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SECOND AUTUMN WORKSHOP ON

CLOUD PHYSICS AND CLIMATE

(23 November - 18 December 1987)

USE OF CLIMATIC DATA FOR THE DESIGN OF BUILDINGS

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USE OF CLIMATIC DATA FOR THE DESIGN OF BUILDINGS

By

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Lecture Delivered at the Second Autumn Workshop on Cloud Physics and Climate.

ICTP, Trieste,
Italy.

(23 November - 18 December 1987)

PREFACE

In the past, climatologists work in isolation from the end-users of their results. Very often, collected data are difficult to interprete leading to wrong applications and assumptions. This has been the case when some climatic data used for building design produce poor results.

This lecture will introduce meteorologists to the application of climatic data for building design.IIt is hoped that some of the information provided in these lecture notes will equip climatologists adequately towards effective interaction with building design teams. Some previous works of the author, and those of J. Page, O. Ayeni, and A. Loudon will be used to illustrate the techniques involved in the application of climatic data to building design.

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November, 1987
ICTP, Trieste.

A FIELD STUDY OF THERMAL BEHAVIOUR OF SELECTED NIGERIAN TRADITIONAL BUILDINGS

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ABSTRACT

This paper presents the results obtained from field work carried out in three climatic regions of Nigeria on thermal behaviour of traditional buildings.

There is a good correlation between measured and calculated results. As expected, the thick walled structure of the semi-arid north was more effective in controlling solar heat gain than the lighter structure used in the warm-humid region. On the other hand, the well ventilated lightweight structure of the warm-humid region influenced the reduction in internal room air temperature.

INTRODUCTION

The problem of building design in the tropics to control the harsh external climate has been highlighted by various authors (1,2,3,4). Some of these have led to prediction techniques using data for the United Kingdom (5,6) and other parts of the world. Some work have also been carried out on models of buildings and specially constructed buildings (7,8). There is, however, limited quantitative data which give the actual situation in existing traditional buildings.

It was therefore decided to carry out field studies on thermal behaviour in a number of traditional buildings located in the three main climatic zones of Nigeria.

This investigation involved the following:

(i) Measurement of air temperature outside, and internal room air temperature.

(ii) Measurement of external and internal wall surface temperatures, and roof surface temperatures.

(iii) Measurement of ventilation rates.

(iv) Measurement of solar radiation.

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CLIMATE AND BUILDING LOCATION

Several climatic classifications of Nigeria have been made by various authors (9), each with its own merit and demerits.

For the purpose of this study, the buildings selected are located using Thornthwaite and Mather (10) classification of climatic regions. This classification is based on the moisture index of Nigeria as shown in Figure 1.

The buildings are located as follows:

Figure 2 in the Per-humid region (Zone A)

Figure 3 in the dry sub-humid region (Zone B)

and Figure 4 in the semi-arid region, (Zone C).

ESTIMATION OF TEMPERATURE RESPONSE

In order to calculate indoor temperatures in a building, the following factors must be considered:

(i) Heat gain from the building fabric.

(ii) Heat released within the building.

(iii) Heat stored in the building structure.

(iv) Heat gain/loss due to ventilation.

The steady-state equation for the above is given by:

$$Q = (AU + Cv) \ (t_i - t_o) \quad (1)$$

where Q = heat input rate (W)

A = area of exposed facade (m^2)

U = thermal transmittance of facade ($W/m^{2\,o}C$)

Cv = heat loss due to ventilation ($w/^oC$)

t_i = indoor air temperature (^oC)

t_o = outdoor air temperature (^oC)

The steady-state heat flows at a wall is illustrated in Figure 5 for a typical situation.

Temperatures and other climatic factors usually vary with time. Although temperature and climate of a place is variable, it is sometime possible to use equation(1) if any of the following conditions exist:

(a) If the heat storage of the building fabric is negligible compared with the summation of the heat flow. This situation may apply to lightweight strucures.

(b) If the difference in temperature (t), between indoor and outdoor air is large when compared with temperature fluctuations.

As both situation listed above do not exist very often, the steady state equation is usually modified to take account of:

(i) Variation in solar heat gain on all exposed facades.

(ii) Long wave radiation from other internal building surfaces, and air convection.

(iii) Variation in solar gain due to transparent components.

(iv) Sundry heat gains from electric lighting, occupants, and power dissipation from electrical equipments, motors, and process work.

(v) Ventilation heat loss.

Various methods for dealings with these additional heat gains have been proposed (11, 12, 13, 14, 15). Some of these involve intricate and elaborate processes for obtaining indoor temperatures. The work of Danter (11), and Loundon (12) however produced simplified approach which could be conveniently applied. This method assumes that the energy input to the building over a 24-hour period is sinusoidal. Danter's work resulted in the use of the room admittance factor which is a function of the admittance (Y) of each element. Milbank and Harrington-Lynn (16) has shown that the room admittance is the reciprocal of the thermal resistance of an element to the cyclic flow of heat. This is given as

$$Y = q/t \quad Wm^{-2}K^{-1} \quad \ldots\ldots \text{(2)}$$

where q = heat gain per unit area

$$= \frac{Q}{A}$$

t = swing in temperature.

We therefore have,

$$t = \frac{Q}{AY} \quad \ldots\ldots\ldots\ldots \text{(3)}$$

The swing in temperature will be reduced if we increase admittance the swing in temperature is inversely proportional to admittance.

Thermal diffusivity and thickness of any material will affect their admittance capabilities. Diffusivity is usually found by dividing thermal conductivity by the volume specific heat. Dense material normally have larger admittance values than lighter structures.

Environmental temperature swing can be found (12) as follows:

$$tei = \frac{Q}{(AY + Cv)} \quad {}^oC \ldots\ldots\ldots \text{(4)}$$

Heat input through glazed windows are given as follows:

$$Q_g = Sa \, I_{Gv} \, Ag \quad W. \quad \ldots\ldots\ldots\ldots \text{(5)}$$

where Qg = alternating heat input due to solar radiation

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Sa = Alternating solar gain factor

I = alternating global irradiance on vertical surface, Wm^{-2}

Equation (5) is however not useful for the types of buildings used in this survey because none of the windows were glazed and blinds were absent. It is nevertheless an important factor in thermal analysis of buildings.

Sol-air temperature is also an important parameter in the heat transfer study of buildings. This is because the absorbed solar radiation has similar effect as a rise in outside temperature.

Sol-air temperature can be calculated as follows:

$$t_{sa} = t_o + Ro\,(\alpha Id - \epsilon Ii)$$

where

tsa = sol-air temperature

Ro = external surface resistance, m^2KW^{-1}

α = absorption coefficient

Id = intensity of direct plus diffused solar radiation, on the outer surface, Wm^{-2}

Ii = Intensity of longwave radiation from a black surface at temperature of the environmental air, Wm^{-2}

ϵ = emissivity of the outer surface for longwave radiation.

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DATA COLLECTION

The following instruments were used for data collection during this field study.

Solar Radiation:

A bimetallic actinograph was used to collect daily solar radiation on each of the locations.

Surface Wall/Roof Temperatures.

Hourly readings of external and internal wall temperatures were taken with an electronic temperature probe from 8.00 hr to 1800 hr. External roof temperatures were also recorded at hourly internal during the same period of day.

