - conduction.

2.1. Modes of heat transfer through materials and buildings.

The gain or loss of heat in buildings takes place by conduction, convection, radiation, and moisture evaporation or condensation. It always involves more than one of these modes of transfer. The characteristics inherent in building materials which control the rate of heat transfer are:-

Thermal conductivity	λ	$W m^{-2} \, {}^{o}C^{-1} \, m$
Surface convective coefficient	h_c	"
Surface radiative coefficient	h_r	"
Transparency		
Heat capacity	C	$W h m^{-3} \, {}^{o}C^{-1}$
Porosity to air movement		

The characteristics of the building itself which control the heat transfer are:-

Conductance of the wall, roof elements
Ventilation through openings in the structure
Radiation characteristics of the surface
Transmission of radiation through glazing
Rain penetration potential
Heat capacity

2.2. Conductance: heat transfer from surface to surface.

Building structures are made up of elements each of which has a conductance C_2 ($Wm^{-2}\,{}^{o}C^{-1}$):

$$C_2 = \frac{\lambda}{d}$$

where λ = thermal conductivity
d = thickness of element

The reciprocal of the conductance is the resistance r, which is equivalent to insulation:

$$r = \frac{d}{\lambda} \quad (m^2\,{}^{o}C\,W^{-1})$$

The rate of heat flow across a building element in steady state conditions is given by:

$$Q_{(s-s)} = A\,\frac{\lambda}{d}\,(T_2 - T_1)$$

where A = surface area of element
T_2-T_1 = temperature gradient
$Q_{(s-s)}$ = heat flux from one surface of the element to the other.

2.3. Climatic influences on conductance.

The rate of heat flow between the surfaces of a given element is thus dependent only on the temperature difference between the surfaces, under steady state conditions. However, climatic conditions may have an indirect effect on heat flow through building elements when moisture penetration alters the conductivity of the material within the element. The conductivity of the material with increasing waterlogging will approach 0.6 Wm m^{-2} $^{o}C^{-1}$, the conductivity of non-convecting water. This is ten times the heat flow per degree temperature difference of most standard insulative materials (such as glass wool) and equal to that of conductive materials such as brick and concrete. Therefore the climatic factors having influence on the conductance through building materials are temperature and wind-driven rain. The 'driving rain index' will be discussed in this connection later.

The resistance of cavities in walls (particularly ventilated ones) is definitely altered by internal air movement caused by external wind. The resistance of the cavity is usually considered a fixed quantity based on the principles of surface resistance described below. How much this resistance is reduced by ventilation is not usually considered by engineers and requires empirical test. Diamant (1965) gives a hypothetical example of an uninsulated ventilated brick cavity wall which under a 30 mph wind has a 25% higher conductance between the internal and external surface than under wind still conditions.

The magnitude of ventilation within walls depends on the openings through the outer surface, their location in the wall and relative to the wind, and on the subdivisions and substances in the cavity. The number of unexplored variables is very large, and there is no empirical data to draw on. The 25% increase demonstrated by Diamant is probably an extreme value. With increased insulation and less inner wall ventilation the effect of wind on wall and roof conductance is much less. However, the accepted practice of using one value of the conductance of a wall from surface to surface (with adjustment perhaps for moisture content) should be treated with caution. The influence of wind causing air movement within some types of insulation can be greater than its influence cooling the outside surface.

2.4. Transmittance: heat transfer from interior to exterior space.

The heat flow per unit area per degree temperature difference through a wall of multiple elements is equal to the reciprocal of the sum of the resistances of the various elements. This is analogous to the determination of current in an electrical series. The overall transmittance K of a wall ($Wm^{-2}\ {}^{o}C^{-1}$) includes the conductances of the two surfaces as well as those of the wall elements. The conductance of each surface, or the surface coefficient (h_i and h_e for interior and exterior surfaces) consists of several heat transmission processes which take place simultaneously. These are conduction, convection (in two types) and radiation. In effect, these processes are linked in parallel, so that the surface coefficient is comprised of the sum of the conductances of the heat transmission processes. These processes must be examined individually to determine the effect each exerts on the overall heat transmission. The influence of climate on building heat loss is exerted primarily through these channels.

3. Heat transfer from buildings : convection.

Conductive and convective heat exchange between a solid surface and a fluid are unlike radiant exchange in that they involve the molecular transfer of momentum. The conductivity of still air by molecular transfer is quite low (0.025 $Wm^{-1}\ {}^{o}C^{-1}$), with the result that if a thick layer of immobile air exists the resistance of this layer will be high. In nature a layer of immobile air will exist immediately adjacent to any surface, covered by a layer of laminar flowing air whose heat transmission, for a continuous surface, is also by conduction.

For objects the size of people or buildings in air, a turbulent layer will cover the immobile and laminar layer. The turbulence is induced either by thermal instability or by external wind. The types of turbulence resulting from these two causes are called thermal ('free') and forced convection. The point where the turbulent layer merges into the surrounding air is the top of the 'boundary layer'. This is also the point where the thermal gradient between the surface and air reaches air temperature. The thickness of the boundary layer, and particularly of its laminar lower part, is inversely proportional to the conductivity through the layer.

Thermal convection surface coefficients

From Diamant p.31	$h_c = 1.97(\Delta T)^{\frac{1}{4}}$		$h_c = 2.62(\Delta T)^{\frac{1}{4}}$		$h_c = 1.31(\Delta T)^{\frac{1}{4}}$	
ΔT (^{o}C) Surface-air	Vertical walls		Horiz: roof (Ω)		Horiz: floor (Ω)	
	h_c	R*	h_c	R*	h_c	R
1	1.97	0.51	2.62	0.38	1.31	0.77
2	2.32	0.43	3.08	0.32	1.54	0.65
3	2.59	0.39	3.44	0.29	1.72	0.58
5	2.95(2.6)**	0.34	3.90(3.4)	0.26	1.95(1.7)	0.51
7	3.20	0.31	4.24	0.24	2.12	0.47
10	3.50(3.0)	0.29	4.64(4.0)	0.22	2.32(2.0)	0.43
15	3.88	0.26	5.15	0.19	2.67	0.38
20	4.16(3.6)	0.24	5.52(4.8)	0.18	2.76(7.4)	0.36
30	4.60	0.22	6.12	0.16	3.06	0.33

* useful only in the equation for (T_e) : clear sky Ω.

** bracketed values from EEU text: uses formula

$h_c = 1.74(\Delta T)^{0.25}$ = L dimension = 1m.

3.1. Thermal convection.

The thickness of the boundary layer and its potential conductivity are described by the Nusselt and Prandtl Numbers (Nu, Pr). The Nusselt Number relates the thickness of the boundary layer to the size of the surface. The extent of convection due to thermal instability is described by the Grashof Number, Gr. The thickness and conductivity of the boundary layer under conditions of thermal convection can be described by empirical functions of these numbers. Using the functions of Gates (1962), the following expressions for surface thermal convection coefficients are derived:

$$h_c = 2.1 \left(\frac{T_s - T_a}{L}\right)^{0.25}$$

For walls and roofs, and:

$$h_c = 1.0 \left(\frac{T_s - T_a}{L}\right)^{0.25}$$

For floors, eaves, and soffits when the heat flow is downwards. $T_{s,a}$ are surface and air temperatures, °C. For large surfaces, L is the dimension of the convection cell, in m. Thermal convection is minimized by keeping the convection cell large.

Table 1 lists empirically derived thermal convection coefficients for three surface orientations (Diamant, 1965); the values are somewhat at variance from others listed in another engineering text (E.E.U., 1965). It is felt that the differences are due to variation in the size of convection cell present. Smooth, uninterrupted surfaces have lower heat transfers than rough ones, and walls with interior air spaces show higher heat transfers if the interior spaces are horizontally subdivided. It is unlikely that these considerations have a significant effect on the overall building heat loss under normal building practice.

The interior surface convective coefficient is virtually all thermal convection. On the exterior surface, the scale of thermal convection depends primarily on the climatic element air temperature, which for a given surface orientation and wall conductance determines the difference in temperature between surface and air temperature, and hence h_{ct}. However, if other factors such as radiant cooling or forced convection are occurring, the surface to air temperature difference will be less than that caused under purely thermal convection conditions. The magnitude of thermal convection will then be diminished or even, under strong radiant cooling, reversed.

3.2. Forced convection.

Forced convection by wind exceeds thermal convection in importance as soon as wind becomes appreciable. It is the dominant mode of heat transfer from building exteriors in temperate climates. The forced convection coefficient, h_{cv}, is described in standard engineering texts (IHVE 1970, ASHRAE 1967, EEU, and Diamant 1965) by the following relationships to wind:

$h_{cv} = (a + b\ v)\ F$ for speeds up to 5 ms^{-1}.
$h_{cv} = (c\ v^{0.78})\ F$ for speeds over 5 ms^{-1}.

where v is wind velocity, F is the friction coefficient, and a, b and c are constants.

The values given by the formula when F equals 1 applies to a perfectly smooth surface. As surface roughness increases, the increased friction between surface and air causes greater turbulent exchange and reduction of the laminar boundary layer. This results in higher convection coefficients. Friction coefficients presented by Billington (1952) are given below in Figure 1. Values determined by Rowley et al (1930) are slightly lower: F for stucco is just under 2 and the others are proportionately reduced. For building surfaces it seems advisable to use F=2 for rough natural surfaces and F=1 for glass and metal.

The forced convection formulae and their constants given above are based on wind tunnel experiments of Nusselt and Jurges (1922) which were used by Fishenden and Dufton (1929) in their development of an equation for the surface coefficient. These constants are:

a	5.7
b	4.0
c	7.3

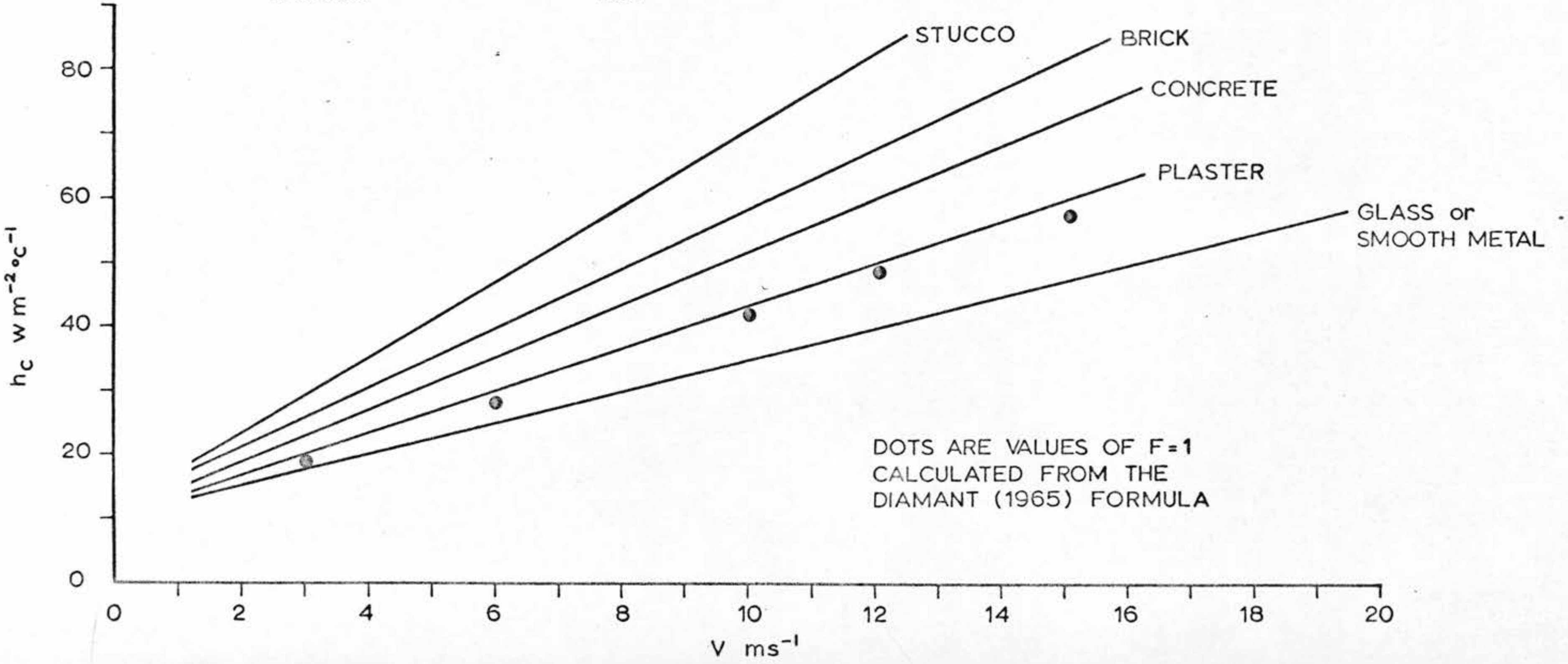
Diamant suggests using the low speed formula for speeds

III FIG. 1

h_{cv} = FORCED CONVECTION

FRICTION COEFFICIENTS OF COMMON WALLING MATERIALS (E.E.U.)

MATERIAL	F
GLASS	1.0
SMOOTH PLASTER	1.20
TIMBER	1.25
CONCRETE	1.62
BRICKWORK	1.78
STUCCO	2.33



under 2 ms^{-1}, and using slightly different constants for the range 2 - 5 ms^{-1}:

a	6.2
b	4.3

There are slight variations in the values given by the texts mentioned above. The surface coefficients resulting from average values of these have been calculated in Table 2.

The Nusselt and Jurges experiment determined the heat transfer from a heated plate mounted flush in the wall of a laminar flow wind tunnel. Application of this data to surfaces of bluff objects such as buildings standing in turbulent wind is of dubious validity. The same doubt applies to the description of the boundary layer by the Reynolds and Prandtl formulae available from tunnel studies on flat plates. Sturrock (1971) has done a current assessment of the heat transfer aspect of this problem. He measured bluff objects (cubes) mounted in a laminar flow wind tunnel, and then measured heat transfer from a limited number of points on the external surface of a tower block in natural wind.

The results of the experiments with the cubes show considerably greater convection coefficients than those predicted by the Nusselt-Jurges work. They include thermal as well as forced convection. The coefficients of the least exposed surfaces were half those of the most exposed, but investigation of Sturrock's wind tunnel data shows that the average h_c for a bluff cross sectioned block would be:

$$h_c = 9 + 5.7\ v$$

The outdoor full scale measurements gave the following relationships:

$$h_c = 11 + 5.7\ v$$

in the most exposed condition, with the wind at a 60° angle of incidence to the surface. The leeward face was found to have a coefficient of approximately:

$$h_c = 6 + 5.7\ v$$

In each case v is the ambient airspeed measured away from the building. The average value for the exposed tower is likely to be approximately the same as that of the cube, with $a = 9$ and $b = 5.7$. Sturrock's relationship is claimed to hold above 5 $m\ s^{-1}$, and discounts the exponential formula with c. His values of h_c are also plotted on Table 2.

It is beyond the scope of this thesis to consider individual building design. However, it is useful to mention the variability of surface coefficients on Sturrock's facades which show the influence of wind direction on heat loss. He estimates the range of h_c on a tower block to be between 15 and 40 $Wm^{-2}\ {}^{o}C^{-1}$. The highest coefficient for any fascade is always at the downstream corner, or at both corners when the wind is normal to a face. Since airflow is nearly completely attached, Sturrock suggests that variability in h_{cv} over a building be assessed by mapping its surface velocities. In this thesis the interior of buildings is assumed to be perfectly connected, so that the directional variability in heat loss has only an average effect on the interior.

In conclusion, convectional heat transfer is by thermal and forced convection. Under conditions of no wind, the thermal convection heat transfer values of Table 1 apply. The interior convective coefficient is entirely thermal. Under conditions of even slight wind, the convective heat loss from exterior surfaces is primarily via forced convection. The forced convection heat loss coefficients are presented in Table 2. Recent average values for a whole building in the wind are included. It is suggested that the influence of F be limited to two values: $F \cong 1$ for smooth surfaces such as glass and metal, and $F = 2$ for rough exterior building surfaces.

TABLE 2

Forced convection surface coefficients

	Formula A		Formula B	
V (m s^{-1})	h_c	R	h_c	R
0.5	7.6	0.13		
1	10	0.10		
2	15	0.06		
3	19	0.05		
4	23	0.04		
5	26	0.04	37	0.03
6	28	0.04	43	0.02
8	36	0.03	54	0.02
10	43	0.02	66	0.02
12	49	0.02	77	0.01
15	58	0.02	94	0.01
20	73	0.01	123	0.01
25	88	0.01	150	-
30	98	0.01	180	-

$F = 1.$

Formula A: from Diamant (1965):

$h_c = 5.6 + 3.9\,V + h_{ct}$ $\quad < 5$ m s^{-1}

$h_c = 6.2 + 4.25\,V$ $\quad 2 - 5$ m s^{-1}

$h_c = 7.25\,(V)^{0.78}$ $\quad > 5$ m s^{-1}

Formula B: from Sturrock (1971):

$h_c = 9 + 5.7\,V$ $\quad > 5$ m s^{-1}

4. Heat transfer from buildings : radiation.

4.1. Longwave radiation.

The other component of surface conductance of building elements is the radiative emission from the solid surface to distant space or other surfaces. The heat radiated from a body follows Stefan Boltzmann's law and is proportional to the body's emissivity and the fourth power of its absolute temperature.

$$Q_r = (5.67 \times 10^{-8})\,\varepsilon T^4 \quad \text{or} \quad 5.67\,\varepsilon \left(\frac{T}{100}\right)^4$$

where Q_r is in Wm^{-2}

5.67×10^{-8} = Stefan Boltzmann Constant ($Wm^{-2}\ {}^oK^{-4}$)

T is in ^oK

ε = emissivity = absorptivity = 1 - reflectivity

The emissivity varies with the wavelength. For ordinary building materials, ε in the longer wavelengths of terrestrial radiation equals 0.90. For reflecting foil and polished metal surfaces it varies from 0.05 to 0.15, but this is the only exception to the value 0.9, and polished exterior surfaces rapidly become tarnished and assume the same emissivity as conventional building materials. As a result, the radiative heat loss from the surface of all buildings can be considered to vary uniformly with T. By contrast, the absorbtivity of shortwave radiation varies from 0.05 (foil), through 0.2 (white paint), 0.4 (light colours), 0.7 (dark colours), to 0.85 (black paint); a fourfold variation of energy acceptance found among commonly used surfaces.

In the absence of an atmosphere, longwave emission from non-metallic building surfaces ($\varepsilon \cong 0.90$) gives the following rates of outward heat transfer at various surface temperatures:

Table 3

Longwave radiation from building surfaces ($\varepsilon = 0.9$) versus surface temperature.

T_b (^{o}C)	Q_r (Wm^{-2})
20	376
15	351
10	327
7	314
5	305
0	283
-5	263
-10	244
-20	209

where T_b is the temperature of the building surface, walls or glass.

In nature, thermal emission from a surface either encounters another surface or passes through the atmosphere. Radiation approaching another surface is reflected or absorbed, the reflected component being returned toward the emitting surface while the absorbed component is reradiated in accordance with the Stefan Boltzmann law.

The net radiation is determinable by a fundamental law which depends only on the temperature of the two surfaces and their emissivities (which in nature is 0.9). Radiation passing through the atmosphere is likewise reflected and absorbed, but some is transmitted, and the proportions depend on a variety of meteorological factors. In engineering usage, it is customary to treat the atmosphere as another surface, assuming a radiating temperature for it and giving it black body properties ($\mathcal{E} = 1.0$). This treatment simplifies the computation procedure considerably, and obviates the need for some meteorological data that is presently scarce. In this section the common engineering solution will be described first, and then it will be estimated whether more detailed knowledge of sky radiation causes significant differences in h_r.

4.2. Radiant heat exchange between surfaces.

The effective emissivity of two parallel surfaces radiating to each other (E) determines the heat exchange between the surfaces:-

$$E = \frac{\mathcal{E}_1 \mathcal{E}_2}{(\mathcal{E}_1 + \mathcal{E}_2) - (\mathcal{E}_1 \mathcal{E}_2)}$$

$$Q_r = (5.67 \times 10^{-8})\ E\ (T_2^4 - T_1^4)$$

with Q_r in Wm^{-2}. In order to express this heat flow in terms of a single thermal conductance on one surface it is necessary to postulate the mean temperature Tm,

TABLE 4

RADIATIVE SURFACE COEFFIDIENT TABLE

$h_r = (22.8 \times 10^{-8}) (\varepsilon) (T_m)^3$ in $W\ m^{-2}\ {}^oC^{-1}$

ε = 0.9 for radiation to air.

$E\ (\varepsilon_1 - \varepsilon_2)$ = 0.8 for radiationtto natural surfaces

T_m		$(T_m)^3$	x 4σ	h_r		R $(\frac{1}{h_r})$	
^oC	^oK		$(x22.8x10^{-8})$	ε = 0.9	E = 0.8	0.9 sky	0.8 ground
20	293	25.0×10^6	5.70	5.14	4.56	0.195	0.22
18	291	24.5×10^6	5.60	5.04	4.48	0.20	0.22
15	288	23.8×10^6	5.43	4.88	4.34	0.20	0.23
13	286	23.4×10^6	5.34	4.80	4.26	0.21	0.23
10	283	22.6×10^6	5.15	4.63	4.12	0.22	0.24
5	278	21.5×10^6	4.90	4.41	3.92	0.23	0.26
0	273	20.4×10^6	4.65	4.18	3.72	0.24	0.27
-5	268	19.2×10^6	4.38	3.97	3.50	0.25	0.29
-10	263	18.2×10^6	4.15	3.73	3.32	0.27	0.30
-15	258	17.2×10^6	3.90	3.50	3.12	0.29	0.32
-20	253	16.2×10^6	3.67	3.30	3.94	0.30	0.34
-30	243	14.4×10^6	3.29	2.96	2.63	0.34	0.38

an average of the surface and the surroundings:-

$$Tm = \frac{(T\ surface + T\ surroundings)}{2} \quad \text{in } {}^{o}K.$$

The radiative surface coefficient h_r becomes:

$$h_r = Q_r = (5.67 \times 10^{-8})\ (\varepsilon T_1^4 - \sigma \varepsilon T_2^4)$$

$$h_r = (22.8 \times 10^{-8})\ (E)\ (T_m^3)\ Wm^{-2}\ {}^{o}C^{-1}$$

where E is equivalent to 0.9 when the surroundings are considered to have black body characteristics, and E is 0.8 when radiation is to another surface. Temperature of the surroundings is taken as screen air temperature. Table 4 gives values of h_r at various mean temperatures and at $E = 0.9$ and 0.8.

4.3. Radiant heat loss to clear sky.

Use of air temperatures for T_m is generally considered satisfactory for radiation to natural objects and the cloudy sky. However, it leads to underestimation of radiation lost during clear skies when transmittance of radiation to outer space is high. The engineering solution to this (EEU Handbook) is an expression for the 'effective external temperature' Te. This formula assumes a radiant heat flux from the surface to a clear sky, $(126\ Wm^{-2}) \times \varepsilon = 114\ Wm^{-2}$. The extent to which this radiant flux will cool the surface below the temperature of the adjacent air depends on the convective coefficient h_c for the ambient air velocity.

The greater the convective coefficient, the less difference there will be between air and surface temperature. Thus radiant cooling is at its most extreme in still air:

$$T_e = T_a - \frac{I_* \varepsilon}{h_c}$$

where T_e = effective external temperature.

T_a = temperature of surrounding air.

I_* = hypothetical black body radiation to a clear sky - given as 125 Wm^{-2}.

ε = external emissivity of surface, 0.9.

T_e is then used as the external temperature for the calculation of heat flow Q. The heat flow at the surface is:

$$Q_s = h_r (T_e - T_s)$$

For the total calculation h_r must be left out of the value for K. The use of T_e is substituted for the addition of h_r into K. This formula rests on the arbitrary value of 114 Wm^{-2}, ($I_* \times 0.9$), chosen for net radiant loss (Q_{ro}) between surface and sky. Clearly this value is dependent on the surface temperature (i.e. internal insulation) as well as sky temperature, and the nature of the atmospheric constituents.

4.4 Appendix 1 reviews the influence of climatic factors on sky radiation in order to determine whether the engineering formulae for clear and cloudy sky heat exchange give adequate representations of Q_r in all climatic conditions.

4.5. Short wave radiant gain : steady state calculation.

The longwave radiative exchange between the building surface and the clear and overcast sky has been described above. During daylight, radiation exchange includes also short wave energy from the sun. This reaches the surface in direct and diffuse forms, the direct from the sun itself and the diffuse from the clear sky vault and through clouds.

In engineering practice the different pathways of shortwave radiation are combined into one term, the hemispherical irradiation I. This is the total shortwave radiation onto a horizontal surface, and is also termed insolation. Geometrical factors are used to apply I to surfaces that are not horizontal. I is converted to heat Q in a building by absorption on opaque surfaces.

The method of calculating the effect of I on heat transmission through a wall is similar to the equivalent external temperature method used to determine the heat loss caused by longwave radiation to a clear sky. Mackey and Wright (1944, 1946) evaluated the effect of solar radiation on the heat flow at a building surface by assuming a hypothetical external temperature which is equivalent to the existing temperature plus the effect of solar radiation. This is called the "sol-air effective temperature" (T_{es}):

$$T_{es} = T_a + \frac{aI}{h_c + h_r}$$

where (a) is the absorptivity to shortwave radiation. (h_c) is computed from formula (3.2). (h_r) is computed by formula (4.2), and represents the longwave radiation exchange in the absence of I. The heat flux between the interior of the wall and the sol-air exterior temperature is then calculated using this value of h_r. More precisely, a new value of h_r should be used to account for the higher surface temperature T_w under insolation. The heat flux Q_s from a surface under insolation is:

$$Q_s = h_s (T_a - T_w) + aI$$

or

$$Q_s = h_s (T_{es} - T_w)$$

where h_s is the total surface coefficient, $(h_r + h_c)$, calculated from T_a and T_w.

I can also be converted to Q by absorption on an internal wall, after passing through glazing. In this case virtually all radiation that passes through the glass is converted to interior heat. For precise calculations of this process, see Threlkeld (1962). Such calculations are required in designs for highly glazed buildings, and buildings with heat absorbent glass. For the ordinary glazing found in domestic houses, the transmission averages 85%. This is the value used in the method (Section 6). No shortwave radiation is assumed to escape, with the result that for windows,

$$Q = 0.85\ I_w$$

where I is the insolation on the vertical wall.

The heat lost or gained from the heat flux under insolation equals the product of Q_I and the time duration of I:t_I. Since I will vary over any lengthy period, the heat lost will be determined by:

$$Q \cdot t_{total} = \sum_{I=1}^{I=n} Q_I \cdot t_I$$

Thus to determine heat loss or gain, the sol-air calculation needs to be performed with the rate I first, and then summed, in terms of gain, over time t_I.

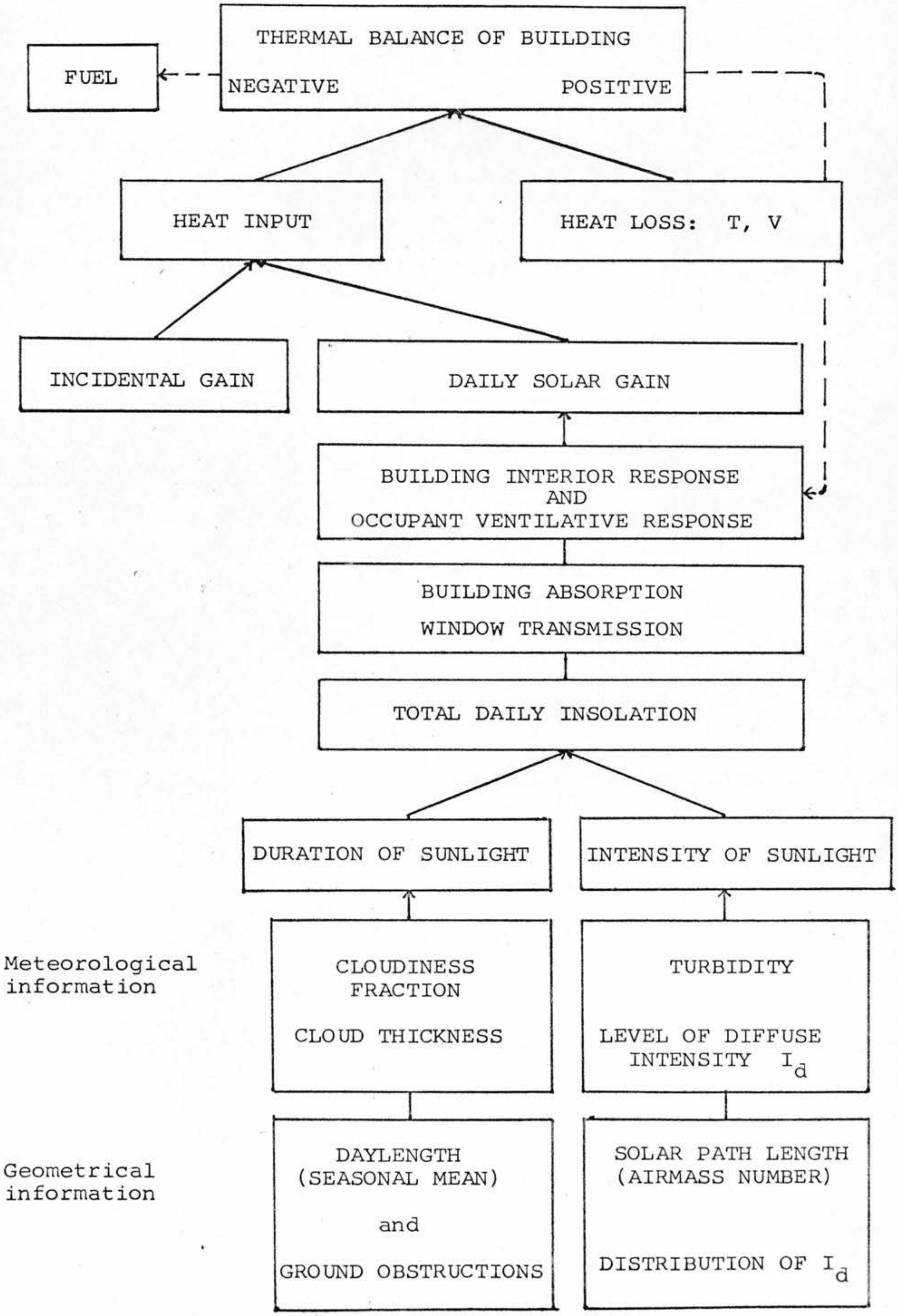
4.6. Required information on insolation: factors involved.

The important data needed to account for the effect of solar gain are the intensity of insolation (I) and the time duration of that intensity (t_I). The variation of I and t_I at the surface depends on a large number of considerations. They include, for I: the transparency of the atmosphere, the elevation of the sun and the number of optical airmasses the radiation passes through, the distribution of scattered radiation across the vault, the distribution of radiation through an overcast sky or reflected from clouds, and the orientation of the surface relative to the different streams of incoming radiation. The considerations determining t_I are: the length of the day, the length of time that ground obstructions block the sun, and the length of time that clouds and other meteorological variables affect I.

These considerations, for both I and t_I, can be subdivided into two categories: the geometrical or astronomical which are independent of weather, and the meteorological or atmospheric. The considerations are organized in a chart, Figure 2. This chart shows the position of shortwave radiation information in the total process of calculating heat loss from buildings. The methods of determining the heat gain from solar radiation, and the behaviour of the occupants, will be described below.

Data on I and t_I is available in numerous forms, in a large literature from diverse disciplines. A survey of general data describing the influence of atmosphere, site, and weather on I and t_I is made in Appendices 2 and 3, under the headings Geometrical and Meteorological Information. This information isolates the influence of each factor affecting I and t_I, and gives some indication of the relative importance of the various climatic and site influences. Such information is necessary in order to predict the radiation on a specific site or plan, where site and climte conditions are likely to be different from the location of the climatological station supplying the regional data. Also, it is needed to acquire the parameters required for the solar gain calculations, if the climatological information available is in a form which is not immediately useable. It is obvious that the data given in the appendices is only a small sample of the information in the literature. A very long review of this subject could be made, but this is not the objective in this thesis.

FIGURE 2 SOLAR INFORMATION IN BUILDING HEAT LOSS



There are several forms of data which can be used for the calculations of solar gain. If one has available daily averages of intensity in absence of clouds, then together with sunlight S or cloud percentage c the heat gain can be determined. With insolation data available in terms of heat units per day, either the daily average of the insolation rate I with cloudless sky, or the sunshine duration S or cloud fraction c will suffice to give values of I and t_I. Information on day length is needed for any of these calculations. When insolation data is available only as totals, general knowledge of the relationship between diffuse radiation from clear and cloudy skies is needed to determine the solar gain during clear and cloudy days.

Before the information on I and t_I can be translated into average heat gain values, the relationships between surface generated solar energy and the heat loss from the building as a whole needs to be assessed. If Q shows a linear relationship to I, then the solar gain can be summed and directly equated to fuel savings. If, however, the occupants exhibit uneven ventilation habits in response to daytime overheating, the solar gain will not be equal to fuel savings. Occupants' ventilation habits will be discussed in Section 5. Generally, solar overheating can be expected to be cancelled out by increased ventilation. The extent of overheating due to sunlight depends on two major factors: 1) the thermal capacity and diffusivity of the structure, and 2) the proportion of glazing, its orientation, and the surface to volume ratio of the building. These factors control the thermal lag and the amplitude of the interior temperature fluctuation during sunlight. In lightweight structures with low diffusivity and high radiation transmission through windows, the interior can be expected to overheat during insolation. This is the case with many office buildings and schools. In more solid conventional buildings, including the domestic houses used as examples in this chapter, the influence of uneven ventilation is present but considerably reduced. It comes into effect only when the exterior temperature approaches the interior temperature. Roughly, the solar gain through walls over the season for this type of building can be assumed proportional to fuel saved. There is no influence by a building's thermal capacity on the total heat lost over a season.

In conclusion, the only data needed to calculate the solar gain through the sol-air concept is I and t_I. The general information contained in Appendices 2 and 3 is only a means of obtaining values of those parameters on the site, or from data in another form. It is also necessary to take the building type into account. Although thermal capacity in a building will have no influence on its long term heat loss (providing it is continuously used and heated), it has an indirect influence through the actions of the occupants.

Buildings with low thermal capacities will have periods of interior overheating during which time the heat loss through ventilation will be accelerated.

4.7. Preferred forms of insolation data.

Data for I is increasingly being measured on vertical surfaces as well as horizontal ones. A method coming increasingly into use is a cube with solarimeters in the vertical walls aligned in the compass directions and one on the top, (Loudon 1967; Bracknell — —). Data for these five surfaces has been published by Stagg (1950), Grafe (1956), and Hardy (1970). This information is directly applicable to building calculations. Hardy's data applies to clear weather, the others are averages. Schedler (1950) and Turner (1958, 1966) have measured radiation on slopes. Examples for Kew (Lat 52°) and Hamburg (Lat 54°) are given in Table 5 . It should be noted that the Hamburg values are considerably higher than the London ones, especially in the Spring, even though the latitude is higher. This is due to less cloudiness. Therefore empirical local data is to be preferred to calculated data. Hardy's data is presented in Figure 3 . These are clear sky values for Newcastle, intended for solar overheating design. They do not give much information for the low values of the winter months.

Petherbridge (1970) has produced a computer programme which calculates the hourly and daily insolation of any sloping surface using the accepted sky vault radiation

TABLE 5

(1) Average daily direct + diffuse radiation ($\frac{W\ H}{m^2 day}$) for vertical and horizontal surfaces. Kew lat. 52°

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Season Av.
Facing:								$\frac{W\ H}{day\ m^2}$
South	1350	660	470	500	950	1500	1800	1030
East	720	280	160	190	470	910	1450	600
West	720	280	160	190	470	910	1450	600
North	440	160	95	130	280	560	820	360
Horizontal	1350	470	280	350	880	1800	2900	1150

Season length 30 weeks.

Season mean on walls: 650

Reflected I from ground on vert. surfaces estimated as 5% I: 60 W H M^{-2}(day^{-1}) of seasonal average.

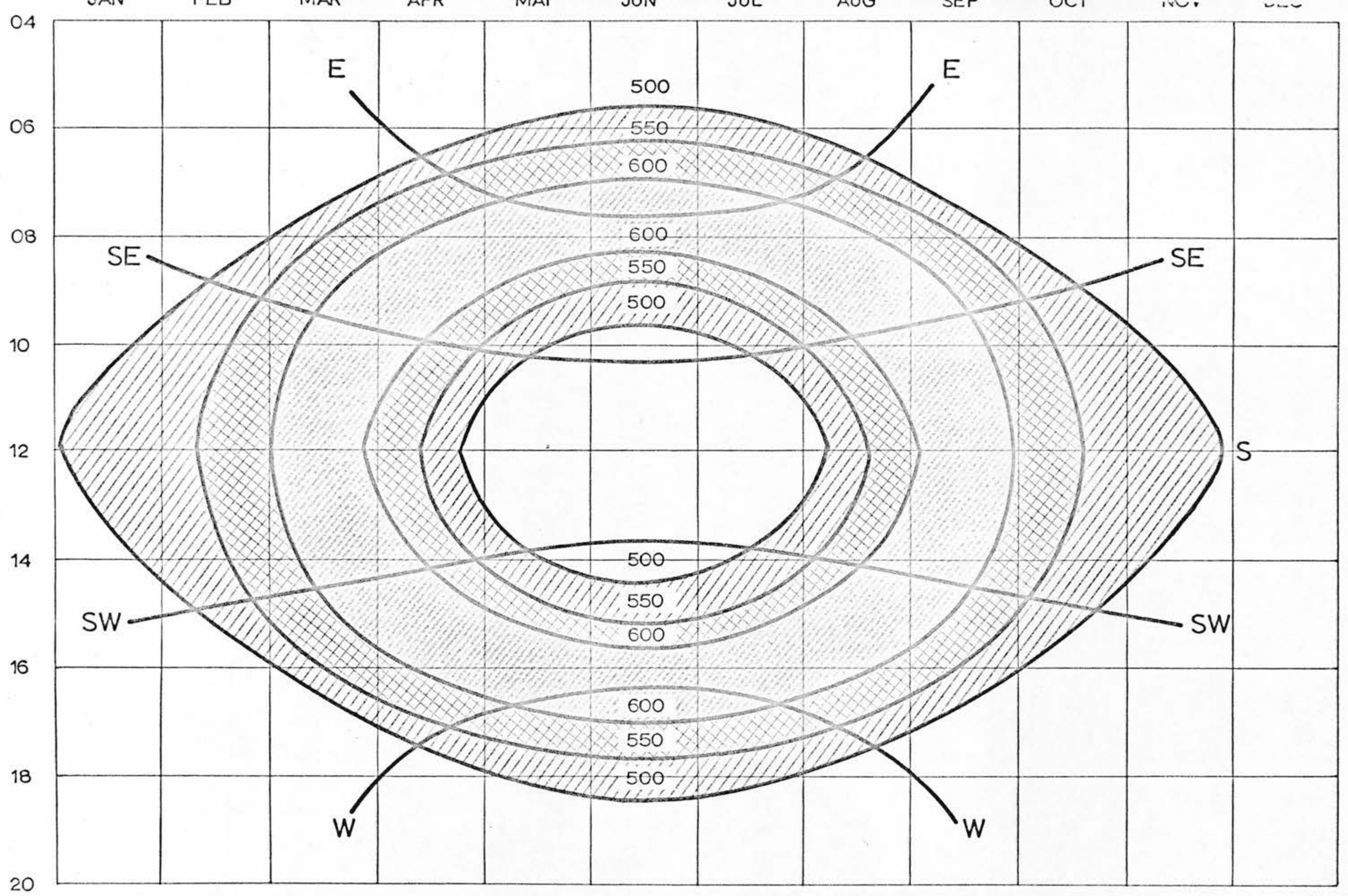
From 14 yrs. Kew data: Stagg, J.M. 1950: Solar radiation at Kew Observatory HMSO, London.

(2) Figures from Hamburg : K. Grafe, 1956. lat. 54°

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Av.
South	1700	850	580	880	1400	2400	3000	1300
East	800	350	230	320	700	1150	2200	800
West	800	350	230	320	700	1150	2200	800
North	570	230	170	210	460	700	1150	500
Horizontal	1400	700	500	570	1150	2200	3700	1400

The Hamburg values are considerably higher than the London ones, especially in the spring, although the latitude is higher. This is due to less cloudiness. Empirical data is thus preferred for each location.

Average daily rates (W m^{-2}) are available in Petherbridge's calculator for clear skies and any cloudiness fraction.



DIRECT SOLAR RADIATION ON VERTICAL SURFACES IN RELATION TO ORIENTATION. NEWCASTLE : FROM HARDY, 1970.
(FIGURES IN WATTS/M²)

distribution data of Moon and Spencer (1941). Provision for cloudiness fraction and for assumptions of atmospheric turbidity are included. Providing that there is data for these meteorological variables, and the assumptions are correct, this offers solutions for any shapes and orientations.

4.8. Conclusions: climatic effects on radiant heat exchange.

1. Heat loss.

Building surfaces all behave essentially the same in the exchange of longwave radiation ($\varepsilon = 0.9$). Radiant exchange is influenced by building type only in that building shape affects the view of the radiating surfaces, and because insulation and internal conditions affect the flow of heat to the surface. These are accounted for by the conventional calculation method.

The convective coefficient (determined by wind velocity, surface roughness, and surface to air temperature difference) has an influence in determining the surface temperature during radiation loss to a clear sky. The effect of V, F, and T is incorporated into the engineer's effective temperature formula.

The meteorological variables temperature and water vapour in the low levels of the atmosphere are the most significant influence of atmosphere on longwave radiation to clear skies. Even they are found, by the Angstrom and Brunt equations, to induce a relatively small variation (approximately 10%) in Q_r at the expected winter temperature range (10 - -20°C). This variation diminishes as the temperature decreases.

Radiant heat loss only approaches the value assumed in the engineering clear sky formula $\left(Q_{ro} = 114 \ Wm^{-2}\right)$ in conditions of extreme cold and dryness. The conclusion is that the engineering formula represents meteorological conditions well for extreme design calculation, but that smaller values of I* should be taken from Table A3 for average clear night heat loss calculations.

Similarly, the meteorological parameters influencing longwave exchange to cloudy skies were found unimportant for planning considerations. The height of cloud base and water vapour induce only a 9% extreme variation from the values calculated with the surface temperature formula.

The important problem in computing long term radiant exchange is in the handling of partial cloudiness, where the cloudy and clear sky formulae both apply. Radiation expressions for partial cloudiness exist but require a large number of empirical coefficients to account for cloud type and height. The method used in this thesis is to equate clear sky percentage observations (1-c), or sunlight percentage S to a clear/cloudy sky ratio. The clear and cloudy sky formulae are then combined by summing Q_r in the proportions of the time each applies. Small errors attend this method, but can be accounted for. First, radiation intensity is not linearly related to cloud amount. However, for the long averaging periods needed for building heat loss, the differences between the linear relationship and observational data are no more than a few percent, and insignificant for practical purposes. Second, S and (1-c) are different by approximately 4% in Britain. Third, if the night time cloudiness is not equal to that of daytime, the value S cannot be used to represent the cloud fraction at night.

In general, data for the longwave heat loss should apply to the period concerned. For example, the clear sky heat loss calculations depend partly on the concurrent wind velocity. The average velocity during clear nights might be less than the mean V in Britain. The climatic information, if in daily or longer averages, would have to represent night time conditions.

2. Shortwave radiant gain. The building characteristics controlling solar gain are absorptivity, with a practical range from 0.15 to 0.85, area of glazing, with a transmissivity and absorptivity of approximately 0.85, and the orientation of the surfaces with reference to the sun. The relationship between interior temperature fluctuations and occupant ventilation has been mentioned, and will be described in Section 6. It is only through the agency of this controlled ventilation that the thermal capacity

of a building has any influence on its accumulated heat loss over a season.

An organization of SW radiation information has been made in Figure 2. This order is applied here:

1) I = geometric effects.

   a) Solar path length through a clear atmosphere causes I_s to vary from 210 - 890 Wm^{-2} between $\beta = 90^{\circ}$ to $\beta = 30^{\circ}$ (minimum in Britain).
      I_{dh} varies from 20 to 105 Wm^{-2}.
      I_o varies from 40 to 880 Wm^{-2}.

   b) Altitude has insignificant effects below 2000' and increases I only 10% at 3000'. Therefore it is insignificant in Britain, although it can have considerable effect in higher parts of the world.

2) I = meteorological effects.

   a) Air pressure and air gaseous composition have insignificant effect on I. Water vapour has some influence, but it is insignificant as a factor in Britain.

   b) Turbidity primarily due to dust causes a 30% variation in I in rural areas across the U.S. It is unlikely that rural turbidity is a factor in Britain. In industrial areas, direct radiation is decreased by more than 50% of clear sky radiation. Diffuse radiation is decreased by 20%.

c) Clouds transmit between 15 to 85 per cent of direct sunlight, depending on the type and thickness of cloud. The average transmission for full overcast taken from a selection of empirical formulae is 35% I_s. Since this radiation is distributed across the sky vault, it causes higher levels of diffuse radiation than a clear sky, where the average is around 15% I_s. This difference means that if calculations are made of heat flux of a building under clear and cloudy conditions, the non-sunlit surfaces will have higher insolation under cloudy conditions. Therefore, if the insolation data is in the preferred form, with values for 4 vertical walls and roof, it is desirable that the data be obtained for clear sky and cloudy sky separately. Otherwise the overall averages need to be broken down into clear and cloudy components using the approximate levels of transmitted and scattered radiation mentioned above.

3) t_I = geometric effects.

The length of daylight and the length of time that any surface is under direct radiation can be computed by a variety of calculators.

4) t_I = meteorological effects

In Appendix 3 several formulae are listed which relate I_c linearly to c and S. Because of the linear relationship, the total heat transferred to or from a building during the average daytime can be determined by adding $f(I_o - t_{Io})$ and $f(I_c - t_{Ic})$. These two day functions are added to the two night functions, for clear and cloudy sky, in order to give the daily average.

These four average conditions, two each for day and night, represent distinct types of radiant heat transfer. Between them they summarize the total radiant transfer. This will be the method of calculation proposed in Section 6.

5. Ventilation.

The heat loss due to flow of heated air from the building through cracks and doors and windows can be as important as the heat lost through conduction, convection, and radiation, especially when there is external wind.

5.1. Pressure and thermal effects.

The heat loss from air flowing through the building can be expressed in terms of the volume of air that is heated and escapes per unit time, its volumetric heat capacity, and the rise of temperature through which it has been raised. The heat capacity C of air is $0.326\ \mathrm{W\ h\ m^{-3}}$. The ventilation rate can be expressed in terms of Q^* ($\mathrm{m^3\ hr^{-1}}$) or in terms of N (number of complete air changes per hour) times the volume Vol of the building ($\mathrm{m^3}$). Hence:

$$Q = 0.326\ Q^*\ (T_1 - T_o)$$
$$Q = 0.326\ N\ \mathrm{Vol}\ (T_1 - T_o)$$

The use of N is preferred, for it describes the ventilation experienced by any interior. Values of N range from 0.3, the minimum N needed for odour control, to over 2. Dick (1950) gives 1.5 as the most common value for Britain, out of a range of 1 to 2. Later, Danter and Dick (1956) give N = 2 as suitable for occupied houses in Britain. The French building code (CSTB 1958) assumes N = 1.25. Sasaki and Wilson (1962) suggest for Canadian building conditions 0.5 N at the design minimum temperatures.

The actual value N depends on the wind resistance of the outside surface of the building and of the windows and doors, as well as how much the windows and doors are opened. It also depends on the climate: the wind causes ventilation through dynamic pressure effects, and the temperature difference between the inside and outside causes thermally induced ventilation.

Taken from Bedford (1948), the following relationships describe air flow through openings in the building fabric:

A. For cracks and pores,

$$Q^* = C\, \Delta p_{,}^{n}$$

where

Q^* = flow rate of air

C = proportionality constant

n = exponent of flow

$\Delta p_{,}$ = pressure drop across the wall or window.

(n) varies from 1 to ½ with increasing size crack. The flow through capillaries such as in porous brickwork is directly proportional to the pressure difference, while the flow through apertures the scale of cracks in windows (minimum 0.03 inch, mean 0.04 in. maximum 0.05 in. according to Harrison, 1961) is proportional to the square root of the pressure difference across the crack. The dynamic pressure $\Delta p_{,}$ caused by V equals

$$\Delta p_{,} = \tfrac{1}{2} p\, V^2$$

where p is the density of air. Since the wind induced pressure varies with the square of V, Q^* is related to V through formula 'A' by:

$Q^* \propto V^2$ infiltration through pores $n = 1$.

$Q^* \propto V$ infiltration through cracks $n = \frac{1}{2}$.

It is likely that the great majority of Q occurs through cracks, as is indicated by Dick 's (1950) empirical finding that air change N of a closed house could be accurately described by:

$N = a + bV$

B. The flow through large openings such as open windows, doors, and ventilators is represented by:

$Q^* = E\,A\,V$

where

V = velocity of wind

A = the area of opening

E = the effectiveness of opening, given as 0.50 - 0.60 for wind perpendicular to the aperture, and 0.25 to 0.35 for diagonal winds.

This relationship should be virtually impossible to employ in assessing building ventilation since the times of opening are so variable. The opening of windows and doors in occupied houses has been only studied by Dick and Thomas (1951) and their analysis will be used for this purpose.

C. Flow due to temperature difference and air density difference is given by Billington (1952) as: (converted to SI units)

$$Q^* = 2.1\ A(h\Delta t)^{0.5}$$

where A is the area of inlets or outlets (assumed equal) in m^2.

h is the height from inlets to outlets in m.

Δt is the average $T_i - T_o$: $^{\circ}C$.

2.1 is the constant of proportionality assuming E = 0.65 for the openings. This formula applies only if there is no significant internal resistance. The ventilation produced by this effect is pronounced in tall buildings where there is a substantial height difference. The influence is less important in low buildings or within any vertically sealed floor of a high building. In the great majority of tall buildings there is relatively unimpeded vertical circulation. Two analogue studies (Harrison 1961, Jackman 1969) have been made of the complicated problem of infiltration in tall buildings. Their results will be used in the discussion below.

The presence of a heated flue in low buildings increases the thermal effect markedly. Dick (1950) found that a flue produced the following effect in comparison to the other sources of heat loss from a low building.

Table 6

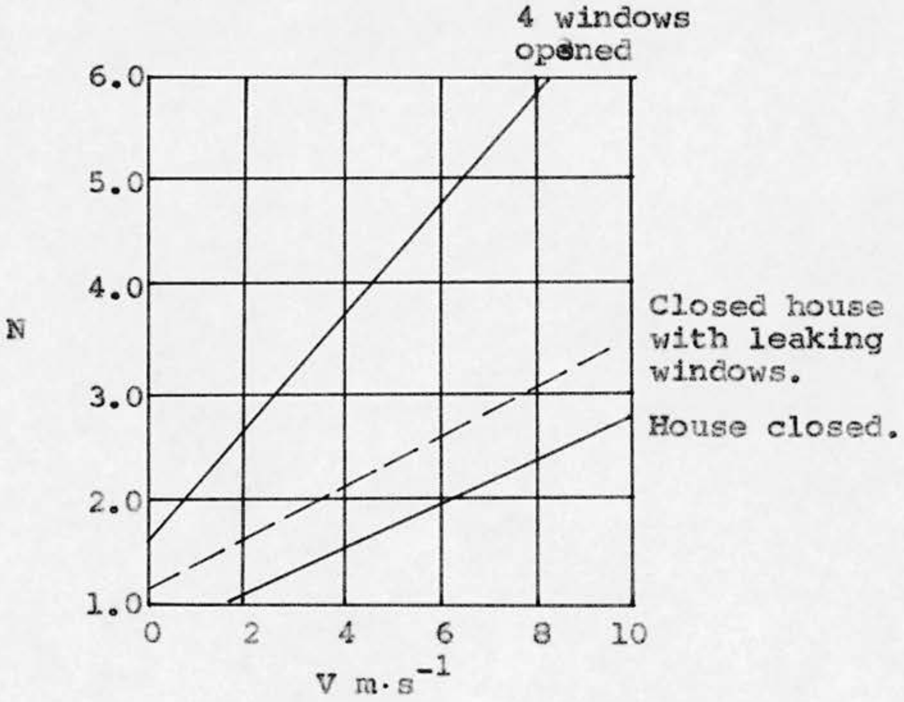
Relative Q^*,N	pressure (in w.g.)	Effect of a heated flue on Q^*
2.6	0.07	9m flue $38^{\circ}C$
0.75		House stack effect: $h = 5m.\ \Delta T = 5^{\circ}C$
1	0.01	House stack effect: $h = 5m.\ \Delta T = 11^{\circ}C$
1.1		House stack effect: $h = 5m.\ \Delta T = 16^{\circ}C$
2	0.04	External wind $V = 3.8\ m\ s^{-1}$
0.6	0.004	External wind $V = 1.3\ m\ s^{-1}$

These values will summarise stack effect for low buildings.