External and Internal Temperature and Relative Humidity

A whirling hygrometer was used for taking hourly readings of both temperature and relative humidity. A thermohygrograph was also installed in each east facing room for continuous recording of both parameters.

Air Velocity

Measurement of air velocity in the rooms were carried out with a Kata thermometer.

Assumed Data

Due to the limitation on instruments available for this field study, some of the data used in the calculation of temperatures were obtained from CIBS Guide (13) and from proposals made by Petherbridge (5). This is presented in Table 1.

Experimental Results

Three distinct types of climatic conditions existed in the regions where each of the building was located. As expected, the greatest daily swing in temperatures were observed in the semi-arid location. Relative humidities were also higher in the per-humid region than in the semi-arid.

Figures 6, 7, and 8 show the relationship between external air temperature and sol-air temperature for each location. The surface temperatures observed for the wall and roof and the room environmental temperatures are presented in Figures 9 and 10.

Discussion of Results

The results show that the Sol-air temperature is generally higher than the external air temperatures, especially during peak solar radiation when these difference are more pronounced. For example, in the semi-arid region, the average difference between Sol-air temperature and external air temperature at 1500 hrs is about 10°C. These values are lower for the two other regions where lower solar radiation are experienced.

Table 1: Assumed data used for Computation of Temperatures

Location of Building	Type of Construction: Wall	Type of Construction: Roof	Ground Reflectance	External surface Resistance ($m^2 {}^\circ C/W$): Wall	External surface Resistance ($m^2 {}^\circ C/W$): Roof	Absorption Coefficients: Wall	Absorption Coefficients: Roof	Longwave radiation loss for roof W/m^2	Emissivity
Perhumid Region (Zone A)	100mm thick rectangular mud wall with bamboo reinforcement	Pitched thatch roof	0.2	0.05	0.04	0.5	0.5	90	0.9
Humid Region (Zone B)	300mm thick Cylindrical mudwall	Straw on conical wood frame	0.4	0.05	0.04	0.8	0.5	90	0.9
Semi-arid Region (Zone C)	450mm thick mudwall	Mud flat roof	0.5	0.05	0.04	0.9	0.9	90	0.9

Fig. 9 show that there is a wide difference (upto 14°C at peak periods) between roof surface temperature and the internal room air temperature. The thermal mass of the roof structure contributes towards the control of heat transmittance into the building. This is an important factor for thermal control." There is close relationship between the observed and computed internal room air temperatures.

For the dry sub-humid zone, the temperature profiles for various measurements made are similar. Unlike the situation in the semi-arid zone, the magnitude of the differences between the values for each surface is small. This is attributed to the lower intensities of solar radiation and poor thermal storage of the roof system adopted in this region. Contrary to the situation in the semi-arid zone, the thatch roof used here produced lower surface temperatures than the mud wall. In the per-humid region where high ventilation rates were experienced, the lightweight structures used for construction of the buildings affected the level of thermal storage. As a result of this, temperatures measured in and around the buildings were very close in value.

Conclusions

The results obtained from this field studys show that the thermal performance of the heavyweight building in the semi-arid zone is supervisor to that of the lightweight structures. However, in the humid region, where lower solar insolation prevail, the combination of high ventilation rates and lightweight structures meets with the thermal control requirements expected"

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Acknowledgements

I wish to express my gratitude to my Technical Assistant, Mr. C. Onye for data collection. This work was partially funded by the United Nations University Tokyo under the Rural Energy System Project of the University of Ife. I wish to express my gratitude to the Project Co-ordinator, Professor G.J. Afolabi Ojo for his encouragement.

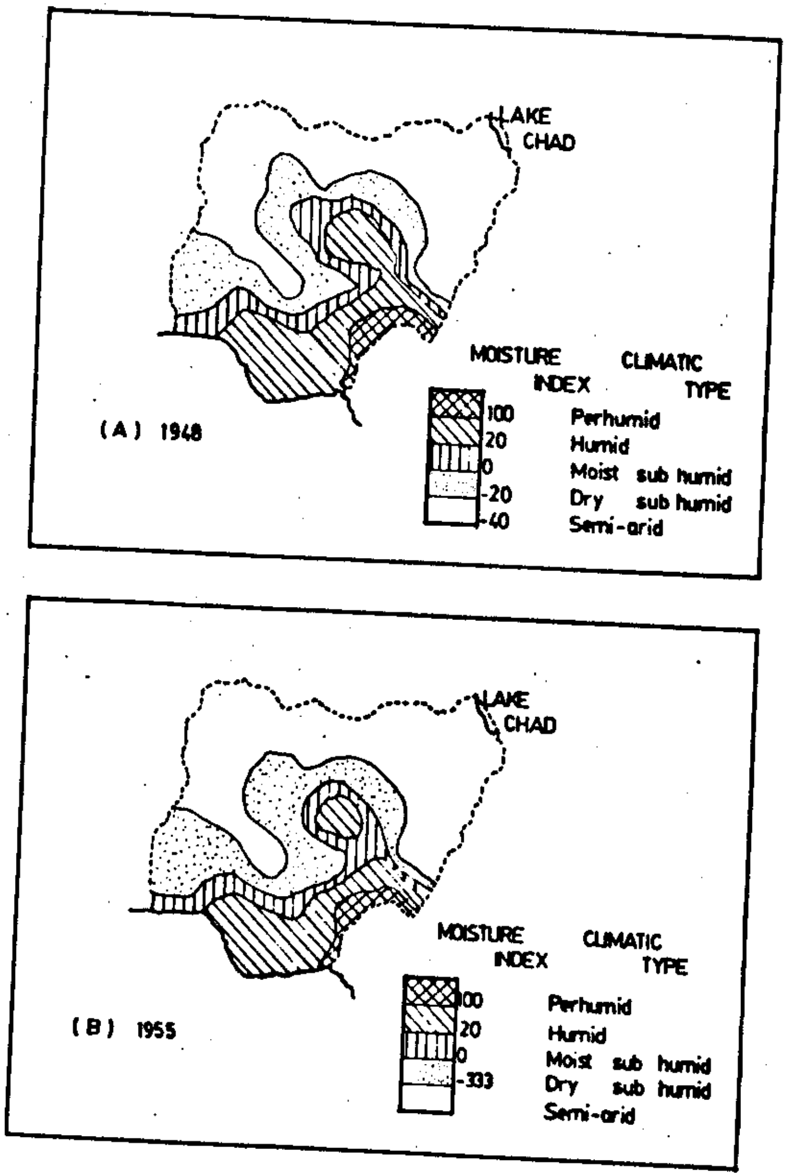

Fig 1 Climatic regions of Nigeria according to Thornthwaite and Mather

FIG. 2. BUILDING IN THE PER-HUMID REGION (ZONE A)

FIG. 3 BUILDING IN THE DRY SUB-HUMID REGION (ZONE B)

FIG. 4. BUILDING IN THE SEMI-ARID REGION (ZONE C)