5.2. Ventilation in occupied houses

The studies by Dick (1949, 1950) and by Dick and Thomas (1951) compared two groups of two storey postwar council houses, one on an exposed and one on a sheltered site. Observations were made of the climate's effect on house ventilation and weekly heat loss at the two sites. The houses were observed both when closed (unoccupied) and when subject to normal use. The results are most useful because of the comparisons that can be made. The following figure shows a result of occupancy on air change rate.

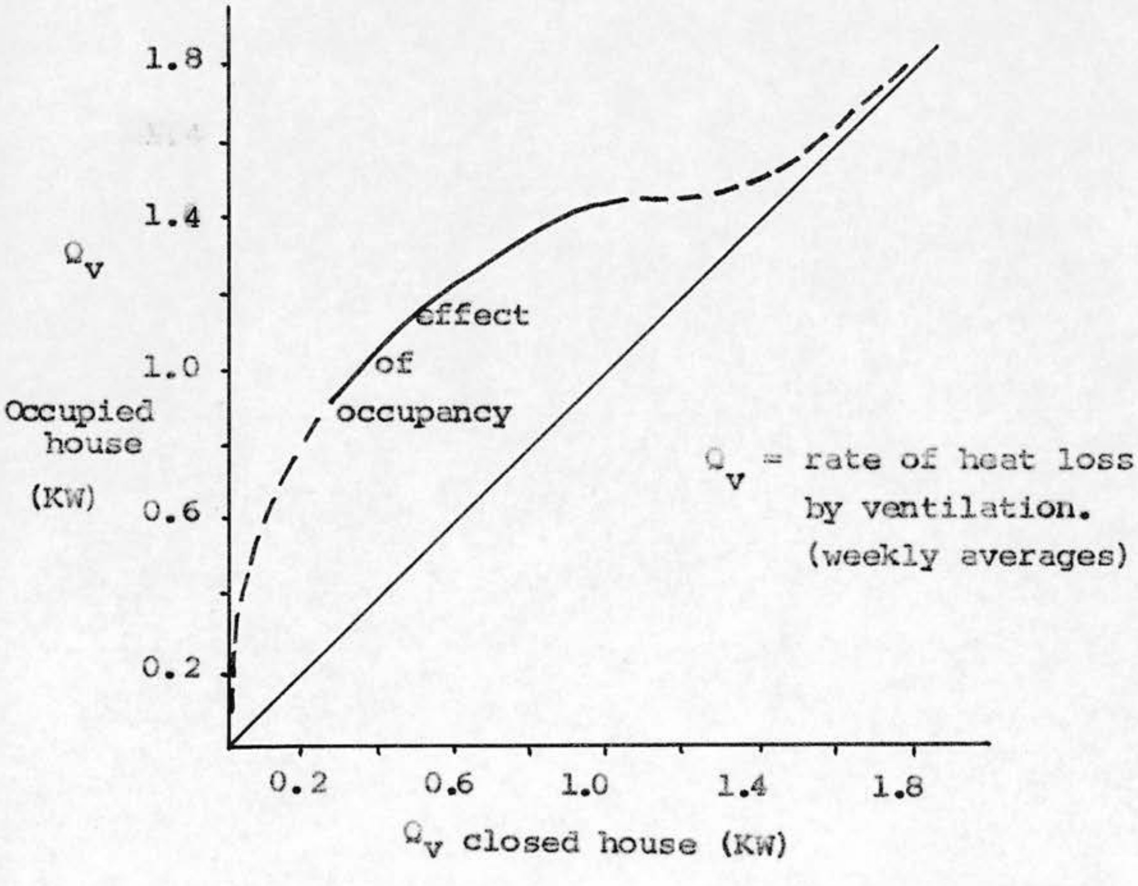
Figure 4. Air change rate N of houses with closed and open windows.



A house with no windows open is compared against a house with four windows opened. The dashed line represents N in houses with poorer fitting windows. Four open windows was the maximum number observed by Dick; the number decreased to an average of 0.25 windows open per house at the coldest external temperatures. "Open windows" here include partially opened windows. At the exposed site (3.8 m S^{-1}) cold season mean) the air change rate varied from 3.1 at 11°C T_a to 1.6 at 1°C, while at the sheltered site (2 m S^{-1}) the variation was from 3.0 to 1.0. The means were 2.5 and 2.0. These exceed the figures given by the IHVE Guide (1965) which give N as varying from 1.5 to 2 under normal use, and add 0.5 N to this figure for houses in severe exposure. Danter and Dick (1956) recommend 2 N for general use. The values given by Dick are used here, although houses are probably being built to a higher standard now here and in more continental climates.

The following figure gives a comparison of occupied to closed houses in terms of effect on ventilative heat loss.

Figure 5. Effect of occupancy on heat loss through ventilation. From Dick and Thomas.



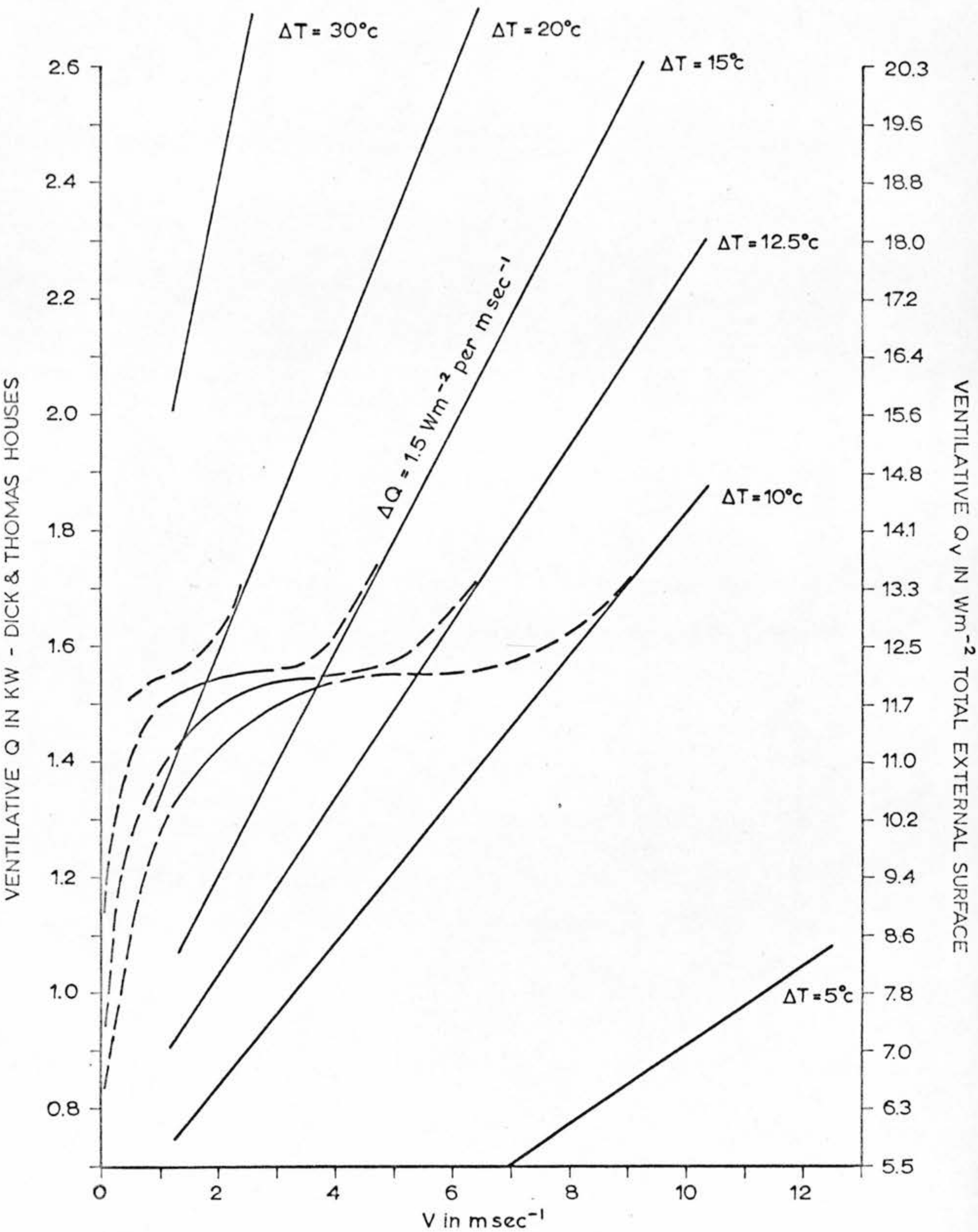
The range in these values suggests that neither theoretical ventilation analysis nor the values of N in the building codes should be used in planning for domestic houses with openable windows, unless the habits of the occupants are very different from the Britons observed in 1950. The tendency to control N when the heat loss rate is increased means that N will nearly equal the closed house equivalent under design extreme conditions. Ventilation of occupied houses must be assessed in terms of heat loss rate. In less severe climatic conditions one can deduce from Dick's data that in his houses there will be 600 W additional heat loss due to occupation when the closed house ventilation loss is between 175 and 800 Watts. Between 800 and 960 W loss for the closed house, there will be an additional 530 W due to occupation.

For total loss due to wind and temperature, the data on Figures 4 and 5 is related by

$$Q_V = 66.5 \Delta T N$$

where Q_V is ventilative heat loss rate (W).

The constant was derived by Dick and Thomas for the dwellings they measured. It corresponds to an interior volume of 200 m^3, a floor area of 86 m^2, and a ceiling height of 2.31 m. From this we are able to compute Figure 6, which relates approximately the heat loss due to ventilation to wind and external temperature. The effects of occupancy as taken from Dick's data are included. The $Q_V \cdot m^{-2}$ scale is described below.



III FIG. 6

VENTILATIVE HEAT LOSS Q_V FOR A CLOSED AND OCCUPIED $200 m^3$ HOUSE

BASED ON $Q = 66.5 \Delta T N$ AND ON FIGS. 4 and 5

DASHED LINES ARE PROJECTIONS OF MEASURED CURVES

Heat loss information in previous sections has been related to the surface areas through which the heat flows. Ventilative heat loss, measured in N, depends on the volume of air in the interior. In order to add the two modes of loss, building volume needs to be linked to building surface area. This can be conveniently done by making an assumption of ceiling height. For domestic houses 2.28 m (7'-6" feet) or

2.43 m (8 feet)

are good approximations. Any interior volume (m^3) divided by 2.28 or 2.43 gives the floor area of the building. The ratios of floor areas to external surface areas of different styles of housing are given in Table 7. (Danter and Dick 1956).

Table 7

Ratios of exposed wall, roof, and window areas to floor area.

Plan type	Wall to floor	Roof to floor	Window to floor
Semi detached	1.0	0.5	0,19
Terraced	0.75	0.5	0.17
Flatted	0.75	0.0 or 1.0	0.15
Detached (2 storey)	1.25	0.5	wide variation

The semi-detached plan (3 walls) represents the average condition and the data gathered by Dick is for this plan. In the situation of a house with a roof the floor area is 67% of the exterior surface area, and equals the exterior wall area. If the heat loss rates of the walls and roof are added separately, or if one is dealing with multi=storey flats, it is most convenient to link ventilative Q_v to wall surface area alone and add in roof conductance Q without the ventilation component. For planners dealing with two storey houses, the ventilative Q_V can be linked to total surface area. The formulae are:

(1) Semi detached house. (Assuming 2.43 m ceiling)

$$Q_V = 0.78 \times A_W \, N \, \Delta T$$

where A_W = external wall area in m^2

$$Q_V = W_m-2$$

Assuming a ceiling height of 2.28 m, the constant becomes 0.75.

(2) Flats and terrace houses.

$$Q_V = 1.0 \times A_W \, N \, \Delta T$$

(3) Two storey houses in general.

$$Q_V = 0.52 \, A_T \, N \, \Delta T$$

where A_T = total exterior building surface area in m^2.

with the 2.28 m ceiling, the constant = 0.5.

It is questionable whether values of N for flats and terrace houses are equivalent to those of semi detached houses. Considering the influence of intentional ventilation by the occupant, the above formula is probably adequate. Figure 6 utilizes formula 3 and the entire building surface area. In the calculations of combined heat loss which follow in Section 6, both formulae 2 and 3 are used, depending on the type of building under consideration.

5.3. Ventilation in tall buildings.

The natural ventilation of tall buildings is a different problem from that of the domestic house. The studies done by Harrison (1961) and Jackman (1969) apply to offices primarily, and assume that external windows and doors are kept closed. They take no account of the effect of pressure in the ventilating system. The factors they consider as determining the infiltration are: the external wind stack effect as determined by temperature difference and the height of the building, the floor plan and resistance of internal partitions, and the fit of the windows and the length of the crack around the openable portions. All these factors have a significant influence on ventilation. However, the combined action of the wind and stack effects was found here, as in Dick (1950), to be approximately equivalent to that of the greater of these motive forces acting along, and the resistance of internal partitions was often so small as to be negligible.

Jackman, using an electrical resistance analogue and wind pressure data from Davenport (1960), was able to produce a nomogram giving a ventilation rate (per foot of opening window joint) based on the building height, the meteorological wind speeds, 0, 10, and 20 mph, the severity of location (rural or urban - a reduction factor for V), and the window quality. To determine total ventilation the ventilation per foot of window joint must be multiplied by an area factor (cross sectional area over area of glazed building surface). The results of this study show values of N considerably lower than those given in the IHVE Guide (N varies from an optimum of 0.2 to 1.3, as opposed to 1.5 to 1.75 in the IHVE Guide).

The influence of wind predominated over stack effect above 5 m s^{-1}, but the existence of vertical circulation in the building caused markedly higher infiltration of the lower floors than if the floors were isolated. The ventilation rate of every floor under stack effect was found to be quite constant, although the immediate cooling was more pronounced on the lower floors where cold air was penetrating inward.

Harrison (1961) simplified the relationships in tall building ventilation to the following table:

Table 8

Air change in tall buildings.

Recommended design values of N due to infiltration in buildings heated at night.

	Height of Building			
	50 ft and under		over 50 ft	
	day	night	day	night
Buildings with little or partial partitioning (Open Plan). Cross ventilation.	1.50	0.75	2	1
Buildings with partitions (corridors and doors) on each floor, and with sealing doors to stairs and lifts)	0.75	0.33	1	0.5

On the partitioned plan building, the interior doors are assumed closed, since this is night cooling. The temperature drop interior to exterior = 35°C.

A study was done by Min (1958) on the infiltration through the entrance doors under the heavy traffic which is common for high buildings. The relationships derived are too detailed for description here, but one example might give an indication. In still air, a 350 foot building with the high T of 36°C will have an infiltration through the entrance of N = 0.25. The effect of ambient wind directly at the entrance itself causes no appreciable effect (Banfleth et al, 1957).

Harrison presents the values in Figure 8 as applicable to any wind direction and building shape. The Jackman work suggests that due to the higher loss from rectangular buildings than from square buildings a conversion factor would be possible to account for building shape. The magnitude of this difference is not given. It is likely that the influence of both shape and wind direction is negligible considering the range of error in the other assumptions that have to be made. This was found to be true for wind direction in the Dick work on domestic houses.

If this is the case, the problem for the planner is considerably simplified. He is not required to know the specifics of the structures he is planning for, but only the exposure of the site. The effect of wind on the ventilation of a few types of building can be assumed to represent the wind effect on all similar types of building. Knowing the exposure of the site involves knowledge of wind direction and of obstructions upwind of the sites. The IHVE Guide presents a method which is probably not applicable to either the domestic or tall building situations described above. However the method might be adapted to apply. It defines three degrees of exposure:

Sheltered = in town, the bottom 2 storeys and the ground floor.
Normal = suburban, country, 3, 4, 5 storeys in town.
Severe = hill sites, coast, riverside, 6 storey+ in town.

The method suggests that, for severe exposures, ½ N is to be added to expected ventilation.

The German Building Standard (DIN 4701) gives a very similar list of exposures for their ventilative heat loss factor. There is little need for accurate meteorological data with crude exposure subdivisions such as these.

6. Climate and total heat transfer from buildings.

6.1. Proposed method of calculation.

It has been shown in Section 4.8. that one can consider four basic radiation exchange systems to which a building's surfaces are exposed. These are:
(1) cloudy night, (2) cloudy day, (3) clear night
(4) clear day. This enumeration will be used below. Addition of averaged radiation balances of these systems, in the proportions of time that they apply, will give the total average radiation balance. The other major climatic influences on heat loss, temperature and wind, behave the same regardless of weather or time of day. Thus, the total climatic influence on a building can be summarized from averages of these four climatic situations. This is expressed in the following relationship:

When $f_{1,2,3,4}(X_{1,2,3,4}) = Q$ for a given climatic situation $X_{1,\dots,}$ the total Q for a period of time will be:

$$Q_{total} = P_1\ f_1(X_1) + P_2\ f_2(X_2) + P_3\ f_3(X_3) + P_4\ f_4(X_4) \qquad (1)$$

where $P_{1,2,3,4}$ is the probability, in time, of the climatic situation $X_{1,\dots}$ occurring.

Climatic influence on Q is calculated for uniform surfaces, such as walls of a given conductance, roofs, or windows. Each climatic situation in the above relationship can be expanded to encompass the individual climatic influences on each of the surface types of the building:

$$P_1 f_1(X_1) = P_1 \left[P'_a f_{a,1}(X_1) + P'_b f_{b,1}(X_1) + P'_c f_{c,1}(X_1) \right]$$

and so on, where a = wall surface, b = window, c = roof, and P' is the proportion of the total building surface that each of these surfaces represents.

The directional nature of the climatic elements sun and wind could be introduced into the equation by a further expansion, affecting both P and f. However, this refinement is of little use in determining building heat loss, and directional irregularities have been averaged out in advance, within the data applied to the function. For example, P_4 and f_4 include both sunlit and shaded surfaces. The mixture is accommodated by using radiation data averaged over four walls and perhaps the roof of a cube. Local site shading is also taken into account in the data applied to the function, as is described in Chapter IV. The same is true for the directional nature of wind.

Formula (1) can be expanded again to specify the relationships comprising the many forms of f (X). All the climatic elements found to be important in heat transfer would be found in the appropriate $f_n(X_n)$: temperature, wind, sunlight intensity, vapour pressure, and cloud type. The cloudiness percentage and daylength data would be isolated from P_n. The result would be a formidable equation, in which the influence of the individual climatic elements would be hard to visualize. It would, however, be straightforward for computer calculations. In this thesis, it has been deliberately chosen to calculate the total heat loss function for a building as a series of discrete single steps which are compounded to the total. This method lends itself best to a graphical presentation, which is a desirable format for use by planners. It also simplifies the manipulation of any of the steps in order to suit specific building or climatic conditions.

Considering the four basic (uniform) climate situations and the three basic surfaces mentioned above, the number of single calculating steps (graphs) required to solve formula (1) is:

A. Basic surfaces:

$$\begin{matrix} f_{a,1} & f_{a,2} & f_{a,3} & f_{a,4} \\ f_{b,1} & f_{b,2} & f_{b,3} & f_{b,4} \\ f_{c,1} & f_{c,2} & f_{c,3} & f_{c,4} \end{matrix}$$

B. A function to represent ventilative heat loss: f.

C. Combined surfaces: basic surfaces of a given house exterior are combined by their respective proportions P', for each climate.

$$f_1 \quad f_2 \quad f_3 \quad f_4$$

D. Combined climates: the combined uniform surfaces of a given house exterior in each climatic situation are combined, by their respective percentages P, to represent the climate in question. This is probably best done by first dividing the climate into its cloudy and clear components, using geometrical daylength information, in order to make use of available meteorological data on S and c. Then the final climate is represented:

$$f_{1+2}\ ,\quad f_{3+4}\ ,\quad f_{1+2+3+4}$$

The total number of functions (graphs) calculated is thus 20.

Several simplifying assumptions about the basic surfaces can be made to reduce this number of graphs. In the method presented here, the total number of steps is 13, and smaller numbers are quite possible at the expense of some accuracy. There are some additional graphs presented which are replicates of the essential ones, but which apply to different types of buildings, and for differing insolation levels.

Of the basic surfaces, it is assumed that the walls and roof are both $K = 1$. This means that, aside from the differing view that these two surfaces have of the sky, they can be considered identical for heat loss calculation. Since the radiation data used in this method is an average of walls and roof, the two surfaces can be considered identical in the clear day situation. The only difference occurs in the clear night situation, where the roof experiences clear sky radiation over its entire surface area, whereas the wall surface views a hemisphere at least one half of which is surrounding ground or building surface. This ground radiation is equivalent to cloudy sky radiation, and is assumed here to cover one half the view (thus, the area) of the wall. Hence one can assume:

$$f_{a,3} = \frac{f_{a,1} + f_{c,3}}{2}$$

The effect of diffuse radiation during cloudy weather on heat loss through walls is extremely small, and a separate step for this is omitted. The effect of this diffuse radiation is shown in an additional graph which is presented to show heat gain under varying T, V, and I for a K = 1 surface. This could substitute for both $f_{a,2}$ and $f_{a,4}$.

Similarly, the effect of shortwave radiation through windows is considered constant at 85%. The steps $f_{b,2}$ and $f_{b,4}$ are omitted and the radiation effect introduced in f_2 and f_4.

The basic surface graphs calculated are:

$$f_{a,1} \quad f_{a,4} \quad f_{b,1} \quad f_{b,3} \quad f_{c,3}$$

The combined surfaces graphs represent a semi-detached house of 100 m^2 floor area. The additional graphs presented in this section give the effect of f_1, f_3 and f_4

on a flat without a roof, f_1 for a house with a higher proportion of glass, the ventilation function for tall buildings, and the influence of varying levels of I on the semi-detached house.

Modifications to the graph series can be made at any stage, and the modifications are then carried through to the final graph by simple arithmetic. The graphs serve a useful purpose in allowing the comparison of the scales of heat loss through the different building and climatic channels.

6.2. Combined influence of h_r and h_c: uniform surfaces.

A number of calculations go into the functions for each basic surface. These primarily involve the surface coefficients.

a.) The surface coefficients h_{ct}, h_{cv}, and h_r are added to produce h_s. The magnitude of h_s for a given temperature drop and wind speed depends on the insulation of the wall. Tables 9 and 10 give the surface coefficients for various temperatures, wind velocities, surface temperature drops, and cloud conditions for a surface of approximately $K = 1$. Figure 7 presents the resistances, surface temperatures, and effect of cloud condition on walls of differing transmittance. The following values for interior surface resistance are used (interior $T_{ai} = 20^{\circ}$): T_s greater than $18^{\circ}C$: $R_i = 0.14$.

TABLE 9

External surface coefficients in cloudy conditions.

R_s and h_s for wall or roof (K = 1), against T_a, V, and T_s.

Two values of R and h_{cv} are listed:

R_1 applies to smooth surfaces, where F = 1.

R_2 applies to rough surfaces, where F = 2.

Calculations based on Sections 3.2. and 4.2.

		Air temp=10°C			Air temp = 0°C				
	(T_s-T_a)	1	2	3	1	2	3	5	10
V = 0	Wall T	11	12	13	1	2	3	5	10
	T_m	10.5	11	11.5	0.5	1	1.5	2.5	5
	h_r	4.65	4.68	4.70	4.20	4.22	4.24	4.28	4.41
	h_{ct}	1.97	2.32	2.59	1.97	2.32	2.59	2.95	3.50
	h_s	6.62	7.00	7.29	6.17	6.54	6.83	7.23	7.91
	R	0.15	0.14	0.14	0.16	0.15	0.15	0.14	0.13
V = 0.5 m sec^{-1}	h_{cv1}	7.6	-	-	-	-	-	-	-
	h_s	14.2	14.6	14.9	13.8	14.1	14.4	14.8	15.5
	R_1	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06
	h_{cv2}	15	-	-	-	-	-	-	-
	R_2	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04
V = 1 m sec^{-1}	h_{cv1}	10	-	-	-	-	-	-	-
	h_s	16.6	17	17.3	16.2	16.5	16.8	17.2	17.9
	R_1	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	h_{cv2}	20	-	-	-	-	-	-	-
	R_2	0.04	0.04	0.04	0.04	-	-	-	-
V = 2 m sec^{-1}	h_{cv1}	15	-	-	-	-	-	-	-
	h_s	21.6	22	22.3	21.2	21.5	21.8	22.2	22.9
	R	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.05
	h^1_{cv2}	30	-	-	-	-	-	-	-
	R_2	0.03	0.03	0.03	0.03	-	-	-	-

V = 3	h_{cv1}	19	-	-	-	-	-	-	-
m sec^{-1}	h_s	25.6	26	26.3	25.2	25.5	25.8	26.2	26.9
	R_1	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
	h_{cv2}	38	-	-	-	-	-	-	-
	R_2	0.02	0.02	0.02	0.02	-	-	-	-
V = 4	h_{cv1}	23	-	-	-	-	-	-	-
m sec^{-1}	h_s	29.6	30	30.3	29.2	29.5	29.8	30.2	30.9
	R_1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	h_{cv2}	46	-	-	-	-	-	-	-
	R_2	0.02	0.02	0.02	0.02	-	-	-	-
V = 5	h_{cv1}	26	-	-	-	-	-	-	-
m sec^{-1}	h_s	32.6	33	33.3	32	33	33	33	34
	R_1	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	h_{cv2}	52	-	-	-	-	-	-	-
	R_2	0.02	-	-	-	-	-	-	-
V = 10	h_{cv1}	43	-	-	-	-	-	-	-
m sec^{-1}	h_s	49.6	50.0	50.3	49	50	50	50	51
	R_1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	h_{cv2}	86	-	-	-	-	-	-	-
	R_2	0.01	-	-	-	-	-	-	-
V = 15	h_{cv1}	58	-	-	-	-	-	-	-
m sec	h_s	65	65	65	64	65	65	65	66
	R_1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
	h_{cv2}	116	-	-	-	-	-	-	-
	R_2	0.01	-	-	-	-	-	-	-

Additional coefficients at V = 0 for T_a = 15, 5, and -10°C

$T_a = 15^\circ C$

	(T_s-T_a)	1	2	3
V = 0	Wall T	16	17	18
	T_m	15.5	16	16.5
	h_r	4.90	4.93	4.95
	h_s	6.37	7.25	7.54
	R	0.145	0.14	0.13

$T_a = 5^\circ C$

	(T_s-T_a)	1	2	3	5
V = 0	Wall T	6°	7°	8°	10°
	T_m	5.5	6	6.5	7.5
	h_c	1.97	2.32	2.59	2.95
	h_r	4.43	4.45	4.47	4.51
	h_s	6.40	6.77	7.06	7.46
	R	0.16	0.15	0.14	0.13

$T_a = -10^\circ C$

	(T_s-T_a)	1	2	3	5	10	15
V = 0	Wall T	-9°	-8°	-7°	-5°	-0°	5°
	T_m	-9.5	-9	-8.5	-7.5	-5	-2.5
	h_c	1.97	2.32	2.59	2.95	3.50	3.88
	h_r	3.75	3.77	3.79	3.83	3.97	4.08
	h_s	5.72	6.09	6.38	6.78	7.47	7.96
	R	0.17	0.16	0.16	0.15	0.13	0.13

TABLE 10

External surface coefficients in clear night conditions.

Clear sky radiant loss Q_{ro} assumed to be 114 W m^{-2}

R and $(T_a - T_e)$ presented in two forms: 1.) F = 1
2.) F = 2

For calculation procedure see Sections 4.3. and 3.2.

	Surface T	1	2	3	5	10	15
V = 0	h_{ct}, h_c	1.97	2.32	2.59	2.95	3.50	3.88
	R_1	0.51	0.43	0.39	0.34	0.29	0.26
	R_2	0.25	0.22	0.20	0.17	0.15	0.13
	$\frac{Q_{ro}}{h_{c1}} = (T_a-T_e)_1$	58°	49°	44°	39°	33°	29°
	$\frac{Q_{ro}}{h_{c2}} = (T_a-T_e)_2$	29°	25°	22°	20°	16°	15°
V = 0.5	h_{ct}	1.97	2.32	2.59	2.95	3.50	3.88
	h_{cr}	7.6	-	-	-	-	-
	h_c	9.6	9.9	10.2	10.6	11.1	11.4
	R_1	0.10	0.10	0.10	0.09	0.09	0.09
	R_2	0.05	-	-	-	-	-
	$(T_a-T_e)_1$	12°	11.5°	11°	11°	10°	10°
	$(T_a-T_e)_2$	6°	6°	6°	5°	5°	5°
V = 1	h_{ct}	2.0	2.3	2.6	3.0	3.5	3.9
	h_{cv}	10.0	-	-	-	-	-
	h_c	12.0	12.3	12.6	13.0	13.5	13.9
	R_1	0.08	0.08	0.08	0.08	0.07	0.07
	R_2	0.04	-	-	-	-	-
	$(T_a-T_e)_1$	9.5°	9°	9°	9°	8°	8°
	$(T_a-T_e)_2$	5°	5°	4°	4°	4°	4°

V = 2	h_{cv}	15.0	-	-	-	-	-
	h_c	17.0	17.3	17.6	18.0	18.5	18.9
	R_1	0.06	0.06	0.06	0.06	0.05	0.05
	R_2	0.03	-	-	-	-	-
	$(T_a-T_e)_1$	7°	7°	6.5°	6°	6°	6°
	$(T_a-T_e)_2$	4°	3°	3°	3°	3°	3°
V = 3	h_{cv}	19	-	-	-	-	-
	h_c	21	21	22	22	23	23
	R	0.05	0.05	0.05	0.05	0.04	0.04
	R_2	0.02	-	-	-	-	-
	$(T_a-T_e)_1$	5°	-	-	-	-	-
	$(T_a-T_e)_2$	3°	2°	-	-	-	-
V = 4	h_{cv}	23					
	h_c	26					
	R	0.04					
	$(T_a-T_e)_1$	4°					
	$(T_a-T_e)_2$	2°					
V = 5	h_{cv}	26					
	h_c	29					
	R	0.03					
	$(T_a-T_e)_1$	4°					
	$(T_a-T_e)_2$	2°					
V = 10	h_{cv}	43					
	h_c	46					
	R	0.02					
	$(T_a-T_e)_1$	3°					
	$(T_a-T_e)_2$	1°					
V = 15	h_{cv}	58					
	h_c	61					
	R	0.02					
	$(T_a-T_e)_1$	2°					
	$(T_a-T_e)_2$	1°					

III FIGURE 7:

Resistances, surface temperatures for walls of differing transmittance in cloudy and clear conditions.

V = 0

Note: for f = 2, $\frac{(T_a-T_e)}{2}$ and $\frac{h_{ce}}{2}$

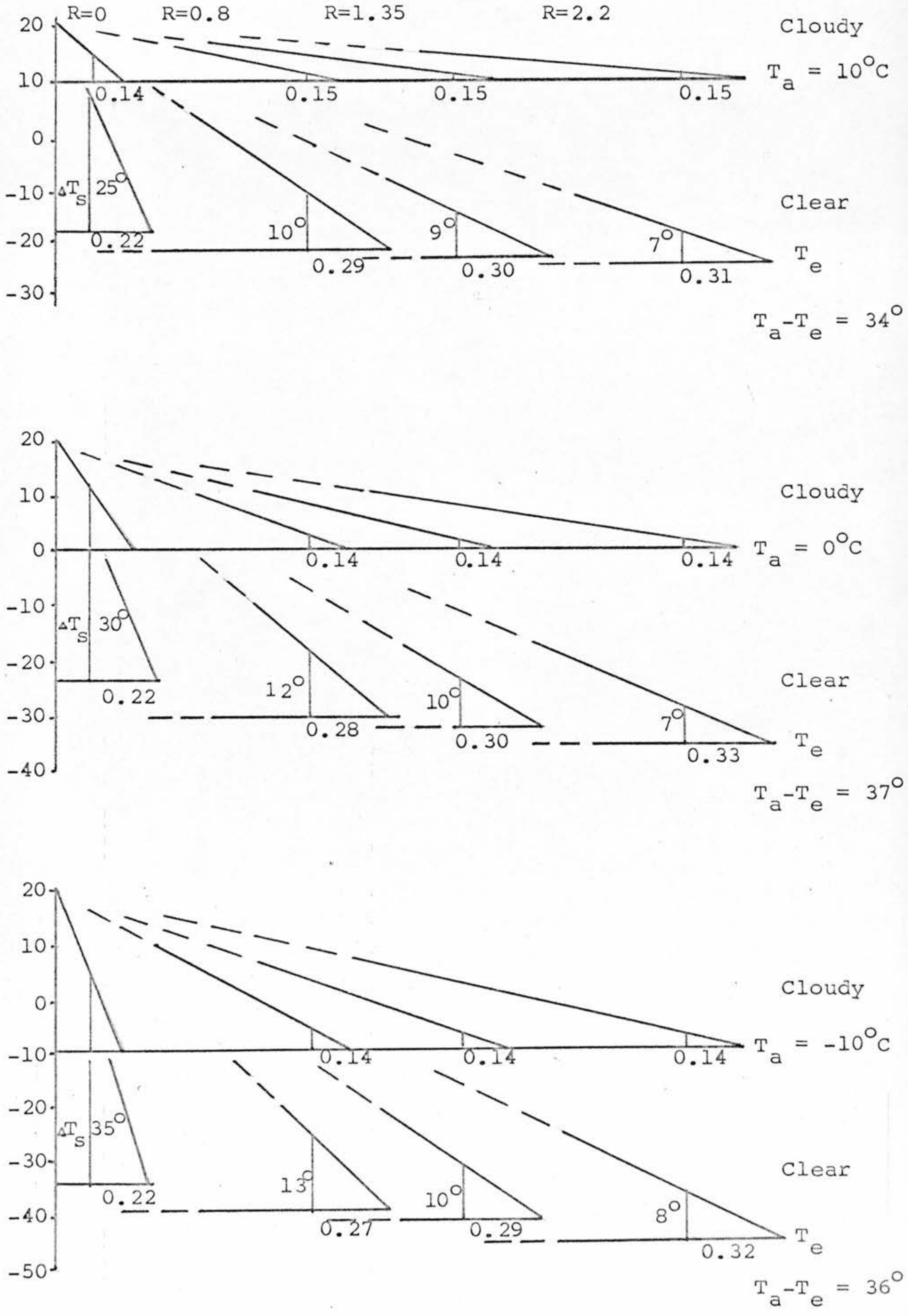
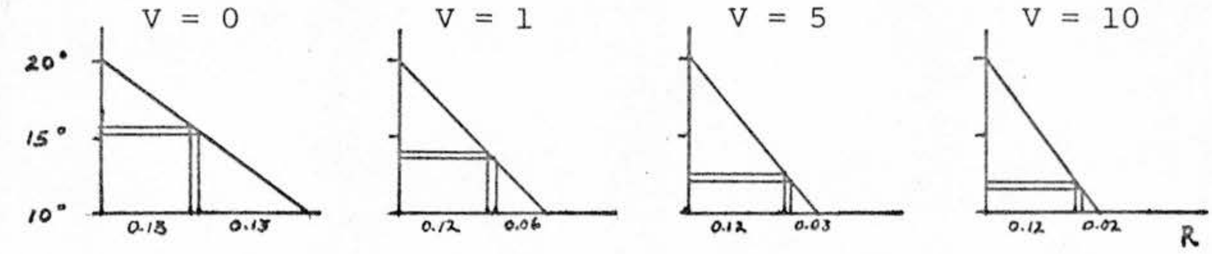
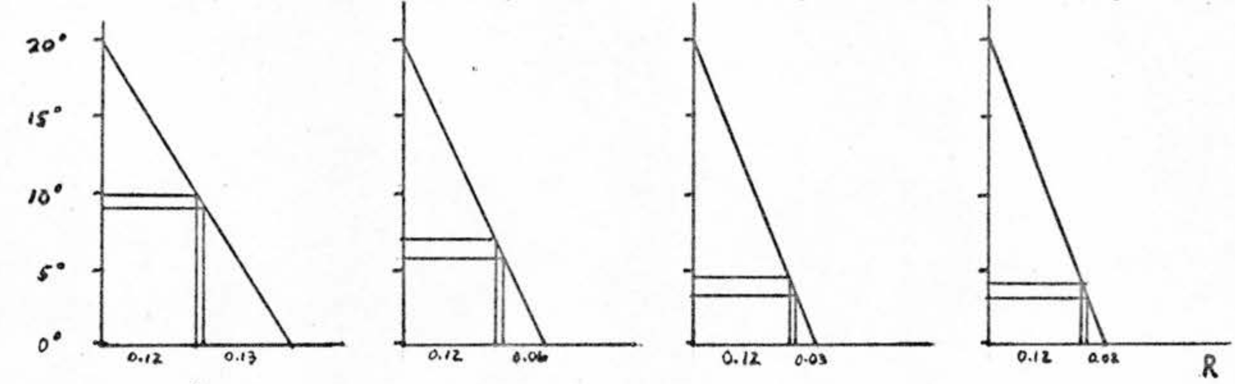


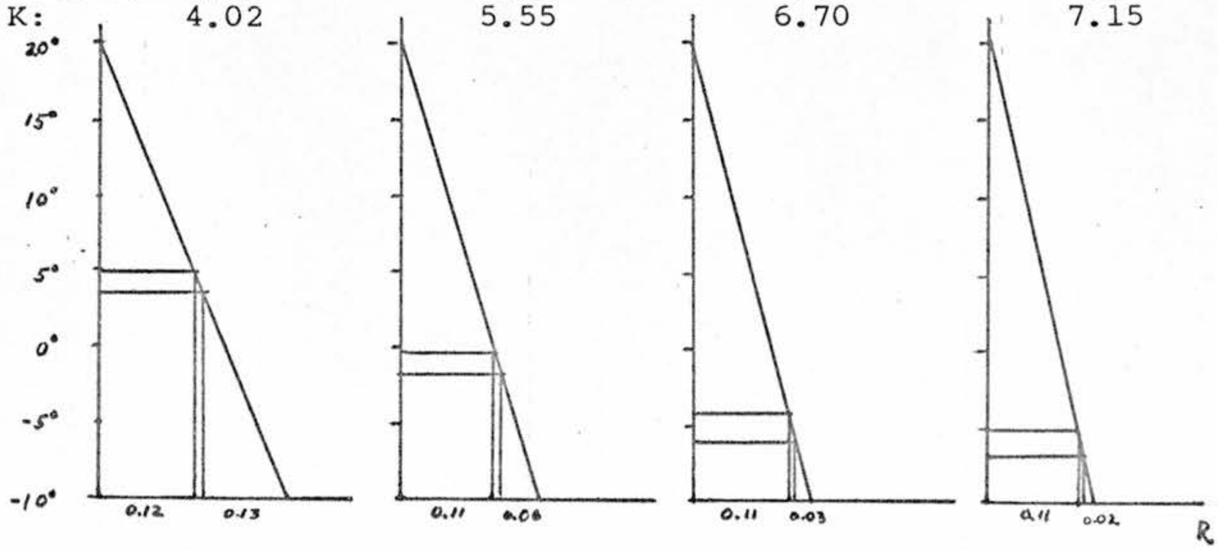
FIGURE 8: Resistance and surface temperature of glazing, against T_a and V. (1/4": λ= 1.04 Wm m^{-2} $^oC^{-1}$).



	I	E	I	E	I	E	I	E
h_r:	5.00	4.79	4.90	4.75	4.90	4.65	4.88	----
h_c:	2.95	2.95	3.20	2.60	3.25	2.32	3.25	----
h_{cv}:	----	----	----	10	----	26	----	50
h:	7.95	7.74	8.10	17	8.15	33	8.13	50
R:	0.13	0.13	0.12	0.06	0.12	0.03	0.12	0.02
Tot. R:	0.26		0.19		0.16		0.15	
K:	3.85		5.3		6.2		6.7	



	I	E	I	E	I	E	I	E
h_r:	4.88	4.41	4.80	4.30	4.80	4.30	4.80	4.30
h_c:	3.50	3.50	3.88	2.95	3.88	2.95	3.88	2.95
h_{cv}:	----	----	----	10	----	26	----	43
h:	8.38	7.91	8.68	18	8.68	33	8.68	50
R:	0.12	0.13	0.12	0.06	0.12	0.03	0.12	0.02
Tot. R:	0.25		0.18		0.15		0.14	
K:	4.02		5.55		6.70		7.15	



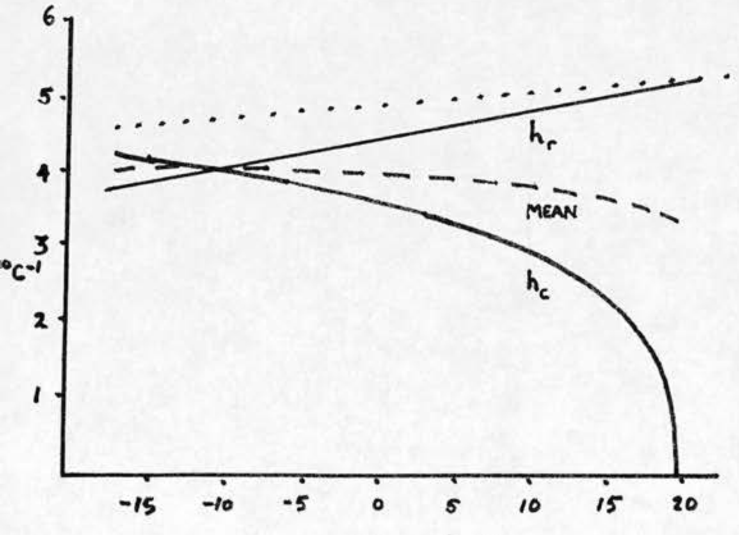
	I	E	I	E	I	E	I	E
h_r:	4.80	4.08	4.63	3.97	4.60	3.76	4.60	3.76
h_c:	3.88	3.88	4.16	3.50	4.20	3.20	4.40	3.00
h_{cv}:	----	----	----	10	----	26	----	43
h:	8.68	7.96	8.79	17	8.80	33	9.00	50
R:	0.12	0.13	0.11	0.06	0.11	0.03	0.11	0.02
Tot. R:	0.25		0.18		0.14		0.13	
K:	4.05		5.6		7.1		7.7	

T_s between 14 and 18°C: $R_i = 0.13$. T_s less than 13°: $R_i = 0.12$.

b.) Figure 8 presents the resistances, surface temperatures, and effect of wind velocity on glazing. Glazing, because of its high transmittance, is particularly important to the overall heat loss of a house. Figure 9 plots the relationship of the two exterior surface coefficients h_r and h_c against T_a in still air conditions. The interior coefficients are also shown. It can be seen that h_s remains effectively the same with decreasing external temperature because the falling surface radiation is balanced by increasing thermal convection. It also illustrates the constancy of the internal surface coefficient regardless of the glass temperature. On an insulated surface, the surface coefficient falls with decreasing temperature, but the values are of much smaller magnitude than they are for glass and are not plotted.

<u>Figure 9</u>: Relationship of T_a to h_e and h_i on ¼" glazing.

$V = 0$



Glass. R negligible = 0.007 $m^oC\ W^{-1}$
(interior air assumed = 20°C)
h_r is effectively straight = $(253)^3$ to $(293)^3$ °K
h_c is curved after $(20^o - T\ air)^{0.25}$

Note: with glass, the internal h_r and h_c vary the same as the external coefficients, but the internal h_r is higher (dotted line). (h_{ci}) identical to h_{ce}. With insulation or external wind, the effect of internal h change is obscured.

TABLE 11

Clear day insolation on walls and roof, Lat. 52^{o}

							Clear day I_o $(W\ m^{-2})$				Cloud rate = $0.25\ I_o$	
	Av.daylight						4 walls only		4 walls and roof			
Month			Hor.	N	S	E,W						
	hrs	day					daily	daylight	daily	daylight	daily	daylight
Mar - Sept	12	0.5	165	31	200	108	85	170	101	202	25	50
Feb - Oct	10	0.42	96	21	178	69	67	160	73	175	18	44
Jan - Nov	8.3	0.35	48	13	131	38	45	130	46	130	12	33
Dec	7.5	0.31	33	9	106	27	35	113	35	113	9	28
Seasonal average rates:							58	143	64	155	16	39

c.) 2. and 4.). The effect of shortwave radiation on the rate of heat loss through a surface is needed to account for both sunny and cloudy days. For a wall or roof with transmittance K = 1, the heat flux solar gain is roughly proportional to I:

$$Q_I = (T_{es} - T_a) = aI\, h_s^{-2}$$

since a and h_s are roughly constant. Absorptivity for building surfaces is assumed to = 0.6. h_s varies only slightly at V = 0. From table 9 it can be seen that (for $T_s - T_a = 1$):

		h_s ($Wm^{-2}\ {}^{o}C^{-1}$)					
		0	0.5	1	5	10	15
T_a	-10	5.7	"	"	"	"	"
	0	6.2	"	"	"	"	"
	10	6.6	14	16	21	33	65
	15	6.8	"	"	"	"	"
	20	7.0	"	"	"	"	"

Thus, with a value for I and a (0.6), solar gain can be determined.

The climatic data used for these calculations in this chapter follows (Petherbridge 1971): (Table 11):

The assumption for diffuse radiation on cloudy days is that I_{dc} is 25% of I_o, the transmission of average stratus cloud through a range of solar angles (Table A3,9). This estimate differs from the zero intercepts of the cloud model formulae in App.3, which average 0.35 I_o. Thus it is possible that the average cloudy diffuse radiation values are too low by as much as 15 Wm^{-2}. In the absence of local data, the assumption $I_{dc} = 0.25\ I_o$ is used in the calculations here. Adjusting this amount upward is not complicated.

Thus, considering the house with walls and roof,

$I\ a = 155 \times 0.6 = 93$ absorbed I, clear sky (Wm^{-2})

$I\ a = 39 \times 0.6 = 23$ absorbed I, cloudy sky.

($T_{es} - T_a$), °C, and solar gain Q, Wm^{-2} (for transmittance K = 1) equal:

		$V\ m\ s^{-1}$					
		0	0.5	1	5	10	15
	-10	16 (4)	6.6 (2)	5.8 (1)	4.4 (1)	2.8 (1)	1.4 (-)
T_a	10	14 (3.5)	"	"	"	"	"
	20	13 (3)	"	"	"	"	"

Where the bracketed values apply to cloudy sky. It is seen that the heat gain through insulation is almost constant over the full range of temperature. The values for still air agree with Danter and Dick's estimate (1956) that 10% of radiation incident on walls warms the interior of a house with medium insulation. At any wind speed, however, the proportion passing through is much less.

The solar gain is then subtracted from the heat flux to a cloudy sky. In clear atmospheres this may result in an overestimate of the downward LW radiation, and an underestimate of heat loss, but the amount is very variable depending on the turbidity of the atmosphere. This method uses the cloudy sky radiation flux as a simplification. The transmission of windows is independent of temperature and wind at 85% I.

d.) The series of figures representing heat flux through the basic surfaces is now presented. The interior temperature is assumed to be 20°C, for ease of calculation. Although this value is somewhat high at present, the trend in interior heating in Britain is toward the 20° common in the U.S. and on the continent. This value is used by Fournol (1948) and Bruckmayer (1960) in their heating requirement studies.

Figure 10: ($f_{a,1}$): Wall, heat loss to cloudy sky.
Figure 11: ($f_{c,3}$): Roof, heat loss to clear sky.
The effect of wind can be seen to be marginal at this insulation level, except under conditions of radiant cooling. The extreme heat loss found at $V = 0$ in Fig. 11 applies primarily to horizontal surfaces, since surface cooling on slopes and walls induces greater thermal convection (Sect. 3.1.).

Figure 12: ($f_{a,4}$): Average wall and roof: heat loss during exposure to average winter sunshine.

The crossover line at which heat loss becomes solar gain is evident. The solar gain in cloudy conditions is 25% of the gain here. The cloudy sky loss is included for comparison.

Figure 13: a) Solar gain against air temperature and wind, and b) solar gain against I and wind. Both of these are derived from the calculations above. Part a) shows the small influence of temperature on solar gain, permitting its omission in part b).

Figure 14: Glazing: heat loss to cloudy sky.
Figure 15: Glazing: heat loss to clear night sky.
The heat flux through glass (here 1/4" plate) is so high that the vertical scale on these figures is double that of the others.