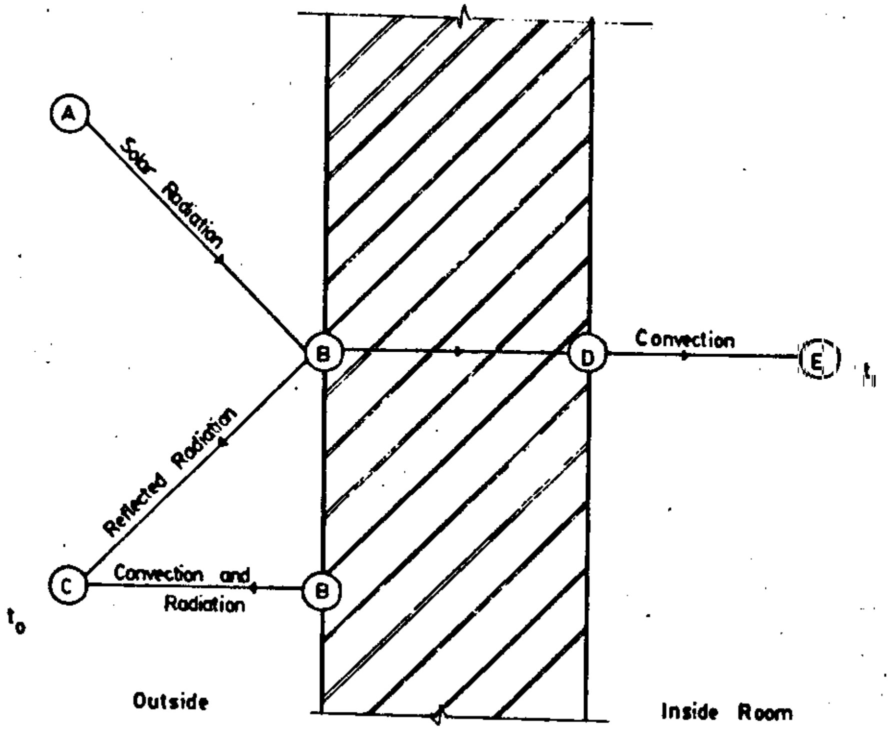

Fig 5 Steady-State Situation

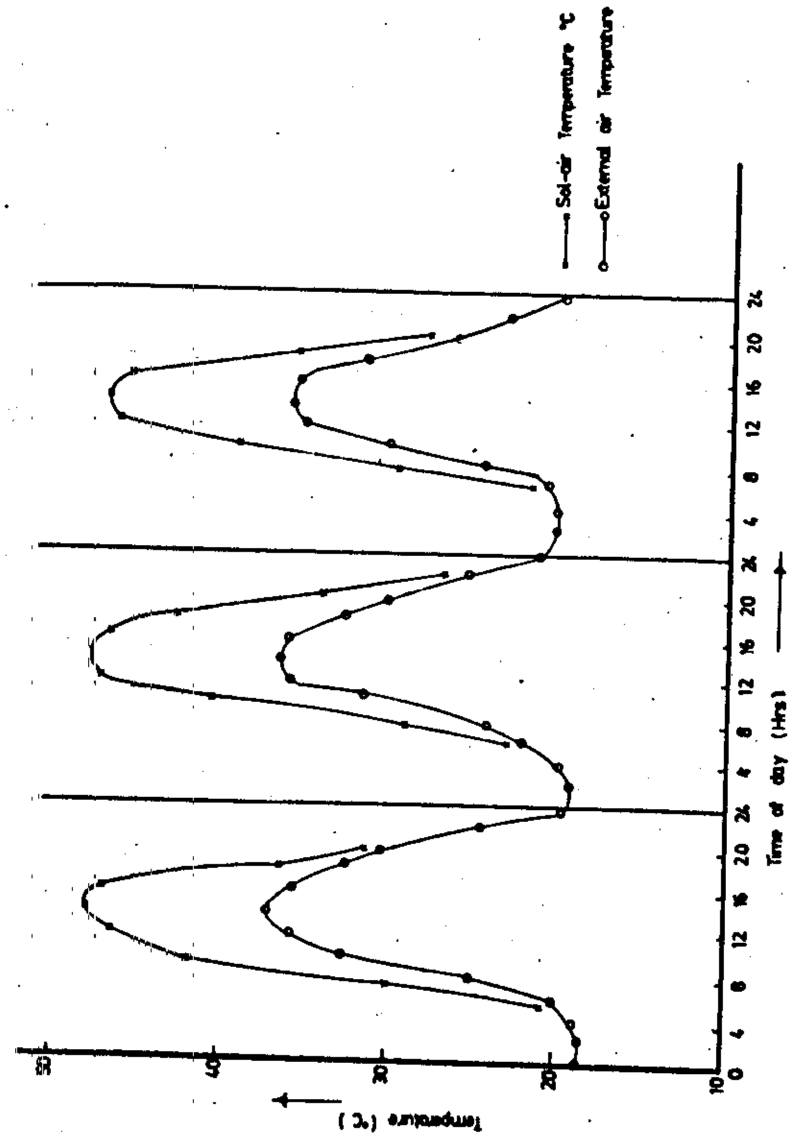

Fig 6 Comparison of measured external temperatures and calculated sol-air temperatures. Semi-arid region

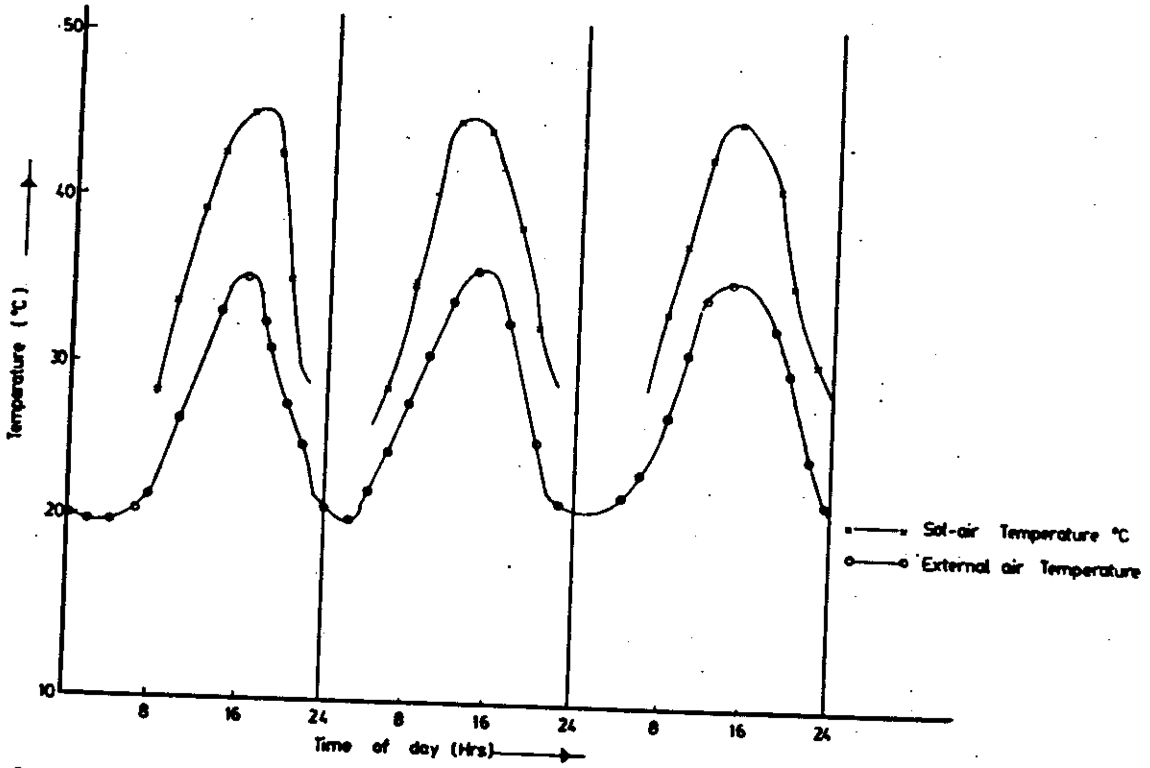

Fig 7 Comparison of measured external temperatures and calculated Sol-air temperatures
Dry sub-humid zone