6.3. Total heat transfer from buildings: uniform climates.

6.3.1. Combined influence of h_s and ventilation.

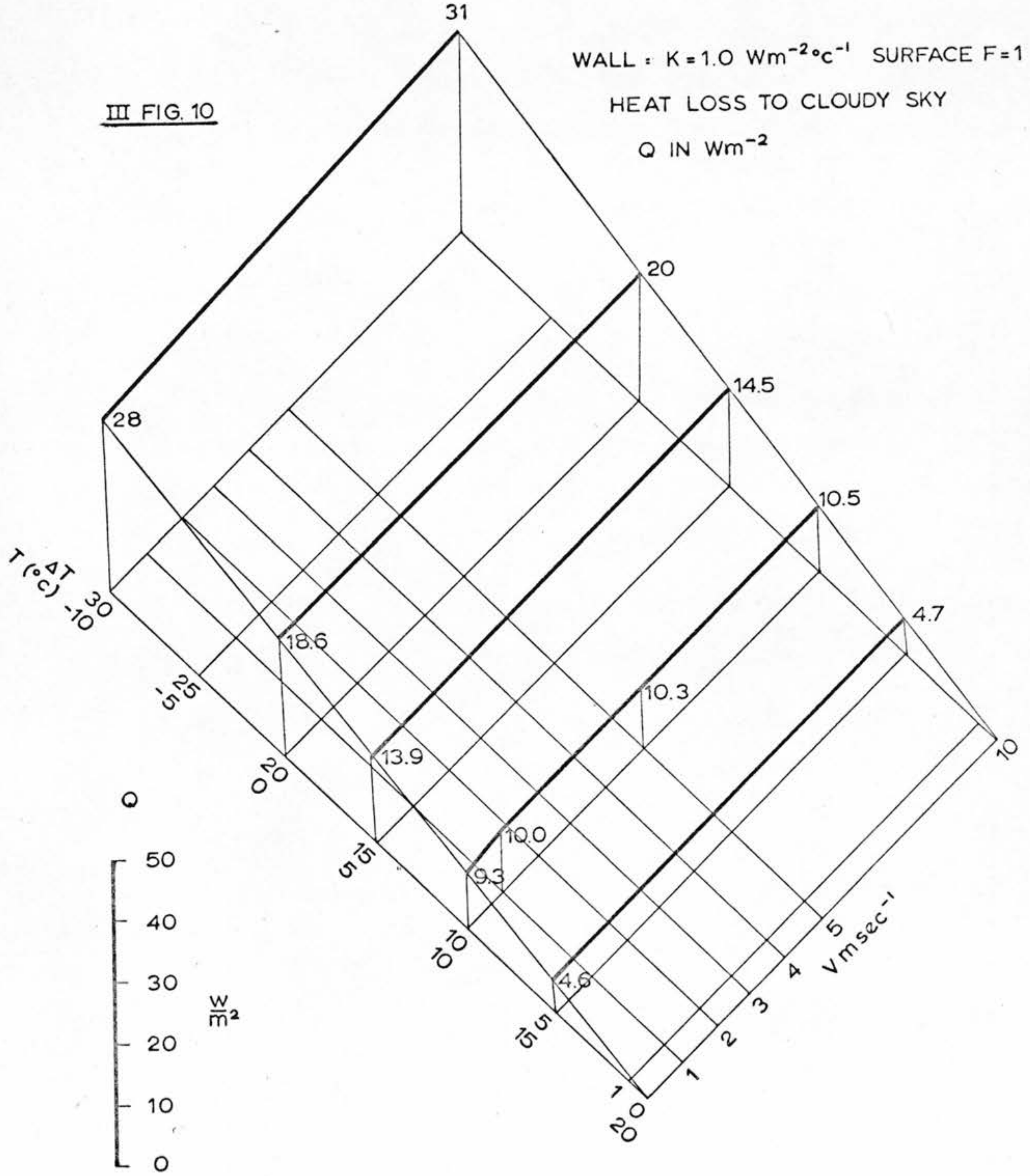
The combination of ventilation and surface heat loss must be done by assuming a single unit of heat loss. In this example, ventilation of the house is related to its surface area by assumed volume to surface area ratios for standard types of house and flat. This permits combination with surface heat transmission per unit area. Conversely, surface transmission could be

III FIG. 10

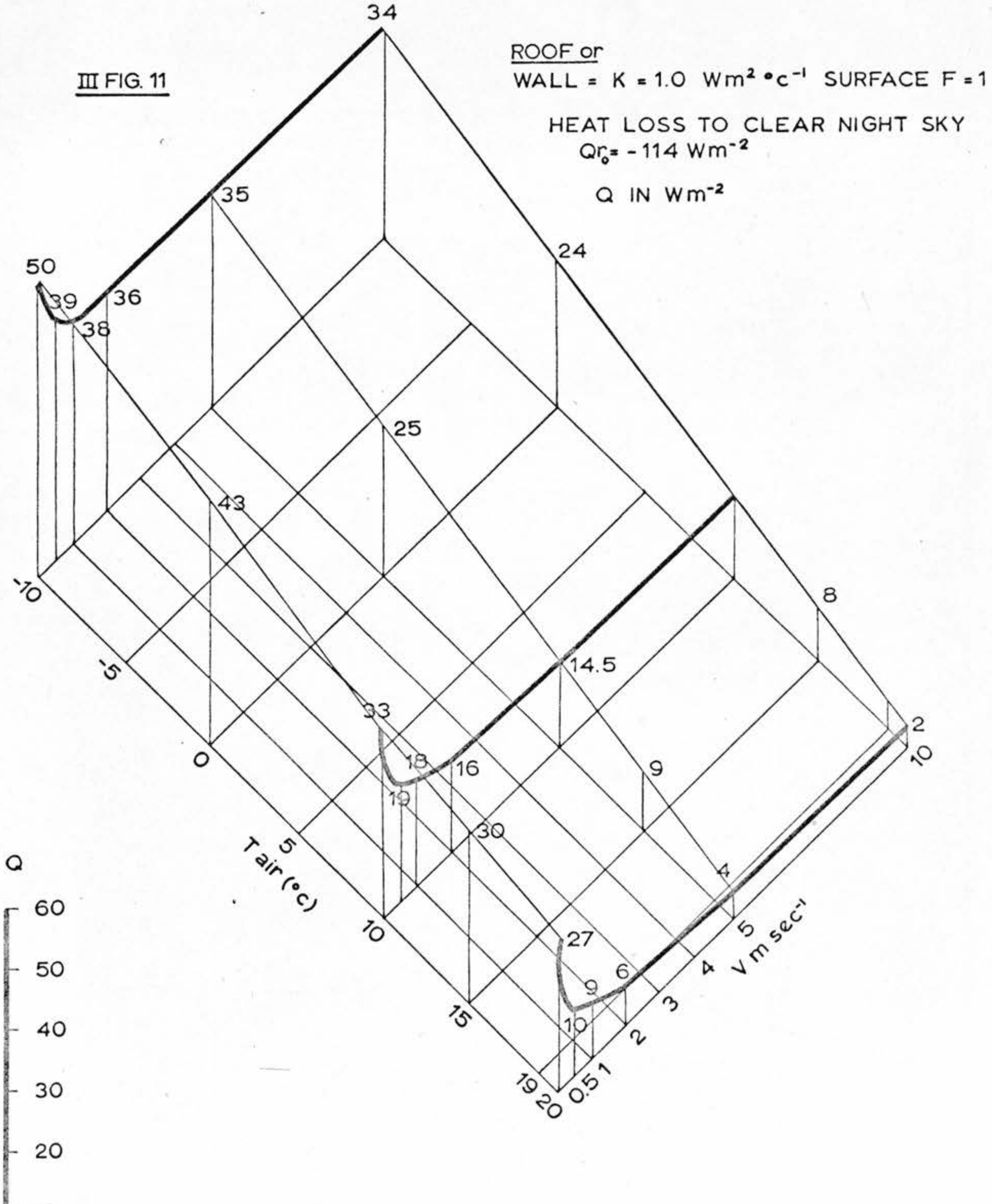
WALL : K = 1.0 $Wm^{-2}{}^{\circ}c^{-1}$ SURFACE F = 1

HEAT LOSS TO CLOUDY SKY

Q IN Wm^{-2}



III FIG. 11



ROOF or
WALL = K = 1.0 Wm² °c⁻¹ SURFACE F = 1

HEAT LOSS TO CLEAR NIGHT SKY
$Qr_0 = -114\ Wm^{-2}$

Q IN Wm^{-2}

III FIG. 12

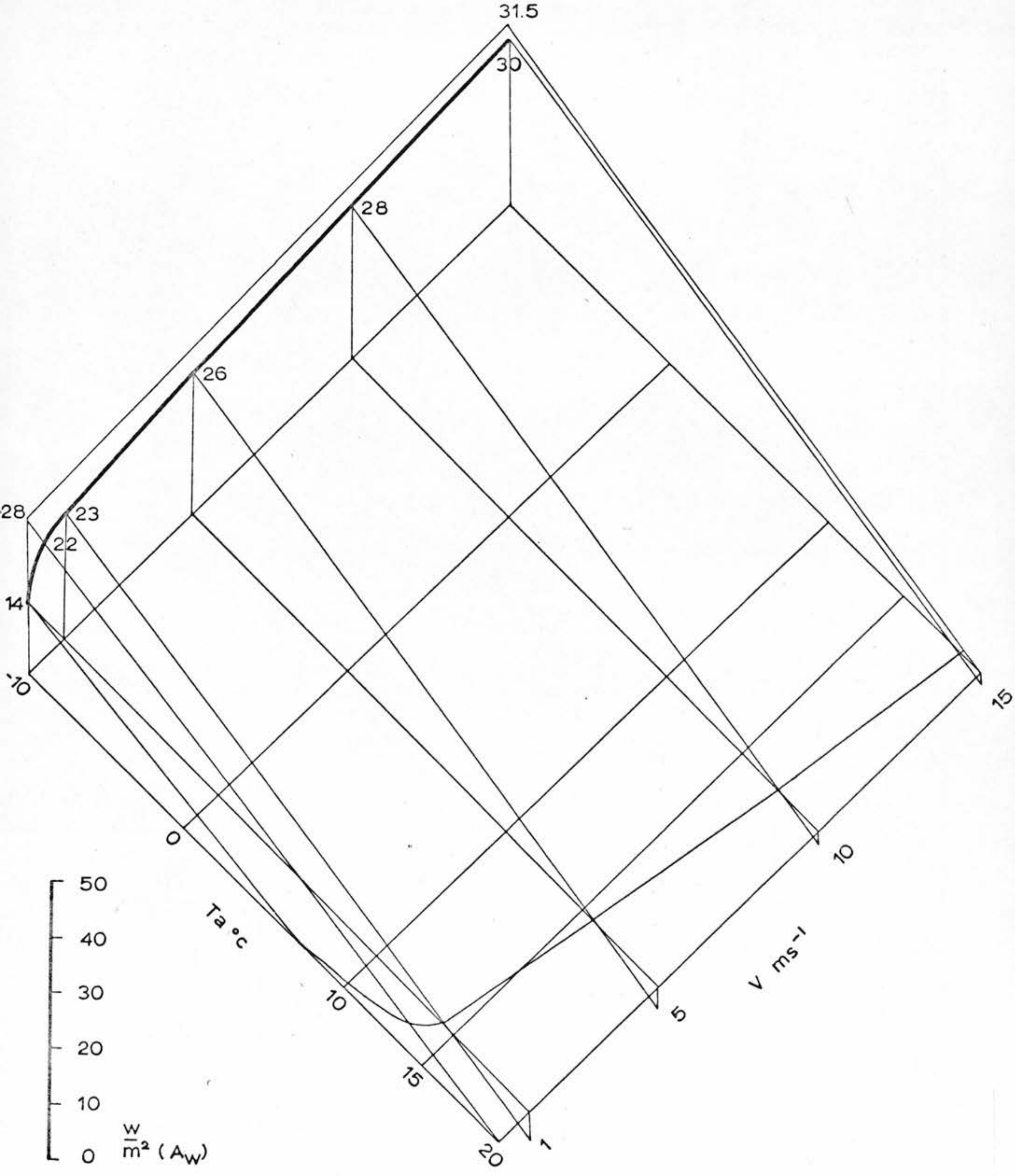
WALL = K = 1.0 $Wm^{-2}°c^{-1}$, AVERAGE ORIENTATION

HEAT LOSS DURING EXPOSURE TO WINTER SUNSHINE - RADIATION INTENSITIES ARE AVERAGES FOR SIX WINTER MONTHS DURING CLEAR WEATHER

DIRECT & DIFFUSE RADIATION DURING	DAYTIME	=	155 Wm^{-2}
DIFFUSE	"	"	"	39 Wm^{-2}
DIRECT	"	"	"	116 Wm^{-2}

DERIVED FROM PETHERBRIDGE 1971.

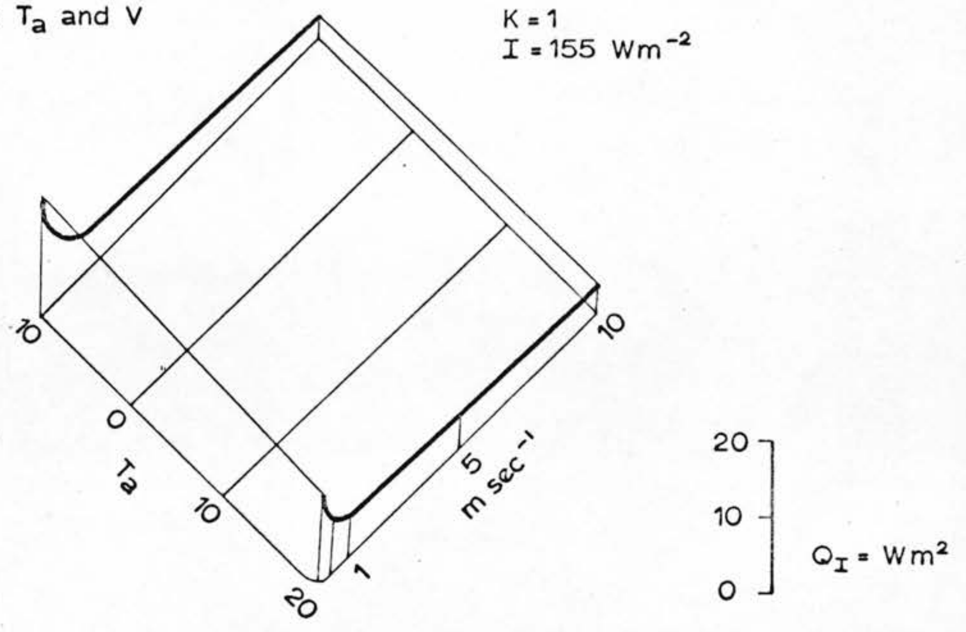
UPPER LINE REPRESENTS HEAT LOSS
TO CLOUDY SKY



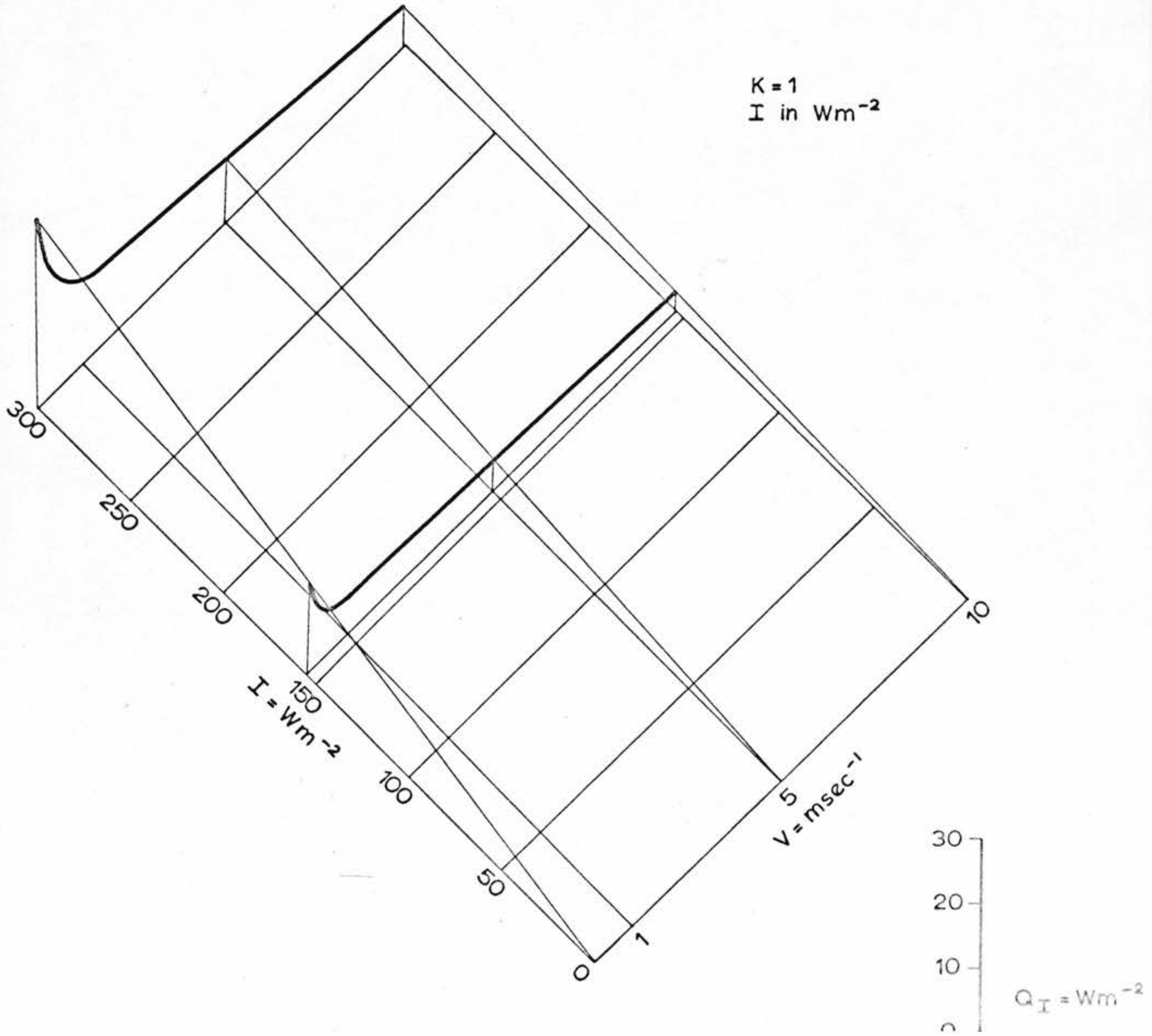
SOLAR GAIN Q_I

III FIG. 13

a) Q_I VERSUS T_a and V


K = 1
I = 155 Wm^{-2}

b) Q_I VERSUS I and V

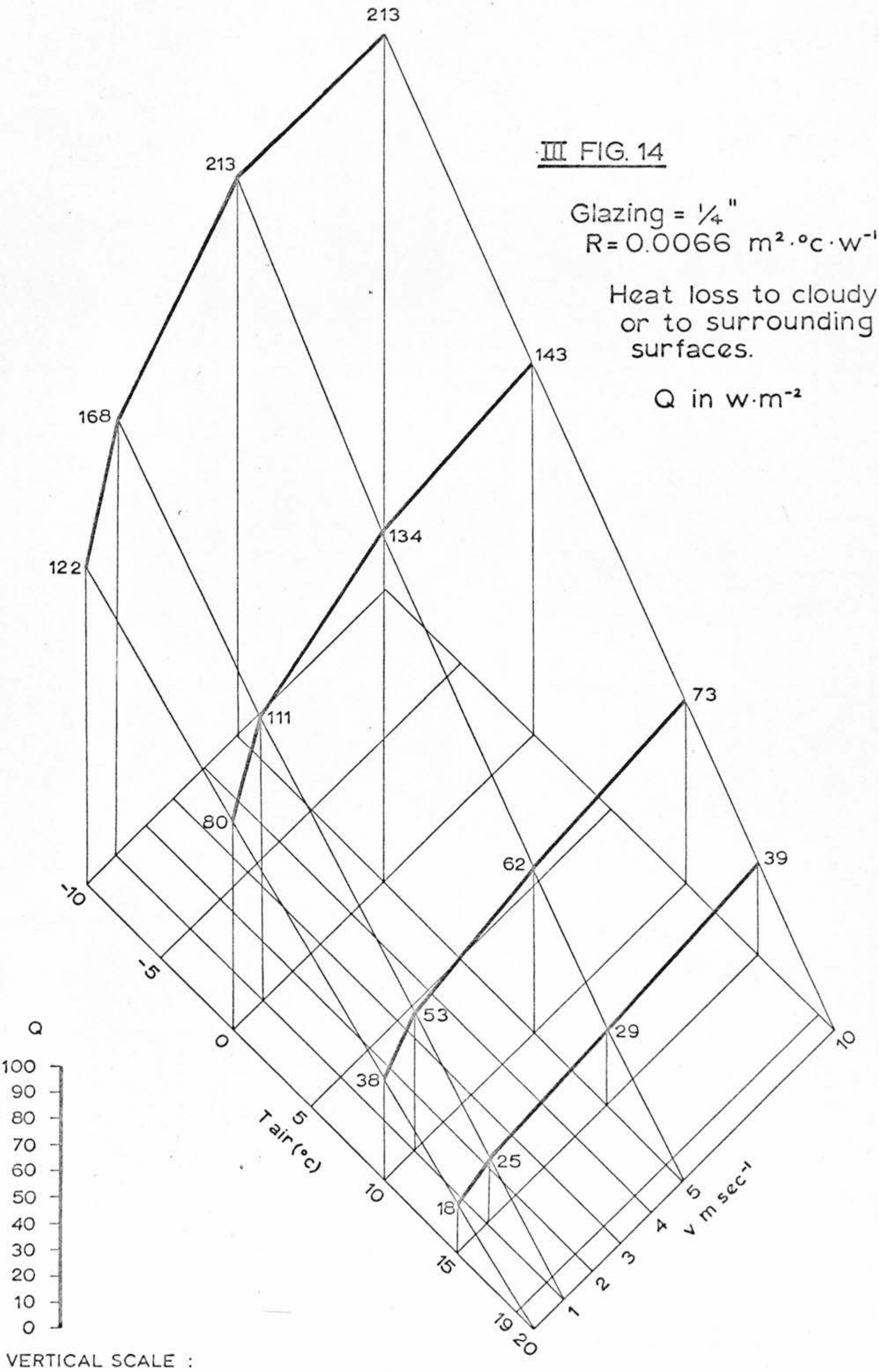

K = 1
I in Wm^{-2}

III FIG. 14

Glazing = ¼"
R = 0.0066 m²·°c·w⁻¹

Heat loss to cloudy sky or to surrounding surfaces.

Q in w·m⁻²



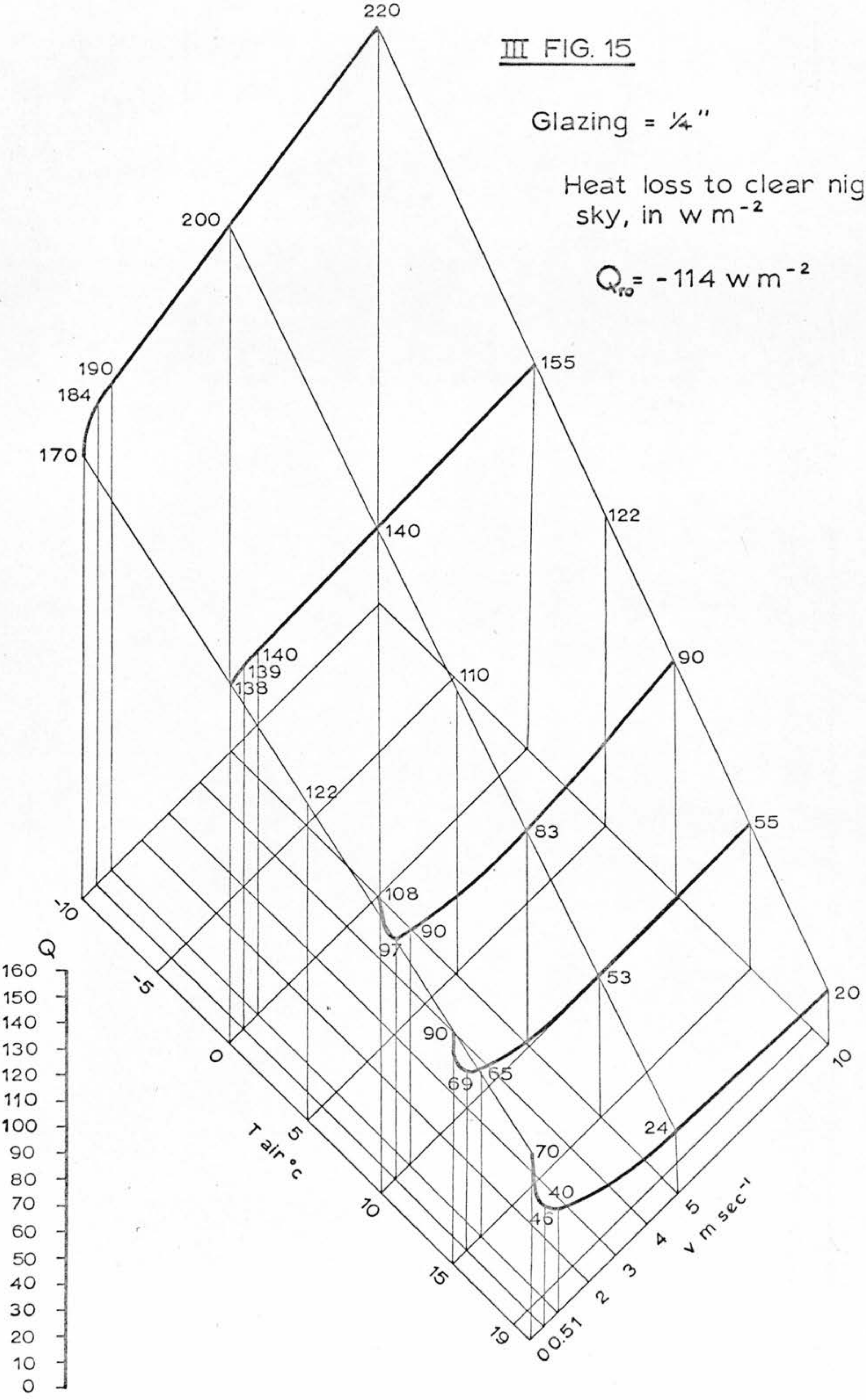
VERTICAL SCALE :
HALF SCALE TO OTHER CHARTS

III FIG. 15

Glazing = ¼"

Heat loss to clear night sky, in w m^{-2}

Q_{ro} = -114 w m^{-2}



VERTICAL SCALE :
HALF SCALE TO OTHER CHARTS

converted to a volume loss for each house type; this would permit direct combination with ventilation loss.

The French CSTB uses a volumetric heat loss coefficient G_1 as a standard measure by which the thermal quality of buildings can be compared. (Givoni 1969).
G_1 is defined as:

$$G_1 = \frac{Q}{V_o \ (T_i - T_a)} \qquad (Wm^{-3} \ {}^oC^{-1})$$

where Q is the heat supplied to the interior, V_o is the interior volume, and $T_i - T_e$ is regarded as a constant. Q is then computed for the specific house type in question as a sum of ventilation and transmission, adjusted for their proportion of volume loss. G_1 is employed in the building codes to specify the maximum heat requirements by the relationship:

$$Q = G_1 \ V_o \ (T_i - T_{e \text{ minimum}})$$

Where $T_{e \text{ minimum}}$ is the outdoor minimum design temperature. It is assumed here that surface area is the most useful measure for combined ventilation and surface heat loss because of the variety of surface exchanges per building which must be considered. Volume loss occurs only through the single factor ventilation. Surface loss is influenced by the orientation and nature of the different surfaces as well as by the climates and obstructions that they face. The different forms of surface loss need to be typed and calculated for generalized surfaces, as in Sect. 6.2.

When this is done, the complicated surface exchanges for any building can be combined by adding their respective proportions. A volumetric heat exchange coefficient would make this flexibility impossible.

Figure 16: Ventilative heat loss of domestic house, per unit total exterior area.
Figure 17: Ventilative heat loss of office building per unit exterior wall area. (open and closed floor plans).
These figures apply formulae described in Sects. 5.2. and 5.3.

6.3.2. Building surfaces facing uniform climatic conditions.

1.) General.

Figures 18 - 26 apply to the four uniform climatic situations described above. They are completed for houses with roofs and flats without exposed roofs, and an example for a house with additional glazing is included. The proportions of wall, window, and roof are presented on the figures. The heat flow from the composite surfaces are derived from Figures 10 - 15 (heat flow from uniform surfaces) and from Figure 16, for the ventilative component which is added at the top. Each building surface can be described as a sum of varying proportions of Figures 10 - 15.

An alternative method of dealing with a house surface is to average the differing K values to give one for the entire house. Danter and Dick (1956) give:

2.) Cloudy night conditions.

Figure 18: House, with roof: Q and Q_v in cloudy conditions.

Figure 19: Flat, without roof: Q and Q_v in cloudy conditions.

Figure 20: House, with roof, and extra area of glazing: Q and Q_v in cloudy conditions.

The calculations for Figure 19 indicate that at 0 m s^{-1}, the heat transmission through the 20% window area equals that through the walls which cover 80% of the external surface. At 10 m s^{-1}, the window transmission is twice that of the walls, hence two thirds of the total transmitted heat loss. Comparison of Figures 18 and 20 shows that increasing the proportion of window area from 20 to 30% of the wall increases the total transmitted heat loss by an average of 20%.

3.) Clear night conditions.

Figure 21: House, with roof: Q and Q_v in clear night conditions.

Figure 22: Flat, no roof: Q and Q_v in clear night conditions.

The high rate of radiant cooling is somewhat submerged by the ventilation rate increasing with wind velocity, and by the amount of surface radiating to natural surfaces.

4.) Sunlight.

Figure 23: House, with roof: Q while exposed to sunlight

at average winter intensity.

Figure 24: Flat, no roof: Q while exposed to sunlight at average winter intensity.

Figure 25: House, with roof: Q during cloudy daytime, I_d assumed to equal 0.25 I_o.

Figure 26: House, with roof: Q_I, solar gain, while exposed to varying intensity insolation, and wind.

Although the eventual aim of heat loss curves is information for a minimum period of a full day, the daytime heat balance under insolation needs to be graphed, since it will show the point where solar transmittance through walls (Figures 11 and 12) and windows (85% transmittance) causes overall heat gain into the building. Beyond this point the building is in the hot zone and the occupants will begin to alter ventilation in a different way then that assumed during heat loss.

The increasing ventilation as $T_i - T_a$ and Q decrease has been noted (Figure 6) and incorporated into Figures 16 - 25. It is assumed here that, averaged over daylight hours, the occupants will remove all internal temperature above 20°C by ventilation. This means that solar gain theoretically occurring from the computation of transmission through glass and walls will not necessarily be available to substitute for heating Q during the night. It is necessary to complete these daytime figures to determine which portions of solar gain are not to be averaged into the daily figures. Figures 23, 24, and 25 show the lines above which the heat loss or gain is assumed zero.

It is recognized that daylight-length averages of I do not give information on instantaneous overheating, and will tend to underestimate it. The insolation curve over the day can be determined from Figure 3, or from Table A8. At 55° latitude, the summer insolation on a perpendicular surface varies four-fold from soon after sunrise to noon. In winter, with noon zenith angles varying from 80° on December 22 to 57° on March and October 21, the insolation varies from very slightly to three-fold. The amount of actual gain depends greatly on the orientation of the building surfaces. Since the greatest gain is through glass, the relatively weak low-angle insolation has a much greater relative effect than the stronger high angle insolation. In the absence of a way to deal with these detailed relationships in a general way, the planner is justified in using the whole day insolation rate (as distributed over the faces of a cube) for the radiation during any part of the day. This averaging unit approximates the shape of a house or flat (subtracting roof), and shows less variation with zenith angle than radiation on a horizontal surface.

Solar gain through windows exceeds that through walls by a factor varying from 1.2 in still air to 8 at 10 m s^{-1}. This compares to a seasonal average factor from Danter and

Dick (1956) of 4.5.

The values of Figure 26 are subtracted from those on Figure 18 to get the solar gain, during daytime, of any level of I. To convert to daily averages, the solar gain above the heat balance line has to be discarded, as described above.

The values for I_o are taken from Table 11. The radiation averaged over four walls is slightly lower (143 Wm^{-2}) than averaged over roof and four walls (155 Wm^{-2}). The cloudy diffuse radiation is 39 Wm^{-2}.

6.4. Total heat transfer from buildings: combined climates.

6.4.1. Heat transfer under clear and cloudy weather.

Figure 27: House: average daily Q during cloudy weather, winter, 55° latitude.

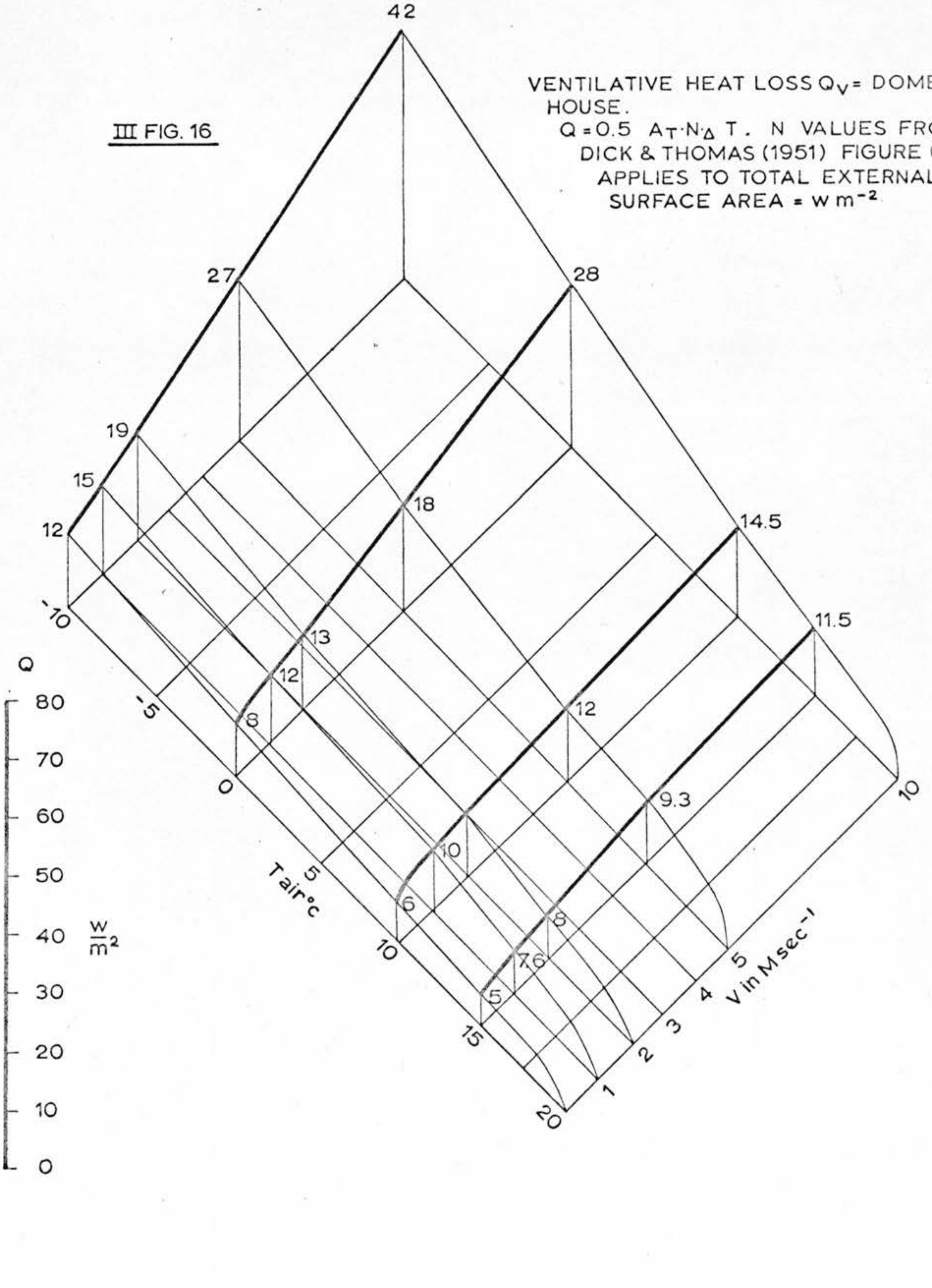
Figure 28: House: average daily Q during clear (sunny) weather, winter, 55° latitude.

The day and night figures for each weather condition are combined in the proportions of average winter day and average winter night. With an average daylength of 9.7 hours, October through April, these proportions are 0.4 and 0.6.

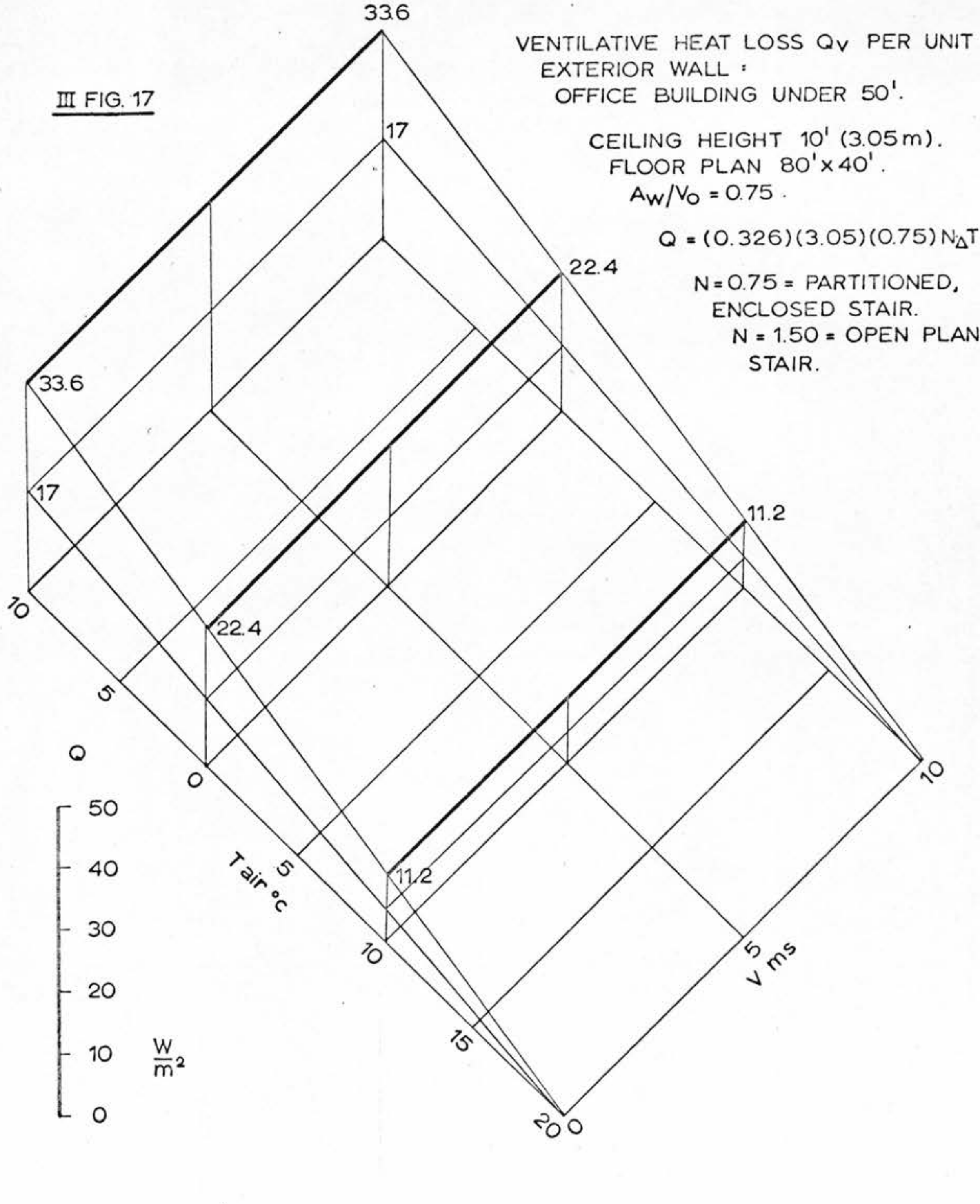
Comparison of Figures 27 and 28 shows very similar heat loss for clear and cloudy weather in latitude 55°.

III FIG. 16

VENTILATIVE HEAT LOSS Q_V = DOMESTIC HOUSE.
$Q = 0.5\ A_T \cdot N \cdot \Delta T$. N VALUES FROM DICK & THOMAS (1951) FIGURE 6.
APPLIES TO TOTAL EXTERNAL SURFACE AREA = $\mathrm{w\,m^{-2}}$



III FIG. 17



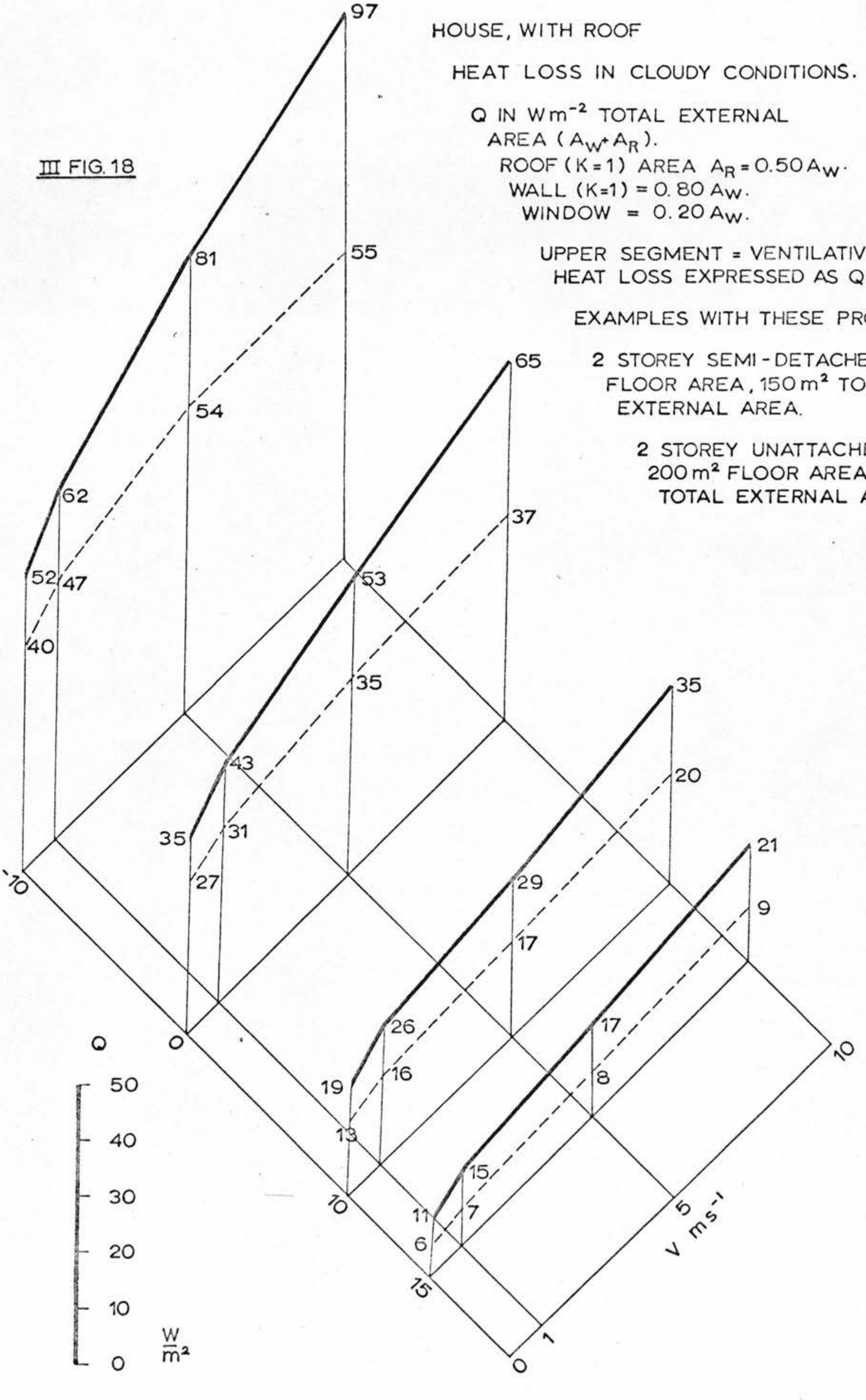
VENTILATIVE HEAT LOSS Q_V PER UNIT EXTERIOR WALL : OFFICE BUILDING UNDER 50'.

CEILING HEIGHT 10' (3.05 m).
FLOOR PLAN 80'x40'.
$A_W/V_O = 0.75$.

$Q = (0.326)(3.05)(0.75)\,N\Delta T$.

N = 0.75 = PARTITIONED, ENCLOSED STAIR.
N = 1.50 = OPEN PLAN, STAIR.

III FIG. 18



HOUSE, WITH ROOF

HEAT LOSS IN CLOUDY CONDITIONS.

Q IN Wm^{-2} TOTAL EXTERNAL
AREA ($A_W + A_R$).
ROOF (K = 1) AREA $A_R = 0.50 A_W$.
WALL (K=1) = 0.80 A_W.
WINDOW = 0.20 A_W.

UPPER SEGMENT = VENTILATIVE
HEAT LOSS EXPRESSED AS Q.

EXAMPLES WITH THESE PROPORTIONS:

2 STOREY SEMI-DETACHED 100 m^2
FLOOR AREA, 150 m^2 TOTAL
EXTERNAL AREA.

2 STOREY UNATTACHED HOUSE
200 m^2 FLOOR AREA, 300 m^2
TOTAL EXTERNAL AREA.

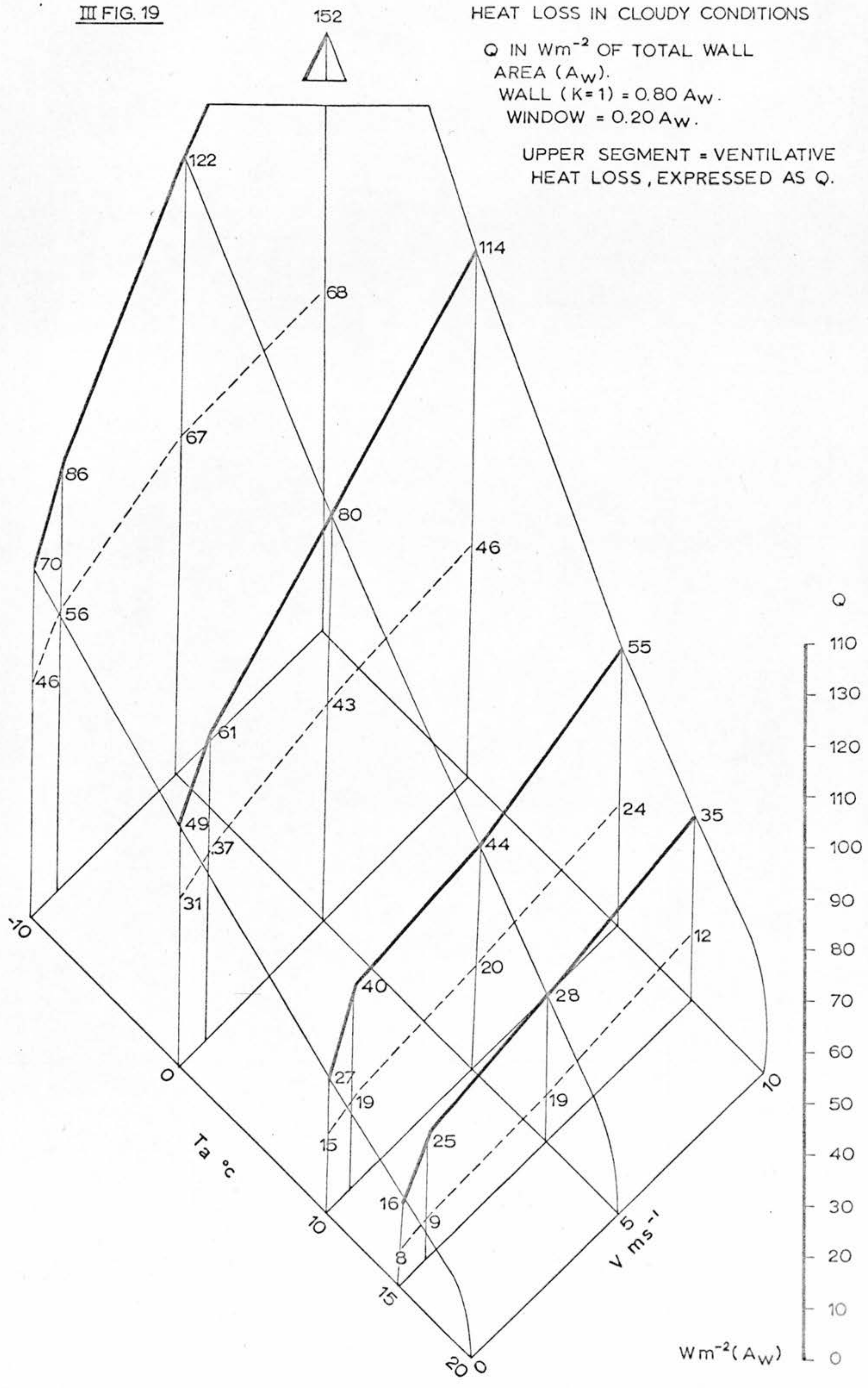
III FIG. 19

FLAT = NO ROOF

HEAT LOSS IN CLOUDY CONDITIONS

Q IN Wm^{-2} OF TOTAL WALL
AREA (A_W).
WALL (K = 1) = 0.80 A_W.
WINDOW = 0.20 A_W.

UPPER SEGMENT = VENTILATIVE
HEAT LOSS, EXPRESSED AS Q.



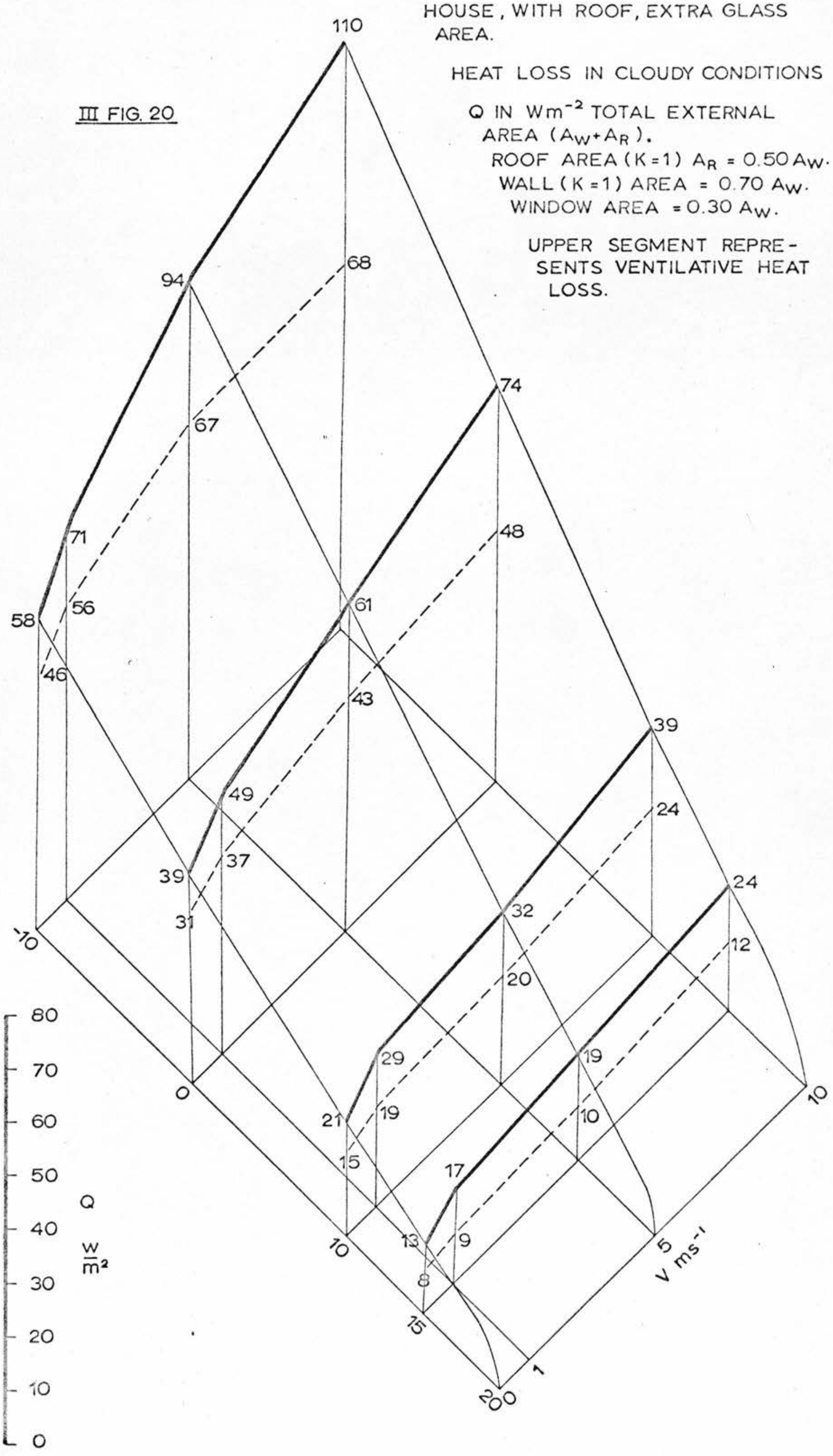
III FIG. 20

HOUSE, WITH ROOF, EXTRA GLASS AREA.

HEAT LOSS IN CLOUDY CONDITIONS

Q IN Wm^{-2} TOTAL EXTERNAL AREA ($A_W + A_R$).
ROOF AREA (K = 1) $A_R = 0.50 A_W$.
WALL (K = 1) AREA = $0.70 A_W$.
WINDOW AREA = $0.30 A_W$.

UPPER SEGMENT REPRESENTS VENTILATIVE HEAT LOSS.



III FIG. 21

HOUSE, WITH ROOF

HEAT LOSS IN CLEAR NIGHT CONDITIONS, $Qr_o = -114\ Wm^{-2}$.

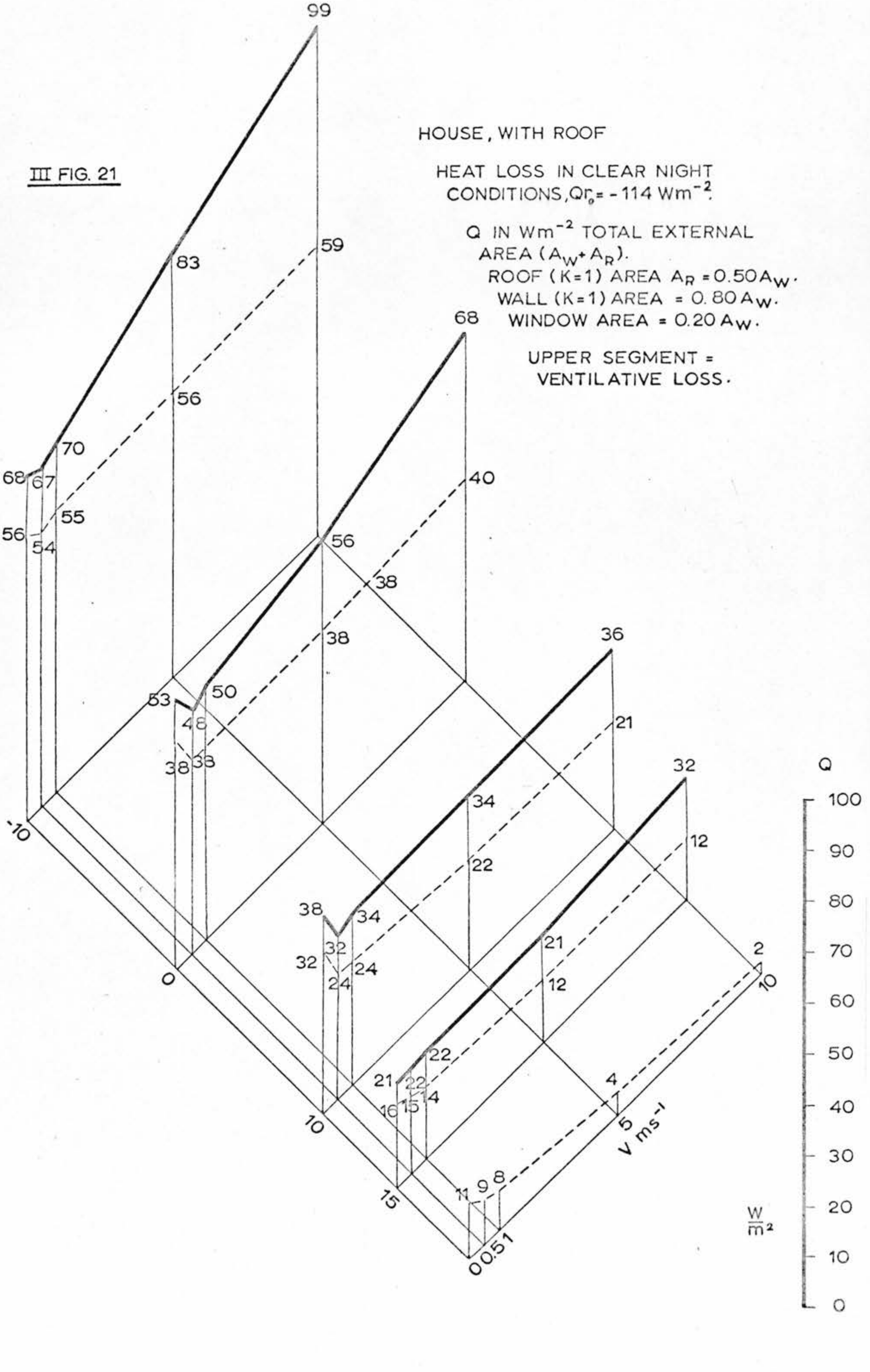
Q IN Wm^{-2} TOTAL EXTERNAL AREA $(A_W + A_R)$.

ROOF (K=1) AREA $A_R = 0.50\,A_W$.

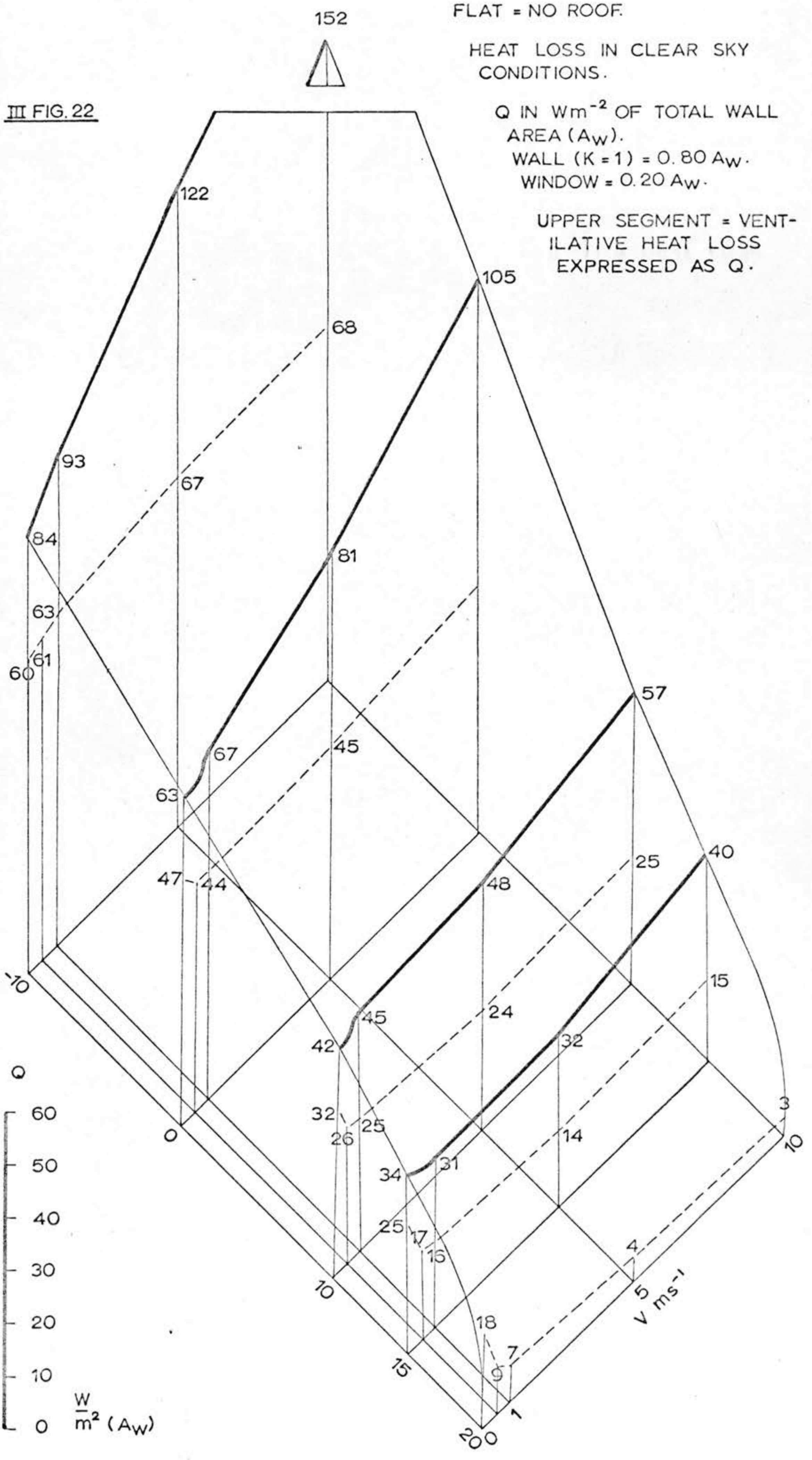
WALL (K=1) AREA $= 0.80\,A_W$.

WINDOW AREA $= 0.20\,A_W$.

UPPER SEGMENT = VENTILATIVE LOSS.



III FIG. 22



FLAT = NO ROOF.

HEAT LOSS IN CLEAR SKY CONDITIONS.

Q IN Wm^{-2} OF TOTAL WALL AREA (A_W).
WALL (K = 1) = 0.80 A_W.
WINDOW = 0.20 A_W.

UPPER SEGMENT = VENTILATIVE HEAT LOSS EXPRESSED AS Q.

III FIG. 23

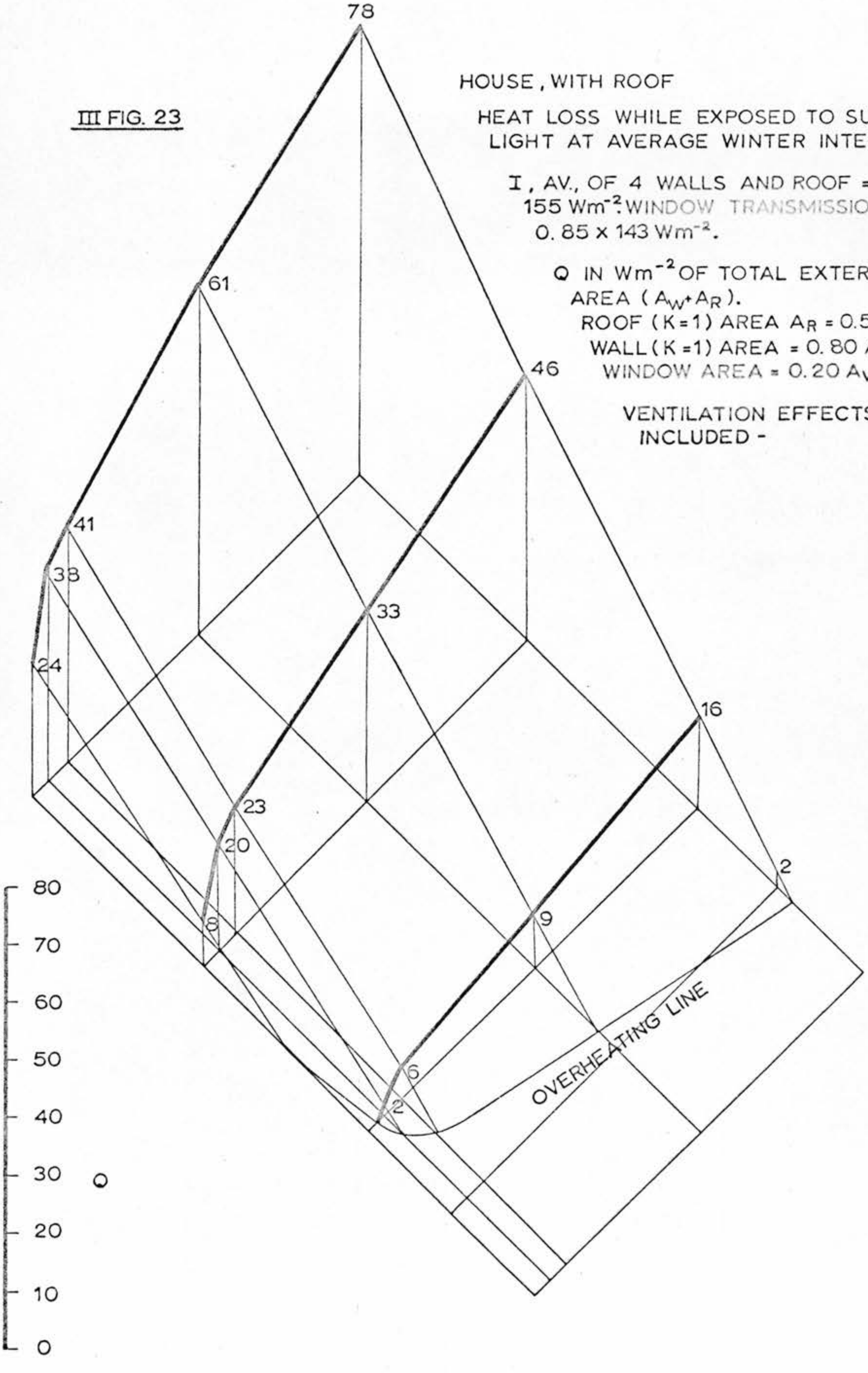
HOUSE, WITH ROOF

HEAT LOSS WHILE EXPOSED TO SUN-LIGHT AT AVERAGE WINTER INTENSITY.

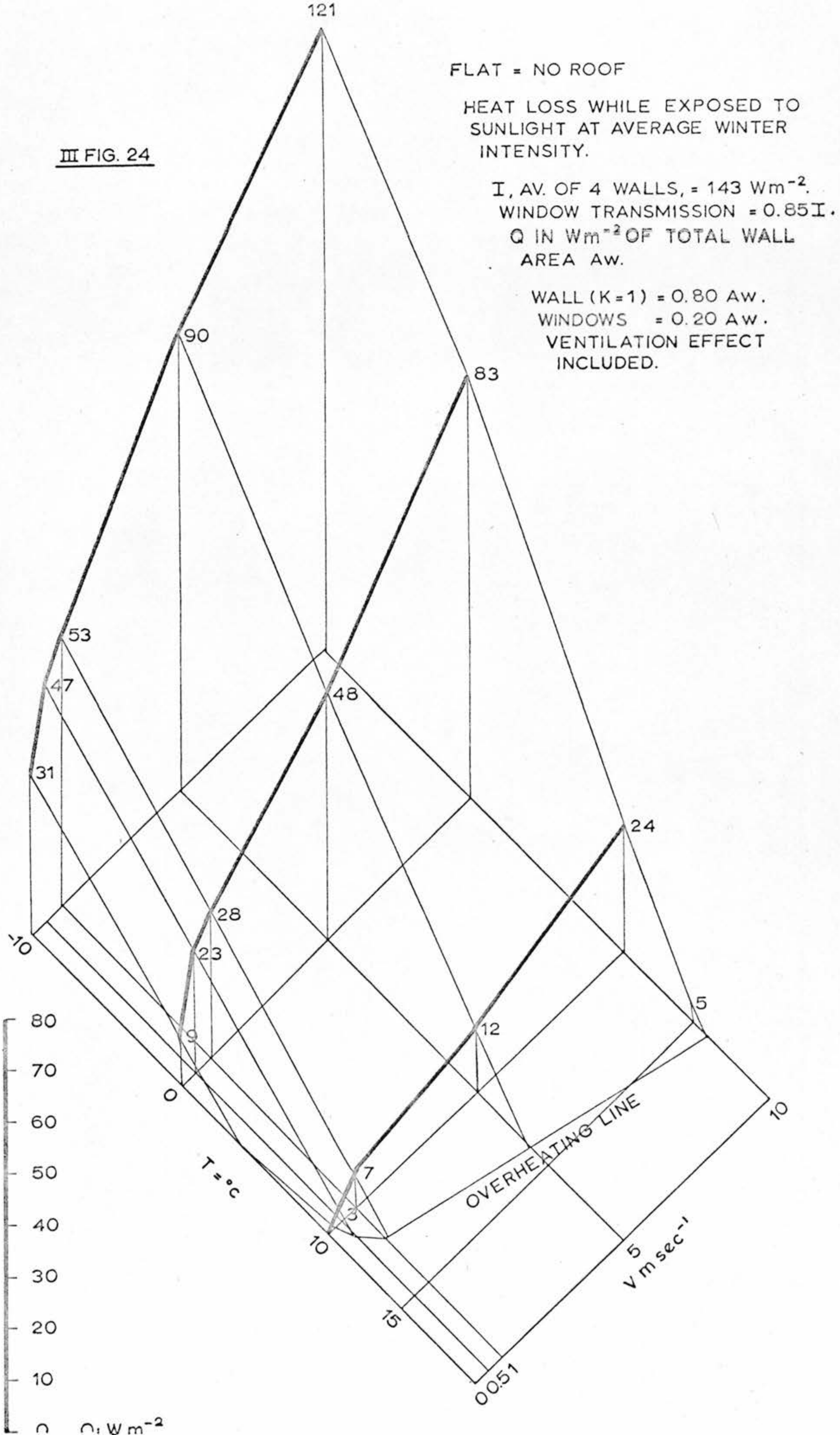
I, AV., OF 4 WALLS AND ROOF = 155 Wm^{-2}. WINDOW TRANSMISSION = 0.85 x 143 Wm^{-2}.

Q IN Wm^{-2} OF TOTAL EXTERNAL AREA ($A_W + A_R$).
ROOF (K=1) AREA A_R = 0.50 A_W.
WALL (K=1) AREA = 0.80 A_W.
WINDOW AREA = 0.20 A_W.

VENTILATION EFFECTS INCLUDED -



III FIG. 24



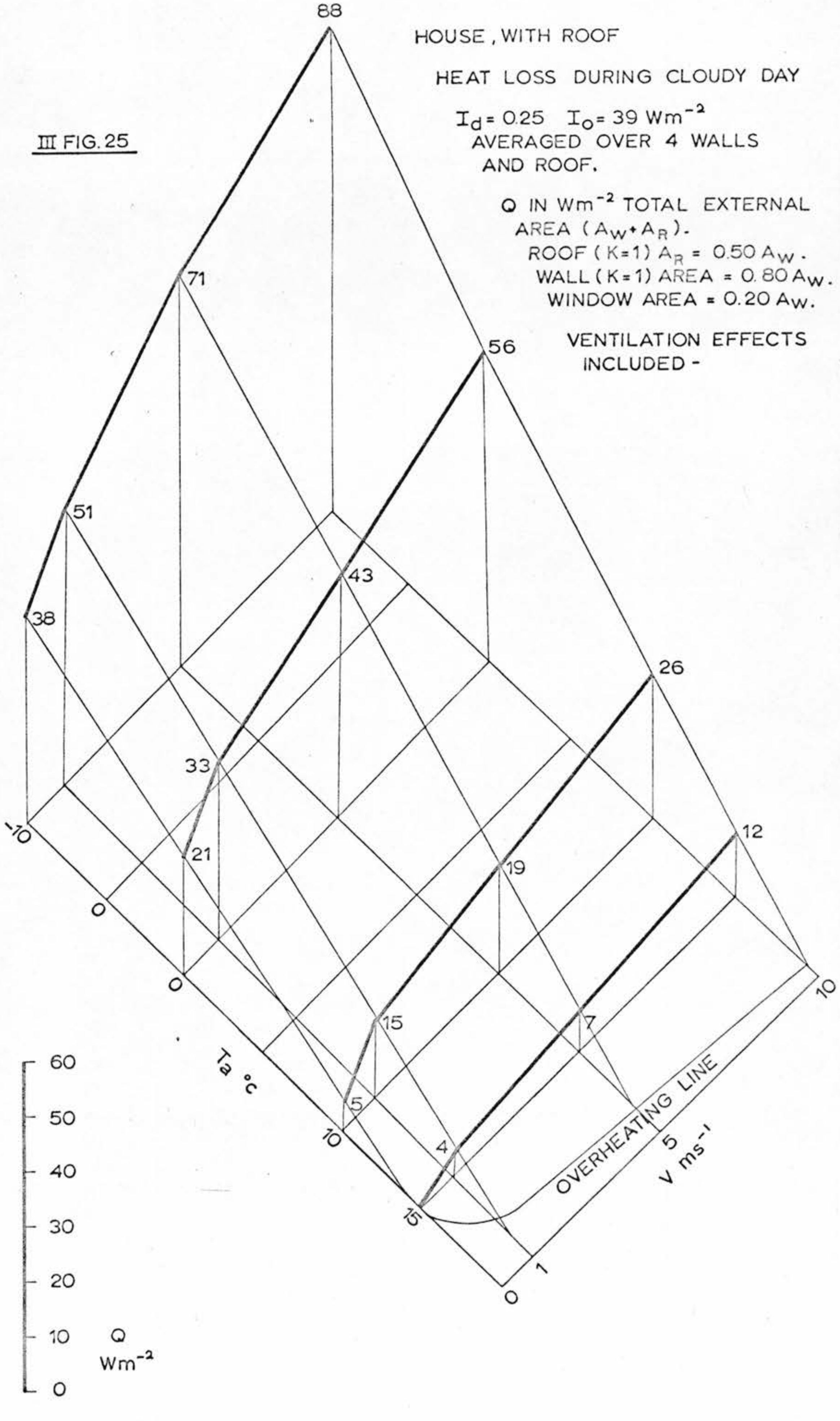
FLAT = NO ROOF

HEAT LOSS WHILE EXPOSED TO SUNLIGHT AT AVERAGE WINTER INTENSITY.

I, AV. OF 4 WALLS, = 143 Wm^{-2}.
WINDOW TRANSMISSION = 0.85I.
Q IN Wm^{-2} OF TOTAL WALL AREA Aw.

WALL (K = 1) = 0.80 Aw.
WINDOWS = 0.20 Aw.
VENTILATION EFFECT INCLUDED.

III FIG. 25



HOUSE, WITH ROOF

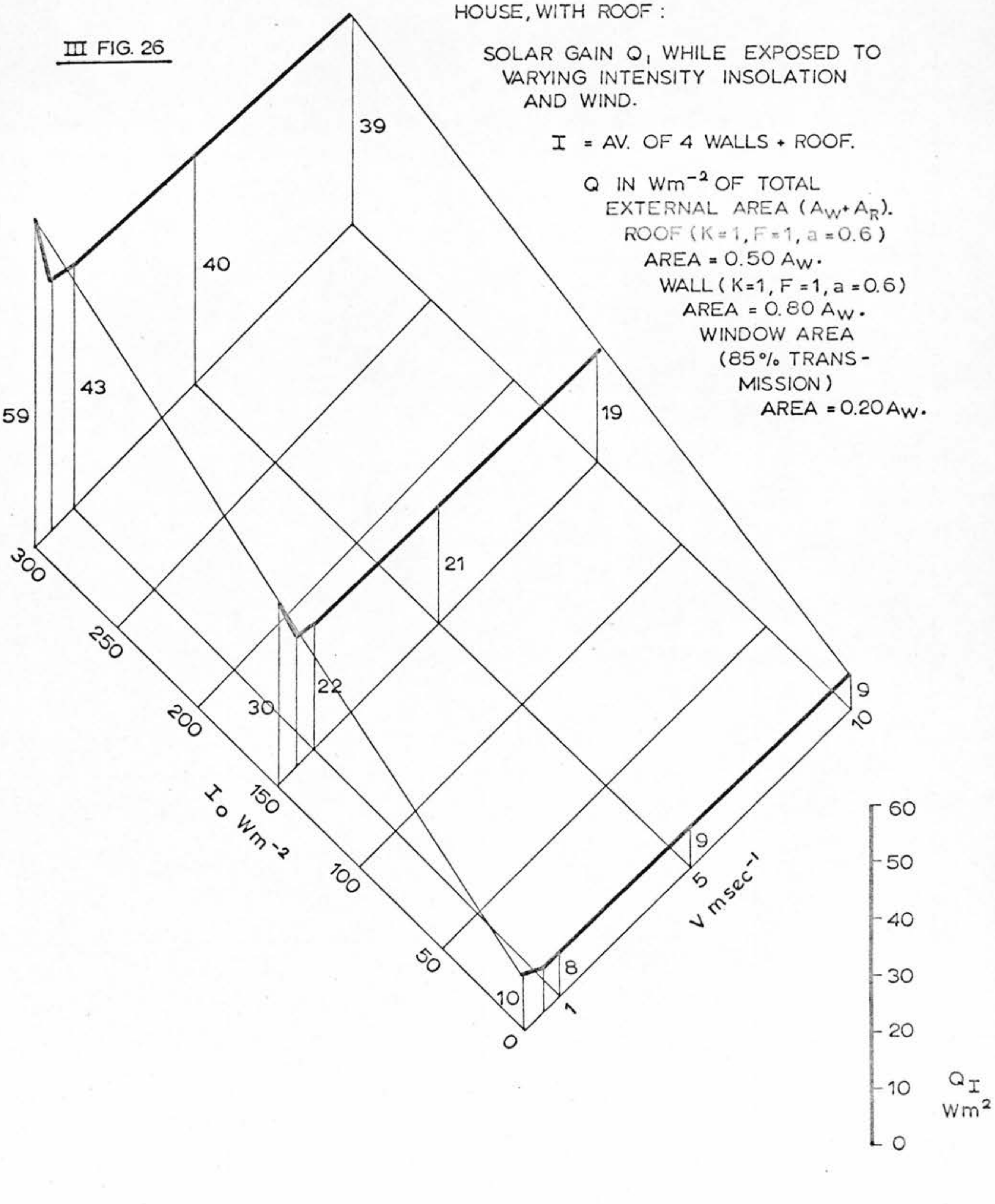
HEAT LOSS DURING CLOUDY DAY

$I_d = 0.25$ $I_o = 39$ Wm^{-2}
AVERAGED OVER 4 WALLS
AND ROOF.

Q IN Wm^{-2} TOTAL EXTERNAL
AREA ($A_W + A_R$).
ROOF (K=1) $A_R = 0.50\,A_W$.
WALL (K=1) AREA = $0.80\,A_W$.
WINDOW AREA = $0.20\,A_W$.

VENTILATION EFFECTS
INCLUDED -

III FIG. 26



HOUSE, WITH ROOF :

SOLAR GAIN Q_I WHILE EXPOSED TO VARYING INTENSITY INSOLATION AND WIND.

I = AV. OF 4 WALLS + ROOF.

Q IN Wm^{-2} OF TOTAL EXTERNAL AREA ($A_W + A_R$).
ROOF (K = 1, F = 1, a = 0.6)
AREA = 0.50 A_W.
WALL (K=1, F = 1, a = 0.6)
AREA = 0.80 A_W.
WINDOW AREA (85% TRANSMISSION)
AREA = 0.20 A_W.

This is because the heat gain by insolation during clear weather is counteracted by the additional radiative loss at night, so that the daily heat loss rate is similar to that of cloudy weather. The loss for cloudy weather is slightly greater in wind, but less in still air conditions.

6.4.2. Heat transfer under a combined climate.

Combining the average daily cloudy weather figure (f_{1+2}) and the average daily clear weather figure (f_{3+4}) is done by the following relationships:

If the meteorological data available is c, the average fractional cloudiness, then Q on the combined figure will be obtained by adding:

$$c\,(f_{1+2}) + (1-c)\,(f_{3+4}) = Q$$

Conversely, if the meteorological data used is S, the proportion of recorded to possible sunlight hours, the figures are added:

$$S\,(f_{3+4}) + (1-S)\,(f_{1+2}) = Q$$

This second relationship can also use in place of S the ratio $(I_c)\cdot(I_o)^{-1}$, where I could be either in W m^{-2} or W hr m^{-2}. The recorded insolation values are compared to the possible insolation as computed by the calculators of Petherbridge or Frank and Lee.

Figure 29: House: Daily averaged Q during Edinburgh

winter, S = 0.28.

Figure 30: House: Daily averaged Q isobars against V
and T, Edinburgh.

These figures are prepared using the Edinburgh winter (October through April) value S = 0.28. (Plant, 1968). Figure 29 is the final step in the series aimed at determining the effect of climate on the average heat loss rate of buildings in winter. A transposition of the base grid of Figure 29 gives Figure 30, on which the contours of equal heat loss rate are plotted versus the climatic parameters temperature and wind.

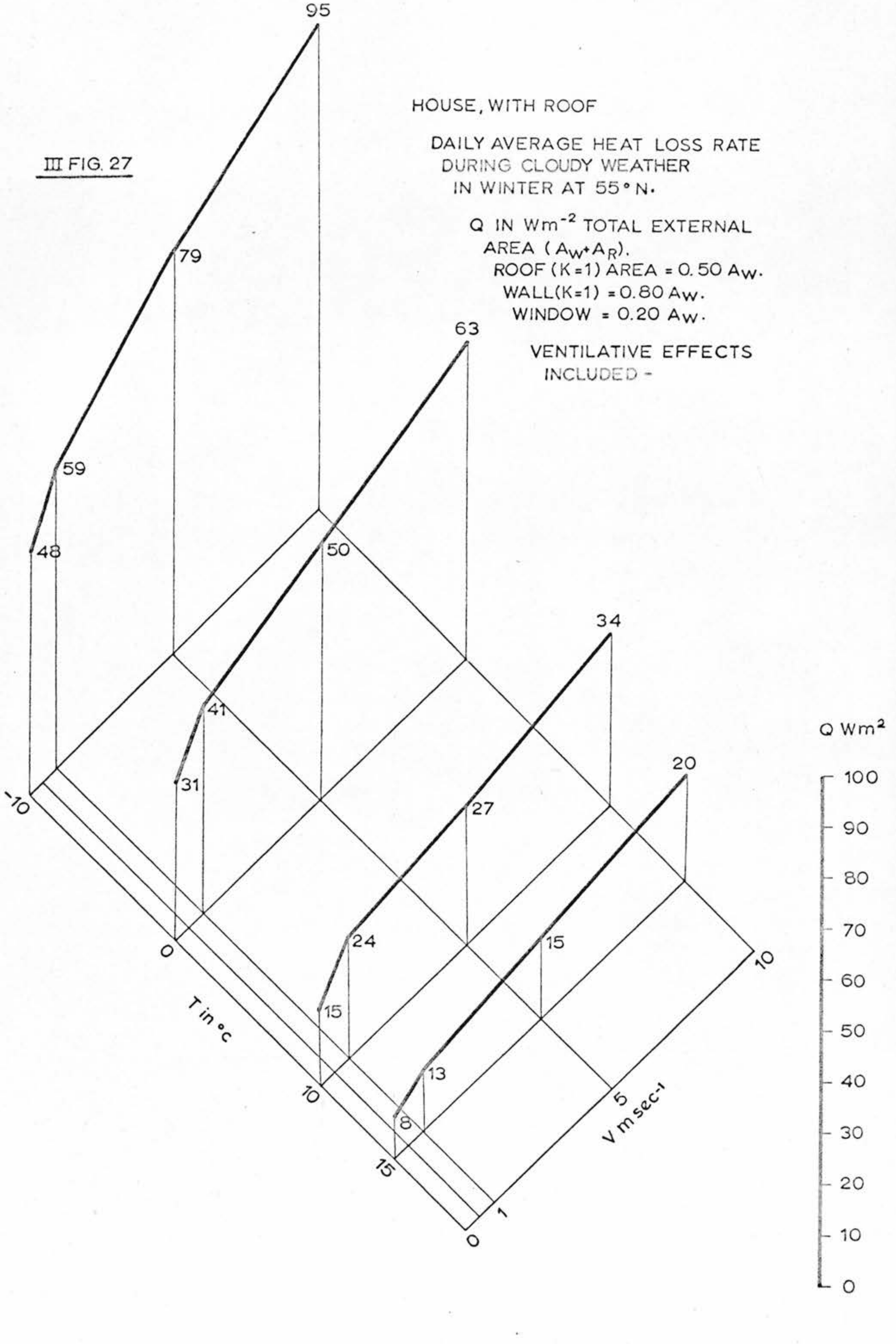
III FIG. 27

HOUSE, WITH ROOF

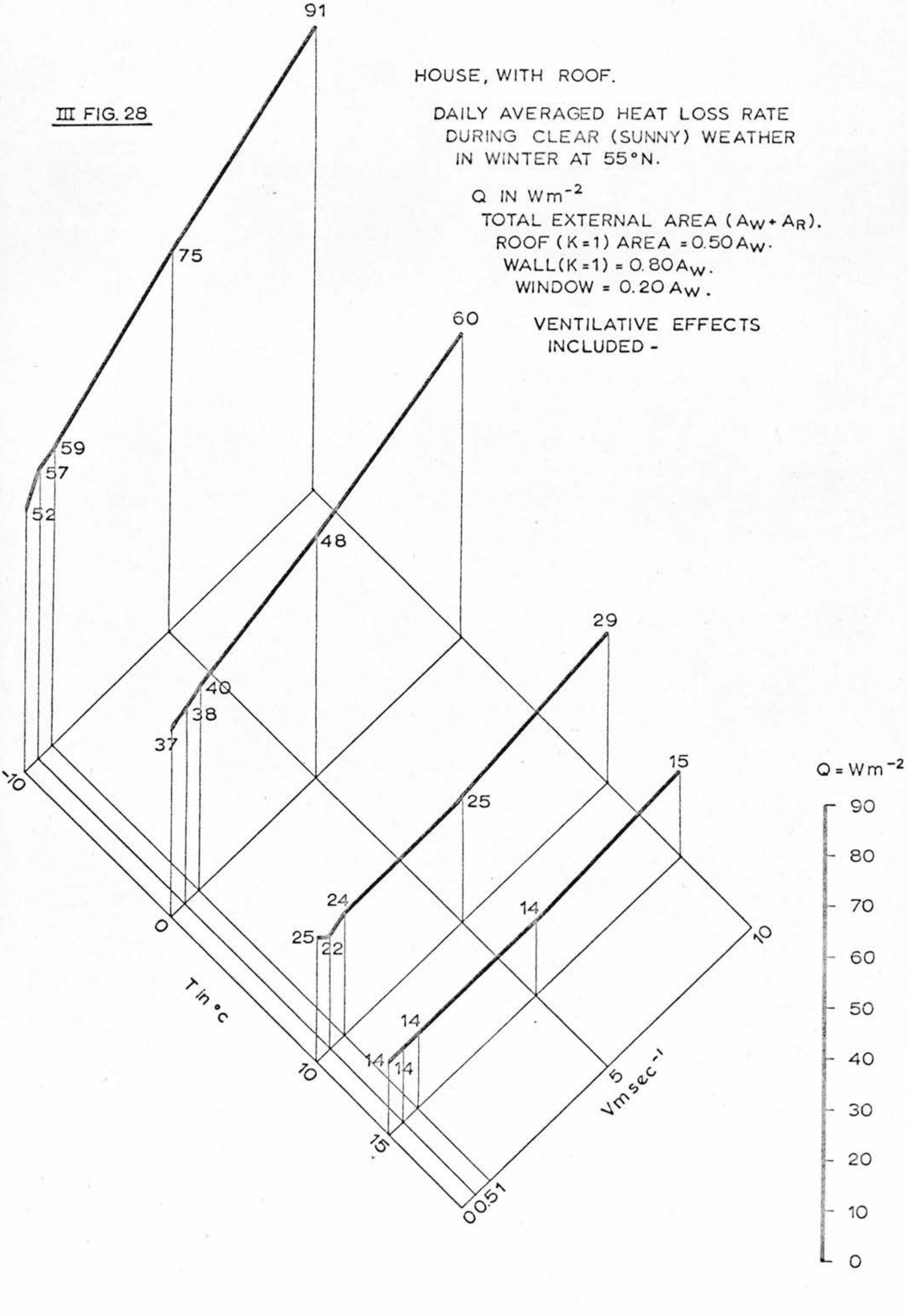
DAILY AVERAGE HEAT LOSS RATE
DURING CLOUDY WEATHER
IN WINTER AT 55° N.

Q IN Wm^{-2} TOTAL EXTERNAL
AREA ($A_W + A_R$).
ROOF (K=1) AREA = 0.50 A_W.
WALL(K=1) = 0.80 A_W.
WINDOW = 0.20 A_W.

VENTILATIVE EFFECTS
INCLUDED -



III FIG. 28



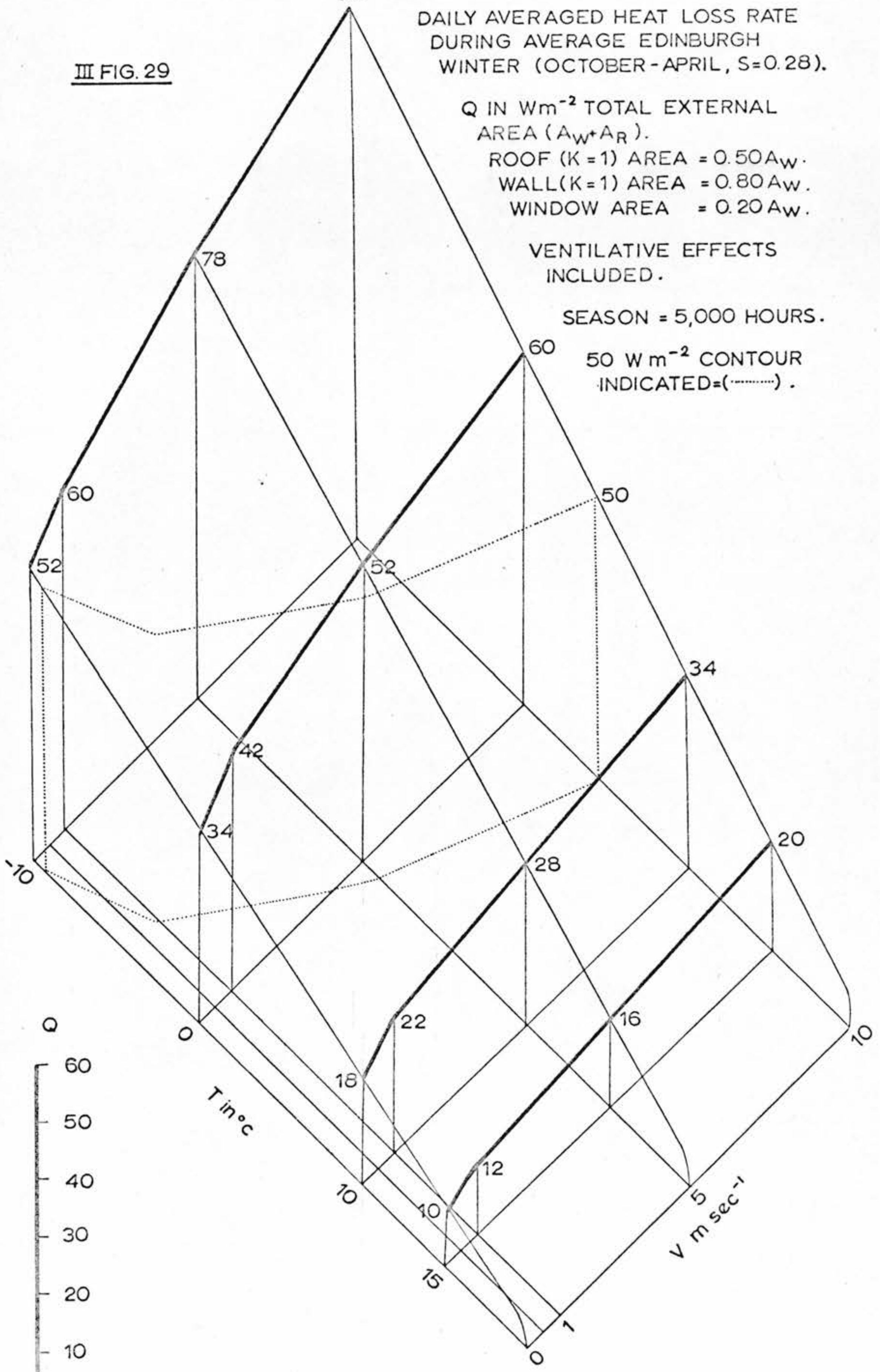
HOUSE, WITH ROOF.

DAILY AVERAGED HEAT LOSS RATE
DURING CLEAR (SUNNY) WEATHER
IN WINTER AT 55°N.

Q IN Wm^{-2}
TOTAL EXTERNAL AREA $(A_W + A_R)$.
ROOF (K=1) AREA = 0.50 A_W.
WALL (K=1) = 0.80 A_W.
WINDOW = 0.20 A_W.

VENTILATIVE EFFECTS
INCLUDED -

III FIG. 29



HOUSE, WITH ROOF

DAILY AVERAGED HEAT LOSS RATE DURING AVERAGE EDINBURGH WINTER (OCTOBER-APRIL, S=0.28).

Q IN Wm^{-2} TOTAL EXTERNAL AREA (A_W+A_R).

ROOF (K=1) AREA = 0.50 A_W.

WALL (K=1) AREA = 0.80 A_W.

WINDOW AREA = 0.20 A_W.

VENTILATIVE EFFECTS INCLUDED.

SEASON = 5,000 HOURS.

50 W m^{-2} CONTOUR INDICATED=(··········).

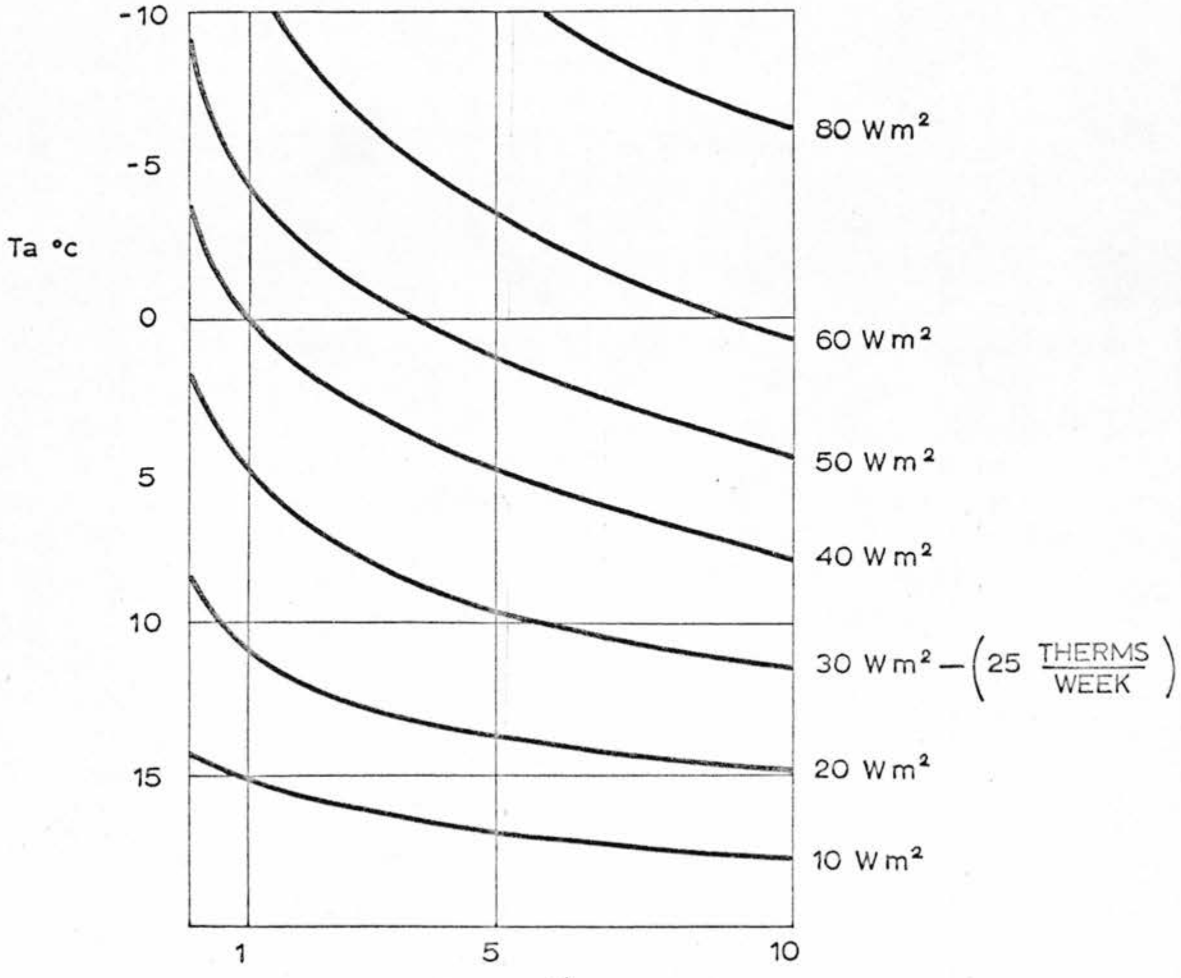
III FIG. 30

HOUSE, AS IN FIGURE 29.

DAILY AVERAGED Q ISOBARS AGAINST V AND Ta, FOR AVERAGE EDINBURGH WINTER (OCTOBER - APRIL, 5,000 HOURS, S = 0.28).

FOR HOUSE OF 150 $m^2 (A_W + A_r)$ = 1 $Wm^{-2} \times 150 m^2 = 150 W \times 24 hr.$ = 3.6 kw H DAY^{-1} = 25 kw H WEEK = 756 kw H $SEASON^{-1}$.

176 W = 1 THERM $WEEK^{-1}$.



7. Conclusions.

7.1. Results of heat transfer calculations.

Heat loss rates as described in the Figures are related to total energy consumption as follows:

Q rate of 1 W m^{-2} for the 150 m^2 house surface = 150W, x 24 hours = 3.6 KW h day^{-1} = 25 KW h $week^{-1}$ = 756 KW·h·(season of 30 weeks or 7 months)$^{-1}$.

The 10 KW h day^{-1} constant incidental gain given by Hardy (in Ferguson, — —) and Danter and Dick (1956) becomes 2.5 Wm^{-2} for the 150 m^2 house. This value should be subtracted from the values given in Figures 29 and 30 when determining fuel requirements.

A check on the values given in Figures 29 and 30 is possible by comparing them with Danter and Dick's estimated seasonal heat loss for a semi-detached house of 92 m^2 floor area. The semi-detached house in Figure 30 is 100 m^2 area; the values in the table (13) need to be increased by a factor of 1.1.

TABLE 12

Total K values: Per unit floor area of different plan types

($Wm^{-2}\ {}^{o}C^{-1}$)

	Insulation Standard		
	Low	Medium	High
Semi-detached	5.3	3.9	2.4
Terraced	4.7	3.4	2.0
Flatted (ground)	4.3	3.0	2.3
Flatted (intermediate)	2.4	1.8	1.1
Flatted (top floor)	4.8	3.7	1.7

K values of the building elements of above flats

Walls	9" solid brick (2.4)	11" cavity brick (1.7)	11" brick + insulation (0.85)
Floor	Suspended timber (2.0)	Solid concrete (1.1)	Solid concrete (1.1)
Roof	Tiles on battens (2.4)	Tiles on felted battens (2.0)	Insulated ceiling (0.57)
Windows	Single, curtains (3.4)	Single, curtains (3.4)	Single, curtains (3.4)

The insulation assumed in our examples of semi-detached houses and flats works out between medium and high (1.5) for the flat, and high (2.1) for the semi-detached house. This method, although compact, does not permit modification to suit changes in climate, surroundings, or the building surface.

Table 13

Seasonal heat loss for dwellings of 92 m^2 (1000 ft^2) floor area. (KW h $^{\circ}C^{-1}$)

Insolation:	Low			Medium			High		
N (h^{-1})	1	2	3	1	2	3	1	2	3
Semi-detached	3200	3800	4100	2500	2900	3400	1700	2200	2600
Terraced	2900	3300	3800	2200	2700	3100	1500	2000	2400
Flatted (ground)	2700	3200	3800	2000	2400	2900	1600	2100	2500
Flatted (intermed)	1700	2200	2600	1400	1900	2300	1100	1500	2000
Flatted (top)	2900	3400	3900	2400	2900	3300	1300	1800	2300

33 week (5544 hour) heating season. Conversion used: 1 Therm/$^{\circ}$F = 53 KW h $^{\circ}C^{-1}$. Climatic data used from Kew.

When the mean external temperature during the heating season is 5°C and the mean wind speed is 3 m s^{-1}, Figure 30 gives a seasonal loss of 1900 KW h $^{\circ}$C for the 100 m^2 semi-detached house. This corresponds to 1850 for the highly insulated house in Table 13 with an air change rate N = 1. This suggests that the model presented in Figure 30 represents a more highly insulated house than the average.

An experimental regression of the effect of London climate on the daily heat loss of two temporary (assumed closed) bungalows was done by Lacy (1951). The climatic variables assessed were temperature, wind, and sunshine. The formula derived (transposed to metric units) is:

$Q = -580 + 226 \Delta T + 17 V \Delta T - 42 S$

where Q = watts

ΔT = temperature difference internal-external ($^{\circ}C$)

V = mean wind speed $m\ sec^{-1}$

S = duration of bright sunshine in hours per day.

For percentage of possible sunshine hours, this becomes:

$Q = -580 + 226 \Delta T + 17 V \Delta T - 340 S$

where S is percentage of possible sunshine hours/100 (average possible sun hours assumed = 8 hours) Figure 31 is a plot of this formula relating Q to change in T and to V.

The graph shows a very close similarity to the results on Figure 29, if one assumes the bungalow external surface area to be 150 m^2.

The values in Figure 31 are uniformly lower than those on Figure 29 by the amount that would be expected from ventilation due to occupancy. The proximity of fit of these independently derived relationships offers some validation to Figure 29.

The purpose of Lacy's paper was to assess the variations of heating requirements as caused by variations of the winter means of temperature, wind, and sunshine. Using 30 years data from Kew, he concluded that for 2/3 of years, heating requirements will vary within 8% of the mean. During extreme years total Q may vary 15% from mean.

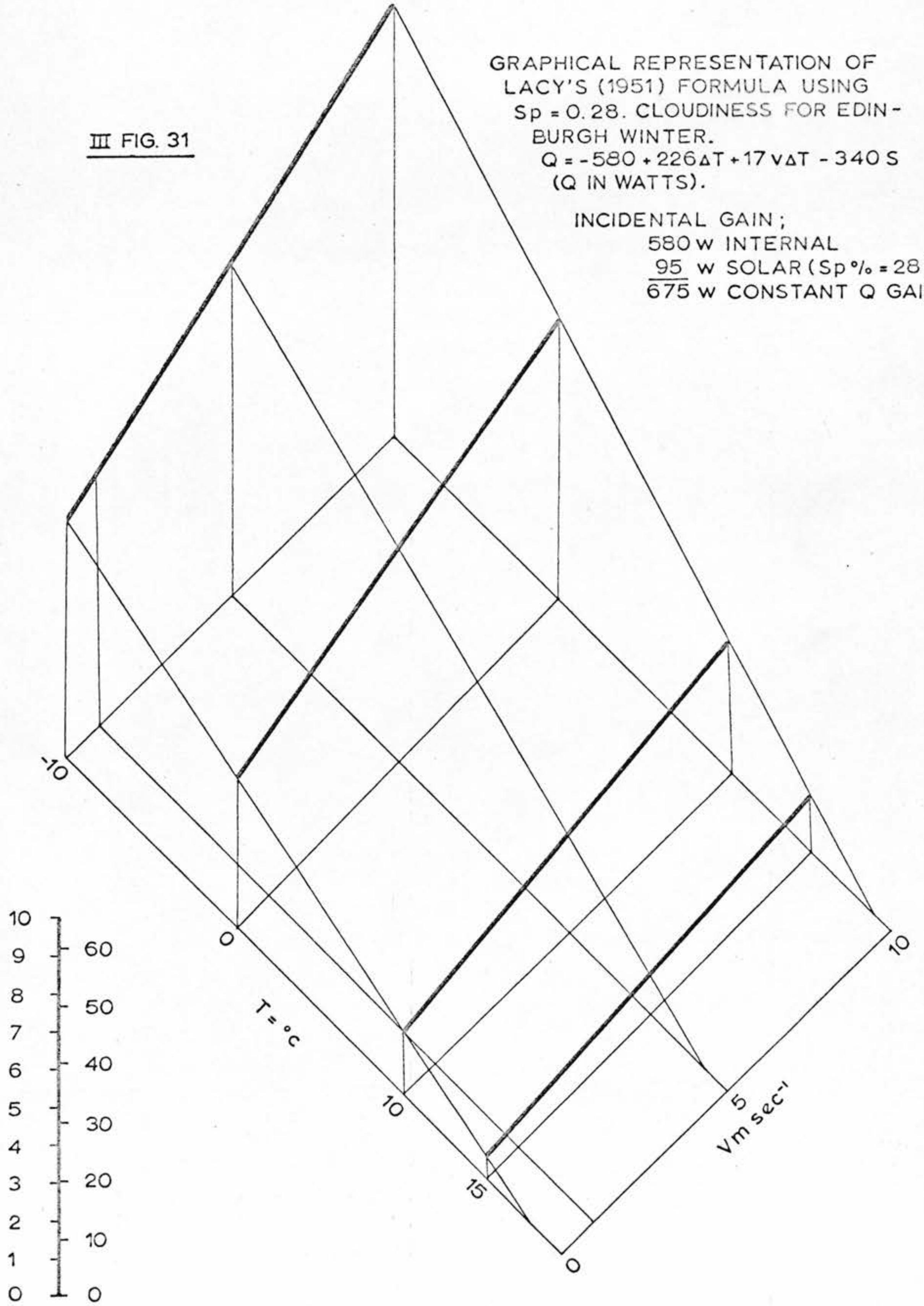
III FIG. 31

GRAPHICAL REPRESENTATION OF LACY'S (1951) FORMULA USING Sp = 0.28. CLOUDINESS FOR EDINBURGH WINTER.

$Q = -580 + 226\Delta T + 17 v\Delta T - 340 S$

(Q IN WATTS).

INCIDENTAL GAIN;
580 w INTERNAL
95 w SOLAR (Sp% = 28)
675 w CONSTANT Q GAIN.



Appendix 4 presents the results of other studies of building heat loss and climate. They are not directly comparable to the results of this method.

It is also possible to isolate and compare solar gain to other forms of gain. Using the Kew radiation figure (155 W m^{-2}) and Figure 26, the solar gain in a semi-detached house at any wind speed above 0 and temperature below the overheating line will average 22 W m^{-2}. The average daily insolation time in winter for Edinburgh is 2.75 hours. Thus the average daily insolation gain will be 60.5 W hr m^{-2}. For the 150 m^2 surface of the semi-detached house, this equals 9.1 KW hr daily. Over the seven month (5000 hour) winter season assumed here, the radiation gain equals 1900 KW hr. This value compares to an estimate by Danter and Dick of 2400 KW hr over a heating period 21 days longer and with a house with an extra two square metres of fenestration. The solar gain compares to the seasonal values:

1,640 KW hr	gas cooker gain
730 KW hr	human heat production
290 KW hr	lights
2,650 KW hr	total incidental gains.

The sum of these incidental gains represents a daily gain of 10 KW h or a rate per surface area of 2.8 Wm^{-2}. This is 10% higher than the daily rate of solar gain.