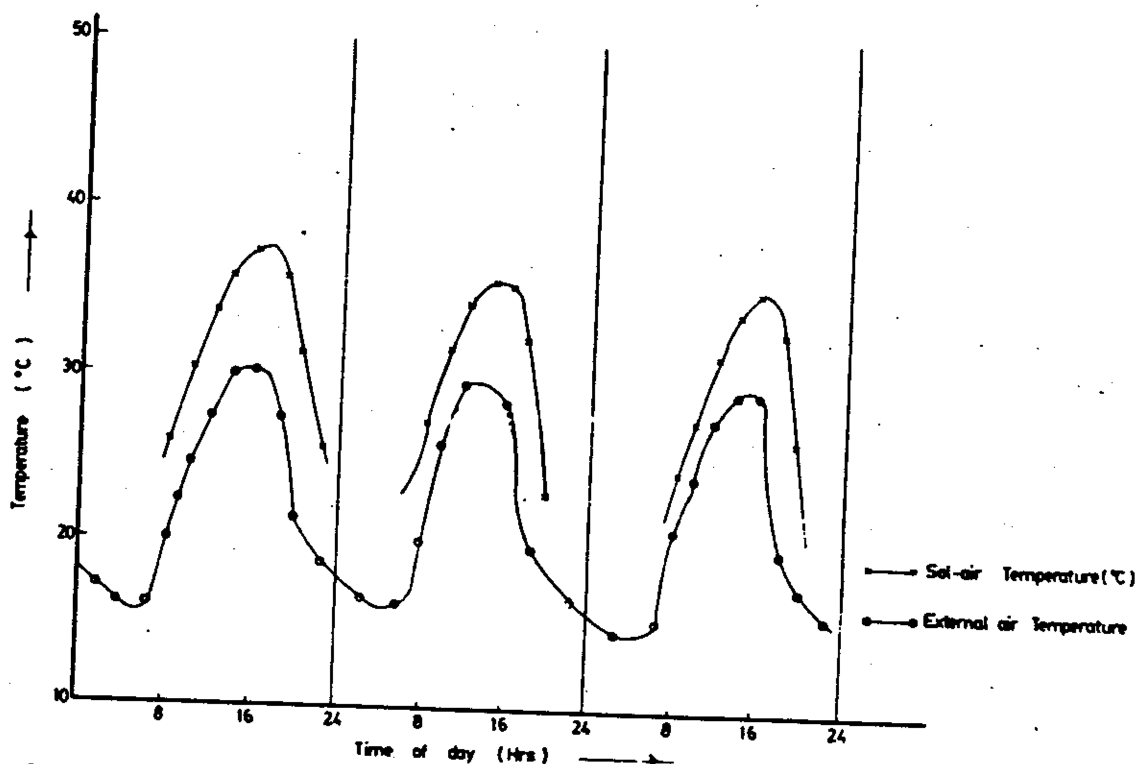

Fig 8 Comparison of measured external temperatures and calculated Sol-air temperatures
Perhumid zone

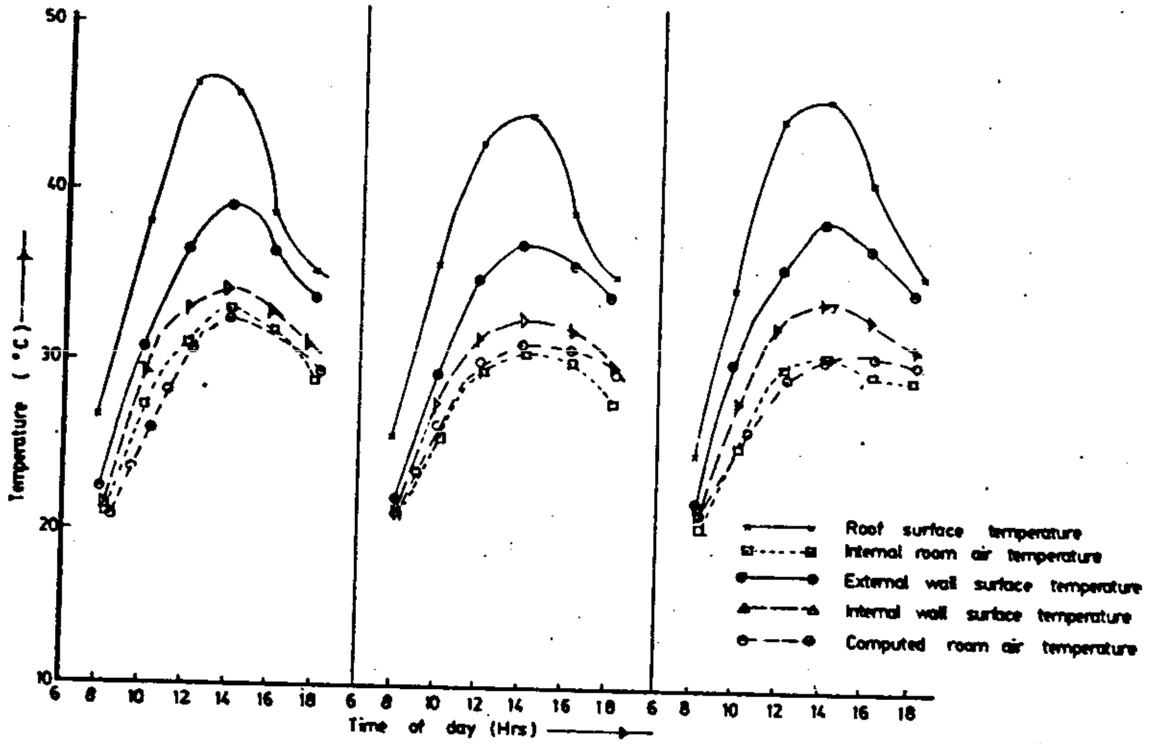

Fig 9 Measured temperatures for wall, roof and building interior
Semi-arid region