7.2. Effect of site climates on heat loss.

From Figure 29, it can be seen that the seasonal heat loss rate for a winter mean temperature of $3^{o}C$ and 4 m sec^{-1} is 40 Wm^{-2}. This equals 30,000 KW hr per season, of which over 27,000 are to be supplied by fuel. If the temperature were $1^{o}C$ lower, the wind velocity 1 m sec faster, and no solar radiation whatever, the fuel requirement would be for 34,000 KW hr. The difference of 7,000 KW hr (240 therms) between these two climates represents a 25% increase.

Such an extreme climate might exist, at least for part of the winter, at Swanston village on the north slope of the Pentland Hills. The solar insolation is cut off there, and the temperature conditions should approximate the low values at Bush Station outside Edinburgh. The wind exposure in exposed places near Swanston is severe.

A study of sites in Bath, Reading and Nottingham for variations in possible fuel requirements was made by Parry (1957). Differences in temperature (degree days) were measured in all sites, and wind at Reading. Using a formula based on Dick's work, Parry calculated a variation of 32% in the heat requirements of a semi-detached house on the different sites. No particularly extreme sites were chosen, but there were differences in elevation and openness of the sites.

In the Edinburgh area, it is likely that variations in wind speed have the most important influence on heat loss. How much this variation exceeds that caused by temperature difference is only conjecture. If the mean wind speed range in Edinburgh were from 1 to 6 m sec^{-1}, the ΔQ would be 10 Wm^{-2}, compared to an average ΔQ of 3.6 Wm^{-2} due to the 1.5^{o} difference in mean temperatures recorded. It is possible that such a range in mean winter wind speed could exist between the urban center and a ridge on a hill, but for the majority of sites it should be less.

The daily heat loss would increase by 2.5 Wm^{-2} if all sunlight were eliminated by obstructions. This value is obviously an extreme one, but since ½ - ⅔ of the insolation gain occurs through windows, the exposure of these vertical surfaces is quite important. Building codes prevent complete solar block-off from at least part of each modern house. The influence of urban pollution versus suburban (upwind) clear atmosphere causes a maximum of 0.5 Wm^{-2} ΔQ.

The high humidity inherent at low temperatures in Britain reduces the effect of still air radiant cooling below that shown in the Figures and reduces the probability of frost hollow effects on temperature. Humidity will not vary much between sites.

7.3. Conclusions about method.

The method of calculating building heat loss which has been presented above is most significantly a framework for handling and simplifying a great deal of climatic information, and for making the many assumptions necessary when dealing with averaged, incomplete, data. Since the calculating procedure is a sequence, the decisions which have to be made come up in a logical order. These decisions are about two things: the building surface, and the climatic data.

1. The surfaces of the buildings are treated as composites of uniform basic surface types. The climatic influence on the heat loss of these uniform surfaces is calculated first, and then the losses of the surfaces are added together in their respective proportions to represent the loss of the combined building surface. Thus the influence of climate needs only to be determined in relation to each of the basic surface types into which the building surface is divided. With sufficient simplification (in this case, two surface types) this is not too complicated. Once done, the heat loss of many different forms of buildings having these surface types can be calculated simply by altering the proportions of the basic surfaces.

In addition, the ventilative heat loss is expressed in terms of surface loss, in order that it may be combined most flexibly with the surface losses.

2. In calculating a relationship between any building and climate, much climatic data needs only be considered at the outset of the calculation procedure. The procedure is arranged so that climatic elements which do not vary between sites, and climatic elements for which there is little local data available, are assessed from general data for their influence on the uniform surfaces. Thus it is chosen to divide climate into basic types representing different radiation regimes, so that the only information needed on site for radiation is the amount of time each regime is present. These regimes ('climatic situations') are:

1.) cloudy night
2.) cloudy day
3.) clear night
4.) clear (sunny) day.

The influence of these four uniform types of climate is determined for each of the building surface types. During this procedure, decisions can be made as to which climatic variables can be eliminated as having insignificant influence. Once there is a figure or formula for each climatic type on each surface type, the building-climate relationship for each type of climate can be constructed. The only climatic information then needed on site to determine the heat loss of the building is temperature, wind and the expected proportion of cloud. The latter is the one form of data on radiation which is generally available for specific locations.

The influence of a number of climatic elements on radiation has been described in Appendices 1, 2, and 3. The conclusion is that water vapour, cloud, and turbidity have significant influences on building heat loss.

CHAPTER IV

IV. Evaluation and prediction of the climates of sites and plans.

1. Procedure and requirements.

1.1. Introduction.

1.1.1. Climate evaluation as part of the planning and design process.

The evaluation of the cost of the climate on a site gives the planner information about the cost of the site itself. This relationship holds regardless of the nature of the costs considered. The 'cost of the climate' could be the cost of climatic influence on any number of activities, processes, or materials planned to occur on the site. The cost of the site could be the operating cost incorporating the above climatic cost, or the cost of building to accommodate or alter the climate's influence. In either case, an evaluation of the cost of the climate enables a planner or designer to relate the influence of climate to the other factors determining the cost of acquiring sites and building on them.

Climatic evaluation can be used in several ways. The planner can compare the climatic cost figure directly to the other costs of the project. For this the absolute value of the climatic cost should be preferably in equally empirical detail as the other costs, and all forms of climatic cost should be included to give proper weight to the climatic part of costs. This summation of climatic costs from an arbitrary base of 'no climate cost' is complex, since there is no experience of a 'no climate' condition.

The planner can also compare the climatic cost of the site or proposed plan to that of another site or plan. By comparing two sites or plans, using the same climatic standards, the judgment of relative expense is sometimes simplified. The difference in cost between one level of climate and another is likely to be more easily costed, since the arbitrary assumptions about a 'no climate' base level are avoided, and all the climatic influences are in the range of experience. Moreover, the task of evaluation is reduced in cases where similar climates make relative costing unnecessary.

A further aspect of comparing the climates of sites is its potential use as an indicator of quality and as a suggester of design solutions. The planner can compare the climate of his site or plan with that of a successful model where climatic influences are favorable. The comparison can move the planner to decide on plans whose climatic influences are not yet priced or priceable. The evaluation in such a case would be based on an intuitive judgment of quality or suitability. A similar concept is presented by Page (1971 b), called a "target microclimate", which the planner aims toward equalling.

The evaluation of site climate, in pointing up the specific climatic elements which are the causes of the climatic influence, suggests the design solutions needed to respond to those elements. The cost and convenience of such design solutions are then added to the site evaluation.

In conclusion, the objective of climatic evaluation in practice will primarily be to compare sites, plans, and designs for their cost, quality, and feasibility, and to suggest design solutions. The purpose is not to compare the climates themselves, nor to describe the climate. Climatic evaluation is essentially a measuring and form suggesting tool for planners in their site selection, planning, and design process. The climatic elements which make up climate are merely the dimensions of this design tool.

1.1.2. Required order of consideration.

The traditional handling and presentation of climatological data by meteorologists and climatologists has resulted in a tendency to think of a climatic evaluation as a collection of climatic parameters, independent in itself. Such a collection is accumulated in the most compact and logical way, from the climatologist's viewpoint. It is perhaps analysed in a way to prove useful to aviation, navigation, or agriculture. It is not directly useable for evaluation of any climate-influenced phenomenon in urban planning or architecture. Since the climatologists are not involved in the design process and are not costing the effect of climate, their climatic analyses effectively end with the compilation of records of the climatic variables which they suspect will be most useful. This type of 'analysis' or 'evaluation' can be seen in countless planning studies, where the inevitable section on climate contains an assorted collection of climatic variables, with no reference to the way they are to be applied, or to what they are to be applied. An exception is Olgyay (1963) who bases his regional climatic analyses entirely on one costable effect of climate, comfort, as it is related to climate in his Bioclimatic Chart.

The evaluation of climate requires a standard or scale to be measured by. This scale is provided by any one of the climate-influenced phenomena being designed for, which are 'objectives of the design', or 'design problems'. The climate influenced design problem is linked to the climate by 'relationships', 'interactions', or 'functions' like those derived in Chapters II and III. Such relationships should enable the planner's criteria about the design problem to become criteria for the characteristics of the climate itself. Boer (1970) is one of the few to recognize the necessity of relating climate to climate-influenced design problems, which he calls 'activities'. The significant part of his paper is quoted below. He outlines the interactions of architects and meteorologists in terms of an information system. "....the efficiency of the information system is essentially controlled by the state of knowledge of the interaction between the meteorological parameters and processes and the building activities, for single structures and built-up areas. This knowledge is represented in the information system in the nature of a control input; i.e., it is chiefly controlling the extent of the potential usable information.".... "It ought to be the supreme concern of meteorologists, building engineers, and architects to coordinate their research and extend permanently the fund of reliable knowledge on the interaction between meteorological parameters and processes and those essential to buildings". It is interesting to note that in an earlier paper (1954), Boer presented the far more common view that climatological problems in city planning can be solved as long as there is close discussion between the meteorologists and planners as the problems come up. This is clearly not the case, since the climate's influence on the phenomena being designed for is not quantified, and the discovery of the relationships between them requires extensive research. Page (1971 a,b) also discusses such relationships, and schematically suggests the mathematical forms that they might take. Lacy (1972) has just published the most comprehensive view yet of climate's influence on architecture and building.

Terminology. The term 'activity' is used in this thesis to signify the meaning of 'climate-influenced phenomenon', 'climate-influenced design objective', or "design problem" of Page (1971 b). This is an arbitrary choice which is not very successful in some applications, but is necessitated by the lack of any other single word. Thus, human behaviour (human comfort) is an 'activity', as are outdoor work efficiency, aviation safety, and air pollution emission. The word applies less satisfactorily to heat loss from buildings, agricultural production, building material deterioration, and storm sewer run-off, which are also 'activities'. These latter are 'active' only in the sense that they react to climate.

In conclusion, the order of consideration needed for climatic evaluation is summarized below. The climate-affected activity has to be decided on first in any climatic evaluation. Next, the priceable or comparable aspects of the activity have to be determined. Then the relationships, inter-actions, or functions between the priceable aspects and the climatic elements can be investigated. It is only after these steps have been taken that the climate influencing the activity can be described, analysed, and evaluated, in terms of cost or other means of comparison.

The relationships between the activity and climate naturally refer to the climate that acts upon the activity, i.e., the site climate. Thus, although the relationships between climate and activity are general ones, in any given practical instance they will refer to a specific climate. It is necessary to obtain this specific climatic information to accomplish the evaluation of a site's climate. However, obtaining the site climate is a separate problem from the initial one of determining the relationships between climate, generally, and the activity. For this reason the topics "obtaining the required climatic data" and "site influences on regional climate" are postponed to Chapter IV.2. and IV.3. respectively. The overall order in which all these steps should be approached is given in flow diagrams in these sections. In this section, only the essential first step of determining the influence of climate on an activity is considered. In the scarce literature on this subject, however, the processes of determining the specific site climate are nearly always mixed with the process of determining the general relationships (Page 1971 a and b). This prevents an organized approach to the evaluation of the climate of sites.

Chart A (appended) summarizes the suggested procedure of climatic evaluation in relation to an activity. It proceeds only up to the stage of obtaining the specific climatic data, but it specifies in what form the data is needed. It is worked through for a number of selected activities. It is only schematic, and the relationships are necessarily simplified. The order of procedure that is presented in this chart is followed in the remainder of this section.

1.1.3. The activity.

The activities evaluated in Chart A have been chosen to show two types of climate-activity relationships, as will be described later. The activities are: 1 and 2.) Building heat loss, as evaluated by accumulated fuel cost and by rate of heat generating capability. 3) Pedestrian comfort, as evaluated by resulting behaviour. 4.) Vegetative production, in a very simplified model measured in terms of quantity of production. 5.) Building material deterioration, measured in terms of cost of accumulated deterioration. 6.) Air pollution, evaluated in terms of concentration levels and accumulated dosage. This is also a very simplified model.

There are many other activities that are influenced by and which could be related to climate. As mentioned in Chapter I, some of these are: outdoor work efficiency, transport efficiency, navigation and aviation security, recreation (sportsfields, ski areas), health, pollution; agricultural, horticultural, and forestry production; forest fire control, avalanche control, flood control; civil engineering, storm sewer capacity, hydrological works; structural engineering, building heating and cooling plant design. The list is limitless, but the number of activities in a given project is not likely to be great. There is considerable overlap between many activities.

1.2. Priceable aspect of climate-influenced activity. Suitability criteria.

The effect of the climate must be related to a priceable aspect of the activity being considered in order that the effect be evaluated. If the climate is to be compared to other costs of the project, the pricing must be economic. Other measures can be used by the planner as his suitability criteria. He might form a decision based on intuitive or aesthetic opinion of the climate's influence which is not tied to economic costing.

The best example of non economic pricing is in the codes for daylight in schools and sunlight in domestic houses, commodities virtually uncostable in the marketplace or any other way (Silverman, 1971). The legislation to enforce daily sunlight in houses is based on an intuitive assumption that sunlight is beneficial to the activity of life. Sunlight specifications do not make the attempt to describe the relationships between sun and the indoor life. Such relationships do, however, have to be described for most climate-influenced activities, and this requires close definition of the part of the activity that one wishes to measure. The relationships are usually sufficiently complex that a general intuitive approach to the activity will yield no results.

For example, in the activity 'pedestrian comfort', the method is not yet available that will relate the climate to relative degrees of comfort. It is not possible to eavluate one site as a certain amount 'more comfortable' than another. At best, the relationships available describe the comfort-discomfort line, and possibly suggest a few levels of discomfort. Thus the 'priceable aspect' of the activity 'comfort' is defined as the amount of time that a pedestrian is comfortable out of the total, in other words the time probability of comfort. Thus a site can be costed for its probability of comfort or discomfort, or a planner who is comparing sites can obtain a feeling for the quality of sites with different probabilities of comfort. Either way, the planner's suitability criteria will be based on a firmly defined aspect of the activity.

The priceable aspect in itself is measured by an 'activity' parameter'. This is the unit of measure by which climate is related to activity. In the case of pedestrian comfort determined by thermal balance, this is heat flux.

Via the relationships of Chapter II the climatic conditions are converted to heat flux which, when it exceeds a limit, determines comfort and the length of time of its occurrence. In the case of 'building heat loss', heat flux or total heat can be used as the activity parameter. The terms 'design variable' and 'applied variable' as used statistically are synonomous to 'activity parameter' (Thom, 1966).

In conclusion, the evaluation of climate should depend on a 'priceable aspect' of the activity, which is measured by an 'activity parameter'. The relationships between the climate and the priceable aspect might be intuitive, though efforts should be made to define them quantitatively. Similarly, the planner's suitability criteria for the priceable aspect are preferably costed in some way.

1.3. Function relating activity to climate.

1.3.1. Types of function.

The relationship between the activity and the climate is described in this thesis as a 'function', in the mathematical sense. There are two main types of function. One is 'accumulative', where the climatic influences cause production of the activity parameter, which is summed and converted to the priceable aspect of the activity. The function of 'building heat loss' as described in Chapter III is accumulative: the heat lost over time is summed and converted directly to fuel cost. The rate of loss at any given time is unimportant. The formula for this type of function is:

$$\sum_{1}^{n}\left[f\ (C_n)\cdot t_n\right] = \sum(X) \qquad 1.)$$

where f = climate : activity parameter function

C_n = climatic data, in n classes

t_n = time, for corresponding C_n

X = activity parameter

The other type of function describes a rate of production of the activity parameter, which is related to the priceable aspect of the activity by comparison against limits, thresholds, and levels of failure. This type is called a 'rate-limit-failure probability' function in this thesis. The example in Chapter II of pedestrian comfort is based on a function of this sort. The heat loss rate (the activity parameter) is significant only when compared to a metabolic rate. The balance of these two rates provides a limit for comfort, a threshold for discomfort. The priceable aspect of the activity is framed in terms of the probability, in terms of total time, of success or failure of comfort relative to this limit. Empirical observations of the behaviour of uncomfortable pedestrians lead to an assessment of the probable economic consequences of climate. The proposed scheme of 'levels of discomfort' operates in the identical way as the comfort-discomfort threshold. When the heat loss exceeds production by a given amount, a new level of discomfort or comfort failure is distinguished. The time probability of this new level is then costed in terms of its effect on behaviour. Unlike the function of building heat loss, the accumulated sum of the heat lost by the pedestrian is meaningless. The formula for this type of function is:

$$\sum_{1}^{n} \frac{t_n \left[f\ (C_n) > \left(\frac{X}{t}\right)_L \right]}{t_{(total)}} = \text{percentage of failure time, or probability of failure} \qquad 2.)$$

where f = climate : activity parameter function

C_n = climatic data, at corresponding time t_n

$\left(\frac{X}{t}\right)_L$ = rate of production of activity parameter which is defined as a limit.

The most common example of the rate-limit-failure type of function is the relation of wind to structural design. The activity parameter is force, and only the time that the force exceeds a given limit is important. This is not included in Chart A because the climatic elements involved number only one (wind), and the probability theory is quite different. The main difference between this function and the comfort function mentioned above is that it is not the amount of time expected above the limit that is important, but the number of times (occurrences) that the limit is expected to be exceeded. This is a 'high risk failure' function, and the comparable equation for this type is:

$$\sum N_n \left[f(C_n) > \frac{X}{t}_L \right] t_{\text{(total expected life)}} = \begin{array}{l}\text{probability}\\ \text{of single}\\ \text{failure}\end{array} \qquad 3.)$$

where N_n = number of occurrences, per unit time, of C_n. Chart A has an entry for the type of climate-activity function for each of the activities. It can be seen that some activities (building heat loss, deterioration of building materials) have accumulative functions; some (pedestrian comfort, building heating plant maximum capacity) have functions of the rate-limit-failure probability type. Two activities (vegetative production, air pollution concentration and dosage) show both types of function even in this very simplified format. Undoubtedly, as each activity is examined in more depth, more priceable aspects and functions will be found showing the effect of climate; and it is likely that most general activities will have functions of each sort operative.

The next entry on Chart A shows the place of the climatic elements (in this case temperature, wind, and insolation only) in the function. The formulae are essentially the same as formulae 1 and 2 above, with the climatic elements involved listed. The format in which these elements are required is developed in the sections below, as is the determination of the function f.

In conclusion, there are two basic types of climate-activity function. The accumulative type sums the activity parameter. In the case of the building heat loss functions developed in Chapter III, this is represented by the product of the rate of production of the activity parameter (Q) and time. The rate-limit-failure type sums the time that the rate of production of the activity parameter exceeds a limit, and expresses this in terms of probability of failure. In the rate-limit-failure functions where high risk is involved, the probability of failure will be measured in terms of occurrences of failure, and expressed in terms of the return period of failure.

1.3.2. Separation of the function from data.

In describing climate functions a distinction needs to be made at the outset between the climatic elements incorporated within the climate-activity function and the climatic data used to interpret the function. The need for climatic data within the function arises when averaged data is used for interpreting the function. The functions as derived in Chapters II and III are preferably expressed in the simplest climatic terms possible, where no climatic assumptions are made within the function, and the climatic data is used only to interpret the function. This form can be ideally approached in the rate-limit type of function where the relationships are expressed in instantaneous terms, and no climatic assumptions have to be made about averaging data. But when averaged data has to be used, as is usually in accumulative functions, or when dictated by lack of data available for the rate type functions, climatic information has to be included within the function itself to account for irregularities within the averaging period. The more averaging there is in the data applied to a function, the more short period general information must be built into it to approximate the original data.

An example of climatic information within a function is the consideration of radiation gain in the function for building heat loss. Since the data available to interpret this function will necessarily be averaged for a longer time span than one day, there can be no information on the unequal rate of insolation throughout the 24 hour day. Since the rate of heat gain into a building is not fully proportional to the rate of insolation (ventilation increases when the heat gain for insolation is high), the total gain to the building is not directly related to the amount of insolation. Accordingly, general information on the hourly insolation curve is built into the function itself, so that the eventual result is totals of building heat gain proportional to the daily or monthly totals of insolation. See the method developed in Chapter III.

The format of the function, incorporating climatic data, allows a logical separation between the climatic function for an activity and the climatic data used to interpret it.

The state of knowledge about human physiology and building heat loss, for example, involves forms of climatic data and relationships which are not presently contained in climatic records. The physiologist and the heating engineer should not be required to express their experimental findings on climatic effects in terms of existing record keeping procedures in the meteorological office, or in terms of how the planner wishes to interpret their results. This connection is made in the development of the appropriate functions, such as suggested in Chapters II and III. Should either of these disciplines become important to users, methods of climatic recordkeeping could be changed or added to more closely suit them and the purpose of the users. This subject is discussed at length below. A future method of obtaining immediately usable climate-activity information is described in Section IV 2.3. below.

1.3.3. Time frame of the function.

The planner must decide what the time frame of his activity and function is. The more tightly the frame is defined, the more accurate the function will be. For example, the planner has knowledge of the time dependence of the activity of human comfort. The outer time frame is the length of the cold season. Another time frame occurs within the day, since the probability of pedestrians being exposed can be estimated for any time. 95% of pedestrian activity might occur between 0830 and 2330, and 80% between 0830 and

1700. Such figures can be determined by an activity survey. They are conveniently entered on an activity chart (U.N.O. Climate and House Design 1971). By such methods it might be judged that the function need not be applied to the extreme data of night-time, since the number of pedestrians exposed then would be negligible. The same type of frame can be determined for any of the activities. Some are simple, such as for building heat loss, which applies full time during the cold season.

Another type of time frame is one related to the length of the activity itself. This becomes significant if there is a function:time relationship. In Section II.5, a non steady state comfort:time relationship is proposed, to be applied to the comfort:climate function. Use of such a function would require this type of time frame. For example, a walk takes a given length of time, determined by its distance. The planner laying out this walk would use a time:comfort relationship to determine how comfortable the people are likely to be at varying distances along the walk. A similar frame would apply to the design of stadiums, where the matches are of known durations.

There is an entry in Chart A for the time frame of the function and of the required data.

1.3.4. Time integrals of the function

The activity and function dictate what is the most desirable calculating integral for the function, and the best intervals, or periods, for the corresponding data required. Small integrals of the function are used when the activity is sensitive to very small time scale fluctuations, and is evaluated over a small time frame. An example is comfort. Large integrals are permissable (perhaps preferable from the labour point of view) when it is an average or an accumulation over a long time span (such as fuel cost). The minimum interval for a comfort function would be somewhere in the range of one minute, determined by the body's normal vascular response time. Comfort functions based on thermal balance relationships should ideally use no time integrals shorter than an hour, which is approximately equilibrium time.

With buildings, the fluctuating heat loss on an hourly basis would be of interest only to the designers of the interior environment and the heating plant capacity. The hourly values for fuel consumed are meaningless since they are not directly related to climate in the steady state condition that the function assumes. The thermal lag of buildings makes daily heat loss totals the minimum averaging integral for the function of this activity. Each day's heat loss can be compared to the next, and the relationship to daily climate drawn. The composition of the function for heat loss, as mentioned before, includes daily averaging of radiation effects. As such, the function itself dictates that the minimum integral is not less than a day. The figures for the daily averaged radiation are a seasonal average, which means that, if radiation variations have a large effect in the cold season, the function of Chapter III should be applied to season length integrals only. The radiation variation effect actually is very small.

Other integrals are presented on Chart A. It is interesting that ecologists, equipped with comprehensive data collecting equipment, are proposing to automatically monitor such a long term accumulation as vegetative production by integrals as short or shorter than one hour. Whether this approach will yield significant results is not determined as yet, but is being justified on the following grounds:
1. Plant growth response to light is very rapid and the pattern of exposure within short intervals of time might make a large difference in growth rate. 2. Sites are being measured to very fine margins of productivity. This information is from J. Grace, Production ecology, Dept. Forestry, Edinburgh.

In conclusion, the smaller the integrals of time over which a function is computed and accumulated, the more accurate the final integration. However, a minimum size integral is dictated by both the nature of the activity and by the type of function that describes it. Beyond this, the size of integrals is further limited by the minimum periods of the climatic data available, and by the labour involved in calculating large numbers of small integrals.

1.3.5. The construction of functions.

The influence of climate can be due to the effect of one single element. An example is the physical wind limit to human comfort described in Section II.6. Another influence of wind alone is wind loading design in structural engineering. A single influence for temperature is 'time of freezing'. In these cases the influence of the element can be directly converted into a 'weather design value' (Thom, 1970). This type of function is not stressed in this thesis, since the developments of Chapters II and III both demand the simultaneous influence of at least two climatic elements.

Most climate influences result from the action of more than one climate element working at the same time. The combined action of the elements on the activity parameter can be analysed in two ways. First, a multiple regression of empirical data can give a weighted function in which each variable plays a part. Multi-variate analysis to establish the function is a standard procedure, necessary when the physical basis of the function is not understood. However, it has the following disadvantages: it requires a large amount of empirical data; the function applies only to the conditions of the experiment in which the data was obtained, with no provision for altering an inapplicable part; and the specific interaction of each element is not visible for understanding. Munn (1970) recommends that it be used only as a last resort, and that it is likely to produce unintelligible results.

The other method of analysing combined influence of elements is to obtain an understanding of the action of each of the elements in isolation, either by experiment or by a physical model from first principles, and to combine these independent functions into combined functions. This is the method used in the examples given in this thesis. It is open to better understanding of, and manipulation of, the components of the function. On Chart A, as in Chapters II and III, this is done graphically; but tabular methods and conversion to a formula can also be used. The disadvantage of this method is that the number of individual functions that can be considered may be limited. There may be influential relationships which have not been investigated, or which have not been recognised and are left out. Moreover, in the graphic and tabular forms of analysis the maximum number of variables is three, and since one of these is the activity parameter, this allows only the combinations of two climatic elements. Hatched lines and series of graphs or tables allow one or two further elements to be considered, but this is effectively the limit. Because of the possibility or necessity of neglecting some climatic elements, there may be a relationship between the functions of two elements which causes a response in the activity parameter which is not equal to the sum of the two functions.

An example of such an interaction in Chapter III is the influence of longwave radiation on the combined relationships of temperature and wind. In the absence of radiation, wind and temperature functions combine arithmetically. With radiation present, there are two measurable temperatures, those of the air and the surface. These are combined in engineering practice in the 'effective external air temperature', which is measured in terms of temperature only. The wind has a direct influence on the temperature of the surface which cannot be taken into account by either one of these temperatures. As a result of combining either of these temperatures with wind to give heat loss under radiant cooling conditions, the anomaly arises where, at low speeds, an increasing wind reduces heat loss. The effective temperature calculation method is justified by its elimination of the otherwise minor variable longwave radiation from the other functions. Similarly on Chart A, the deterioration of building materials due to the freeze-thaw cycle is affected by radiation. The freeze thaw cycles have a reduced range at high wind velocity because of reduced influence of radiation on surface temperature. This influence has been empirically added to the combined T:V function, without introducing a separate function for radiation. In the same way, other minor elements might be included into the combination of the major elements.

the combination of the major elements.

The functions developed in the next entries in Chart A isolate the relationships between the individual climatic elements temperature, wind, and insolation and the activity parameter. These relationships are expressed as two dimensional graphs. The functions assume the time frame and averaging integrals used. Any limits to the individual functions are introduced at this stage. Following this, the elements temperature and wind are combined as the x and y axes on a three dimensional graph with the activity parameter as the z axis. The element I 'insolation' is added to this basic combined graph by means of dotted lines or separate graphs showing its influence in terms of the T:V:activity parameter relationship. This order was chosen because of the subsidiary influence of I in most of the activities considered. The major exception is vegetative production, where the insolation has photosynthetic as well as thermal effects, and is the most important single element. As a result, the T:V:Production arrangement is not successful in describing vegetative production, T:I:Production being a better choice. T:V: Production is adequate to describe the zones of growth and no-growth, since these are dependent on the thermal effects of insolation only.

The reasons and references for the shape of the curves on Chart A are given in Appendix 1. The relative magnitude of the effects along the different axes is hypothetical in all cases except building heat loss and human comfort.

The following entry of Chart A presents the limits, or thresholds, of the rate-limit functions in terms of the combined influence of the chosen climatic elements. Limits to single elements can be handled like the wind limit on the comfort graph. The principle axes used in the chart are again T and V, but they could as well represent other elements. An example would be V and R, rainfall, for a driving rain limit to comfort.

Following the development of such combined climatic charts, which relate the climatic elements to the activity parameter, the planner needs a description of the temporal distribution of the climate to apply it to. If he is dealing with graphic presentation, as in Chart A, he will want the climatic description distributed on the same axes as the combined element graphs. This equalizing permits superpositioning of the two graphs, and makes it possible to read off the activity parameter. The process for the remainder of Chart A will be described in Section IV.2.3.

1.3.6. Conclusions about climate:activity functions.

Basically, there are two types of function which relate climate to activities. These are the accumulative and the rate-limit-failure type, which give their results in terms of the activity parameter, and time probability of failure, respectively.

In order to develop a function, the following characteristics need to be determined: which climatic elements are involved in the function; the place of these elements in the function; the limits for rate-limit functions; the time frame,or period within which the function is of interest; the time integrals over which the function is to be calculated and integrated, and the corresponding periods of the climatic data needed; the influence of the climatic elements on the activity parameter, in isolation and in combination; and the presentation of the data to be required.

The development of a function is traced in generalized form in Chart A. Specific functions of both basic types have been developed in detail in Chapters II and III.

1.4. Climatic classifications.

Climatic classifications should be mentioned at this point. Various attempts have been made to bypass or minimize the need for a function relating climatic data to an activity. The climate is assessed for its suitability for an activity on the basis of simplified assumptions equating suitability to some climatic data readily available from existing records. This permits extensive mapping of type classified climates over large areas. It is chiefly a geographical method. Prohaska (1967) summarizes classification and terminology.

Climate classifications of comfort have been developed by Maunder (1962) and Terjung (1966,67). Maunder's classification is based on a totally subjective weighting of five climatic elements, each of which receives an intuitive score before summing to a final score. It is an attempt to use existing climatic information for a new purpose, but since it has no physical basis whatever its usefulness is questionable.

Terjung's classification has had wide publicity. Its physical basis and assumptions have been discussed in Chapter II. Its success or usefulness to planners for evaluating climate can be described here as a comment on classification systems in general. The climatic data used is very simplified, to the maximum and minimum temperatures for a day representing day and night. This permits no analysis of the climate within the day. The combination of the elements temperature and wind is not considered. The generality of the data used precludes shifting the classification to the location of a site.

Forced to minimize variables by the classification system, Terjung's method applies only to inactive people and makes no provision for the influence of clothing. Thus it cannot be specifically tied to activities anticipated by the planner. It is described in terms such as keen, cool, cold, which have a subjective value but are not open to evaluation. A map of a classified climate cannot be adjusted upon the changing of the basic system.

The limits to the variables in a classification system permit only very broad conclusions to be reached about climate and an activity. The system works only for very large areas or for localized areas with extreme climate variation. Terjung's example in southern California is an example. Atlases with such information might be of momentary use at the earliest stage of very large scale design decision making, in areas the designer has not experienced. It is not surprising that most human climate classification systems have been originally prepared for military planners interested in remote parts of the globe (Plummer, Siple and Ionides 1945; Falkowski and Hastings 1958).

Orlenko (1970) prepared a climate classification for buildings based on another version of 'effective temperature' which comprises temperature and wind. This system of evaluating windchill of buildings omits short and longwave radiative influence and applies only to the probability of a maximum heat loss rate being exceeded. Wind direction cannot be included for consideration.

Another classification system is the driving rain index, depending on an arbitrary scale of wind and precipitation. This (Lacy 1971), combining non correlated data on two variables, is capable of only very general maps, with four zones in the British Isles. They are, however, sufficient for the precision of prediction needed by building engineers. The simplicity and slow action of the rain-penetration function makes it possible to evaluate this climate classification by comparison. The index is accompanied by wind roses to associate the wind with direction.

In conclusion, climatic classification systems are not likely to be of much use in planning for activities whose climate-activity function is complex. For such functions, the process of developing a function and selecting the appropriate data must be followed. Climatic classifications, especially if based on a climate:activity function, are only useful in planning for activities whose relationships with climate are slow acting and not complex.

2. Climatic data required to evaluate climate.

2.1. Introduction. Averaging intervals.

Data on the climatic elements is meaningful only with specification of time, averaging interval, direction, location, and scale. The latter two conditions will be discussed later with their relation to the site (Section IV. 3.). "Time" includes time of occurrence (during day, month, season), time frame, and time duration or persistence. The "averaging interval", or period, of data is synonymous with "time integral", as used above to describe the summing of a function. "Direction" refers to the vector properties of wind, which often forms a natural subdivision of the other climatic data. As has been described in Section IV.

1.3.3., the nature of the climate:activity function determines what type of information is required. If the data directly corresponding to the required information is not available or is inconvenient to obtain, compromises can be made and approximating assumptions accepted. Similarly, approximations are accepted to reduce the work in processing data.

Functions can be accumulated in very small integrals, by continuous calculation using the immediate, simultaneous climatic data. Such data needs no specifications other than the time frame within which it is applied. Functions using averaged data (as discussed in Section IV.1.3.2., and in the climate:time graphs) require short interval general data to be built into the function to correctly assess the long interval averaged data which is used. This short interval data provides the distribution about the average of each element, and the contingency or simultaneous occurrence of the different elements.

2.2. Single elements: frequency distribution.

Use of averaged data of any sort requires information on its numerical distribution; but this is rarely the case with climatological data. There are many possible distribution formulations and each requires great effort to compute. Since the climatologist does not know which distributions are to be required, he understandably accumulates and averages his data in the most compact way.

For example, Bingham (1963) computed the probability distributions for three climatic variates for 150 stations in the Northeast region of the U.S. These variates were: the weekly averages of the diurnal temperature maximum, minimum, and range. The calculation required a large amount of computer time and labour, even though no extreme value analysis was done. Yet for the functions pedestrian comfort, building heat loss, and heating plant maximum capacity, these are not the variates that are most immediately useful. For pedestrian comfort, the probabilities of temperatures at selected hours during the working day, or the range during the working day, are values the planner can apply to his function. For building heat loss, the probability distribution of the average would be sufficient, although information on the range as calculated by Bingham is useful in setting up the function. For heating plant maximum capacity, the probabilities of minimum temperatures would have to be computed for less than the 5 per cent level by a different form of probability analysis than that used by Bingham. It is clear that climatologists cannot be expected to perform any such analyses without a clear specification of what type of distribution is needed.

In another example, Greenwood (1971), calculates probability distribution of seasonal mean T for cities and rural areas in Great Britain. It is supposedly for 'balance point' calculations, in the design of heating and cooling plants.

The exact application is not discussed however.

The lack of the appropriate probability distribution leads to difficulty in interpreting functions in which the relationship between the climatic element and the activity parameter are not linear. The width of a normal distribution strongly influences the value of a non linear function based on the mean. Non linear functions include all the wind effects on Chart A, wind chill being the most notable. Data with a non-Gaussian distribution will further influence the value of non linear functions, and will also affect the value of linear functions. Air pollution concentrations and wind fluctuations within a short period are examples cited by Munn (1970) which have truncated extremes and for which averaging methods do not work. Furthermore, the existence of a limit to an individual element requires knowledge of the probability of the element exceeding it. This is directly dependent on the distribution of the element.

The nature of the function calls for different types of distribution analysis. Thom (1970) gives a distinction between the parts of the distribution needed, by the magnitude of the risk of failure. 'Extreme quantiles' are for serious risks, which use extreme value analysis. Examples of these are the influence of the single element wind and structural failure, and of rain and flood control failure. 'Subextreme quantiles' are for risks where losses are not as severe, as with comfort or storm sewers. The probability of extreme quantities occurring is often measured in terms of a return period, perhaps in years; while the subextreme type is measured by the percentage of total time that the failure occurs. The emphasis here is on the subextreme type of distribution, although the method applies generally to the extreme type also.

In conclusion, knowledge of the frequency distribution of a climatic element is usually needed for accurate appraisal of functions. The form of frequency distribution analysis needed is, however, specified by the function. Distribution analysis cannot practically be undertaken by the climatologist without having the form of analysis specified.

2.3. Multiple elements: contingency and distribution of the function.

The frequency distributions of associated variables are affected by the degree of association. Thus interactions between climatic elements cause their combined, multivariate, distributions to be distorted. Such interactions are common in climate data: temperature and wind, temperature and insolation often have statistical correlation. In the same way as interactions distort the distribution of the elements, they distort the results of functions which use averaged combined data. The simple arithmetic combination of functions using averaged single elements presumes independence between the elements. If there are interactions between the elements the combined function will yield biased results. An example would result from applying seasonal averages to the function graphs in Chapter III. Also, when limits are defined for the functions, the distribution of the results (accumulating the function over time) depends on the interaction between the elements. Court (1948) and Scorer (1956) give examples where using monthly averages of interacting elements (for windchill and pollution, respectively) gives large magnitude errors.

The distribution of combined elements is expressed as a multivariate distribution or contingency table. Methods of multivariate analysis are available to determine the associations or correlation of multiple elements in a collection of data. However, they are not helpful in gaining an understanding of the reasons for the association, if any. The most common method of obtaining contingencies of most forms of the elements is to make a present sample of raw simultaneous data and apply it to the summarized independent data of the past.

The analysis of interaction between climatic variables could be avoided by continual calculations of the function using constantly monitored simultaneous climatological data. From this, the function distribution is determined as a single variable distribution. It is noteworthy that no conventional meteorological or climatological instruments measure combinations of elements in relation to a function. This is due to lack of usable functions. One device similar to such an instrument is Hill's Katathermometer, which takes the elements T, V, I, and humidity into account. There is,however, no direct relationship between the physical response of this instrument and the response of a human being, which it is meant to describe. Whatever useful similarities there are are totally empirical. Another device which measures more than one element in terms of its effect is the tatter flag, used to assess exposure. However there is no function to which it is related, and the individual influences of wind and rain are not known.

It is suggested here that once a function between an important activity and climate is formulated, attempts be made to measure and record the associated climatic elements required for that activity. With these, the climate of a location could be continuously summarized in terms of its effect on an activity. This would be a useful addition to the present practice of summarizing data in averages and accumulations of itself. It would also yield far more accurate results than are possible with estimated contingencies from summarized records of individual elements. However, such summaries of activity suitability are liable to be inflexible, permitting no change in the function which determined them without negating previous records. The data on the associated climatic elements which underlies the function must be retained.

In the future, it is likely that the machine storage, retrieval, and analysis of simultaneously recorded raw data will permit any user to apply any function to the original observations over long periods of record as easily as he could now handle summarized data, and get more accurate results. As the number of functions and climate uses are discovered, this means of data storage should prove to be far more efficient to all users than the summarized data of the past. This is clear, because each use requires a unique combination of elements and time intervals which are not foreseen at present.

In conclusion, contingencies are required to show the distribution of combined climatic elements when there is interaction between the elements. If a function requiring combined elements is continuously calculated and integrated from the raw combined data, the resulting totals will give the most complete representation of the climate's influence. This is the eventual aim of data storage, but at the present, contingencies must be estimated from samples.

2.4. Wind direction.

The directional variability of wind adds another consideration to distributions of wind or multivariable contingencies which have wind as one of the variables. The direction of the wind is important for two reasons: first, many climatic contingencies vary considerably with differing wind directions. When wind is combined with temperature, for example, east winds might be colder but weaker than west winds, which are warm but strong. Jacobs (1947) combined wind and precipitation to show the very different probabilities of rain with different wind directions over Hokkaido. Second, as with sunlight, the site or plan can exert a very strong directional influence on wind. This affects functions which involve only the single element wind as well as multiple variable functions.

Considering a single element function such as physical wind limits to human comfort, or air pollution transport distance: if the wind from a given direction is blocked or reduced, it would be useful for the planner to know what the percentage of the total wind came from that direction, and what influence the blocking of the wind had on the total, omnidirectional, wind distribution. This information can be gained from a standard windspeed-grouped wind rose. Considering multiple variables, such as the wind temperature contingency required for the human thermal comfort function; if the wind from one direction were blocked, it would be useful to know how the T,V contingency for that wind direction was affected. From this, it would be possible to determine what influence the wind blockage had on the total, omnidirectional, T,V contingency. It would not be possible to accurately determine the influence of this wind modification on total T,V by taking wind frequency information from a wind rose and applying it to total T,V. Because of the variability of climatic contingencies with winds from differing directions, an equal amount of wind blockage from, say, east and west, could have sizeably different effects on the multivariable T,V distribution.

Figure 1 shows two contingencies, for a hypothetical east and west wind. Figure 1a gives the directional site effects on the elements T, V, and I. Figure 1b shows the influence of these directional site effects as applied to contingencies derived from: directional associated T and V data; directional V frequency distributions against a non directional T frequency distribution; and non directional T and V data. Increasing inaccuracies attend the more incomplete data.

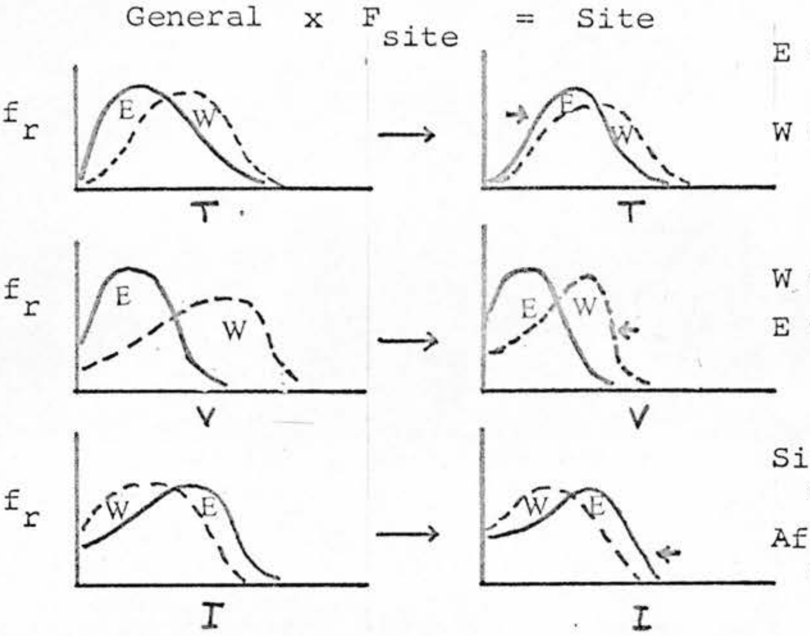
The conclusion from this graph is that for many functions it would be desirable to have multivariate data broken down into directional distributions. Since the chief need for this information is caused by the influence of the site on wind, it will be discussed under site effects later.

2.5. Form of data presentation and its application.

The actual handling of data and the discovery of its distribution characteristics will not be done by the designer but by the climatologist supplying the data. The designer's main task is to know which data he needs

IV FIGURE 1. EFFECT OF WIND DIRECTION ON CLIMATIC CONTINGENCIES.

a.) Site influence on hourly distribution of T,V, and I, by wind direction.



E wind: T increased by urban heat

W wind: No T effect

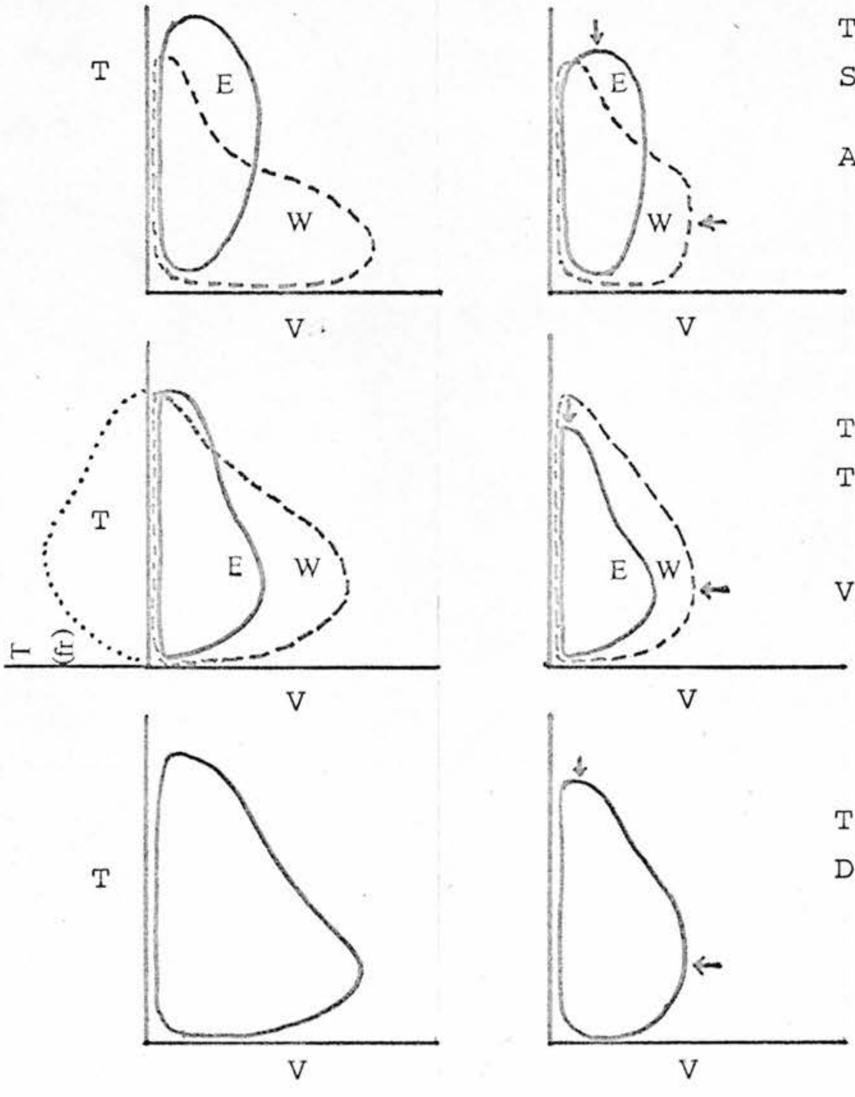
W wind blocked

E wind unaffected

Site influence: blockage of noon sun.

Affects both I_d values equally.

b.) Site influence on T,V contingencies. I fixed.



T_d,V_d contingency.

Site influence on T_e and V_w as above.

Arbitrary frequency contours

T,V_d contingency.

T from a non directional distribution (dotted line).

V_d from frequency curves above.

T,V contingency.

Directional site influences applied to omnidirectional contingency.

distribution for. From the function, he should know which elements should be combined in contingencies, and whether the contingencies should be subdivided by wind direction. These specifications are then modified by the climatologist, reflecting the natural relationships between climatic elements, and the availability of data. These climatological considerations are discussed below under Sections 2.6. and 2.7.

The planner should also be able to specify which type of distribution is needed (extreme quantiles) and to what degree of resolution the information should be presented. The degree of resolution refers to the size of the class intervals into which the range of the climatic elements is subdivided. Thom (1966) states that 10 to 20 classes for any range is best. It is likely that some activities do not require fine subdivisions of data because of insensitivity of the activity or because of crudeness of the relationship function available. In functions where high accuracy is desirable, it might not be possible to give such information. The number of class intervals in a distribution is controlled by the amount of data available. The rule of thumb for a single element distribution is that the number of classes should not exceed 5 times the logarithm (to base 10) of the number of observations. Since the observations required increase logarithmically for an arithmetic increase in classes, a limit is soon reached to the number possible. The number of observations per class of a multivariate contingency is necessarily less.

The accumulated frequency distribution, also known as the cumulative distribution or probability curve, has the advantage of avoiding class intervals in the data and giving more statistically reliable results for a given number of observations. Thus it is the preferred format for discovering the probability of any single element. There is no practical way to apply this method to multi-element distributions, however. The more cumbersome frequency distribution is necessary for the example in this thesis.

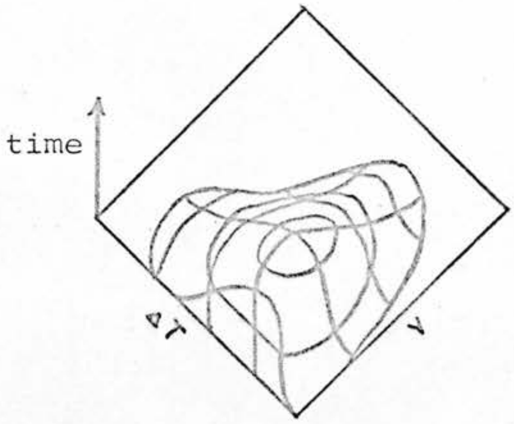
The designer will also be interested in the means of presentation of the climatic data, since this has a direct bearing on the reading of the results of his function. Multivariate information will initially be in the form of a table of classes of one variable arrayed against classes of another. Both Conrad and Pollak (1950) and Munn (1970), in their books on climatological methods, stress the use of three dimensional graphs as means of understanding the distributions of more than one climatic variable. An example of this has been schematically given in Figures 1a and b. Two normally distributed uncorrelated variates are on the bottom axes, while the vertical axis represents either the percentage of time, or the total time, each multiple variable (or contingency) applies. The classes here are smooth enough to permit smooth curves. However, to apply a total or percentage time vertical axis, the size of the class intervals of the elements must be specified. The smaller the class, the smaller the percentage of time that the observed data will be within that class.

The percentage of time at each contingency is best used as the vertical axis for functions involving a rate, such as Q; and the total time at each contingency is more useful for functions describing the accumulation of a commodity such as heat, Q·Time. The means of handling the multivariate curves is depicted in Figure 2 and in the next entry of Chart A using the variates temperature and wind.

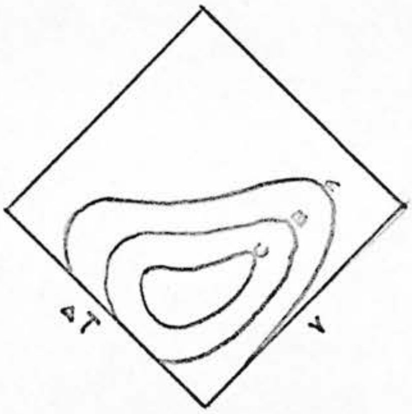
Taking the rate-limit type of function first: the probability surface is constructed from a table or graph of time against the T,V contingency. This is done in Figure 2 for a hypothetical climate with an irregular contingency T,V. This contingency could represent anything, for example the climate from 1500 to 1600 daily, or the foregoing only during east winds. From the probability surface, lines of equal probability are projected downward onto the base, forming isolines on a graph with T and V as the axes. This graph can be directly superposed on a graph of the function, as the comfort curves from Chapter II. This graph gives information about the probabilities of the limits being exceeded, and about the probabilities of any specific point on the comfort curve actually occurring. The

Accumulative functions.

Climate contingency T,V



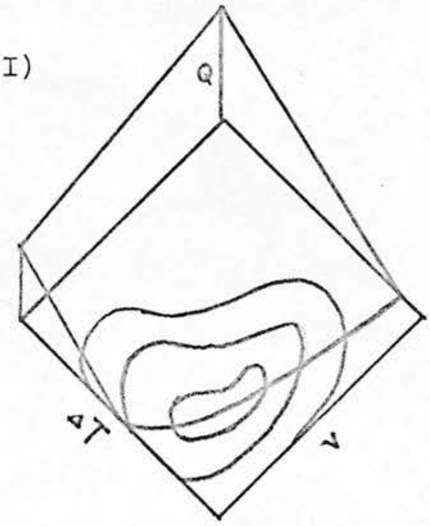
Equal time contours



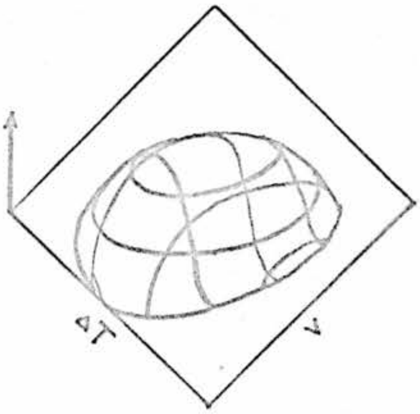
Heat loss function (Chapter III) superposed.

To obtain heat loss, time is multiplied by rate Q.

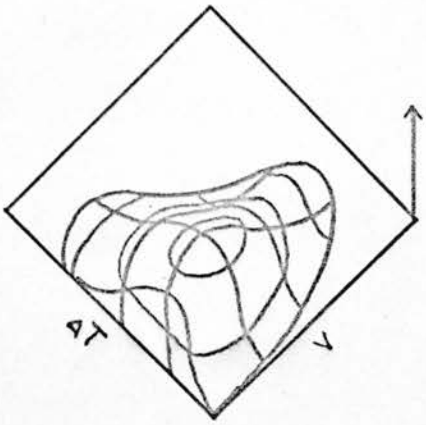
The surface of the products represents the heat lost at any T,V combination, and the volume represents total heat loss.



Design decisions might result from finding maximum loss at one corner of the T,V array..

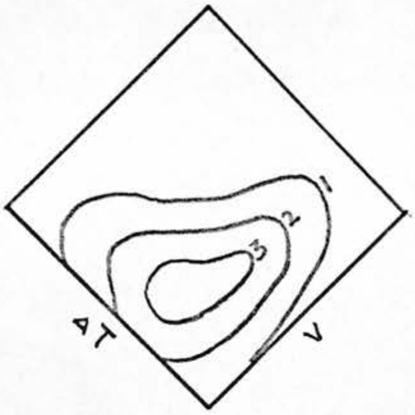


Rate - failure functions.

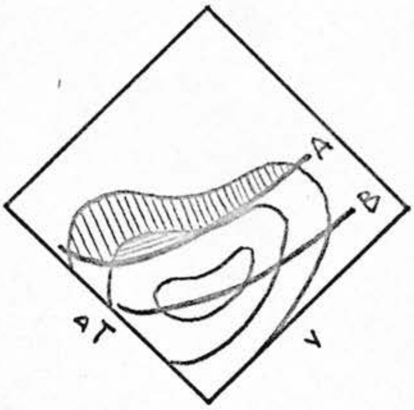


Probability, or % of time

Climate contingency T,V.

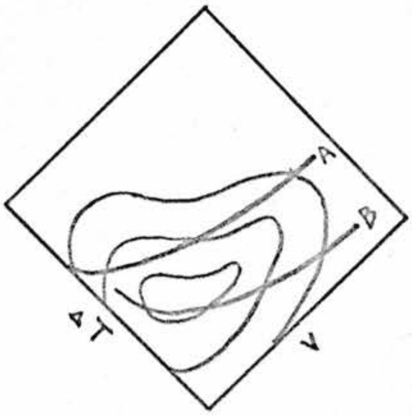


Equal probability contours.



Pedestrian comfort functions A and B (Chapter II) superposed:

To obtain the probability of discomfort in this climate with function A, the percentages above A are summed. (Equal to the shaded area). This sum equals the overall probability of discomfort (failure).



Design decisions might result from inspection of climatic elements causing most failure. (i.e. wind control will not reduce discomfort much for A, but would be helpful for B.)

former is obtained by measuring the area above the curve, or adding the percentages in the classes above the curve. This could be done numerically from a matrix or table. The advantage of the graphical contour method is the specific probability of each point on the comfort curve can be directly read from the intersection of the curve and a contour. By indicating where the discomfort is likely to take place (either at high winds and high temperatures or at low winds and low temperatures, for example) additional information is present to help in design decisions, above the single figure of overall discomfort probability.

With the accumulative type of function, the amount of time at each multiple variable (each intersection of T and V) is multiplied by the value of the activity parameter as determined by the function. In this example, the three dimensional surface of the heat loss function (from Chapter III) is superposed on the time contingency, and the surface of the products is above. This gives the heat loss expected at each combination of T and V. These values have to be summed to obtain the total heat loss resulting from the climate represented by the contingency. In this case again, additional information is given by inspecting the surface of the products. Design decisions would be helped by the knowledge of in which section of a climate's T,V contingency the maximum heat loss will occur.

Concluding, the planner should know what climatic information to specify from the climatologist. This information comes primarily from an examination of the function. It also depends, in considering wind direction, on the physical situation of the site and proposed plan. The planner should also know in what form of presentation the climatic information can be most effectively applied to the function. The examples given here, for rate-limit and accumulative functions, have been presented for graphical means of climate evaluation.

2.6. Obtaining the climatic data required by comfort functions.

This section will attempt to show the considerations needed to obtain data for a rate-limit function which is sensitive to short periods of climate. The climatic elements influencing comfort are temperature, wind, insolation, and rain. The first three have an effect on the thermal balance function derived in Sections II.4. and 5. The elements wind and rain have a physical influence on comfort, as described in Section II.6.

2.6.1. Thermal comfort.

The information the planner would find useful for the thermal comfort function is given below, in increasing stages of function complexity:

1. Steady state thermal comfort or discomfort, and physical comfort or discomfort, as probabilities of time.
2. Steady state levels of thermal and physical discomfort, as probabilities of time.
3. The length of exposure time before discomfort develops, involving the effect of heat storage and comfort in a state of thermal imbalance.
4. A finer point which could influence comfort is the probability of changes in climate during the day which would adversely affect the choice of clothing or activity made before the change - i.e. in the morning, or at the outset of a walk. This could occur through a drop in temperature, rise in wind, a drop in insolation, or the onset of rain. Such a consideration involves psychological factors for, as the probability of a given change increases, the pedestrian will become accustomed to it and plan for it in advance. Examples where such changes are highly probable are the onset of sea or mountain breezes, of afternoon fog (San Francisco) or of afternoon showers and thunder showers.

For the steady state thermal functions, the planner could ideally (at most) use the monthly averages of the hourly probabilities, for each wind direction, or every value of the array $(T_d, V_d, I_{(on-off)d})$. This would allow him to calculate, via the heat loss function, the hourly probability of discomfort (or level of discomfort) for each level of activity and clothing in any month. This minimum limit of hourly values within monthly subframes is dictated by the practical limits of activity planning, where the activities of the day are not conveniently subdivided into units less than an hour, and the variation of these hourly values from month to month is sufficiently small to make further subdivision (as to week) superfluous). Some exceptions are possible where information may be required for specific periods of less than a month, i.e. the week of a festival or holiday.

The climatic data comprising these hourly probabilities should be preferably of a shorter interval than one hour, summed to the hourly value. However, if short interval or hourly data is not obtainable, the closest approximation within the daily time frame will have to suffice. Also, if data for different elements is for different periods, estimates will have to be made as to their association. Any such data is at present scarce. The Meteorological Office has a study of temperature, wind contingencies at the London Airport (Cottis and Groom, 1958). The time intervals are broken down into 6, 12, 18, and 24 hour sequences, and the temperature subdivided, in 2°F intervals, between 26 and 36°F. Another study, (Brown 1961) deals only with daily means of T and V in six locations in Britain. There are no contingencies of temperature versus directional subdivided wind known to the author, and no examples of T_d, V_d, I_d.

2.6.1.1. (T,V) directional approximations.

Ignoring I for the moment, it is necessary to investigate the ways in which a directional T,V contingency can be obtained. This is important because of the selective influence of topography and buildings on winds of different directions. In figure 1a and b it was shown that it is necessary to have a T,V for each direction that is modified to get an accurate picture of the way any directionally selective modification of the wind affects the overall T,V contingency. Such a directional T,V is denoted as $(T,V)_d$ or (T_d,V_d). If the planner has directional contingencies, and knows the directional wind modifications expected on his plan, then he can "condense" or "expand" each directional contingency along the wind axis by the proportion that the wind is expected to be reduced or increased for that direction. These modified contingencies are then summed to give the overall (T,V) for that plan.

As mentioned above, directional T,V contingencies very possibly do not exist yet. Approximation methods are shown below for decreasing obtainable data, and giving decreasingly accurate results:

Decreasingly preferred forms of T,V data.

(1) (T_d,V_d)

T: Temperature distribution associated with directional velocity.

V: Directional velocity distribution and directional probability.

(2) $(T,V).V_d$

T: Temperature distribution associated with omnidirectional velocity distribution.

V: Directional velocity distribution and directional probability. (V_d found in velocity wind rose).

(3) (T_d and V_d)

T: Temperature distribution associated with wind direction.

V: Directional velocity distribution and directional probability.

(4) (T and V_d)

T: Temperature distribution for all wind directions.

V: Directional velocity distribution and directional probability.

(5) $(T$ and $V)._d$

T: Temperature distribution for all wind directions.

V: Velocity distribution (omnidirectional), and directional probability (simple wind rose).

(6) $(T_{av}$ and $V_{av}).V_d$. $(T_{av}$ and $V_{av})._d$.

T: Temperature average.

V: Velocity average and directional distribution and/or directional probability. (Velocity or simple wind rose).

If an omnidirectional (T,V) exists, as in (2) above, it can be roughly adjusted to approximate directional wind by multiplying it by a value proportional to the expected frequency of the wind from that direction. This frequency is the information contained in a simple wind rose. If the wind rose is subdivided into velocity groups (the common velocity wind rose), the omnidirectional (T,V) can be adjusted by as many of these proportional values as there are velocity groups. This takes into account the velocity distribution from each direction.

If, as in (3), there is no T,V contingency, it would be preferable to have a temperature distribution which is subdivided into groups corresponding to each wind direction. The independent distributions of T_d and V_d (velocity wind rose) would be arrayed against each other. If, as is likely, temperature is more dependent on wind direction than wind strength, this method could give an accurate representation of T_d,V_d with considerably less labour.

In (4) and (5), the independent distributions of temperature (for all wind directions) and omnidirectional wind are used. The velocity distribution is adjusted by the proportions taken from the two wind roses, as above.

If, as in (6), there is available only an average temperature, average velocity, and velocity wind rose, the temperature distribution will have to be estimated. If there is only a simple wind rose, the velocity distribution will also have to be estimated.

2.6.1.2. Insolation: T,V, and I.

Definition of I as used in comfort functions.

I technically represents the total hemispherical short-wave irradiation rate on a horizontal surface (see Chapter III appendix). The value of I rises from zero at night, through diffuse light of a shaded area (av. 0.15 I direct), diffuse light through clouds (av. 0.35 I direct) to the value of I direct in bright sunlight. Under ideal circumstances, information on I should be in the form of a time distribution, as with T and V. For each value of $I_{1..n}$ there would be a corresponding comfort curve $f \cdot (T:V:I)$, n in number, and the total comfort time would be calculated by adding the times each function applies:

$$\sum_{I=1}^{I=n} \left[(T,V,I_{1..n}) \cdot f_{1..n} \right] = \text{Total comfort time.}$$

This method is not useful to the planner for two reasons: first, the comfort functions are at present not even remotely precise enough to account for small differences in I level. Second, and ultimately more importantly, the presenting of I data for a site in terms of expected levels of intensity gives an array of information which is inflexible to the most variable aspect of irradiation on a site: the presence or absence of direct sunlight. As the planner manipulates the proportion of shade and sunlight on his plan, the entire I distribution needs complex adjustments at each level. It is preferable, therefore, to break irradiation information into two categories, average intensity in the presence and absence of sun. The manipulation of sun and shade then entails only an adjustment of the relative proportion of each.

In Chapter II the basic comfort function curve is developed for shade (overcast). The curve for comfort in sunlight is developed for the average value of I under direct sunshine. I then represents irradiation under sunlight, "insolation", and consists of the components $I_{occurrence}$ and $I_{intensity}$. See Chapter III for this breakdown. The level of I in shade, clear sky, is considered equal in its effect on pedestrians to that of a cloudy sky. This permits the combination of shade from meteorological and site causes.

Independence of I data from (T,V).

This climatic data desired for I would preferably be as in (T,V), averaged per hour of day, collected in monthly averages. Ideally (T,V) could be arrayed against I as a three variate contingency. Such a contingency is however very complex, requires a great deal of data, and is difficult to utilize in planning. It is not used in the functional method proposed in Section II. For this, and for the other non agricultural activities considered in this thesis, the independent probability of I is sufficient. This is for the following reasons:

(1) Presence or absence of sun. Although the presence of sunlight probably shows some correlation with temperature and wind on a macrometeorological scale, important influences on sunlight presence are due to latitude (controlling daylength) and the effect of the site. The site affects sunlight presence through topographical and building obstructions which cause areas to be shaded for certain hours for any given day with geometrical certainty. In a built environment such areas make up a substantial proportion of the total outdoor area. Another influence which can be considered site induced is mesometeorological fog, smog, and cloud formation which cause the T,V,I association on site to be different from surrounding areas. Coastal, mountain, and urban locations cause a variety of such effects, some of which have a strong influence on the hours in which the sun shines. Because of the strong influence of these geographical site effects, which are independent of the T,V contingency, the meteorological association of sunlight presence to the other climatic factors is obscured. The mesoscale site effects could show correlation, however, with the direction of the ambient wind. The dependence of orographic cloud and fog on wind direction is well known.

(2) Intensity of sunlight. Intensity of sunlight probably shows negligible correlation with T,V. Although clarity

might increase with the weather conditions associated with a drop in temperature, so does the emission of pollutants and the resulting haze. The variation in intensity is caused by turbidity and by solar path length, a correlary of solar altitude, which depends on latitude and time of day. Turbidity frequently shows a correlation to the direction that the wind is blowing from. This could be due to the direction of sources of pollution, or the direction of the sea for haze and fog. The length of the solar path due to solar altitude is strictly geometrically controlled by the time of year and the time of day.

From the foregoing discussion of insolation duration and intensity, it is suggested that insolation is not related to the T,V contingency, but should be associated with the T,V contingency for each separate direction of wind. Thus insolation can be considered an independent variable, but preferably subdivided into one separate value for each directional T,V contingency.

Conclusion: most desirable form of data on insolation. Ideally, the planner could use the following data on insolation in planning for pedestrian activities: the monthly averages of hourly probability of sun presence or absence, subdivided by associated wind direction; and the monthly averages of hourly intensity when sun is shining. This same information is available from hourly totals of solar gain with a simultaneous record of length of time of sun or shade. The prospective Meteorological Office data system will provide this form of meteorological information. Sun angle calculators provide the remaining information on hours of shade.

Less complete data is required by the accuracy of the function in Chapter II. The procedure presented in Chapter II is very basic, using a single value of I intensity for all calculations. This value represents an average intensity at noon throughout the season, and it is suggested that it can be applied through the function to any hour of any day. The justification for using a single value to represent the varying intensity of any hour of any day is taken from Blum's research (1945) which suggests that the variation of solar intensity due to solar angle change is cancelled out by the inverse variation of the surface area exposed to the solar beam. Undoubtedly it would be preferable to create more sets of comfort curves for varying solar intensities, and to refine the calculations to take the exact hourly intensity and hourly exposed surfaces of the pedestrian into account. When the functions are sufficiently accurate to do so, hourly intensity data would be useful.

Once the appropriate level of intensity has been selected for the period of time under consideration, and a comfort curve has been calculated using this intensity, the planner has to use the data on duration to decide how much the sunlight curve applies. This is best expressed as a percentage or probability of the time that the sun curve applies, and that the shade curve applies. The data on meteorological probability of sun would preferably be in hourly periods. The geometric component is known from sun angle calculators. The overall probability is in the form of

$$\left[P\ (\text{sun})_{\text{geometric}}\right]\cdot\left[P\ (\text{sun})_{\text{meteorological}}\right] = P\ (\text{sun})$$

The sun and shade curves, in their respective proportions, are then applied to the climatic contingency and the overall probability of comfort and discomfort is obtained by:

$$P(\text{discomfort}) = P\left[f(T:V)_{\text{sun}} > \text{Limit}\right]\cdot P(\text{sun}) + P\left[f(T:V)_{\text{shade}} > \text{Limit}\right]\cdot P(\text{shade})$$

In conclusion, the various aspects of insolation information have been discussed from an ideal viewpoint and from a practical one, using approximations as necessitated by lack of precise functions and by lack of data. Several types of approximations have been described, and the method used in the functions of Chapter II repeated. The overall position of this insolation information is summarised in Section 2.6.3.

2.6.2. Data required: physical wind function.

(1) Average values: time in excess of limit.
The planner would like to know the time probability of wind exceeding the physical limit. This information

for averaged velocities, can be obtained from the T,V contingencies described for the thermal comfort function, by reading the velocity axis. If the data for the suggested T,V contingency is not very specific, the designer could treat the wind separately, obtaining more detail from the generally more complete data on wind alone.

In this case he could use the hourly values of the monthly percentage frequencies of wind direction and velocity. If values for hourly periods (or periods such as morning, afternoon, or evening) are not available, he can opt for the daily average, i.e. the monthly percentage frequency of wind direction and velocity. Such data is presently published for various locations in Great Britain (Plant 1968).

When using average values, an estimate of the frequency distribution within the hour or within the day is needed to determine the probability of gusts with periods as short as one second, or whatever length has a significant effect on comfort.

(2) Intermittent values: probability of gusts above the physical limit occurring within a period (Return time). Turbulence in the wind causes a frequency distribution of velocities around a mean velocity for a given period. This is a result of the mean velocity, eddy velocity, and eddy size, and causes fluctuations in V of a probable

magnitude within any period of time. These are gusts.

The wind limit function in this thesis is steady state, with no means of considering intermittent gusts. It might, however, be useful to know the probable number of such gusts over the physical comfort limit which are likely to occur for a given mean velocity within certain lengths of time. Such a time period might be, for example, the time required to traverse a planned space, or to carry out an activity requiring a known length of time. This number of expected gusts for a mean velocity, if not evaluateable in itself, would help the planner decide whether this prospective mean velocity were acceptable. In highly gusty conditions, a given percentage frequency of a mean velocity near the comfort limit is going to cause more discomfort than the same mean velocity frequency in conditions where the velocity does not vary.

For a simple wind physical limit function as in this thesis, the influence of velocity variation is suggested to be best (most simply) described in terms of a linear function of steady wind, i.e. a 'gust factor' applied to the mean velocity. This factor is a measure of the frequency of gusts over the comfort limit, or in other words a measure of the frequency and magnitude of wind fluctuations. For example, if the hourly mean is $5\ m\cdot s^{-1}$, the number and magnitude of gusts might suggest that the "effective design mean" should be $(1.5)\cdot(5) =$

7.5 m s^{-1}. The mechanism of assessing such a gust factor depends on the limit in the function, and on an intuitive judgment of the importance of gusts on discomfort. A similar type of factor is applied in engineering practice to plan for maximum gusts, and to consider the effects of different sites intensifying or reducing the mean ambient wind (Davenport, 1960).

The physical and psychological effects of intermittent gusts are not determined for the clothing disturbance and buffeting function. Thus very detailed information on gusts is not needed, and a factor as outlined above is presently sufficient. However, for the problems of grit lifting and particle driving, the frequency of gusts and knowledge of their structure would be useful. The directional components of gusts, horizontal and vertical, have particular significance. These relationships were discussed in Section II.6. The data for them comes from two sources, depending on the scale of the turbulence.

Wind turbulence is determined largely by the nature of the surface and the site. General meteorological wind information for a large area will give information only on large scale fluctuations of windspeed. As the scale of the turbulence decreases, the effects of the immediate surroundings (topography, site) become dominant. For this smaller scale turbulence, the source of data will be the relationships between site form and wind which can be model tested and are being extensively studied.

This will be briefly discussed in Section IV.3. The form of presentation will depend on the further development of the grit lifting function. It will also require a great deal of work on the spatial effects of site on climate. Neither of these are attempted in this thesis.

In conclusion, the planner would like to know the probability of the wind being above the physical limit, in terms of time and in terms of occurrence. With the precision of the physical wind limits suggested in this thesis, the use of gust factors would satisfactorily cover the velocity fluctuations in the wind. Gust factors can be developed for wind variations resulting from site as well as meteorological causes.

2.6.3. Data required: rain.

2.6.3.1. Rain alone: probability of rain during the day. As with the other information, the planner could use the percentage of rain occurring or not occurring during short periods during the day. A monthly chart with decreasing time subdivisions as presented in Figure 3, would be most useful in planning for outdoor activities.

Figure 3

Hypothetical probabilities of rain occurrence during month of ______.

	Full day 10%											
	Working day 12%											
	Morning 9%				Afternoon 14%					Evening 13%		
hr	08	09	10	11	12	13	14	15	16	17	18	19
%	7	9	10	11	12	13	16	15	14	13	13	12

Obviously there would need to be a decision on the rate of rainfall at which rain is considered to begin. The Meteorological Office divides rain into slight, moderate, and heavy, and the point of onset in Plant's climatic summary is 0.05 mm. per hour (1968). However, a higher rate of precipitation would probably be needed to be used as a threshold for discomfort, particularly in Britain. Capstick (1969) assumes that the lower limit for rain stopping outdoor work is 0.5 mm. hr^{-1}, and presents percentages of time 'lost' per month due to rain above this limit, and due to associated low temperature (less than $1^{\circ}C$) and rain (above 0.5 mm. hr^{-1}). Plant's summary also includes a cumulative rain distribution, in which the number of hours at increasing rates are listed.

The combination of rain discomfort time with thermal and physical discomfort time gives total discomfort time. Since the functions for R and T,V are not using associated data, the assumption is made that R is evenly distributed across T,V.

There are two other parameters which could be very useful. These are the frequency of rain initiation, and the persistence of rain storms. They are related to the probability of rain as follows:

Rain occurrence (%) = (Rain persistence) (Frequency of onset)

Knowing the probability of rain occurrence, and the duration of the average storm, the average frequency (per hour, per day) can be determined. In summer conditions, for example, the frequency distribution of shower length might peak at 30 minutes due to the uniform size of cumulonimbus convection cells and average windspeed. Knowing this, together with the probability of rain, the planner can estimate the probability of being caught in a shower during any length period. This can be directly related to the planning of walks ways which take a given length of time to traverse.

2.6.3.2. Wind : rain association.

Although no function was developed in Chapter II for the wind:rain physical effect, it could be developed by empirical test. Information on the association of wind and rain would preferably follow the same form as the other information, in hourly probabilities of occurrence per month, and subdivided as to direction. The threshold for rain occurrence would have to be an empirically derived limit above which comfort is unlikely. If a function can be obtained which related rainfall rate, together with wind, to comfort, then a contingency of V and R will be required. An existing format of the wind: rain association is the "driving rain index", presented by Lacy (1971) for the whole British Isles. The data used for V is the annual average and R is the total annual precipitation. Lacy suggests that the two variables are independently distributed during rain. The driving rain index is presented together with a wind rose to give an indication of the directions from which the driven rain will come. The possible correlation of rain with wind direction is not discussed. It is felt here that although the driving rain index might give a planner a qualitative idea of a site's discomfort potential, it cannot be directly related to human activity. The information needed is the rain occurrence time, not the rain amount. And monthly averages, preferably with average daily distributions, are the minimum acceptable.

One other influence of V,R should be mentioned. This is the effect of long dry spells combined with wind which cause increased dust and grit lifting. For this, information on sequences of rain-free days would be needed, and the present functions are not precise enough to require this. However, the effect is noticeable in Edinburgh during Spring easterlies, and especially so in climates with dry seasons.

2.6.4. Conclusions: data required for pedestrian comfort. For evaluation of climate for comfort, the planner needs information on T, V, I, and R. This information is best presented in terms of frequency distributions per hour, averaged over monthly periods. This information enables the planner to plan for any outdoor activity within the working day.

Knowledge of the associated direction of wind is important for all of these elements. This is largely because, first, the site has a directionally selective influence on wind speed; and second, the location of the site relative to sources of turbidity and orographic conditions of cloud formation cause sunlight intensity and duration to be dependent on wind direction.

The multi-element contingencies that are important are T,V and V,R. Because the site is likely to modify V selectively in a pedestrian environment, both these contingencies should be available for at least two wind direction groups, and preferably four.

The omnidirectional contingency for a site is formed from the directional contingencies of the surrounding climate in the following way:

$$\begin{array}{lclcl} \text{Regional} & & \text{Site wind modification} & & \text{Site} \\ (T,V_w) & \cdot & f_w'\ (V) & = & T,V_w' \\ (T,V_n) & \cdot & f_n'\ (V) & = & T,V_n' \\ (T,V_e) & \cdot & f_e'\ (V) & = & T,V_e' \\ +\ (T,V_s) & \cdot & f_s'\ (V) & = & T,V_s' \\ \cline{1-1} \cline{5-5} \text{Regional } T,V & & & & \text{Site } T,V' \end{array}$$

The probabilities in this omnidirectional site contingency are the ones used in the thermal comfort function for determining the probability of the site being comfortable during a period of time.

Insolation can be treated as an independent variable because the large influence of the site and of the geometry of sunlight obscures its meteorological association with the other elements. However, as mentioned above, its intensity is frequently sensitive to wind direction and should, if it is, be subdivided into the insolation values associated with each wind direction. Insolation can be treated as a distribution or divided into two classes as mentioned above: average cloudy (shade) and average sunny. The complete information required for use of the comfort function can be symbolized as:

$$\sum_{d=1}^{d=4}\left[\sum_{I=1}^{I=n}\left[(P_{1\ldots n})\cdot(I_{1\ldots n})\right]_{d}\cdot(T_{d},V_{d})\right] = \text{omnidirectional T,V and I.}$$

where $(d = 1)$ to $(d = 4)$ = N,E,S,W ; $I_{1\ldots n}$ are number of classes of I, and $P_{1\ldots n}$ are their respective probabilities. However, the comfort function is computed for each direction separately.

The treatment of insolation in Chapter II is very simplified, using only a single daily intensity value. Further research into the comfort function is needed to take advantage of hourly values of I, under the new Meteorological Office data system.

The physical influence of wind on comfort requires a variety of types of information. The most complex of these types are required for further understanding of the discomfort function, as for example the influence of gust frequency, or the relationships between the fine scale of turbulence and the mechanism of grit lifting. Two areas of research are indicated: investigation of these aspects of the comfort function, and development of relationships between site form and wind turbulence structure which will permit the estimation from simplified ambient data of the complex turbulence information that will be demanded by the function. For the present function from Section II.6., average values, perhaps augmented by a suggested 'gust factor', should suffice.

Rain probability information should include either average persistence or average frequency of rain onset. With these the planner can determine the probability of being caught out in the rain during any activity. The R,V contingency should employ the same periods and gust factors as the velocity information above. When combining rain probability with thermal comfort probability, the rain occurs during the shade portion of the T:V contingency. Thus the expression for discomfort time is:

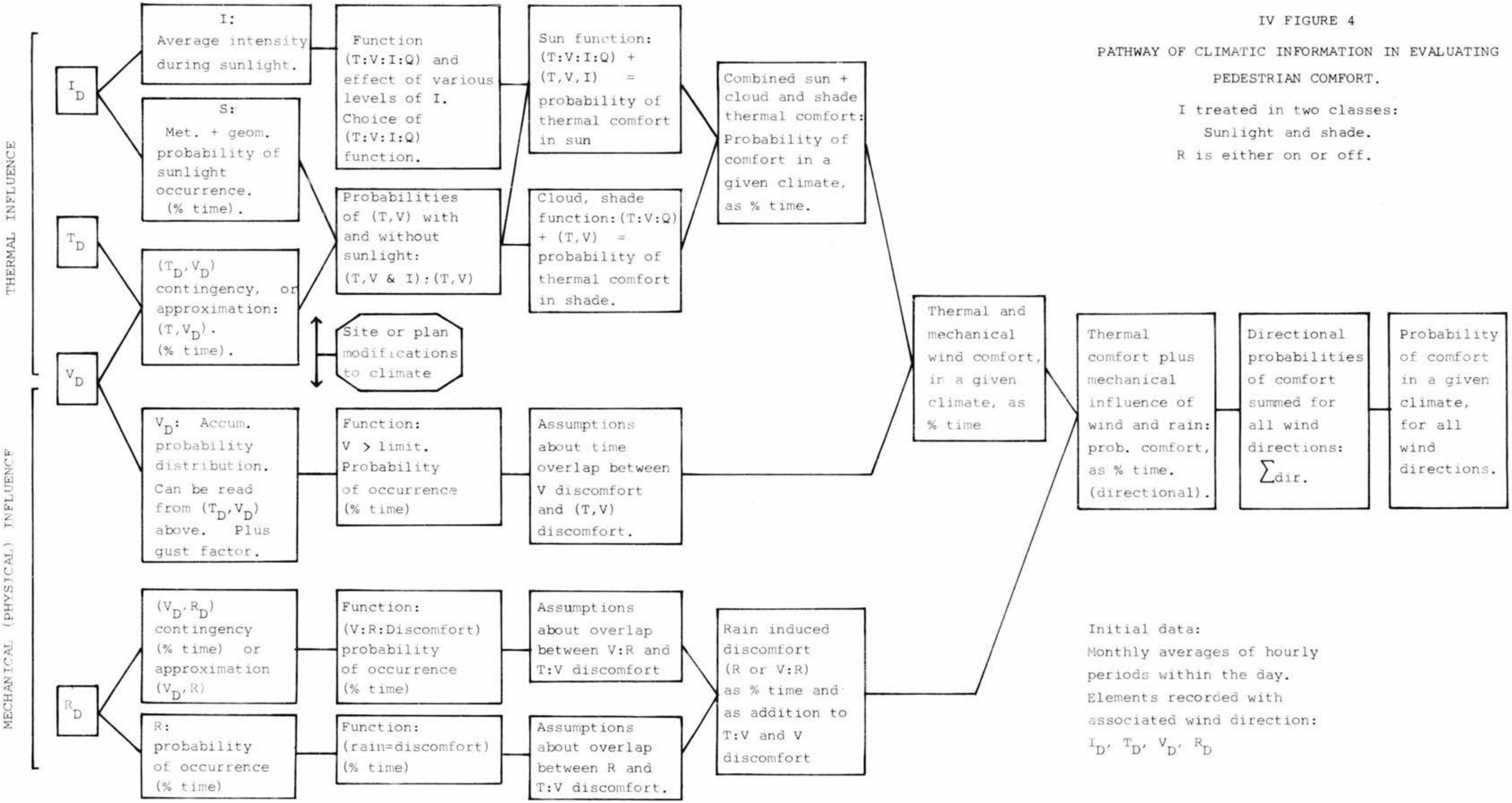
$$\text{Total discomfort time} = \text{thermal discomfort time}_{(\text{sun+shade})} + \Big[\text{Prob.(rain)}\Big]\cdot(\text{thermal comfort time}_{(\text{shade})}$$

The overall flow of climatic information for evaluating

IV FIGURE 4

PATHWAY OF CLIMATIC INFORMATION IN EVALUATING PEDESTRIAN COMFORT.

I treated in two classes:
Sunlight and shade.
R is either on or off.



Initial data:
Monthly averages of hourly periods within the day.
Elements recorded with associated wind direction:
I_D, T_D, V_D, R_D

human comfort is presented in Figure 4. The position in the evaluation process of site modifications of the climate is noted.

2.7. Obtaining the climatic data required by building heat loss functions.

The climatic elements influencing building heat loss are temperature, wind, insolation, and rain. The effect of rain is undetermined, depending on the degree of rain penetration and the nature of the wall surface and insulation. The functions follow those of Chapter III, relating T, V, and I.

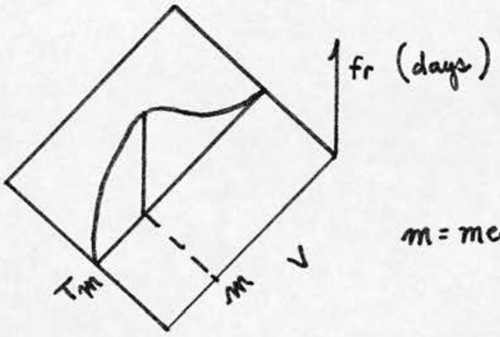
The only information needed by the planner about accumulated building heat loss is the total fuel bill for the season. This permits much simpler climatic data to be used than that required for the evaluation of comfort. First, this single aspect of building heat loss can be contrasted against the many relationships between climate and comfort. Second, the single period of interest is much less complex than the many periods both hourly and monthly, which are required for an understanding of the comfort potential of a location. Although the accumulated heat loss is the result of the sum of many short periods, the unimportance of the instantaneous rates allow the variability of these short periods to be averaged out in the formulation of the function. Variations of rate within the day are averaged into daily rates in Chapter III. Detailed information might go into the research formulating a function, but the data required to apply it is very simplified. Thus the only information needed to feed into the function is the distribution of daily averages over a season period, and for T and I, the seasonal average is sufficient. However, directional subdivision of T,V by the directions of V_d is desirable for planning purposes.

The method of combining a contingency and an accumulative function was described in Section IV.2.5. The time frequency of the climate contingency is multiplied by the corresponding value of the function and the products are summed for the entire contingency. The contingency in this case would consist of sums of daily averages for T and V_d over the length of the season. The directional subdivision of wind is desirable for taking site modifications into account. Data for I is independent from T,V for the same reasons given above in Section IV,2.6.1.

Examination of the final three dimensional function curves in Chapter III shows that the effect of temperature on heat loss in British winter conditions is linear. In such an instance, the variation in the temperature distribution about the seasonal mean will have no influence on heat loss. Thus the only temperature data needed for these functions is the seasonal mean and the length of the season. In climates where the sun is stronger, or in buildings with a greater proportion of glass than those studied here, the temperature curve of the function will tend to be more flat at higher temperatures as the buildings become overheated. For these, the full climate contingency T,V would be required.

The curves for heat loss with velocity are not linear. Therefore the distribution of daily velocity averages about the seasonal mean will be needed to correctly accumulate heat loss. The resulting contingency needed for the heat loss functions in Section III resembles the following figure:

FIG. 5.



m = mean

In the functions of Chapter III, the effect of sun is taken into account by having two functions for average cloudy and average clear (i.e. sunny) days. The clear weather function is formulated using the seasonal average intensity on the exposed faces of a cube during sunlight. In this process, the average day length during the season is needed to determine in which proportions to combine day and night functions into daily clear weather function:

$$f_{3+4}(T,V) = P_4 \; f_4(T,V) + P_3 \; f_3(T,V)$$

where P_3 and P_4 are the time percentages of the clear night and clear day functions F_3 and F_4 respectively. Daylength determines P_4. The same procedure is used in combining F_1 and F_2, the cloudy night and day functions.

The clear and cloudy functions are combined in the seasonal proportions of clear and cloudy weather:

$$Q_{total} = P_{3+4}\ f_{3+4}(T,V) + P_{1+2}\ f_{1+2}(T,V)$$

where P is determined from S or c, and from site shading.

Thus the information required to account for sun and clear weather is the seasonal intensity of sunlight (during sunny hours) on the faces of a cube, the latitude determined day length, and the duration of clear weather. The chief site influence, obstruction of direct I, is taken as a modification of the clear-cloudy ratio. Ideally it might be helpful to subdivide I as to wind direction, as is recommended for human comfort, to get more accurate sub-totals of heat loss on site. This is judged insignificant here as the site influence on V and I is going to be too large and difficult to assess to permit such accuracy.

Data on daylengths and of the duration of clear weather per month is available from the Meteorological Office. For data presentation methods, see Reidat (1957). Some stations are measuring intensity with solarimeters mounted on the faces of a cube, and empirical data for various areas is becoming available (Hardy, 1971, B.R.S., Bracknell). Otherwise this information can be

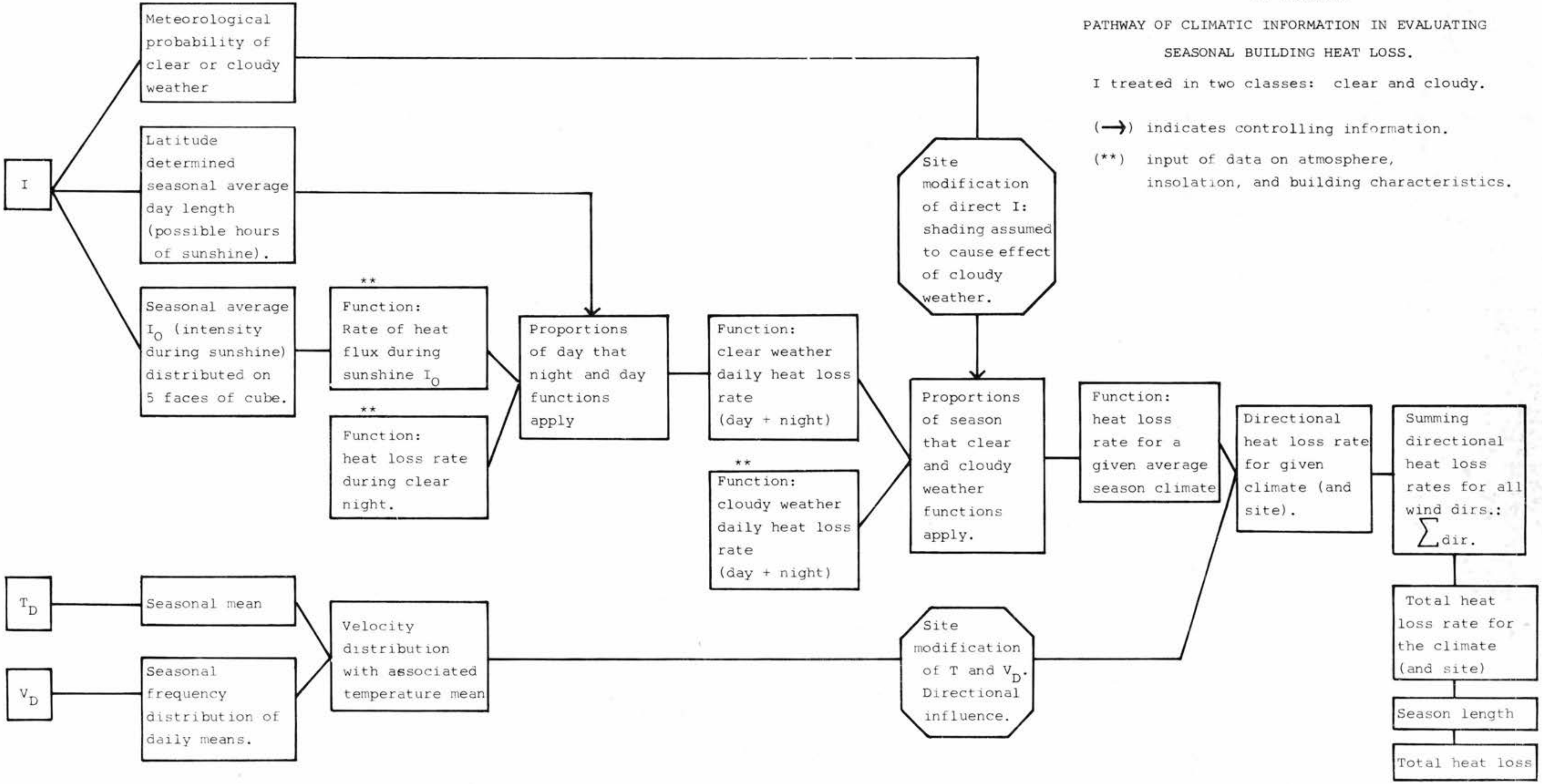
IV FIGURE 6

PATHWAY OF CLIMATIC INFORMATION IN EVALUATING SEASONAL BUILDING HEAT LOSS.

I treated in two classes: clear and cloudy.

(⟶) indicates controlling information.

(**) input of data on atmosphere, insolation, and building characteristics.



calculated from Moon and Spencer's data, as is done in the computer calculator of Petherbridge (1971). More precise consideration of atmospheric conditions is possible using formulae such as are presented in Appendix III.

An interesting presentation of solar radiation data is given by Fritz and MacDonald (1960) for four cities in the U.S. Although not directly applicable to the functions derived in Chapter III, it does form a useable summary of radiation information. Four seasonal curves resembling accumulative frequency curves are drawn with increasing radiation daily totals on the abscissa and 'total number of days with radiation values below the indicated value' on the ordinate. A second graph presents 'number of consecutive days with radiation below the indicated value'. Such information could also be used for assessment of comfort.

In conclusion, the overall flow of climatic data for evaluating building heat loss is presented in the Figure 6. It is evident here that all insolation information goes into determining the specific function for the climate through which heat loss is finally obtained from averaged T and V data. Such a process is required for graphical solution of functions with more than two variables. It is also required for functions with much averaging of short term data. However, the stepwise elimination of variables in this method is considered an advantage in comprehending and manipulating the function. It is useful in the planning process. The position at which site modification enters is noted.

2.8. Conclusions.

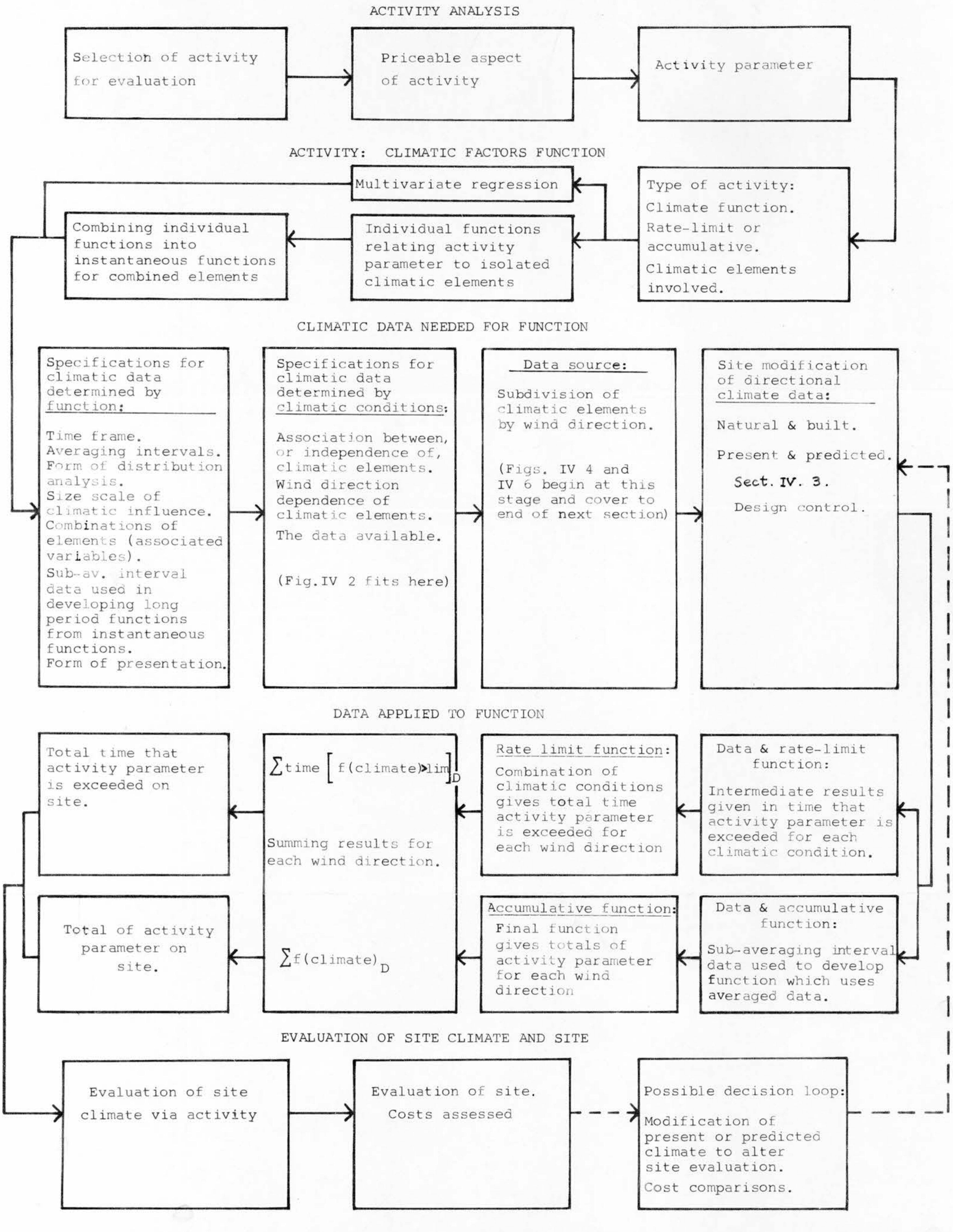
Comparison of the climatic information pathways for comfort and building heat loss (Figures 4 and 6) points up a primary difference. In the rate-limit function very complete contingencies are fed into basic functions in the beginning, giving intermediate results in terms of the activity parameter. The influence of the third variable I is in splitting the contingencies into time percentages for each level of I. Thus, the intermediate results of the process are in the same evaluatable terms as the final results, i.e. the time probability of thermal comfort in shade, in sun, and then for the combined levels of I. These results for isolated climatic conditions are useful in the planning process.

In the building heat loss function, with its long averaging periods, reduced data is fed into the function at the end of the process. The influence of the third variable I is to act as a control in constructing the combined, complete function. Intermediate results in terms of the activity parameter are not obtained (and not needed). Instead, relationships under various climatic conditions are produced. Thus, the functions at intermediate stages of the process deal in terms of rate (heat flux) under the isolated conditions which make up a climate, until the simplified (T,V) contingency is applied to the combined climate function to give total heat loss.

As long as functions are built up from their isolated components, such as from functions for single climatic elements, the types of procedures outlined above will be used. If the overall function is derived from a multivariate regression, the appropriate data can be directly applied to the function for the final result. Such functions are inflexible for planning processes, however, and are reliable only for relatively simplified functions and activities.

The following chart(7) shows the information pathway for evaluating the climate of a site. In it the functions are developed, the data for them is obtained, and the data is applied to them to give evaluatable results. The development of functions has been described in Section IV.1., and the application of data to them in Section 2.6 and 2.7. It is evident here that the type and form of climatic data needed are determined both by the function and by the nature of climatic conditions. This data, when obtained from the data source, is then subject to the modifying influence of the site before it is applied to the function to give the evaluatable results. This is the point at which the designer can also modify the climatic results. A 'decision loop' is shown leading from the site evaluation to site climate modification. By circling through this loop with various modifications, the minimum cost of climate on the activity can be established.

IV FIGURE 7: INFORMATION PATHWAY FOR EVALUATING THE CLIMATE OF A SITE.



IV. 3. The climate on the site.

3.1. Introduction.

The 'site' depends on the geographical location and the activity that is being designed for. In any given location there are many possible 'sites', depending on the size scale that one is interested in. These can generally be expressed in terms of heights from the surface. Ie., for the activity building heat loss, the climate from 0 to 10 m in height might be needed, for pedestrians 0 - 2 m, and for dust lifting or wind erosion 0 - 0.02 m.

At each of these scales the influence of the surface on the climate differs. Moreover the influence of the surrounding objects differs, in that there are different surroundings significant at each scale. The wind climate for a pedestrian will be significantly affected by the presence of a tree canopy overhead, but not by the presence of grass underfoot. The climate for a soil particle is determined initially by the tree canopy, but the presence of a grass canopy immediately above it causes the most significant effect.

Basically, the influence of site on climate can be seen as a sequence of modifying factors, of decreasing scale, applied in series to the synoptic climate. At any given scale, only the modifying factors of larger scales influence the climate:

$$\text{Site climate} = (\text{regional climate})\cdot f_1\cdot f_2\cdot f_3\cdot f_4\cdot\ldots f_n$$

Where 1 to n refer to decreasing scales.

The site modifications at each scale may vary with time of day and season. The activity, as described in Section IV.2., determines the time of interest. Thus the modifications at a given site might differ for two activities of the same size. An example would be time of shading at a given point. An example of a diurnal change in site modification is the inversion (temperature, or humidity) in which the normal gradient from surface to upper atmosphere becomes reversed below some distance from the surface. The discontinuity can occur at any size scale from the smallest to the largest, thus affecting any part of the site modification series described above. Assuming that the nocturnal reverse temperature gradient builds up from the surface, the 'modified' night time modifications f^* affect site climate as follows:

$$\text{Site climate} = (\text{regional climate})\cdot f_1\cdot f_2\cdot f_3^*\cdot f_4^*\cdot\ldots f_n^*$$

where the inversion has reached level 3.

3.2. Means of determining site climate.

Site climate can be determined by empirical or analytical methods, or by a combination of the two. The most empirical method is having a long term record for each site. Since records have to be accumulated over a period of years, this is an impossible requirement. A commonly used empirical method, however, is the comparison of relatively short-term records on site with long term records in the vicinity. The site effect can be deduced from the differences. The length of record required for the on-site station depends on the variability of the climatic element, the type of record required, and the degree of accuracy. Such a method cannot be extended to future sites. It does not require knowledge of the physical influence of the site on climate.

The lengths of record required for an empirical climatic characterisation of a known accuracy is a complex statistical problem dealt with in Conrad and Pollak (1950), and W.M.O. (1967). It requires too much information about the climate, the type of data required, and the type of site to be discussed here.

The analytic method uses general principles of the site's influence on the climatic elements, and employs them on the regional empirical climatic data to obtain estimates of the site climate. It includes testing with models. This method is not capable of the accuracy of the empirical approach, but it is more easily applied and can be used to predict climates on future, non-existent, sites. Generally a combination is recommended, using empirical data for large scale areas and dealing with the small areas analytically.

On the largest scale, the analytic modification of regional data to the vicinity of the site is called "translocation of data" (Conrad and Pollak). The term "site modification" usually applies to the smaller scales, down to the microclimate. The regional data which is available for a network of stations can be translocated to estimate the open exposure (met station) climate near a site by means of "geographic interpolation". This, done graphically or by calculation, requires the area within the network of stations to be "climatically coherent", meaning that the differences or quotients between elements at different stations vary continuously with distance or height up to "climatic divides". This is dealt with in climatology texts.

3.3. Site influence: scale.

The analytical assessment of site influence requires the specification of scale. Common terms for scale in which experimental results have been presented are 'macro', 'meso', and 'micro' scale. These terms are not sufficiently specific to serve in a catalogue or checklist of site influences. It is proposed here that the minimum number of scales for planning purposes be:

1. Topographic
2. Urban
3. Building
4. Vegetation
5. Surface

Figure 8: Site influences on the climatic elements.

When related to regional climatic data, these categories represent the site modification of climate. a, b, c, d roughly in order of decreasing scale.

Description of these categories given in Appendix IV 2.

	1: T	2: V	3: I	4: R	5: RH
A: Topography	a. Coastal effects. b. Altitude. c. Effect of slope on radiant air & ground heating.	a. Roughness of topography. b. Wind profile. c. Ridge amplifications. d. Wind deflection, channelling. e. Turbulence. f. Local winds: mt. and sea.	a. Meteorological shading: orographic cloud. b. Geometric shade and angle of solar incidence on slopes. c. Altitude: transmission.	a. Orographic rain. Rain shadows. Cumulus convect. sources.	a. Coastal influence. b. Terrain.
B: rban scale	a. Heat island: shape, intensity.	a. Urban influence on gradient V: roughness, profile, direction, turbulence. b. Urban induced local winds.	a. Insolation intensity and duration: atm. turbidity. Albedo.	a. Possible effect of dust, heat on cloudbursts.	a. Reduction due to lack of surface moisture and higher T.

C: Building scale	a. Heat islands in courtyard-sized spaces.	a. Wind deflection & acceleration, turbulent wakes: single buildings and complexes. b. Structural: V & pressure on bldg. surfaces.	a. Shading: outdoor spaces around single buildings and complexes.	a. Overhead shelter & exposure to driving rain.	a. No effect.
D: Vegetation	a. Effects of shade, evaporation, albedo & surface roughness on air temperature avs. & range: forests, open land. b. Vegetation topo. effects: frost pockets.	a. Trees: momentum absorption in & out of leaf. b. Shelterbelts. c. Forest canopies. d. Short vegetation.	a. Insolation penetration thru canopies. b. Daylight duration in forests. c. Albedo of veg. surfaces.	a. Rain interception, penetration time thru trees. b. Leaf drip.	a. Vapour profiles in forests, above crops. Influence of shelterbelts.
E: Surface	a. Temperature profiles. b. Diurnal ranges.	a. Wind profile. b. Wind turbulence. c. Surface drag.	a. Albedo.	a. No effect.	a. Surface moisture vapour profiles.

Figure 8 is a matrix of site influences, at the above five scales, on five climatic elements which are likely to occur in climate : activity functions. The site influences which are listed are briefly described in Appendix IV.2., together with a selective bibliography. There is no pretense of completeness here: Figure 8 covers virtually the entire fields of meso and micro-climatology. What is suggested is that the experimental data on site effects be sorted and catalogued in such a matrix in order to avoid errors of scale when determining site influences. Existing experimental data is frequently used out of context to represent a site phenomenon at a completely different scale.

The modifications represented by the appropriate scales in Figure 8 should be applied in sequence, in order of decreasing scale, to give the influence of a given site. In the design process, this represents the 'site modification process' as shown on Figures IV 4, 6, and 7.

3.4. Methods of testing and predicting site climate.

Testing on site. Obtaining climatic records on site, either for a complete record or to use as a comparison to established records, has been mentioned above. Shorter term simultaneous readings might be taken within the site to determine the relative climatic quality. Simultaneous wind readings taken over very brief periods, for example, will give the effect of local shelter or topography, even if the link to regional weather records is impossible. There are instruments for measuring potential radiation on a site (Horizontoscop, Globoscope, Robin Hill camera).