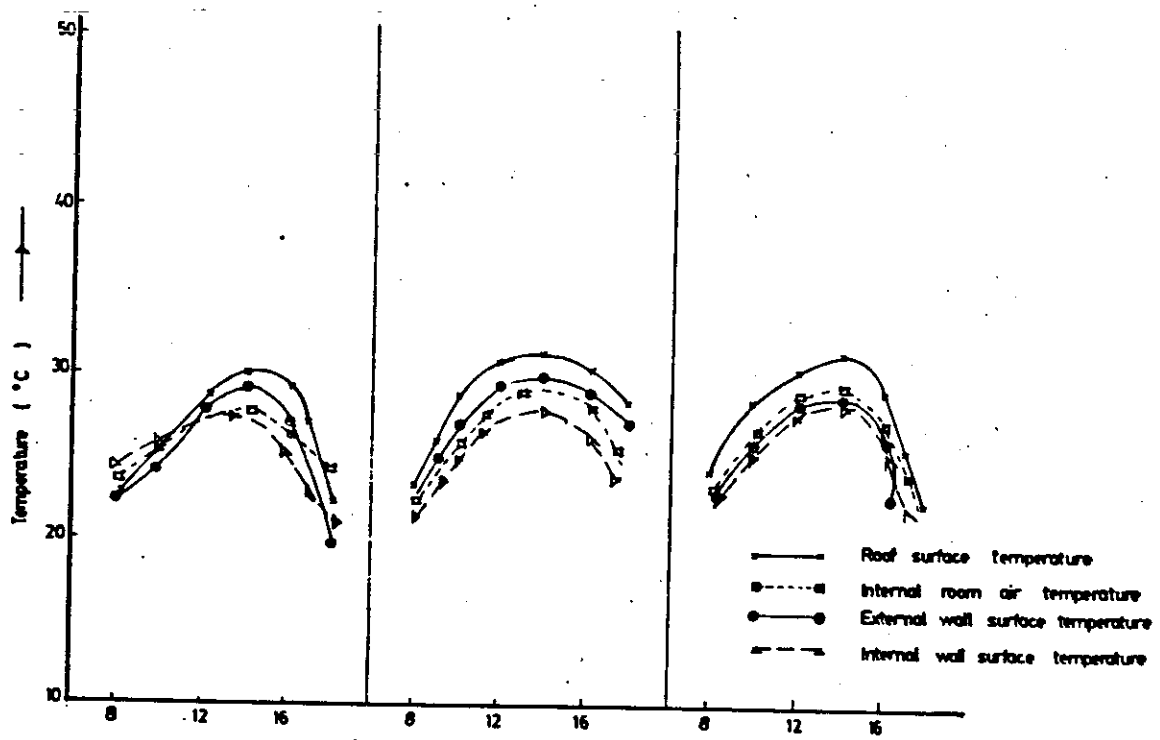

Fig 11 Measured temperatures for wall, roof and building interior
Per humid region

Opening lecture

Geographical variations in the climatic factors influencing solar building design

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Abstract

This paper discusses geographical variations in the climatological factors to be considered in the systematic design of solar houses. Special attention is given to the short wave radiation climatology of vertical and inclined surfaces in different parts of the world under different conditions of cloudiness and atmospheric turbidity. As diffuse radiation is dominant in high latitudes and in Equatorial regions the need to estimate diffuse radiation exchanges accurately is stressed. The various meteorological factors affecting heat losses are also considered, including the effects of wind, long wave radiation exchanges and temperature. The need to give greater attention to micrometeorological aspects of site assessment is also stressed. In addition to drawing from published meteorological data, extensive use has been made of the Department of Building Science's new range of radiation computer programs to prepare diagrams for average days for vertical slopes as well as clear day conditions to illustrate the precise effects of latitude on solar energy availability.

Introduction

The meteorological influences that need to be considered in the systematic design of solar houses are extremely complex. It is difficult at our current stage of knowledge to produce simple global climatological classifications to assist architects in solar house design. Weather not only affects the day to day supply of solar energy, but also the magnitude and the temporal patterns of the different demands for the use of that energy, say for space heating or for cooling. Weather in many parts of the world is highly variable from day to day, and in all parts of the world, outside the equatorial regions, the climate also varies strongly from season to season. The need to match the supply of the solar energy with diurnally varying energy demands usually creates a need for energy storage but the establishment of appropriate energy storage design strategies is entirely dependent on the availability of adequate statistical descriptions of the probable relationships between energy demands and solar energy supplies. Figure 1 taken from the UK-ISES Report (1) attempts to describe the complex inter-relationships that exist between component design for solar houses and the multi-dimensional external meteorological environment. Figure 1 distinguishes between the passive collection of solar energy through windows, etc. and the active external collection of solar energy using external solar collectors on the roof, etc. It indicates the problem of solar controls and energy dumping. It also distinguishes between energy storage in the building fabric itself and energy storage in separate specially constructed energy stores. It assumes the potential for energy collaboration with other types of energy supply system, ambiently based, fossil fuel based, and where appropriate nuclear based.

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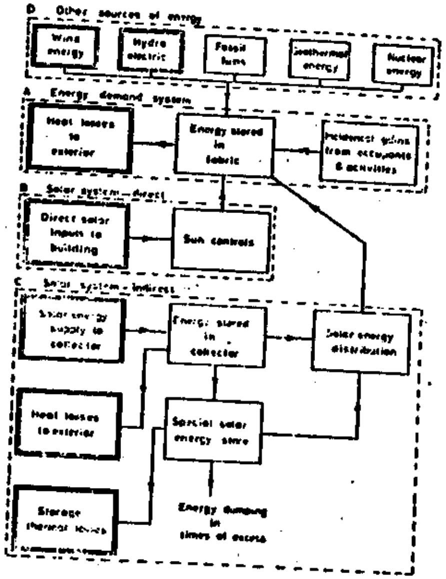
Fig. 1

The systematic design of solar building involves understanding the interactions between the energy demand system and the different energy supply systems, no less than three of which are used in a typical solar building. The solar systems interact with the wider energy supply system. Many of the factors are weather sensitive. These factors are shown in double boxes.

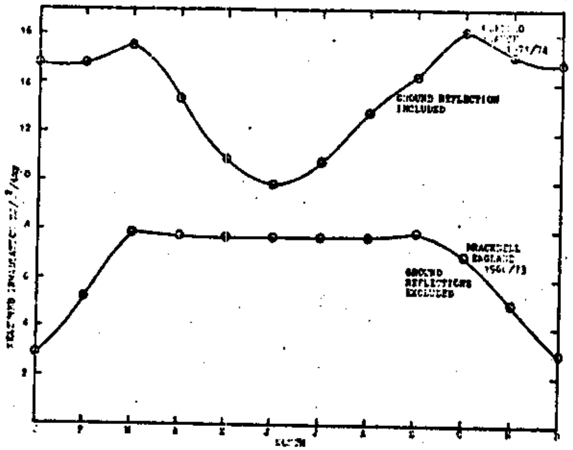


The numerous meteorologically sensitive aspects of system design are all ringed in double boxes. The large number of climatic interactions is the clearest feature of the diagram. It is clear that solar system design is difficult.

The design of solar houses needs to be strongly conditioned by the precise geographical location of the proposed project and its associated climate analysed in detail. This paper attempts to briefly outline some of the variations found across the world in the climatological variables relevant to solar house design. Schemes for particular areas must be seen to rest within a particular climatological context, and their success must be judged within that geographical context. We must seek an appropriate solar technology for each geographical location. The logical form of solar buildings is strongly conditioned by latitude and cloudiness characteristics. Architects must put aside any belief there can be any universal international solar style.