Model testing is done for sun and wind. Numerous solar modelling apparati make use of the direct similarity between model and full scale for light studies. Wind modelling is more complex, and is currently being heavily investigated. The problems involve obtaining geometrical similarity of flow, of wind profile over the surface, and of wind turbulence. These three problems can be approached separately. The first is avoided, for sharp-edged bluff bodies, by proven similarities in flow pattern (Jensen, 1958). However, for studies of curved surfaces this similarity does not hold, which at present rules out the study of most topographic site effects in the wind tunnel. The problem of profile has been approached in basically two ways. In one the retarded flow near the surface is produced by placing an obstructing grid across the airflow, in which the size of the openings decreases toward the surface. In the other, shear is produced by surface drag on a length of roughened tunnel floor upwind of the test section. Neither of these methods necessarily produce turbulence effects in scale with natural turbulence; in fact it is suggested (Armitt and Counihan, 1968; Counihan, 1969), that this is impossible. Instead, empirically derived wedge shaped 'turbulence generators' are being inserted between the profile-generating mechanism and the test section. The results of such modelling are being investigated.

At present, a reasonably profiled wind tunnel is a proven tool for predicting the flow patterns around sharp edged objects. It is still lacking a means of estimating accuracy due to a paucity of confirmatory experiments between model and full scale (Royal Society 1971). At the outset of this thesis work, the author did a comparison between model tests and full scale on a complex of buildings in the University of Edinburgh. This gave a very close prediction of the directions of the flow patterns, as has been noted in other work. The ratios of simultaneous wind velocity between the top of a tall building and fifteen stations on the pavement below were consistently low in the model, which can probably be ascribed to an incorrect profile. The ratios among the surface stations themselves showed quite a close correspondence between model and full scale. This type of experiment is much needed to determine the usefulness of tunnel testing, and has not been systematically carried out. Some of the results of this experiment are presented in the next section as part of a suggested design method.

3.5. Conclusions.

The site imposed modifications of the regional climate have been briefly discussed and an order for their consideration proposed in Figure 8 and Appendix IV.2. No attempt has been made at comprehensive description of the site effects. Appendix IV.2. and its references are used only to point out the important effects. It is suggested that, in the absence of empirical data below a given scale, general climatological principles be applied to obtain an estimate of the climate of smaller scales. These principles, physical or experimental, must not be applied out of the scale limits they were derived for. For this, it is suggested that climatological information from many diverse sources be combined in a matrix with at least as many scale categories as Figure 8. Then, any given site can be seen as a composite of decreasing scales on the matrix, and the appropriate modifications applied in series from large to small scale. The climatic data available for some of these categories is very sparse and difficult to apply, particularly concerning wind at the larger scales. In other categories, however, the physical principles are well understood, and only need to be collected from the various disciplines and ordered to become useable.

Two references which also deal with the ordering of site modification of climatic data, although in different ways, are Page (1971a) and Lacy (1972).

IV. 4. Climatic design: evaluated climatic predictions in the design process.

4.1. Introduction,

The evaluations of site climate and site follow climate prediction in the pathway given in IV Figure 7. It is at the evaluation stage that the influences of other design considerations are combined with those of climate. Economic pricing is too large a subject to be in the range of this thesis. Instead, the place of climatic considerations in the overall planning process will be indicated in Section 4.2. below by expressing the climatic information pathway (IV Fig. 7, Sections IV 1, 2, and 3) in terms of a general design theory which applies to all planning and design problems.

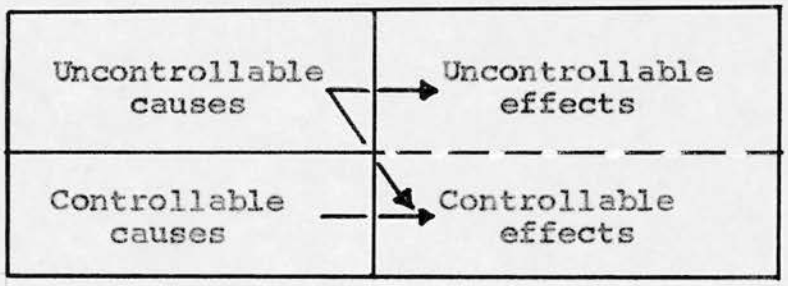
In the design theory given in Section 4.2., the designer's alteration of climate (the decision loop of Figure 7) comes from the last step in the design process: "the comparison of and selection from alternative sets of parameter values". A more specific description of this last step is given, for the problem pedestrian comfort, in an example in Section 4.3.

4.2. The design process.

Levin (1966, 1967) has analysed the planning and design process, and given a sequence of eleven operations essential to the design process. These operations effectively cover the consideration of climate in design which has been described in the previous Sections. Since it is not the intent here to discuss design theory at length, we will accept Levin's sequence and show how the climatic analyses of the previous Sections fit into it. This will put the contents of the thesis into the framework of an overall theory of design. No attempt is made to describe the place of climatic design in relation to other design criteria. The procedure of combining diverse criteria in the design process is analysed by Levin's (1967) and other design theories.

Levin's design analysis is based on two types of causes and effects: those controlled and uncontrolled by the designer. These are shown in Figure 9, from Levin (1966).

Figure 9



In Levin's system the only controllable causes are the characteristics of the design, the "design parameters". Uncontrollable causes (the independent variables in the cause-effect relationship) include the weather. Controllable effects (dependent variables) represent the designer's goals. In the case of weather, the controllable effect would be site climate. The boundary between controlled and uncontrolled effects is blurred, because the extent of design control usually cannot be determined.

For a designer manipulating physical shapes to achieve a desired site climate, his ultimate goal 'comfort' would be a "secondary effect" in Levin's system, following the primary one of design-controlled site climate. The only design manipulation involved comes in the primary stage and follows from the site modification procedure of Section IV.3. The sequence required to find the comfort implications of the designed climate is direct (IV Fig.4) and involves no design or decisions. Likewise, the economic implications of a climate's comfort are seen a secondary effect of comfort, linked by a direct relationship.

It is possible, however, to view the stage 'site climate to comfort' as a design process itself. In this case, the designer manipulates hypothetical site climates to achieve the required comfort. The actual creation of the selected site climate would then be undertaken as a second step, involving the design process mentioned above. In instances where comfort might be very important, this two step procedure working backwards from comfort would be justified. Moreover, the designer does have some control over the degree of exposure of his pedestrians and their level of metabolic activity when exposed. Because of this, design decisions enter into the 'site climate to comfort' stage, and the design parameter here is the 'degree of exposure' or 'effectiveness of exposure'. For these reasons the design process given by Levin will be specifically described for: (a) the design process of making a site climate from ambient climate, and physical planning, and (b) the process of determining comfort from the site climate.

1. The identification of design parameters (measures of controllable causes).
   (a). Assessment of design dimensions which can significantly affect climate, as given in the scales and shapes described in Figure 8.
   (b). The elements of the site climate affecting comfort: T, V, I; from Chapt. II and IV.1.
   The measure of pedestrian exposure to site climate: Times of exposure as expressed on an activity chart, length of exposure, levels of activity; Chapt. II and IV.1 and IV.2.

2. The identification of independent variables (measures of uncontrollable causes and effects).
   (a). Existing climatic conditions.
   (b). Site climate (uncontrolled aspects).
   Pedestrian exposure, resultant of behaviour not under designer's control.

3. The identification of dependent variables (measures of controllable effects).
   - (a). Site climate. (Controllable or predictable part may be used as the design parameter for process (b).)
   - (b). Pedestrian comfort: from IV.1. it is seen that the variable wanted is the time, or probability, of comfort and discomfort.

4. The identification of relationships among parameters and variables.
   - (a). Climate to site relationships summarized in IV.3, Figure 8, A IV 2.
   - (b). Thermal and physical climate to comfort relationships for different types of exposure are derived and schematically proposed in Chapter II, and described in IV.1, IV.2, and Figure A.1. Activity parameter required.

5. The prediction of values of independent variables.
   - (a). Obtaining climatic data: methods and principles described in IV.2., and the site influences summarized in IV.3.
   - (b). The prediction of site climate for the comfort relationships follows from the process (a) above. The prediction of pedestrian behaviour is achieved by survey and the preparation of an activity chart.

6. The identification of constraints governing dependent variables. (Limits on designer's ends, rather than means).
   (a). Limits to which climatic elements can be controlled. From general information, as suggested in IV.3. (Possible heirarchy, in order of decreasing difficulty to control: temperature, wind, rain, radiation).
   (b). Limits on the extent to which comfort is determined by climatic influence. (Comfort might be more significantly influenced by something else, visual or psychological. This has intentionally not been discussed in this thesis.)

7. The identification of constraints governing design parameters. (Limits on the means by which the designer's ends are attained.)
   (a). Limits to the designer's ability to manipulate the form of the design in order to modify climate.
   (b). Limits to the ability to predict comfort from climate-comfort relationships. Limits to the designer's ability to affect the pedestrian's exposure to climate. (Climate-comfort relationships affected by differences between individuals, levels of clothing, levels of metabolic activity. The designer has some control over the latter. Pedestrian exposure is affected by time of exposure and length of exposure. The designer has some control over the latter.)

8. The identification of values of design parameters.
   (a). The dimensions of the design which affect climate follow from operation 1 (a).
   (b). Predicted site climate. Predicted behaviour (exposure) in terms of time (activity chart).

9. The identification of values of expected values of dependent variables.
   (a). Site climate predicted from relationships from IV.3.
   (b). Comfort of a design assessed: procedure of IV Figure 4.

10. The investigation of the consistency of values, relationships, and constraints.
    (a). Consistency of relationships and constraints is obtained by proper selection of functions (IV.3.). The consistency of values obtained is obtained by determining site effects through a series of steps from larger to smaller scales.
    (b). Section IV.1., Figure A.1. and Figure 7 include this.

11. The comparison of, and selection from, alternative sets of parameter values.
    (a). Designs chosen after comfort of each design assessed (and evaluated, perhaps economically). Thus pedestrian comfort, through the comfort function and exposure assessment, suggests a site climate which suggests a design. This is

the 'decision loop' outlined in Figure 7.

(b). Possible decision to alter site climate requirements. Possible decision to influence pedestrian behaviour and exposure.

In conclusion, the decision whether the existing or predicted site climate should be modified is thus entirely part of operation 11, and is seen by Levin as a choice between alternative solutions. For some (usually engineering) activities the relationships might be sufficiently exact that a single solution might result from a sequence of problem solving. With comfort this is likely never to be the case. A suggested way of implementing Operation 11 for an architectural complex is suggested below.

4.3. A way of assessing a proposed design for its pedestrian comfort.

The David Hume Tower complex at Edinburgh University was conceived and constructed as one unit. It includes a complex of surrounding buildings, a pedestrian precinct between them, and a lowered courtyard which was intended as an outdoor extension of the refectory. The wind conditions in the pedestrian areas are generally considered to cause excessive discomfort, and one evidence of this is that the refectory extension has never been opened.

A wind tunnel study was undertaken on a model of this complex, and in order to test the tunnel accuracy, full scale measurements were also run. The model tests were found to be consistent in most respects, indicating that if the model had been tested during the design process, before actual construction, the unsatisfactory results could have been observed and perhaps avoided. The following series of figures briefly suggests some ways in which climate and comfort might be analysed in the design process.

Figure 10a is a schematic activity chart for pedestrian traffic, as obtained by survey.

Figure 10b is a plan of the area modelled showing the main expected pedestrian routes and gathering places.

Figure 11a is a detail of the modelled area, showing the pattern of wind directions at 1.5 m height above the pedestrian precinct around the tower block. The arrow length suggests wind strength. The gradient wind for this study is from the octant SW to W, which applies 40 to 50% of the time during the Edinburgh winter. It can be seen that the tower slab is oriented perpendicularly to this wind, which results in the roller effect described by Wise (1970). Another study should presumably be made for the other predominant wind direction, from the east, which applies 10 to 20% of the time during the Edinburgh winter.

Figure 11b is a contour map of wind strength expressed as a fraction of the gradient wind at 60 m, 5 m above the tower top. During full scale tests, this wind velocity proved to be slightly greater than that recorded by the meteorological station on the exposed site of Edinburgh Airport. Zones of air lifting and dust blowing are also marked.

Figure 12a and b show shadow areas at two hypothetically important periods during the day. Degree of shading time averaged over the entire day can be represented by a system of contour lines. The hourly sun (or shadow) times could be first weighted according to their importance, as shown onthe activity chart Figure 10a, and then integrated into an 'index of shading'. Such an index would apply to any pedestrian space.

Figure 13a shows the sequence of climatic elements experienced by a pedestrian traversing the most commonly used pedestrian route. This diagram could also be presented in isolation, as has been done in some visual experience studies of motorway landscaping.

Figure 13b maps the entire area for its thermal comfort to the average pedestrian, assuming a given temperature, wind speed, and sunlight. The temperature used is 5°C, and the wind speed at tower top 6 m s^{-1}, the average winter velocity. Areas of physical or mechanical wind disturbance are marked also. The thermal comfort is determined very simply by reading from Figures II 17 through 20.

In conclusion, the success of the proposed project can be measured and evaluated from figures such as these.

The designer might decide from such results, at minimum, to spare himself the expense of the sunken courtyard refectory. Preferably he would try several arrangements of the physical layout of tower block and pedestrian areas in order to achieve a more successful result. Detailed design, such as locations of vegetation, wind screens, wind deflectors, and dust particle traps should also follow from such analysis.

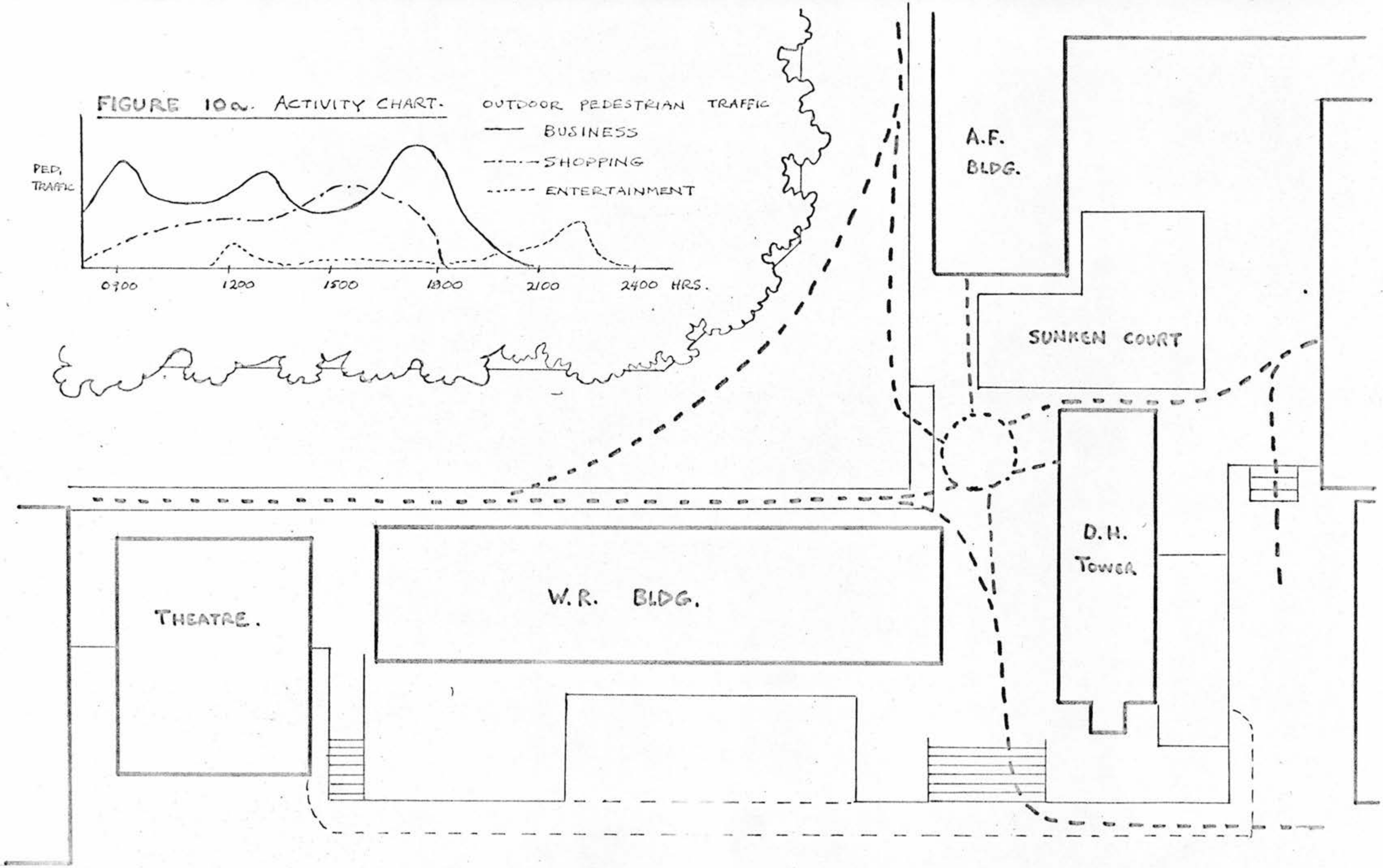


FIGURE 10a. ACTIVITY CHART.

FIGURE 10 b.

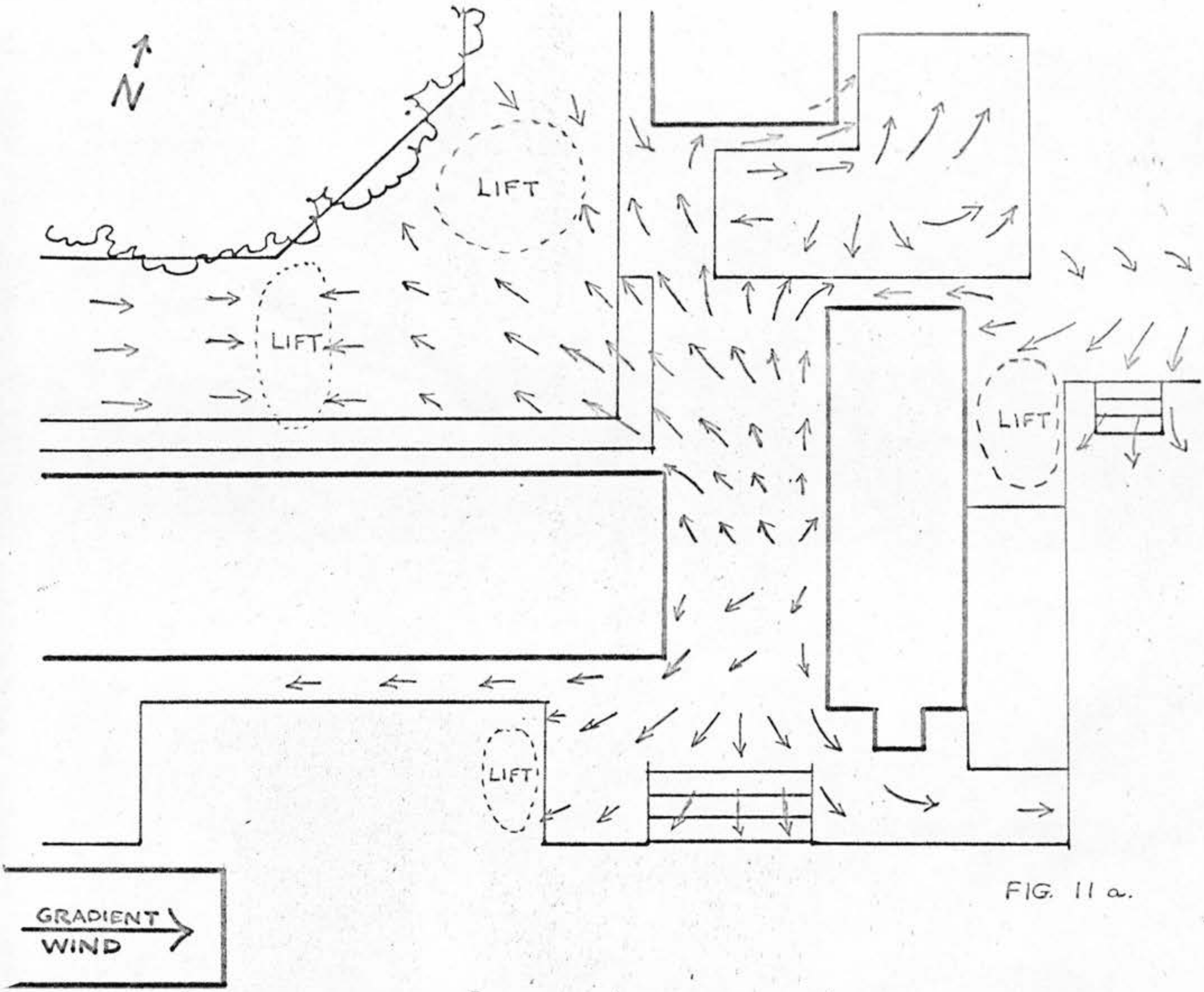
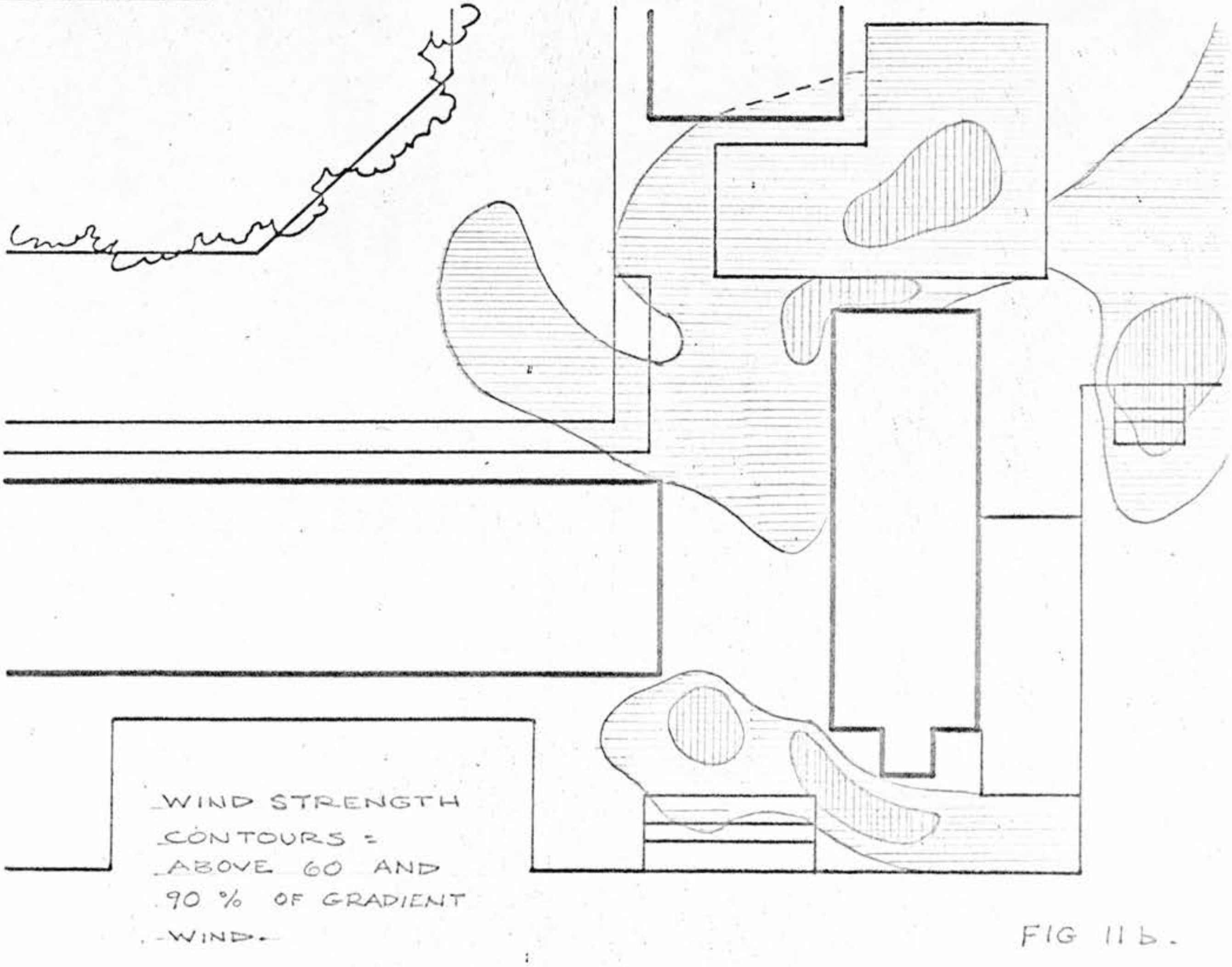


FIG. 11 a.



WIND STRENGTH CONTOURS = ABOVE 60 AND 90 % OF GRADIENT WIND.

FIG 11 b.

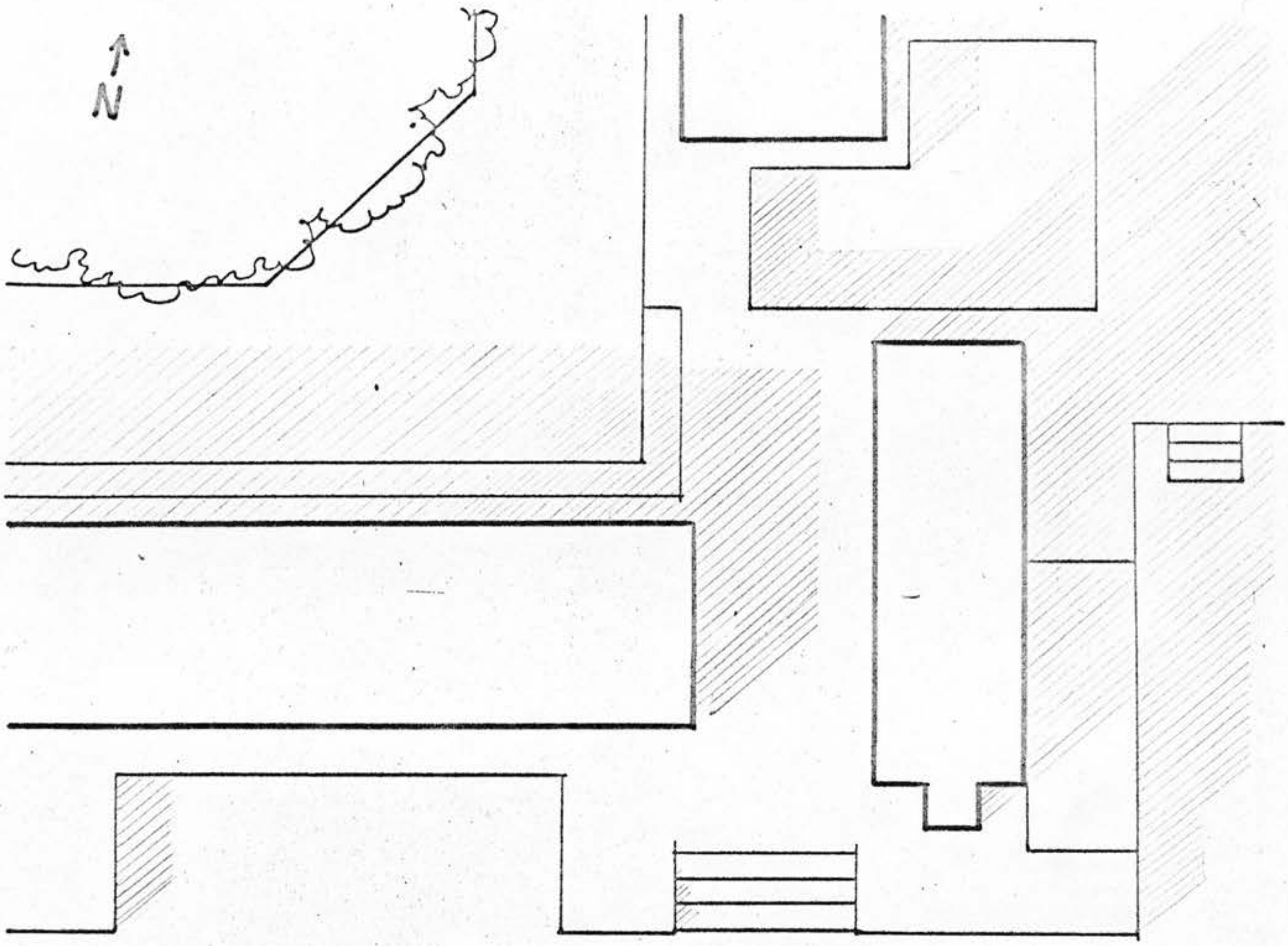
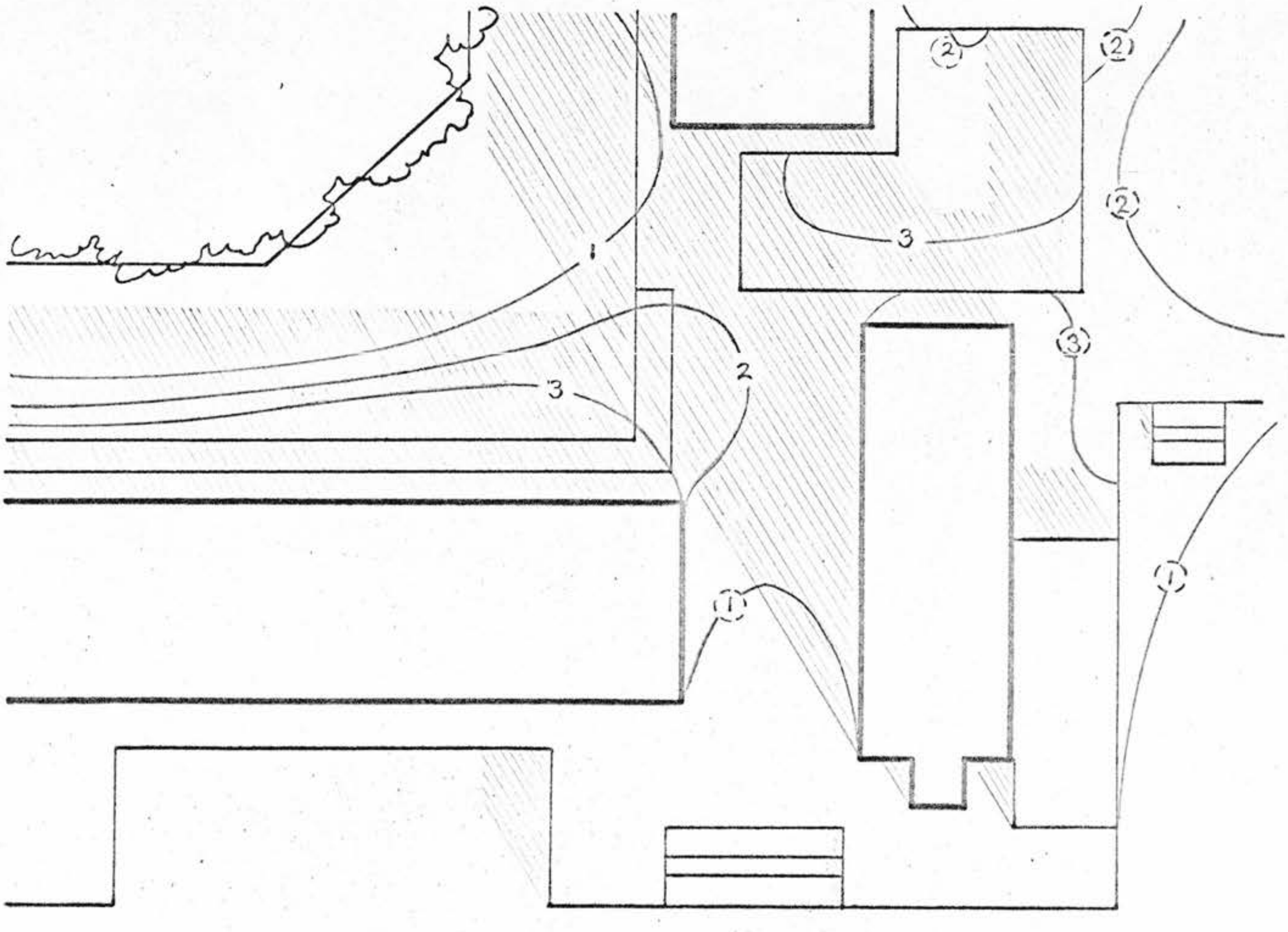


FIG. 12a



1, 2, 3 REPRESENT SHADING CONTOURS

FIG. 12b

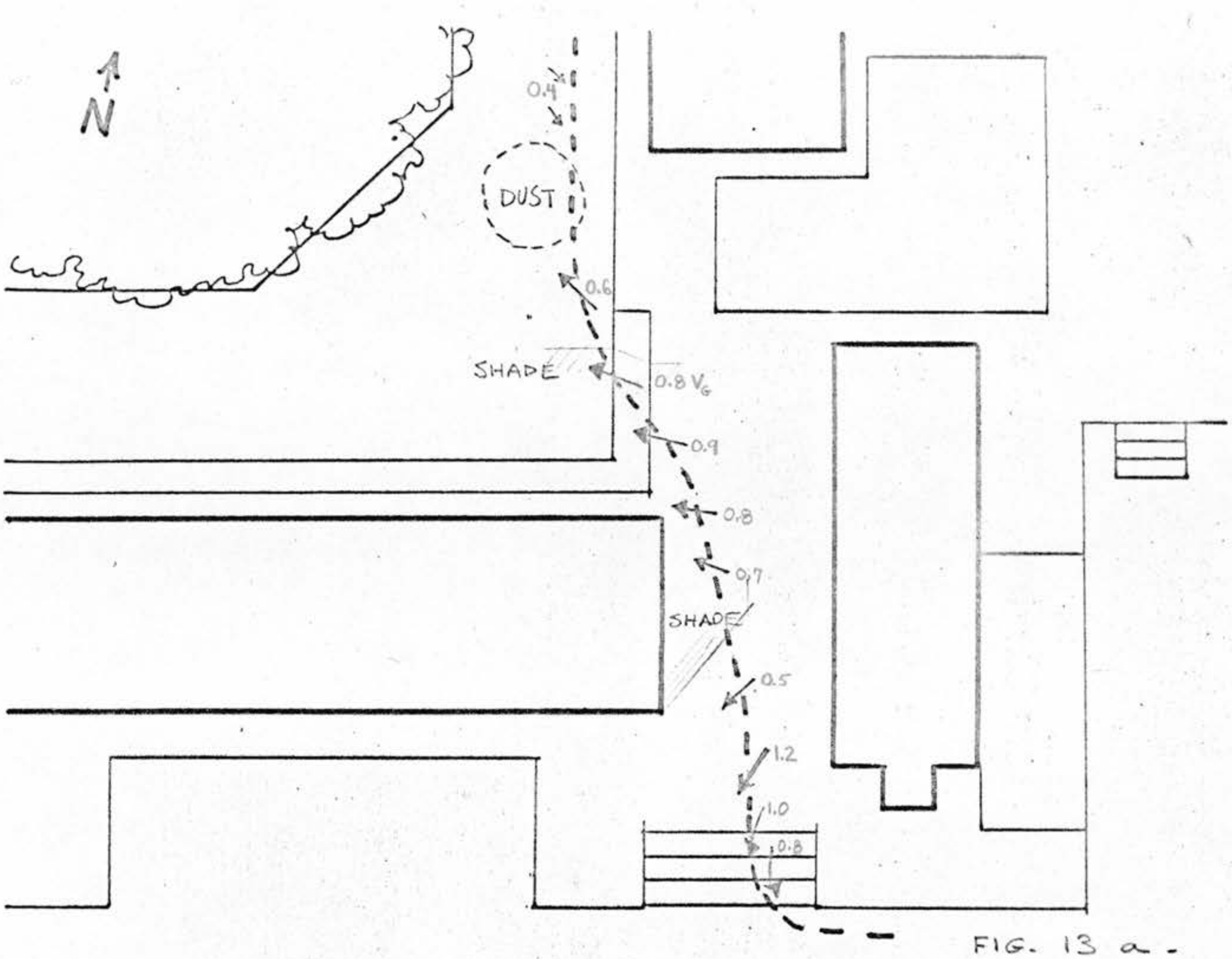
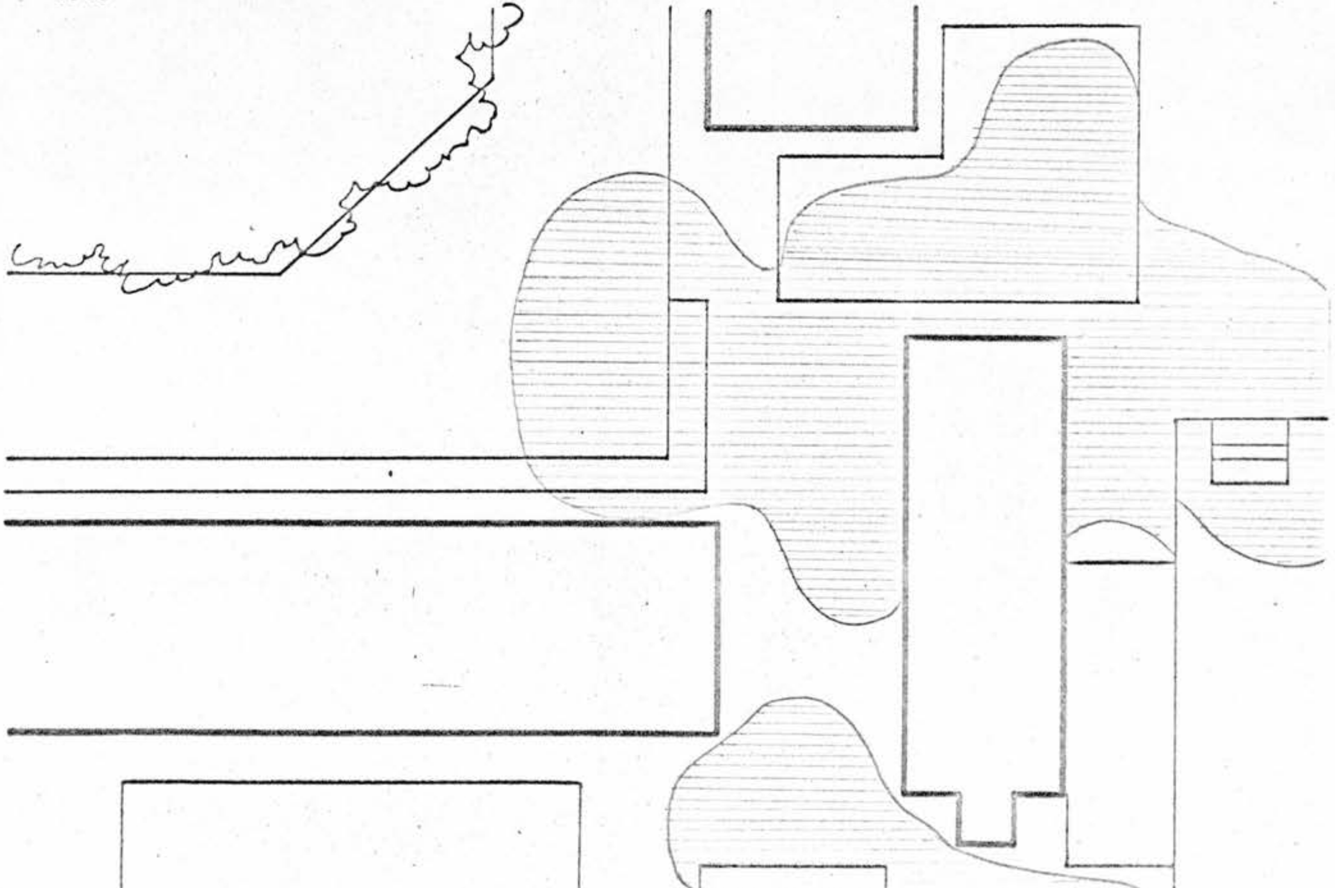


FIG. 13 a.



ZONES OF DISCOMFORT FIG 13 b.

CHAPTER V

V. Conclusion.

Detailed conclusions have been made at the ends of the thermal and physical parts of Chapter II, the end of Chapter III, and the ends of each of the four sections of Chapter IV. These each discuss results, methods used and proposed, and directions for required research. Certain overall observations will be made here.

Chapters II and III give values which are immediately useable in design. It must be recognized that, with the exception of some measurements of physical wind effects, these results are all based on theoretical calculations and experimental data in the literature. Moreover, a number of simplifying assumptions about both the activity and the climate are inevitable. These have been described in the respective chapters. Checks and comparisons of the results with those of all other available sources have been made, and the agreement is generally satisfactory. However, the total amount of work in both these fields is small and dispersed, and for reliability some empirical testing is strongly recommended - the specific nature of such research is suggested in each chapter.

Pedestrian comfort and building heat loss represent two types of function, but also two types of data approach. Pedestrian comfort might well be the more important activity function, but the analysis of required climatic data in Chapter IV shows that it is less interesting from the viewpoint of the climatic information needed. The comfort function, as developed, ideally requires instantaneous data, with averaging periods as short as possible. The data specifications of directionally associated hourly probability distributions of contingencies of T, V, and I are as yet unobtainable, and it is up to the climatological data services to eventually provide such information.

The building heat loss function, on the other hand, inevitably relies on averaged climatic data. For such a low information content description of the climate, a higher general understanding of the climate is required. This is particularly true for the comparison of comfort and building heat loss, where the better understood heat exchange functions for building surfaces make the building heat loss function more sensitive to climatic elements such as cloudy and clear sky, atmospheric conditions, and solar radiation. The climatic appendices to Chapter III reflect this.

The simplifications of the possible climatic regimes ('situations'), the minimization of climatic data required to represent the entire climate accurately, and the method of adding the climatic effects of each situation are part of the achievement of Chapter III.

The discussion of climate and climatic data is represented most concisely in the series of figures IV A 1; 4, 6, 7, and 8. The distinguishing of two classes of function, the methods of function analysis, the pathways of climatic data handling and data prediction, and the design procedure of site evaluation are the most significant contributions.

APPENDICES

Appendix 1: List of symbols used.

Symbol		Dimensions
W	Watt.	
m	Metre.	
s, sec	Second.	
h, hr	Hour.	
T	Temperature	°C
$T_{a,w,b,s}$	Air, wall, building, surface (skin) T.	"
T_e	Effective exterior temperature.	"
T_{es}	Sol-air effective exterior temperature.	"
$T_{D,d.}$	General temperature data (Chapter IV) linked with associated wind direction.	
t	Time.	
t_I	Time at insolation level I.	h
S_p	Possible sunlight hours per day.	$h \cdot day^{-1}$
S	Ratio recorded to possible sunlight hours.	-
c	Fractional cloud cover.	1/10ths sky
z	Height above surface.	m
V, v, U, u	Wind velocity.	$m\ s^{-1}$
	V also refers to general wind data in Chapter IV.	
$V_{D,d.}$	Directionally specific wind data.	
w', v'	Vertical, lateral eddy velocity.	"
U_*	Friction velocity.	"
S^*	Wind steadiness.	
R_*	Run of wind.	km
R	Rain (occurrence or amount)	

Q	Heat flux	W, or $W\ m^{-2}$
Q_v	Heat loss due to ventilation (per unit surface area).	$W\ m^{-2}$
S'	Storage (change of body heat content).	"
M	Metabolic rate.	"
E'	Evaporative heat loss.	"
Q_r	Net radiant Q to or from surface.	"
Q_{ro}	Net radiation surface to clear sky.	"
Q_{rc}	Net radiation surface to cloudy sky.	"
$G_{o,c}$	Atmospheric counterradiation from clear, cloudy sky.	"
I	Insolation: total shortwave radiant flux density (irradiation) of a horizontal surface.	"
	I also refers to general insolation data in Chapter IV.	
I_d	Diffuse (sky) radiation.	"
I_s	Direct beam radiation on normal surface.	"
I_{sh}	Direct beam radiation on horizontal surface.	"
I_o	Insolation from clear sky.	"
I_c	Insolation from overcast or partly cloudy sky.	"
I_e	Extraterrestrial direct beam irradiation.	"
$I_{D,d}$	Insolation data, linked to wind direction.	
k_i	Atmospheric absorption coefficient.	
β	Zenith angle.	
φ	Latitude.	
ε	Emissivity.	
a	Absorptivity.	
α	Albedo, reflectivity.	
E	Effective emissivity $(\varepsilon \cdot \varepsilon)$.	
σ	Stefan Boltzmann constant.	

e	Partial pressure of water vapour.	mb
p	Atmospheric pressure.	mb or mm H_2O
λ	Thermal conductivity.	$W\ m^{-2}\ {}^oC^{-1}\ m$
d	Depth of conducting element.	m
r, R	Resistance: $(1/c_2,\ 1/K)$.	$m^2\ {}^oC\ W^{-1}$
c_2	Conductance.	$W\ m^{-2}\ {}^oC^{-1}$
K	Transmittance.	"
h_c	Surface convective coefficient.	"
h_{ct}	h_c for thermal convection.	"
h_{cv}	h_c for forced convection.	"
F	Friction coefficient.	-
h_r	Surface radiative coefficient.	"
h_s	Combined surface coefficient.	"
$h_{i,e}$	Internal, external combined surface coefficient.	"
c_1	Specific heat.	$W\ h\ kg^{-1}\ {}^oC^{-1}$
C	Heat capacity.	$W\ h\ m^{-3}\ {}^oC^{-1}$
C_d	Heat capacity per unit surface area.	$W\ h\ m^{-2}\ {}^oC^{-1}$
ρ	Density.	$Kg\ m^{-3}$
$\alpha,$	Thermal diffusivity: $(\lambda/\rho c = \lambda/C)$	$m^2\ h^{-1}$
Q^*	Air change rate.	$m^3\ h^{-1}$
V_o	Volume of building.	m^3
N	Air change of building per hour.	-
G_1	Volumetric heat loss coefficient.	$Kgcal\ h\ m^{-3}\ {}^oC^{-1}$
A	Body area.	m^2
$A_{w,r,t}$	Wall, roof, total area of building.	"

X_D, or X_{1-4}: Climatic data associated with wind direction.

T,V Contingency of climatic data T and V.

T:V Function involving climatic elements T and V.

Note: The majority of equations quoted in the thesis have required conversion from other unit systems, and many have had symbols translated. For this reason the conversion has not been mentioned in each case.

II Appendix 1

1. Humidity and long wave radiation.

The information on the effect of humidity in cold and cool temperatures is contradictory. The popular concept of damp cold is well established. Research initiated by Yaglou shows it to be neglectable in cool temperatures once a moisture balance has been attained (Newburgh, 1949): "In continuous exposures of three to four hours, the subjects readily adapted themselves to the test conditions and showed no significant difference in rectal temperature, pulse rate, blood pressure, moisture loss, or impressions of comfort with different humidities at any given temperature".

It was found in the above work that there is an impression of warmth which immediately affects a subject if he walks from a dry to a humid room at the same temperature. This is ascribed to the warmth of moisture adsorption into the skin and the surrounding fabrics. Its reverse, desorption, causes a cooling effect when going into a dry environment from a humid one. In either case the effect is temporary. It would have to be taken into consideration if frequent changes indoors to outdoors were expected, but in the usual outdoor environment this effect could be neglected.

Physiologists generally discount humidity as a factor of comfort in cold temperatures (Nevins and Hardy, 1964).

Experiments on subjects outdoors in Canada were carried out by Piggot (1969) which showed that humidity had a probable warming effect on temperature sensation. The commonly expressed sensation of 'damp' was found to be related to overcast conditions. In the presence of solar radiation all subjects felt warm and dry regardless of the actual humidity. Burton, Snyder, et al (1955) showed that skin temperature remained the same between 30 and 80 per cent relative humidity (at 10 and 15°C), but that more shivering and sensation occur at the low humidity level. A contrary view, however, states that between 7 and 0°C the humidity makes air temperatures seem lower. Below this range humidity is said to be unimportant (below the freezing point) and above it there is a slight warming effect. This opinion was not supplied with any experimental evidence (Terjung, 1966). O'Connor (1936) states the same opinion. Tromp (1963) gives a list of three possible factors which could cause the commonly perceived cooling:

1. Skin absorption of water vapour and loss of insulative capacity.
2. Clothing: increased conductivity due to changes in fabric caused by vapour absorption.
3. Walls: evaporation on surrounding walls and in clothing also chills.

A mist in air definitely increases feelings of cooling, and affects the insulation of clothing. Whether uncondensed humidity adversely affects most insulations is only speculated at by Tromp. Quantitative values for any of the above are not to be found.

2. Effect of thermal radiation on comfort.

For indoor conditions there is a mean radiant temperature (MRT) which is distinct from mean air temperature (MAT). It consists of the temperature of the surrounding objects which radiate to the subject. Evidence for the relative importance of MRT differs. Koch (1962) gives MAT = -1.39 MRT up to a 10°C difference from the comfort zone of 21 to 30°C. Nielsen and Pedersen (1952) show that at low air temperature the resultant temperature is closer to the MAT than the MRT. A contrary view from architectural practice states that wall temperatures produce a warming effect equal to 1.25 times the equivalent air temperature difference: i.e. if the air temperature drops 1°, a rise of 0.8° MRT will compensate for the reduction (Olgyay, 1963). This assertion is perhaps inverted. In actual conditions MRT will not exceed MAT by more than 2.2 to 3°C. In outdoor conditions MRT is probably unimportant.

II Appendix 2

Skin temperature and comfort.

1. Measurement: **Mean Skin Temperature.**

The most satisfactory way of obtaining a temperature measurement corresponding to comfort is to use Mean Skin Temperature. This means that physical measurements can be made in place of subjective judgments, but it is still necessary to calibrate each individual because of the wide variation between different people. Because of the number of measurements needed, the overall procedure is a difficult one. Mean Skin Temperature is measured by taking surface measurements with thermocouples at a number of places on the body, and weighting the readings according to the areas involved. A typical example would be: (Winslow, Gagge, and Herrington, 1938)

Surface temperature readings: 15 points.

Thermocouple	points	weight
head	3	7
hand	1	21
arm	2	
trunk	4	31
leg	5	41

The readings on the head and hand are on exposed surfaces. The readings for arm, trunk and leg are values from under clothing. Thermocouples are sometimes placed on the clothing surface at the same positions on arm, trunk, and leg to be used in conjunction with the head and hand measurements to give a Mean Clothing Temperature, which will occur in Winslow and Herrington's formulae.

2. Temperature of different parts of the body in relation to comfort.

The skin temperatures of different parts of the body vary considerably. When a subject is comfortable with a deep body temperature of 36.9 to 38.0°C and his heat production is equal to heat loss, the surface of the skin of his toes may be at 27°C, the surface of his arms at 31 to 32°, and the forehead and chest at 34 to 35° (Winslow and Herrington, 1949). The following figures show the comfort limits of an average clothed, semi reclining subject (Yaglou and Messer, 1941; Gagge, Herrington, and Winslow, 1938).

Pleasant	Mean Skin Temperature	32.6 - 34.4
Unpleasant	Mean Skin Temperature	< 30
	Head temperature	< 31
	Upper extremities	< 30
	Lower extremities	< 29

The values have been found to apply regardless of the amount of clothing worn during light and sedentary action. For heavy manual work and also for sudden temperature changes, the correlation of skin temperature to comfort ceases. During heavy work the skin temperature is lowered substantially for a time by the diversion of blood to the muscles, without giving the subject an uncomfortable feeling. During rapid temperature changes the skin requires time to settle to its new temperature.

3. Skin temperature and air movement.

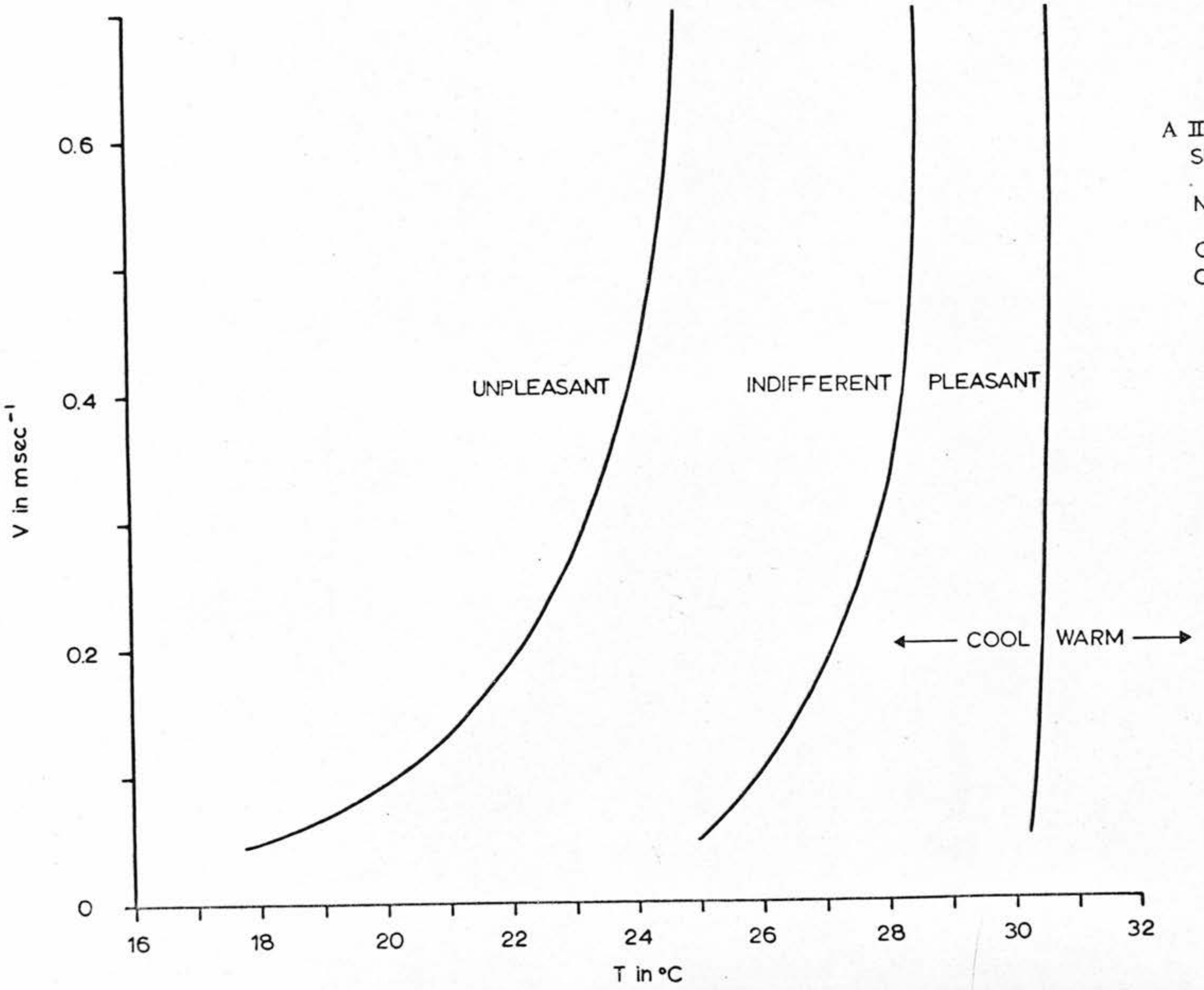
Low speed air flow, draughts, have a significant effect on skin temperature and comfort. The study by Lotz and Wezler (1951) gives a complete list of skin temperatures for the forehead, upper arm, forearm, dorsal part of hand, breast, epigastrium, thigh, leg, and instep at temperatures of 35, 30, 25, 22, 15°C, and at air velocities of 0, 0.2, 1.1, 2.0, and 2.8 m/sec. The following list gives the values for 0 and 2.8 m/sec, both at 15°C:

Positions: nude	Orig.Temp. Still air	2.8 m/sec
Forehead	33.1	21.5
Upper arm	31.5	20.5
Forearm	32.6	20.8
Hand (dorsal)	32.0	17.1
Breast	32.8	24.4
Epigastrium	33.6	21.4
Thigh	32.3	20.7
Leg	31.9	21.1
Instep	31.8	15.4

The study showed that air movement accentuates the observed differences in temperature between the different parts of the body. It was also seen that the skin temperature of women falls faster with increasing wind than that of the males, but that women did not shiver whereas males did.

The study gave no comfort information.

Another set of data (Winslow and Herrington, 1949) gives the feelings of comfort, with skin temperatures, at various air temperatures and low air velocities, for semi-reclining nudes. This is presented in Figure A II 2 1. These values were empirically derived, but formulae for finding skin temperatures of a nude in varying wind speeds and metabolic rates are given in the same reference. They are too specific to be included here. The effect of draught temperatures and velocities on skin temperature was also studied by Houghten et al (1938, 1942). Draughts from above and behind were found to be more noticeable, and the neck was much more sensitive than the ankle, possibly because of the close proximity of the hypothalamus. People with low mean skin temperatures show a higher sensitivity to chilling, (Bedford, 1936).



A II.2 FIG. 1: SKIN TEMPERATURE & COMFORT SENSATIONS.

NUDE SUBJECTS SEMI-RECLINING

OPTIMUM SKIN T RESTING NUDE = 33.5 °C
OPTIMUM SKIN T ACTIVE NUDE = 29.4 °C

II Appendix 3

Sexual, diurnal, and seasonal differences.

Sexual characteristics cause consistent differences in the sensation of temperature. The skin temperature of women in a cool environment is an average of 1.0°C cooler than that of men. This is caused by the additional insulation of the subcutaneous fat layer found on women, which isolates the surface from the warmer deep body temperature. As a result they are comfortable with lower surface temperatures than men are. Women can withstand 2° colder temperatures and lose 10% less heat than men when equally exposed to cold, (Winslow and Herrington, 1949). The usual women's garb is however much less insulative than that of men. This has an overriding influence when women and men are exposed to the same climate, the women being in their usual clothing more susceptible than men. In addition to this, it has been suggested that women can decrease their basal metabolism in warm conditions 15 to 20% below than that of men. As a result, when women move from a warm comfortable environment to a cold one, the immediate effect is greater for them than for men.

Diurnal differences. The time of day also has an effect. Both men and women have a rise in body temperature during the day. The total amount is between 0.6 and 1.3°C (Year book of medicine 1955). Body temperature influences temperature perception and comfort (Section 2). Therefore one could assume that people would be more susceptible to cooling winds during the night and in the early morning than later in the day when their metabolisms have become more active. The same is true for people who have been at equilibrium in a hot or warm indoor environment, and whose metabolisms have not yet responded to exposure to cooler air.

National differences, standards. An optimum effective temperature for still air and lightly clothed people has been observed for summer and winter (Bruce, 1960). This changes slowly with the season, and is unaffected by periodic changes in the weather. There are regional differences to this optimum temperature which are due to acclimatization, heating custom, and the amount of clothing commonly worn. Optimum effective temperature for the U.S. is given as 20°C in the winter and as 22°C in the summer. Women prefer 0.5° higher than this and women over 40, 1.3°C. At night, the optimum E.T. has been found to be 0.6° higher, for the reasons described above (Houghten, et al 1938). There are substantial differences between the U.S. optimum temperature and that of the British (18° at present). These differences are presumably mostly due to indoor heating practice and the amount of clothing correspondingly worn. National differences in preference for indoor temperature seem to be disappearing. Given the choice, British people are now tending toward wearing lighter clothing indoors and preferring American temperature standards (A.Hardy, 1971,lecture).

Sensations of comfort relative to the optimum effective temperature are expressed below:

1.	Cold	-5 ET ° C
2.	Too cool	-3.3
3.	Comfortable cool	-1.7
4.	Ideal comfort	Opt. E.T.
5.	Comfortable warm	+ 1.7
6.	Too warm	+ 3.3
7.	Hot	+ 5

Appendix 1

Climatic influences on Q_r.

The downward flux of thermal radiation from the sky depends on an involved array of considerations. These include the temperature of the different radiating layers of the atmosphere, the concentrations of water vapour and CO_2 below the emitting layers, and the percentage and type of cloud cover, as well as the temperature of the cloud base.

1.) Radiation exchange with a clear sky.

Radiation from a clear sky depends on the temperatures of the radiating layers. The radiation received in the bands 4 to 8 and 13 to over 30 microns is equivalent to that of a black body radiating at $263^{\circ}K$. At 9.6 microns there is a narrow band of emission from the high altitude ozone belt at $235^{\circ}K$. Since the sky radiation curve is irregular (see Robinson, 1966), the integrated energy received will equal the total emission of a black body at an 'effective sky temperature' ranging from $250^{\circ}K$ (Reifsnyder and Lull, 1965) to $230^{\circ}K$ (EEU, 1965) to $223^{\circ}K$ (Mackey and Wright, 1946). In Alaska, clear sky values as low as $193^{\circ}K$ have been recorded (Gates 1962). These values are affected by the transparency and emission of the lower levels of the atmosphere.

Derivation of an analytical expression used to describe atmospheric radiation can be found in Haltiner and Martin (1957). The Elsasser Radiation chart (1960, in the revised form) presents the radiation in terms of the atmospheric temperature and moisture profiles, as well as description of the cloudcover and its temperature. Information from meteorological soundings is required to determine the temperature and moisture profiles.

In order to simplify meteorological data collection, several investigators have proposed empirical expressions of clear sky radiation based on surface air temperature and surface water vapour pressure. The approximation is considered satisfactory because most of the radiation from a clear sky is emitted by water vapour in the lowest few hundred feet. It is suggested that the surface water vapour pressure represents the moisture through this narrow layer. The most important formulae proposed are by:

Angstrom (1915):

$$G_o = \sigma T^4 \ (a - b\ e^{-ce})$$

Brunt (1932):

$$G_o = \sigma T^4 \ (a + b\ e^{0.5})$$

Where G_o is the counterradiation from a clear sky, and σ is the Stefan-Boltzmann constant and e is the partial pressure of water vapour at the surface in mb.

Kondrat'yev (1965) has given a table of constants found by many researchers for the Angstrom and Brunt equations. The variation found is quite high. Most current researchers prefer the Brunt equation because it has one less constant. The constants of Angstrom's equation and their range among seven different investigators is as follows:

a	0.82 - 0.75
b	0.148 - 0.32
c	0.068 - 0.126

The constants of Brunt's equation and their range among nine investigators is:

a	0.66 - 0.34
b	0.033 - 0.127

Downward longwave radiation is calculated in the table below using the constants of Angstrom and Asklof (1920): a = 0.44 and b = 0.08. It is worth mentioning that Goss and Brooks (1956) found values of a = 0.66 and b = 0.04 in California, which gives values of G_o an average of 1/3 higher, and with e having less influence on G_o.

Table A1 Downward LW radiation (after Brunt, with Asklof's constants: a = 0.44, b = 0.08)

G_o in W m^{-2}

T air (^oC)	e in mb 0	1	3	5	10	20	30
20	184	217	242	259	288	335	368
15	172	203	226	242	269	312	
10	160	188	215	226	251		
7	154	183	203	216	241		
5	149	176	196	210	234		
0	139	164	183	196			
-5	128	152	168				
-10	119	141	157				
-20	102	121	134				

Table A2 Typical vapour pressures (in mb)

RH	T air (^oC) -20	-10	0	10	20
100%	1.3	2.7	6.1	12.3	23.4
75%		2.1	4.6	9.3	17.5
50%		1.3	3.1	6.2	11.7
25%			1.5	3.1	5.8

Examination of Brunt's values in the table in conjunction with Table 3 shows that radiant losses from a building surface ($\varepsilon = 0.9$, surface T = air T) rarely exceed the 114 Wm^{-2} assumed for the engineering formula. The following table gives the net radiant loss expected under normal atmospheric conditions, as defined by the table above. The figures are approximate due to the number of uncertainties. In Britain, minimum night temperatures are near RH = 100.

Table A3 Net heat loss Q_r to clear sky in WM^{-2}

T	RH			
	100%	75%	50%	25%
20	25 (77)	55 (79)	80 (86)	112 (105)
10	65 (74)	80 (79)	100 (91)	113 (113)
0	85 (78)	90 (86)	100 (98)	115 (118)
-10	86 (85)	92 (91)	98 (100)	
-20	86 (87)			

These values compare only roughly with net radiation figures, in brackets above, measured by Geiger (1965) on the Baltic coast. Geiger's results are presented on a nomogram combining Q_r, T_a, e, R H, and ΔT (surface -air). It is felt the Geiger values are more realistic, but they correspond closely in the range important for building heat loss.

In situations where the surface temperature exceeds screen temperature by 5°C (as might happen on windows and sky lights or on the human clothing surface) these values would be increased by roughly 20 Wm^{-2}. Conversely, if the surface temperature is decreased below screen air temperature (as would occur on insulated surfaces or the ground during calm nights), the values are decreased 20 Wm^{-2}.

In this section the actual results are not emphasised because the aim is only to establish the order of magnitude of the effect of climatic factors T and e. Within the range of e common in Britain, the influence of humidity is not very great.

2.) Radiation from a cloudy sky.

To determine the radiation from an overcast sky, Angstrom and Asklof (1920) give an adjustment to clear sky radiation:

$$G_c = \sigma T^4 - \varkappa(\sigma T^4 - G_o)$$

where $\varkappa$ is a parameter which depends on the height of the cloud base.

It is 0.17 at 2.0 Km
0.38 at 5.0 Km
0.45 at 8.0 Km

Elevation of cloud base is considered an indicator of cloud temperature, which controls the amount of sky radiation coming from the cloud base. This formula combines the downward radiation from the cloud and from the water vapour in the low air levels. The table below gives its sky radiation values for a range of air temperatures, vapour pressures, and cloud heights.

Table A4 Cloudy sky radiation

		G_c (Wm^{-2})			Q_r $0.9\sigma T_b^4$
T	cloud height (KM)	e = 3	e = 5	e = 10	
20	2		391	396	376
	5		358	368	
	8		346	360	
10	2	339	341	345	327
	5	307	312	321	
	8	297	302	314	
0	2	295	295		283
	5	270	270		
	8	261	261		
-10	2	252	253		244
	5	228	231		
	8	220	223		
-20	2	215	217		209
	5	195	199		
	8	188	192		

The emission of a natural surface ($\varepsilon = 0.9$) at the same surface temperature is included for comparison.

The radiation at any given time from a partially clouded sky is not equal to the sum of clear and cloudy sky radiation in their respective proportions. Work by Sauberer (1951) and Russians quoted in Kondrat'yev (1965) found that the relationship between $G_{(o+c)}$ and c (the percent cloud cover) is a curve, giving higher radiation values in the middle values of c than would arise from the linear combination of G_o and G_c. The instantaneous difference is not very great, about 12% of G_o at most. Sauberer found that over long periods (annual means) the differences cancel to within a few percent. This is an important result for the consideration of radiation and building heat loss, since the averagesradiations of clear and cloudy skies can be added in the proportions of (I - c) and c. Data on partial cloudiness is meteorologically available.

These researchers also found that, for an annual average (central Europe), the outward radiation Q_{ro} to a clear sky is 16 - 18% higher than the average radiation in the presence of any percentage of clouds.

Conclusions: long wave radiation exchange with the sky.

1.) Cloudy sky.

From the figures presented in Appendix 1 it is seen that the radiation from a cloudy sky is very similar to that received from a natural surface at the same screen air temperature. The climatic factors humidity, atmospheric composition, and temperature profile have insignificant effect under cloudy conditions. The variation of G_{rc} for the different cloud heights described is only 12%, and the extreme variation of the sky radiation from the natural surface radiation at the same surface temperature is 9%. This leads to the reasoning that, under any fully overcast conditions, the sky is equivalent to the surrounding ground surface for the calculation of thermal surface coefficients. This permits the use of the simplified formula:

$$h_{rc} = 4 \sigma E T_m^3$$

with $E = (\varepsilon)^2 = 0.81$.

The cloud cover formula of Angstrom and Asklof needs elaboration to bring in the condition of partial cloudiness. Kondratyev (1965) and Sauberer (1951) give evidence that although the radiation to skies with fractional cloudiness is not a linear integration of radiation to clouds and to clear sky, over long periods this simplification can be

2.) Clear sky.

The radiation to a clear sky is shown by many investigators to depend primarily on the surface air temperature and the surface water vapour pressure. The constants in the formulae of Angstrom and Brunt depend on the location and show considerable variation. A table of clear sky radiation versus surface temperature emission is prepared in Table A3. From this it can be seen that the net heat loss to a clear sky around 0°C and 75% RH is in the vicinity of 90 W m^{-2}. This is considerably less than the value Q_r = 114 W m^{-2} suggested by the engineering texts, which is used for the heat loss calculations in Section 6. This heat loss rate would apply only in very extreme conditions in Britain, although they are quite common in continental climates.

III Appendix 2

S.W. radiant gain: geometrical information.

The general information describing solar radiation gain comes from basically two sources, one astronomical or geometrical, and one meteorological or atmospheric. Both these sources are affected by the specific local climate: obstructions cause shading geometrically; while local fog, cloud, and pollution variables are meteorological effects of the site.

Geometrical information

(a) Day length, which determines duration and times of exposure, varies with the season and latitude. Information on daylight hours and times of sunrise and sunset is practically obtained from a variety of sources. The Smithsonian Meteorological Tables (List 1958) is the most complete source. Various naval tables are also used. The meridional stereographic projection (U.S. Navy 1931) can be used as an astrolabe (Lee 1963). For practical purposes the B.RS. has prepared solar calculators (Petherbridge 1965) from which approximate day length can be quickly determined. Frank and Lee (1966) and Petherbridge (unpublished) have produced computer printouts of day length, times of sunrise and sunset, and a variety of radiation information for any latitude. Such programmes also can give the sunrise and sunset times, day lengths, and radiation levels for any slope facing any direction.

A summary of daylight hours against time of year is given in the following table:

Table A5

Approximate daylength (h)

	Latitude		
	40	50	60
June 21	15	15	19
March & Sept 22	11	11	11
December 22	9	7	5

(b) Illumination angle.

The above sources also give the elevation and azimuth of the sun at any time. This is required for computing the intensity of the radiation on the surface being designed. The radiation intensity varies with the angle of incidence of the solar beam according to the cosine law of illumination:-

$$I_s = I_o \cos \beta$$

where I_s is the radiant flux density on the surface.

I_o is the flux density perpendicular of the beam.

β is the angle of incidence of the beam (zenith angle).

With knowledge of the solar angle and the angle of the planned building surface, a designer can compute the direct solar gain to the surface. The graphical aids prepared by the B.R.S. and the Libbey Owens Ford Glass Company make this a simple design task.

(c) Ground obstructions can intercept the direct solar beam and shorten the duration of isolation. These are also easily determined with the aid of sunpath diagrams and devices like Tonne's Horizontoscop (1952) or Pleijel's Globoscope (1952). Such obstructions are site conditions but should be considered simultaneously with any climatic assessment of radiant gain, since their effect is very large.

(d) Solar path length and atmospheric attenuation. The length of the solar beam through the atmosphere depends on the angle of the beam. With the sun at the zenith, the solar beam passes through the smallest thickness of atmosphere. This thickness is known as one optical airmass. As the zenith angle increases, the relative path length increases with the cosine of the angle.

The attenuation of the solar beam is related to the absorption coefficient of the atmosphere (k_1) and to the path length through the atmosphere. The absorption coefficient (also called the extinction or attenuation coefficient) is defined by Bouger's Law:

$$I_x = I_o \, e^{-k_{\lambda} x}$$

where I_x is the radiant flux density at a distance x from the source where the flux density is I_o, and e is the natural log base. The absorptivity of a thickness x of a material with an absorption coefficient k_{λ} is denoted as $a_{\lambda}(x)$ and is equal to:

$$a_\lambda(x) = 1 - e^{-k_\lambda x}$$

Using an atmospheric absorption coefficient of 0.25, the relationship of solar elevation and thickness of the atmosphere to intensities of solar radiation at the earth's surface are given in the following table (from Trewartha, 1954):

Table A6

		Percentage of extraterrestial I_e	
Zenith angle β	Relative path length (optical air masses)	I_s Surface normal to beam	I_h Horizontal surface
0	1.00	78	78
10	1.02	77	76
20	1.06	76	72
30	1.15	75	65
40	1.31	72	55
50	1.56	68	44
60	2.00	62	31
70	2.92	51	17
80	5.70	31	5
85	10.8	15	1
90	45.0	0	0

The influence of the cosine law of illumination is conjunction with increasing atmospheric path is seen in the column for a horizontal surface.

Altitude.

The elevation of the site above sea level reduces the thickness of the atmosphere above, and shortens the solar path. Becker and Boyd (1957) calculated the percentage increase of solar radiation intensity with altitude for

June 21 and December 21 at 40° N latitude. Up to 1,000 feet there is no definite effect.

Table A7

Percentage increase in I with altitude (in percent)

Altitude (feet)	Dec 21	June 21
2000	3	7
3000	7	12
4000	9	15
5000	11	18
6000	13	21
7000	14	23
8000	15	24

The effect at other times of the year can be interpolated.

III Appendix 3

S.W. radiant gain:
Meteorological information.

a) Turbidity.

The transparency of the atmosphere (equal to 1-absorptivity) is related to the absorption coefficient k, as described above. In a cloudless sky, the absorption coefficient is a function of the composition of the dry atmosphere of the dust content of the atmosphere, both in quantity and size, and of the water vapour content. Brooks (1959) prepared a formula for total direct beam radiation in which dry atmosphere, moisture content, and dust content are treated separately and summed. From this it can be seen that dry atmospheric characteristics (the gases CO_2, oxygen and ozone) provide rather constant absorption varying with the air pressure only. The absorption coefficient of different wavelengths vary widely for a given atmosphere, since the gas and particle filters are wavelength selective. However, integration of the energy transmitted cancels the influence of the dryaatmosphere. I at the surface is significantly dependent only on the meteorologically determined variables dust and water vapour.

In non-industrial atmospheres the value of I_s will vary by 30% depending on location and season within the entire U.S. The lowest values are found in the Southern regions where humidity is high and average dust content is greater

Table A8

Insolation through clear and industrial cloudless atmospheres.

Solar zenith angle	Standard cloudless atmosphere			Industrial cloudless atmosphere		
	Direct, perpendicular	Diffuse on horizontal	Total on horizontal	Direct, perpendicular	Diffuse on horizontal	Total on horizontal
85	210	20	40	100	30	35
80	390	40	110	180	55	90
70	620	70	280	330	100	200
60	740	90	460	430	140	350
50	810	100	620	490	170	490
40	860	105	760	540	180	600
30	890	105	880	570	200	700
20	910	110	970	590	220	770
10	920	110	1,000	-	-	-
0	925	110	1,030	-	-	-

Values in $W\ m^{-2}$

due to larger scale thermal convection, (from data in Thelkeld 1962). The variation in I_s across a uniform maritime land mass such as Britain would be very much less. Since the humidity levels are unchanged in Britain, it can be deduced that the only atmospheric factor open to considerable variability (in clear skies) is dust.

The highest dust contents are found in urban and industrial atmospheres. The following table, from Brooks (1959), (A8) gives I_s, I_d, and I_{oh} for clear and industrial atmospheres in Wm^{-2}. The components direct sunlight and scattered sunlight (I_d) are presented separately to give the total insolation on a horizontal surface I_{oh}. The table demonstrates clearly that although direct and total radiation is reduced in a polluted atmosphere, the amount of diffuse radiation from the sky vault is considerably greater.

Further information on the distribution of diffuse energy across the sky is of very minimal importance for the calculation of heat loss. It is important for consideration of thermal overheating and for lighting engineering, but these are not pursued here.

Table A9

Percentage of clear day radiation received for various optical airmasses and overcase cloud types.

Optical airmass m	Zenith angle degrees	Cirrus	Cirro-stratus	Alto-cumulus	Alto-stratus	Strato cumulus	Stratus	Nimbo stratus	Fog
1.1	25	85	84	52	41	35	25	15	17
1.5	48	84	81	51	41	34	25	17	17
2.0	60	84	78	50	41	34	25	19	17
2.5	66	83	74	49	41	33	25	21	18
3.0	71	82	71	47	41	32	24	25	18
3.5	74	81	68	46	41	31	24	-	18
4.0	76	80	65	45	41	31	-	-	18
4.5	77	-	-	-	-	30	-	-	19
5.0	79	-	-	-	-	29	-	-	19

b) Cloudiness is the most important single influence on the solar radiation received at the earth's surface. There is a great deal of meteorological data on cloudiness, which for the purpose of its effect on the solar radiation falls into two categories. The first concerns its effect on the intensity of radiation passing through clouds, while the second describes the duration of cloud cover and its effect on the length of time that direct sunlight reaches the earth.

The transmission of energy through clouds varies considerably with the thickness and type of cloud. Table A9 gives empirically determined diffuse radiation amounts for different cloud types and airmass numbers. The table is from List (1958) taken from observations by Haurwitz (1948).

The considerable variation in diffuse radiation makes it very difficult to predict instantaneous radiation intensities from unspecific meteorological data on percentages of cloud cover. The radiation intensities in the following section on solar duration are all in terms of daily totals or for longer periods. For these an assumption of average cloud type (or average transmissivity) can be made.

Duration of bright sunshine is affected by clouds. It is a common parameter measured at most meteorological stations. Its usefulness is that it permits subjective assessment of climatic pleasantness and radiant warmth, since the intensity difference between direct solar and diffuse radiation is generally great. However, it is insufficient when used by itself to give a quantitative indication of the sum of energy received or the average intensity of radiation. The intensity of the diffuse (and reflected) radiation must be taken into account.

Solar duration combined with intensity of diffuse radiation.

Monteith (1962) produced a formula for the expected attenuation of clear sky radiation depending only on a mean monthly fractional cloudiness. The study was done for Great Britain and involved several assumptions about the oprical properties of the cloud types of the area. For his model, radiation during periods of shading by clouds is represented by

$$\frac{I_c}{I_o} = \frac{1 - c\ (p + \phi)}{(1 - c \alpha P)}$$

where I_o and I_c = the clear sky and cloudy sky radiation, on a surface normal to the beam, in daily averages of Wm^{-2}.

c = fractional cloud cover in tenths as the monthly mean of 0900 and 1500 observations.

p, ϕ = coefficients for back scattering and absorption from cloud defined as the ratio of reflected or absorbed energy to incident radiation.

ϕ = 0.16 and p = 0.50 for British data.

α = surface reflection coefficient = 0.20

The equation includes terms for diffuse radiation from the blue sky, transmitted radiation through the cloud, and doubly reflected radiation from the ground surface and the bottom of the cloud layer.

An approximation of the formula is

$$\frac{I_c}{I_o} = 1 - 0.61\ c$$

which is to be compared to a model formula by Neumann (1954):

$$\frac{I_c}{I_o} = 1 - 0.54\ c$$

and is very similar to Houghton's (1954) equation from North American data between the cloudiness limits $0.6 < c < 0.8$ =

$$\frac{I_c}{I_o} = 1.23 - 0.96\ c$$

Thus these formulae predict a linear relationship between c and I in which I_c equals 30 to 45% of I_o under conditions of full overcast. This can be taken to be the average transmission of full overcast.

Given I_c together with data for cloudless sky radiation mean monthly radiation can be predicted. The two meteorological parameters required for this integration would be c and S, the ratio of actual to possible sunshine hours, or c and a parameter $I_{sc} = (1 - c)\ I_{so}$

where

I_{sc} = Direct solar radiation in the presence of cloud (daily totals),

I_{so} = Direct solar radiation in absence of clouds.

Black (1956) produced the following empirical regression from total radiation figures over the globe:

$$\frac{I_c}{I_e} = (0.803 - 0.340c - 0.458c^2)$$

Where I_e is the extraterrestrial intensity perpendicular to the beam. This formula assumes I_c to be 0.803 I_e under clear weather conditions.

Angstrom (1922) and Savinov (1933) derived the following expression, for which Budyko (1956) has produced charts:

$$\frac{I_c}{I_{oh}} = 1 - (1-k)c$$

in which I_{oh} is the total radiation received on a horizontal surface on clear days. The parameter k is a latitude dependent parameter which represents $\frac{I_c}{I_o}$.

When overcast is complete ($c = 1$), I_c depends on the mean altitude of the sun and the types of clouds and their thickness. The values given in Table A1 above can be substituted to give I values sensitive to cloud types, but means of averaging or accumulating the solar altitudes over the day would have to be found.

A common meteorological parameter is the hours of sunshine. Fritz and MacDonald (1949) derived the following equation from U.S.A. data to estimate the monthly amounts of solar energy received:

$$\frac{I_c}{I_o} = 0.35 + 0.61\ S$$

Where S is the number of hours of sunshine recorded divided by the number of hours of possible sunshine. It is roughly equivalent to (1 - c). This equation corresponds closely to Monteith's, giving results 4% lower.

Hamon, Weiss and Wilson (1954) have also presented a graphical method of converting percent of possible sunshine to daily insolation between the latitudes 25°d and 50°. Glover and McCulloch (1958) include an effect of latitude ρ in their regression:

$$\frac{I_c}{I_o} = 0.29 \cos \rho + 0.52\ S$$

Other formulae correlating radiant energy with hours of sunshine are given by:

Benford and Bock (1939),
Day (1961),
Taylor and Smith (1961) for seasonal averages, and
Page (1961).

III Appendix 4

Comparisons with other results.

A review of the literature revealed a number of studies on heat loss and power requirements whose results are relevant to the present discussion but not directly comparable to the results achieved above. These are in two categories: 1) studies of the records of power companies relating, by regression, instantaneous demand to climatic parameters. 2) Studies testing the accuracy of the degree-day system of comparing fuel requirements.

1) Power companies have records of instantaneous demand which can be correlated to the simultaneous weather information to determine the effect of the climatic variables on heat requirement. A number of such analyses have been published, but comparison of their findings gives very little consistent information to draw conclusions from. This is probably due to differences in the way the data was analysed and presented, and partly because of the different uses for electrical power in different regions. The method holds promise of giving an indication of the climatic effect on heating of the average structure found on a city planning scale.

Dryar (1949) found that in Philadelphia, a 2.7°C drop in temperature from a baseline temperature of 18°C caused a 2% increase in demand on the utilities which the author claimed could be attributed to heating requirements. An equal increase was found with each 2.2 m sec^{-1} wind velocity. Thus the relative effect of each degree Centigrade temperature is equal to the effect of 0.8 m sec^{-1} velocity, and causes a 0.77% increase in Q required. This value is close to those found in Section 7. Davies (1960) found that the power generation for all of England and Wales increased 290 megawatts for each °C sustained fall in temperature around 0°C. At lower temperatures the relationship becomes non-linear, with demand increasing to 360 mw $^{\circ}C^{-1}$. An 11 m sec^{-1} wind, by comparison, caused a 700 mw increase in demand per °C, equivalent to a temperature drop of only 2 to 2.4°C. The relationship of wind and temperature to 'cooling effect' given by Davies is:

$$C = V^{*0.5} (65 - T)$$

with C in megawatts
V* in knots
T in °F.

The cooling effect is proportional to the square root of the velocity. This relationship is similar to the heat loss curves used by physiologists in Chapter II. It is impossible to compare to the wind and temperature relations given in Section 7, but the effect of wind is very much lower in Davies' analysis. It is undetermined from Davies' paper if his wind relationship was checked over a range of ΔT.

Reidat (1951), measuring the electrical heating requirements of urban office buildings, also found heat requirements tending toward the square root of the velocity. His conclusion is that heat loss is due more to convection than ventilation.

Davies found the $Q/\Delta T$ ratio constant over the range -5 to 11° T_a. Below and above this range the ratio increases in value - the lower one presumably due to emergency heating in severe cold spells; the higher one due to sensitivity to short term cold spells in the summer when the usual heating system is not operating. The linear relationship was also fonnd by Maunder (1969) in investigating city gas consumption records over the range -18 to 8°C, and by the Scottish electricity board (Lecture 1971) in the range 0 to 11°C. In Scotland, per capita electricity consumption increases from 2.1 KW at 11°C to 4 KW at 0°C, a rate of 0.2 KW/°C. Neither of the above examples considered the effect of wind simultaneously to that of temperature.

It would appear that electricity supplied to residential areas, particularly estates provided with electric heating, could be profitably monitored to give a continuous indication of the effect of climatic factors on house heating.

Fournol (1948) did a regression between heat loss and numerous climatic variables for a test bungalow similar to Lacy's (1951). The results are expressed in terms of loss per unit surface area. He, however, did not isolate convective from natural ventilative heat loss. As a result, the physical cause of loss to wind is not understood. However, he found that normal wind variation caused a 15% variation in heat loss.

2) The most commonly used parameter for accumulated temperature is the form of the degree day (Dufton 1934). On a given day, the number of degrees that the air temperature is below an arbitrary basic (indoor) temperature equals the number of 'degree days' for that day. The daily totals of degree days are summed up for the period being considered, a week, month, or heating season. Numerous publications give degree day totals. Manley (1957) has compiled a 'monthly degree day' index of fuel requirements which uses monthly means and extends back 250 years. The baseline said to give the correct scale to accurately reflect fuel consumption is 14^{o}C.

Van Zuilen (1941) tested a heated model in the open atmosphere. He found that for short periods, such as less than a week, the variables sun and wind had a significant effect. Averaging over a month showed a very close regression between Q and accumulated ΔT. Comparison to measurements on office and apartment blocks in Holland and England showed that Q could be accurately represented in these buildings by ΔT alone. There were no special wind conditions present however; the model carefully excluded all ventilation and the full scale buildings were in cities exposed only to average weather. The regressions, done over long intervals, took average wind and sun into account, and evidently the climate was not variable temporally. A similar result is found by Maunder (1970) in a study of fuel oil deliveries in Victoria, British Columbia. The average 130 m^2 floor area house consistently consumed 0.14 gallons per Fahrenheit degree day.

Conclusions.

It is probable that comparison of most sites by temperature (degree day) records alone would suffice to represent heating requirements. It would be imperative, however, to take note of any unusual wind or sunshine condition which was not common to both the sites compared. If such conditions existed, one would have to refer to combined functions such as Figures 10 - 30 to get an accurate assessment of the interrelated climatic factors. The accumulated temperature difference method is useful because temperature records are by far the most widespread climatic records (the Edinburgh records by Plant, 1968, are a case in point). If the sun and wind can be assumed to be average, Figure 29 can be read along the 4 m sec^{-1} axis for the Q vs. ΔT relationship. The conversion to KW hr for the degree day comparisons is simple.

IV Appendix 1

Reasons and references to support the general shapes of the three element:activity parameter graphs for each activity.

1. Building heat loss curves are those derived, with references, in Section III.
2. Instantaneous heat loss from buildings uses the same relationships as long term building heat loss, but the effect of human ventilation is not included since this function applies only to extreme heat loss conditions when the house will be sealed as much as possible.
3. Comfort curves are from Section II.
4. Vegetative production. The curve for production against temperature is supported by experiments on three crop species (Wilson 1966). The 5°C growth threshold is used in numerous climate classifications. Its interactions with V and I as shown are hypothetical. The curve of production against wind is also hypothetical. It resembles shelter research results from Russia and the Great Plains where water is the limiting factor. The initial rise of production with wind is due to improved CO_2 exchange. The subsequent drop is largely due to the moisture stress and to some extent evaporative cooling of the leaves. This is still quite uncertain and unproven for plants without limited water supply. The curve for production against insolation level is suggested by any number of sources: De Wit (1965), Monteith (1968), and

McKee and Troughton (1968) being only some of a large number. Production levels off with increasing insolation more for horizontal leaved species than on vertically leaved grain crops.

5. Deterioration of building materials. These curves are conjectural, based on the following principles: materials deteriorate at both high and low temperatures, particularly plastics, bitumens, sealants, and paints. A great deal of deterioration is due to the action of water penetration coupled with the freeze-thaw cycle. Thus the air temperature near 0° is in the vicinity of freezing water, and increased deterioration. The effect of radiation cooling or warming of the surface can cause the freezing point to occur at a spread of air temperatures, and the usual result of radiation effects added to those of air temperature is an increased number of passages through the freeze-thaw line (Brackmayer, 1962). The radiative effect is at its maximum in still air, when the convection is least. The relation to velocity is seen in the T:V curve. At higher velocities the deterioration is assumed to increase due to physical effects. Increased insolation is assumed to increase deterioration, primarily because of thermal expansion and the influence of untraviolet light on the materials mentioned above (Ransom, 1962). Needless to say, the function is very dependent on the materials considered.

6. The air pollution curves are very schematic, representing a 'balance equation' (Munn, 1970) where the concentration downwind of the source is proportional to the emission quantity and inversely proportional to wind speed. The

effect of temperature on the amount of emission is taken from the housing heat loss example, with the assumption that pollution is proportional to heat loss replaced. The relationship of heat loss to temperature is linear between the limits of maximum heating capacity at the cold extreme to intentional ventilative loss at the warm end (Dick 1949). The insolation effect is assumed negligible.

A IV 2. General information: site influence on five climatic elements in five categories of scale.

Figure 8 is a matrix of the site influences found at five scales of site and the five most influential climatic elements as suggested above. They are outlined below with a brief indication of magnitude expected and selected bibliographical references, The effects are roughly in order of decreasing scale.

A. Topography: largest mesoscale influences.

1. Temperature.

a. Coastal effect. The thermal lag of water bodies to heating and cooling causes coastal areas to experience dampened daily and seasonal temperature cycles relative to areas inland. The mean temperatures for these periods are also affected, depending largely on water temperature and coastal cloudiness. 'Coastal effects' apply from a continental scale down to very localized areas within the usual planning scale. At the small scale, coastal influence can change the inland temperature $5^{o}C$ in temperate regions, and more in arid regions. The hourly temperature means are further offset by the patterns of the sea and land breezes.

Coastal influences on climate are generally described in most climatology texts. However, since the influences depend on many factors which cannot be predicted in advance, local data is required for planning purposes. Fortunately meteorological records exist for many coastal stations.

b. Altitude. In British latitudes, temperature decreases with elevation an average of 0.4°C per 100 meters in the winter, and 0.6°C in the summer (Barry and Chorley, 1971). These figures should only be applied generally to large areas, since the lapse rate can be influenced by local meteorological and topographic features. The foremost example of such a local effect is the persistent inversion, as formed in valleys and along coasts. In one such case, San Francisco, the mean monthly temperature at a station 600 m above the city is 10°C higher than city temperature (Pettersen, 1958).

At a smaller scale, katabatic winds flow into topographic hollows forming the well known 'frost pockets' at night. Such hollows range in size from miles to the width of a plough furrow. Depending on the topography and the atmospheric clarity, the nightly temperatures in sizeable frost pockets can exceed 10°C even in an urban situation (Middleton and Millar, 1936). The extent of such topographical influences can be measured by short period tests compared against standard meteorological records, or by making a moving temperature traverse.

c. Effect of slope on solar heating of ground and air. The air temperature above topography is affected by the degree of solar heating of the surface, and can amount to several degrees C in hilly terrain. Surface heating depends on the topographical angle of inclination to the solar beam, and on duration of shading due to topographical obstructions. These are part of A.3. Studies of air temperature around hills and in mountainous terrain have been made notably by: Baumgartner, 1960, Hartmann et al, 1959, Turner, 1966, and Geiger,1965, who provides further summary.

A.2. Topography and wind.

a. Roughness differences over large areas. The wind over the sea and over flat prairies is greater than that over rougher terrain. This causes immediate coastal areas to have high average windspeeds, as is shown in Dutch maps for anticipated building heat loss (B.R.S. 1953) where the coastal velocity is twice that inland.

b. Wind increase with altitude. The velocity profile (summarized by Davenport, 1960) ensures higher velocities at sites which are above the general ground surface. On a plateau a new profile becomes established at the new elevation, but the fetch required for this is substantial.

c. In the transition from low to high ground, the wind is also accelerated due to constriction of its path. This effect is common across ridges and is most pronounced near the surface and in gaps (Scorer, 1949-1955; Corby 1954).

Amplification factors ranging from 1.2 to 2 for hills and ridges are given by Putnam (1948). To the lee of ridges and mountains accelerations may occur due to portions of the lee standing waves touching the surface (Aanensen and Sawyer, 1963).

d. Wind deflection, turning, and channelling. Wind direction can be altered up to 90° in flowing around hills, turning by friction to cross mountain ranges perpendicularly (Tabata, 1956), and by channelling in valleys (Morgans 1931; Schroeder and Buck, 1970: general description). Velocity accelerations occur where valleys constrict flow.

e. Topography and wind turbulence. Turbulence on the largest scale is associated with rotors caused by lee waves behind mountains. Smaller scale turbulence results from flow separation behind cliffs and steep slopes. In flatter terrain, turbulence is a function of surface roughness, atmospheric stability, and windspeed. Sutton (1949) presents the general theories involved. A considerable engineering literature is concerned with gust characteristics during high winds. (See Davenport 1960; and Harris, 1970).

f. Local winds. Many observations of mountain slope, and valley winds have been made, and the theory described (Defant, 1949; Wagner, 1938). The maximum velocity of the cold night wind can exceed 4 m s^{-1}. Such winds are most important in mountainous regions, and attain maximum velocities in high rimmed U shaped valleys.

Sea breezes cause daily wind speeds of typically 4 to 7 m s^{-1} in temperate regions, and land breezes 2 m s^{-1}, with the largest velocities in the summer. Information on the pattern of such breezes must be locally obtained.

A.3. Topography: insolation.

a. Meteorological shading. The formation of orographic cloud over rising ground, or cumulus cloud streets originating over heated surfaces or over sea breeze fronts, can cause strongly localized insolation reduction. Similar shading is caused by coastal advection fog and by radiation fog in valleys. Pollutants collecting under inversions also reduce insolation.

b. Geometric shading and angle of solar incidence. A large literature exists on the radiation climate of slopes. Both the duration of insolation and its intensity are affected. The theory and methods of analysing topography for insolation are presented by Lee (1963). Kondrat'yev and Manolova (1960) give the clear sky values of both direct and diffuse radiation expected for various slopes, and describe the simplifications that may be made concerning the distribution of diffuse radiation across the sky. Cloudy sky diffuse radiation constitutes a substantial part of total radiation in high latitudes (Dirmhirn, 1964, Chapter III). A great amount of earlier work is summarized by Geiger.

Garnet (1935) has made a unique study of settlement in the Alps in relation to the possible daily insolation in winter.

The effect of altitude on solar beam transmission is listed in Appendix III.2. A 10% increase is the maximum possible in British conditions.

A.4. Topography and rain.

Precipitation is increased over rising terrain due to orographic lifting. Barry and Chorley state that the frequency of rainfall in N.W. Britain does not increase appreciably with elevation, but that the mean rainfall per rain-day more than doubles between sea level and the Highlands. Thus the elevation primarily intensifies existing weather. They quote a study in which wooded hills 30 - 50 m high occasionally caused 50 to 80% higher rainfall than the surrounding plain. Rain 'shelter' occurs in the lee of substantial uplands, reducing precipitation totals by as much as 70% in Wales. Precipitation is also affected by sources of cumulus convection, particularly along coasts and slopes heated by the sun.

A.5. Topography and air humidity.

a. Coastal influence. Absolute humidity will be highest near water surfaces both by day and night. However, since relative humidity is linked to temperature, it may be lower near water bodies at night when the ground is strongly cooled and the water remains relatively warm. During daytime, relative humidity will be higher near the cool water surface.

b. Terrain. The dependence of relative humidity on temperature is reflected in the humidity measurements made together with temperature measurements in microclimatic investigations of sloping topography (Turner, 1958).

B.1. Urbmn scale: temperature.

Heat island. The urban scale includes many topographic features, but certain characteristics can be considered specifically urban. The chief of these is the urban heat island. The elevated temperature in a city is due primarily to the higher radiation absorptivity and thermal conductivity of the surfaces, lack of surface water for evaporation, and the escape of heat from buildings. Reduced wind convection and atmospheric pollutants also have an effect. The thermal island is most pronounced in the early evening, when it can be as much as 7°C, although its usual maximum is 3° or 4°C. Average excess temperatures over the year range from

0.5 to 1°C in cities from 100,000 to 1,000,000 inhabitants (Landsberg, 1956, from a variety of sources). The vertical extent of the heated air is three to five times the height of the buildings. Considerable work has been done in this field recently, as described in several papers in WMO (1970). Lowry (1967) summarizes and presents magnitudes for the differences between urban and rural climates. The as yet unpublished bibliography presented to WMO by T.J. Chandler (290 p) is the definitive reference list for all the urban scale phenomena outlined here.

B.2. Urban scale: wind.

a. Urban influence on gradient wind. The friction and roughness of the urban area as a whole causes a decrease in average wind velocity within cities. Annual values for suburban airports and central parks in both New York and London indicate a reduction of 29% at the centre. This reduction increases during strong winds. The velocity profile over urban areas and the mechanism of its generation from the city's edge has become the object of increasing study (Jones and Wilson, 1966; WMO, 1970a; Jones, 1971). The development of the urban velocity profile is found to take several miles of travel across the city. The wind direction of the gradient wind can be changed by as much as 90° by channelling in streets.

b. Urban induced local winds. When the geostrophic wind is light (less than 3 m s^{-1}) the temperature differential between the city and the surrounding country causes a local wind into the city along the surface. Values given for Leicester and London (Chandler, 1960) and Toronto (Findlay and Hirt, 1968) are 2.3 and 2 m s^{-1} respectively.

B.3. Urban scale: insolation.

Solar intensity and duration. The industrial cloudless atmosphere reduces direct radiation intensity between 20 and 40% (III A 2), with increasing reduction in winter. Solar intensities over Vienna are given by Steinhauser (1955), and the shortening of radiation duration due to atmosphere is given by Kratzer (1956), and Chandler (1965). Between 100 and 300 hours of sunlight are lost per year in urban environments. 16 to 44 minutes are lost per day between outer suburbs and central London. The surface geometry reduces possible sunlight further.

B.4. Urban scale: rain.

Several case studies have indicated that the thermal convection and dust above cities triggers cloudbursts (Geiger, 1965; WMO 1970a). There is not enough evidence to carry these suggestions further as yet.

B.5. Urban scale: humidity.

Relative humidity within the city is reduced by higher temperatures and unavailability of surface moisture. The reductions given by Kratzer are 4 to 8%.

C.1. Building scale: temperature.

Observations by Hardy in Newcastle have shown a single brick courtyard to have interior temperatures 5°C in excess of an open site nearby, a difference which lasted as much as three hours in the evening. In enclosed spaces and narrow streets, the surfaces of the surrounding buildings can have an influence on temperature.

C.2. Building scale: wind.

a. Wind deflection around buildings and groups of buildings. Many studies are being made of the airflow around buildings (Jensen and Franck, 1963; Wise et al, 1965; Wise, 1970; WMO, 1970b; Royal Society, 1971), primarily in the wind tunnel. The eventual aim is to develop functions for simplified sizes and spacings which will ameliorate the wind climate for pedestrians in the vicinity of the buildings. Further research is needed to quantify the turbulence in the building wakes and to describe the fixed eddies near the building. The direction of the gradient wind is often reversed to windward and to leeward of tall slabs.

b. The wind velocity and pressure on the building surfaces have been studied extensively for structural engineering purposes. Wind turbulence (in high winds, usually at the height of tall buildings) is also being studied for its effect on structures. This field is too specialized to be included here.

c. Local circulation in streets was studied by Albrecht (1933, 1935). The influence of the gradient wind, and of insolation warming the vertical surfaces on one side of the street, caused definite circulation patterns even at this small scale.

C.3. Building scale: insolation.

a. Shading. A vast literature of calculation methods, charts, instruments, and models exists on the subject of architectural shading. One reference is Hopkinson, ed., (1967). Brezina and Schmidt (1937) first calculated average insolation in narrow streets and urban spaces.

b. Albedo. The other site influence at the building scale is the reflectivity of the building surfaces. These vary from 0.2 to 0.9.

C.4. Building scale: rain.

Rain is affected at the building scale in the provision of shelter overhead and also from the side, should the rain be driven. This applies to the design of building fascades as well as pedestrian walkways.

C.5. Building scale: humidity. No effect.

D.1. Vegetation: temperature.

In summer, vegetation reduces air temperature during insolation by shading, by evapotranspirative cooling, and by somewhat increased albedo (20 to 30% deciduous, lower values for conifers). The effect is particularly pronounced under trees, where temperature is reduced 2 to 4°C below that in the open in summer (F.A.O. 1962). In winter, with shading and evaporation reduced, the temperature within forests is 1 to 2°C higher due largely to restricted convective and thermal radiation loss. Temperature profiles in forest stands are given in Geiger.

Open sites over short vegetation show a greater temperature range than urban sites, largely due to the lower conductivity and heat capacity of vegetated surfaces compared to urban surfaces.

Vegetation is capable of creating topographic effects. Forest clearings can form frost pockets with yearly nightly averages as much as 4°C below open terrain. Dense rows of trees damming the downslope flow of cold air at night also cause frost hollows. The cold air is observed to behave as a viscous fluid, requiring large openings to drain (See Geiger).

D.2. Vegetation: wind.

a. Trees cause a reduction in wind velocity which varies with the amount of foliage exposed. Frederick (1960) found, in a study of wind in an urban area, that the air flow in the vicinity of trees without leaves was 25 to 40% greater than with the trees in leaf, (65 m distance from

20 m trees, measurement height 10 m). The larger increase occurred with sparcer spacing. Geiger presents profiles within a forest with and without leaves. The velocity without leaves is as much as 100% greater. Thom (1971) gives a theoretical relation between momentum absorption of trees and the velocity profile above and among them. This allows the roughness length of any vegetation type to be determined for profile prediction.

b. Shelterbelts. There has been a large amount of work on windbreaks. Noteworthy references include Nagli (1941), Jensen (1954) and Caborn (1957). General characteristics are that a belt of 30 to 40% permeability provides the greatest shelter over a large area. Distances of significant shelter are over 5 heights upwind and 25 heights downwind of the belt.

c. Forest canopies. Work by Fons (1940), Reifsnyder (1955) and others presented by Geiger show the wind reduction expected in forest stands for different canopy types and temperature lapse rates. In moderately dense forests, wind reduction in the first 100 feet of penetration from the forest edge is 20 to 40%, at 200 feet 50%, and at 400 feet as much as 90%.

D.3. Vegetation: insolation.

a. The insolation within the canopies of forests and crops has received a great deal of attention recently

(Anderson, 1964 and 1970; de Wit, 1965). Insolation intensity within average deciduous and conifer forest stands ranges from 20 to 60% of that in the open. In deciduous stands 70% more insolation passes through when the leaves are off. The duration of insolation is also reduced: twilight in moderately dense to tall old forests comes 16 to 40 minutes earlier (Geiger).

b. The albedo of vegetation in temperate regions ranges from 10 (conifers) to 30 percent. In arid regions the values go to 40 percent.

D.4. Vegetation: rain.

Trees will intercept rainfall and hold it on leaf surfaces where it may evaporate or drip to the surface later. It may also flow down the branches and stem as "stem flow". In any of these cases there is a lag in rain penetration which makes trees useful as shelters, at least temporarily. In areas of heavy fog, water will accumulate on leaf surfaces, increasing precipitation by 'leaf drip'. Vegetation does not cause or increase rainfall.

D.5. Vegetation: air humidity.

A large amount of work has been done on evapotranspiration and the flux of moisture away from the surface (Thornthwaite and Hare, 1965). Moisture profiles over various vegetated surfaces are also found in Geiger. The relative humidity in forests is increased 3 to 10%, its profile resembling that of temperature within the stand. Evaporation in the lee of shelterbelts is reduced an average of 15 percent of that in the open.

E. Surface effects. Surface influences on climate are treated very briefly here because any particular emphasis depends on knowing the use of the information.

E.1. Surface: temperature.

Because of radiation effects the temperature at solid surfaces will fluctuate more than the temperature removed from them. Thornthwaite found daily temperature fluctuations over grass at 2 m and 10 cm of 10° and 15°C respectively. The variation over soil is more extreme. Profiles and diurnal ranges are given in Webb (1965), Geiger, and most other micrometeorological texts.

E.2. Surface: wind.

The surface drag, wind profile and turbulence in the boundary layer has received a great deal of attention recently. Good references are Sutton (1949), Thom (1971) and Webb. The commonest description of the wind profile uses Prandtl's formula, in which the characteristics of the surface are represented by a 'roughness length'. This is an empirically derived parameter which is approximately 13 percent of the height of the roughness. The greatest wind gradient is near the surface, at which the velocity is zero. The mechanisms of particle lifting from surfaces are best described in Bagnold (1941).

E.3. Surface: insolation.

Surfaces affect a climate's insolation only in the amount of light they reflect. This varies from less than 20 to over 80 percent among building materials, and from 15 to 40 percent for soils and pavements.

E.4. Surface: rain. No practical effect.

E.5. Surface: humidity.

The surface acts as a source of atmospheric moisture.. Water surfaces and plant canopies with unlimited water provide the most atmospheric moisture. The vapour profile above the surface is determined largely by eddy diffusivity, and is thus dependent on the temperature gradient and wind. The subject is too specialized for general description here. Geiger, Thornthwaite, and Webb are recommended sources.

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