Accurate climatological analysis is the foundation of successful solar house design and borrowing designs out of their climatological context can lead to disaster. For example Figure 2 compares the measured monthly mean daily irradiation on a vertical south facing wall at Odeillo in the French Pyrenees with that measured at Bracknell, just west of London, England. The difference of latitude is just over 10 degrees, but the energy availability in winter

Fig. 2 Measured monthly mean daily irradiation on vertical south walls at Odeillo and Kew. Note large winter differences.



is vastly different. Odeillo has a clear sunny winter climate with an average in January of about five and a half hours of bright sunshine. Bracknell has a typical UK winter climate with a monthly mean bright sunshine level of only about one and a half hours a day. The high level mountain climate of Odeillo is also much clearer than the low level winter climate of the UK and it was for a very good reason that Felix Trombe took the French CRNS Solar Energy Laboratory to Odeillo. The Trombe passive solar wall system may have proved itself successful in Odeillo (2), but Figure 2 shows that one must not assume that it would necessarily be successful in mid-winter in the UK, however attractive the concept might seem at a superficial glance. We need, therefore, to clarify the climatological design principles right at the start of this conference.

Global patterns of solar irradiation

Figure 3 maps the annual mean global irradiance on a horizontal plane. The range across the main inhabited parts of the world is from 100 W/m^2 in high latitude climates to 300 W/m^2 in the Red Sea area. The great desert areas of the world typically located between 20° and 30°N and 20 - 25°S have mean irradiances of 250 W/m^2, over 2½ times as great as countries like the UK. The low mean irradiance values at the Equator are also evident. The Congo Basin and Paris have very similar mean annual irradiances.

Figure 4 shows recorded monthly mean daily totals of irradiation H_h for six stations of widely differing latitude, some north of the Equator and some south. The diffuse irradiation H_{dh} is also shown. The variation in mean daily global irradiation with season increases with latitude. The even supply of solar energy in the equatorial region from month to month is very obvious at Kinshasa. The diffuse irradiation forms a big proportion

Fig. 3 Annual mean global irradiance on a horizontal plane at the surface of the earth (W/m^2 averaged over 24 hours).

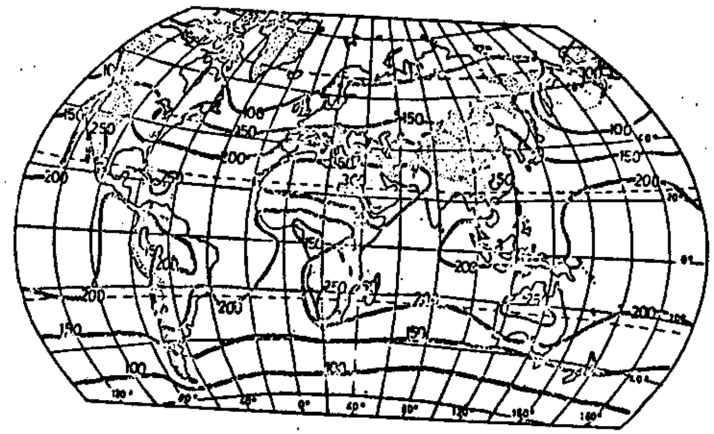
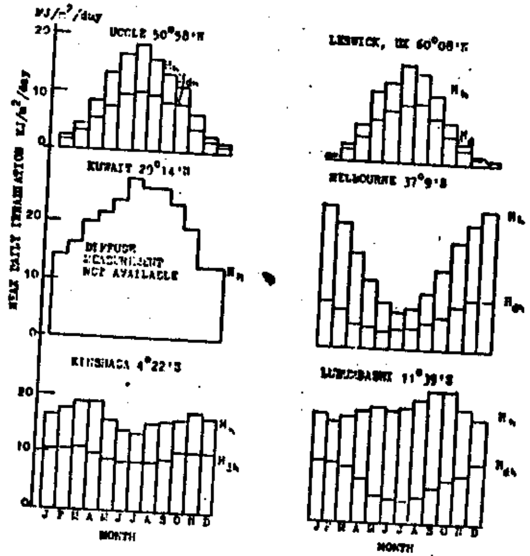


Fig. 4 Measured mean monthly global and diffuse irradiation on a horizontal surface for 6 stations of widely differing latitude. Note high proportion of diffuse irradiation at high latitudes and close to Equator.



of the short wave irradiation at Kinshasa in the Congo Basin. Lubumbashi a few degrees in latitude further to the south from the Equator has a two season climate, sometimes wet and humid and cloudy, sometimes dry and sunny according to the position of the inter-tropical convergence zone. The proportion of diffuse varies accordingly. Kuwait, a desert type area, has a high insolation throughout the year, but, being situated 29°N of the Equator, the horizontal monthly mean irradiation levels during the winter half of the year fall back as the sun moves to its southward position. Melbourne, Australia at 37°S has the minimum global irradiation level in June. The diffuse proportion at Melbourne is relatively high during the southern hemisphere winter, but this proportion decreases in the summer period. Uccle outside Brussels in Belgium shows a big range from summer to winter with a large proportion of diffuse radiation through the year. The annual range is even greater at Lerwick in the Shetlands to the north of the Scottish mainland at latitude 60°N. The winter solar energy availability is very low indeed. The prospects for solar houses close to the Arctic circle are poor.

It is useful to start by looking at the monthly changes of horizontal surface irradiance G_h. Figure 5 presents variations in the measured mean monthly irradiance with time of day at Lubumbashi in Central Africa, for four selected months together with information about the associated percentage possible sunshine. In January with the

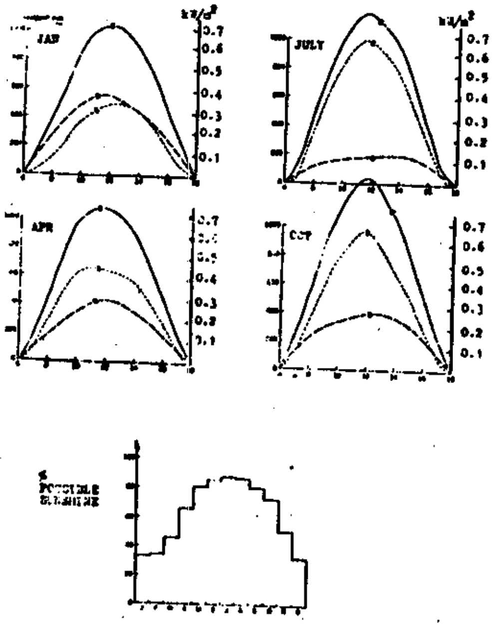


Fig. 5

Variations in mean global, direct, and diffuse irradiance on a horizontal surface in a low latitude climate with a clear and a cloudy season – Lumbumbashi, 11°39'S 27°28'E, 1298m 1955–60

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percentage possible sunshine as low as 34%, the diffuse irradiation exceeds the direct. In July the percentage possible sunshine is about 87%, and every day is virtually cloudless. The direct horizontal surface irradiance dominates, and the proportion of diffuse is very small. In October the sun is overhead, so the mean global irradiance reaches its peak, but there is slightly more cloud and the diffuse has risen compared with July.

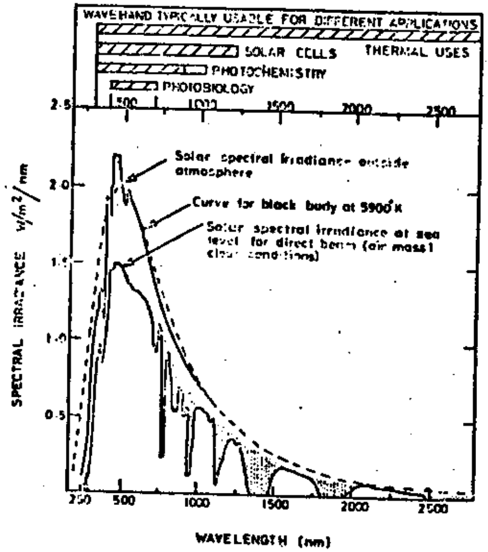
Solar building design involves understanding such radiation patterns in order to make best use of them. The knowledge of irradiation of sloping and vertical surfaces is critical for proper design, and it is essential to have methods for developing architectural design data from basic meteorological information. However understanding the transmission properties of the atmosphere in relation to the astronomical movements of the earth about the sun is complex. I want to devote most of my time to considering the problem of modelling these important properties for architectural design purposes.

The absorption and scattering processes in the atmosphere (3), (4)

The principal extra-terrestrial variations in the solar energy supply arise from the variations in the distance between the earth and sun that are the consequence of the earth's elliptical orbit. The extraterrestrial solar irradiance normal to the beam at mean solar distance G_{sc} known as the solar constant is about 1353 W/m². The extra-terrestrial intensity varies by ± 3.3% being greatest on January 1st and least on July 5th. The direct beam intensity is substantially reduced as it passes through the atmosphere. The lower the sun the greater the path length and the greater the reduction due to absorption and scattering. Some radiation is absorbed by gases in the atmosphere, mainly ozone, oxygen and carbon dioxide, some by water (vapour and cloud droplets) and some by aerosol, man-made and natural. In terms of absorption/unit air mass ozone absorbs about 3% of the solar constant G_{sc}, oxygen and CO_2 absorb less than 2% and water vapour some 10–15% depending on its concentration. Variations in the surface irradiance due to absorption depend mainly on the water vapour distribution. Bannon (5) has mapped global data on the amount of precipitable water vapour in the atmosphere. The precipitable water held gaseously in the atmosphere varies considerably from area to area and is greatest in the equatorial regions where it may reach 100 mm. In high latitudes in winter about 5 mm is typical. The water vapour absorption removes energy mainly from the infra red part of the spectrum. Air molecules scatter the blue light preferentially. Scattering by cloud droplets and aerosols depends strongly on particle size and on wavelength. Scattering by aerosol removes from 5% to 40% of G_{sc} in unit air mass, but a significant part of the scattered radiation still reaches the earth's surface as diffuse radiation. Figure 6 shows the main spectral features of the direct solar beam. The theoretical direct solar irradiance G_{bn} expected at the surface depends on (i) the solar constant G_{sc}, (ii) the sun-earth radius vector, (iii) the total water vapour content of the atmosphere expressed as precipitable water vapour, and (iv)

Fig. 6

Spectral irradiance curves for direct sunlight extraterrestrially and at sea level; shaded areas indicate absorption due to atmospheric constituents, mainly H_2O, CO_2 and O_3. Wavelengths potentially utilised in different solar energy applications are indicated at the top.



the air mass m which is related to solar elevation α by the formula $m = 1/\sin\alpha$ for $\alpha > 10^0$ for stations at or close to sea level. For lower altitudes the Smithsonian Tables (6) provided suitable values. The major variations of G^*_{bn} are due to water vapour and air mass. In practice the measured beam irradiance G_{bn} is almost always less than G^*_{bn} and the additional attenuation is ascribed to aerosol and described by a turbidity coefficient.

A variety of turbidity coefficients have been proposed, many of them depending on radiation measurements in a narrow waveband (for discussion refer Robinson (4)). For solar energy applications there are advantages in using the Monteith and Unsworth turbidity coefficient τ_a which is based on measurements of G_{bn} over the whole solar spectrum 0.3 – 3 μm.

τ_a is defined by the relationship

$$\tau_a = -\frac{1}{m}\log_e \frac{G_{bn}}{G^*_{bn}} \qquad (1)$$

We have used this turbidity coefficient in Sheffield extensively in the development of our computer models for the study of solar radiation.

Geographical variations in atmospheric turbidity

There are very large geographical variations in mean annual atmospheric turbidity. Large seasonal differences are found as well. The clearest region is Antarctic. The Arctic is also very clear, and air masses originating from these polar regions having a low precipitable moisture content and also a low dust burden have low turbidities. The solar beam intensity in such high latitude regions may be surprisingly high in spite of the low solar altitude. In the great desert areas of the world, a considerable amount of dust enters the atmosphere, and the turbidity may be relatively high throughout the year. The high midday solar altitudes associated with lower latitudes mean the midday air mass is low, so that the energy that penetrates is still very considerable. In the humid equatorial regions the turbidity is often lower than in the desert regions on either side, even though there is a lot of cloud which substantially reduces the average irradiation by intercepting the direct beam for a high proportion of the day. In these areas there are a lot of small water droplets which produce substantial forward scattering and a characteristically milky sky. In two season low latitude climates where a rainy season intervenes into a clear season, the rainy season typically reveals lower atmospheric turbidities. The high rainfall tends to wash the dust particles out of the sky. Further the fast growing vegetation and the moist ground surfaces suppress surface dust generation due to turbulence. In temperate mid-latitude climates the turbidity is characteristically lowest in the middle of winter and increases to a maximum around July. The atmospheric water vapour contents also increase from winter to summer so the absorption in the infra red absorption bands increases so reducing summer direct beam irradiance.

Figure 7 shows typical month to month variations in the mean monthly maximum pseudo turbidities for several N. European sites. The pseudo turbidity was derived from the daily totals of direct and diffuse radiation using our computer solar radiation model, by dividing the observed mean monthly daily direct radiation on a horizontal surface by the percentage possible sunshine for the month in question, fixing the daylengths as the length of time during which the direct solar irradiance is above 200 W/m² (which is the intensity at which burning of the sunshine recorder first starts) assuming a Monteith and Unsworth turbidity of $\tau_a = 0.2$. Figure 7 shows the highest turbidities are associated with urban situations, Kew and Hamburg. The remote seashore sites have substantially lower turbidities than the urban sites. The clearest conditions at sea level being found at Valentia in the far west of Ireland, which is a distance from the main continental sources of pollution. Further the air masses come mainly off the clean Atlantic Ocean. One high level French mountain station, Odeillo, is included. The low turbidities associated with this particular site are evident. At Odeillo some turbidity increase from winter to summer is present, but is more subdued than at Kew. Published data for the USA (7) bears out very much the same annual pattern. The global computer solar radiation models which we have developed in the University of Sheffield allow these turbidity variations and the monthly variations in precipitable water vapour to be properly taken account of by the user.

Fig. 7

Annual variations in maximum pseudo turbidity - Northern Europe

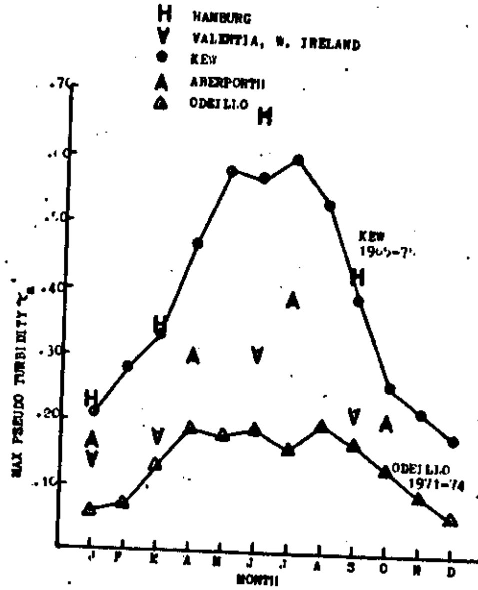
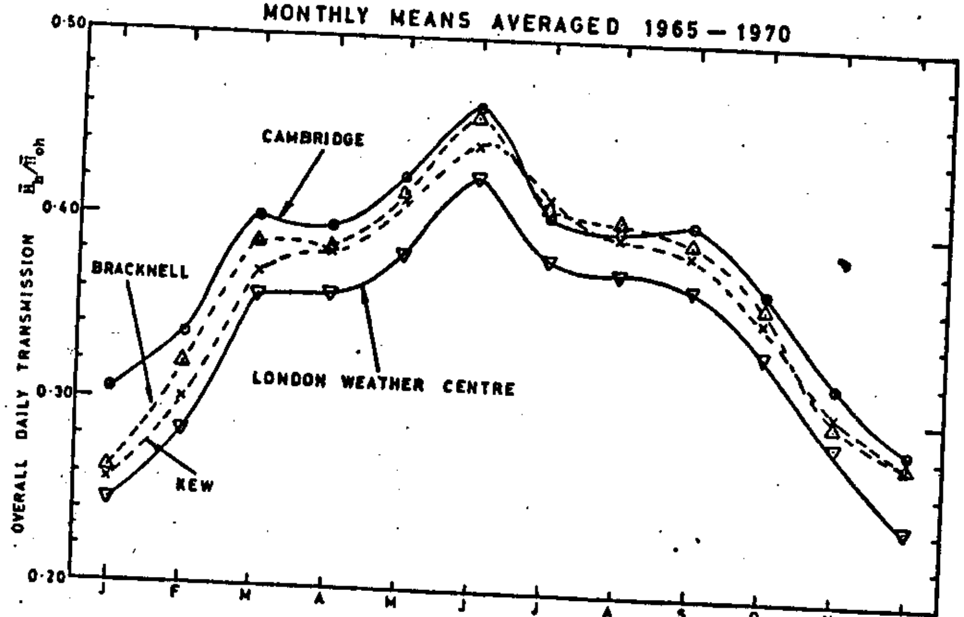


Fig. 8



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Urban influences on turbidity

In addition to the general geographical factors discussed above, one has also to consider urban pollution influences, which may extend over very wide areas. Figure 8 gives data for the mean atmospheric transmission $\bar{H}_h/\bar{H}_{oh}$ around London where $\bar{H}_h$ is the global irradiation and $\bar{H}_{oh}$ is the corresponding extraterrestrial irradiation. The fall off from the centre of London to Cambridge some 100 km away is considerable. Fortunately, under the influence of clean air legislation, the smoke pollution burden of the UK atmosphere has been falling, so over the last decade the turbidities in many of the large towns have decreased.

Table 1

CHARACTERISTIC VALUES OF THE MONTEITH AND UNSWORTH TURBIDITY COEFFICIENTS τ_a FOR THE U.K. SHOWING THE INFLUENCE OF AIR MASS TYPE AND LOCATION IN RELATION TO POLLUTION SOURCES

	Air mass type	τ_a
Northerly island site, minimum pollution from land sources	polar	0.05
	average	0.20
	continental	0.35
Rural or coastal site exposed to natural aerosol pollution and small amounts of smoke	polar	0.10
	average	0.25
	continental	0.40
Urban site within or close to a large town (say population exceeding 100,000)	polar	0.25
	average	0.40
	continental	0.55

Typical values of τ_a for different types of air mass from Unsworth (3) with corrections for urban and other polluting influences in high latitudes are given in Table 1. Figure 9 shows the effect of turbidity on vertical and horizontal surface irradiance on a south facing vertical surface at latitude $50^{\circ}N$ for March 21st for cloudless days. The range of values of τ_a selected were chosen to match the actual range found across the UK from the clearest conditions in the far west to the inland urban polluted situations found in towns with poor control of smoke emissions, fortunately now a minority in the UK. The halving of available energy on cloudless days is a serious loss and careful attention needs to be given to urban pollution effects in assessing the feasibility of solar houses in high latitudes. The effects of ground albedo are also important, and a snow ground cover will substantially increase vertical surface irradiation. One point has been plotted in Figure 9 to demonstrate the influence of increasing the ground albedo from 0.25 to 0.70. As the turbidity increases so the given turbidity value. The mean Monteith and Unsworth turbidity values for Blackwell's cloudless days between 1947-52 at Kew were found to be 0.15 in September, 0.13 in December, 0.23 in June and 0.24 in March. Values of G_{dh}/G_h are tabulated for various values of τ_a in Table 2. Unsworth's values which are independent of solar altitude for air mass 1.15-2.0 in summer are also given in Table 2. They correspond reasonably well with values derived from Parmelee. This ratio however should fall with increasing solar altitude, a phenomenon invariably observed in practice. The errors by using a fixed ratio above 30° are minimal however as the slope of the graph above 30° solar altitude is small. This is not true below 30°.

Parmelee (8) has presented results of diffuse solar irradiance both on horizontal and vertical surfaces. His results were derived from measurements made at Cleveland, Ohio, on days which, although cloudless differed in atmospheric clarity. A study of his results for a horizontal surface shows that, for a fixed solar altitude, α, a linear relationship exists between the diffuse horizontal irradiance and the direct horizontal irradiance. The relationship takes the following form:

$$G_{dh} = a_0 - a_1 G_{bh} \quad (Wm^{-2}) \qquad (2)$$

where G_{dh} is the diffuse irradiance on a horizontal surface, (Wm^{-2}), G_{bh} is the direct irradiance on a horizontal surface, (Wm^{-2}) and a_0 and a_1 are constants for a particular solar altitude α and are given in Table 3.

Equation 2 has been incorporated in our Sheffield clear sky computer programs, the constants a_0 and a_1 being determined for a particular solar altitude by interpolation on the values given in Table 3. Thus knowing the solar altitude one can derive the direct irradiance on the horizontal surface G_{bh} from the Monteith and Unsworth turbidity calculation and estimate the corresponding associated diffuse clear sky irradiance G_{dh} on the horizontal surface.

le 3

The figures in parentheses in Table 3 were obtained by extrapolation.

Solar altitude (degrees)	a_0	a_1
0	(0)	(0.290)
10	(63.1)	(0.295)
20	134.9	0.314
30	222.1	0.360
40	284.3	0.362
50	383.0	0.424
60	484.6	0.492
70	(552.1)	(0.520)
80	(604.3)	(0.545)
90	(624.7)	(0.560)

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Diffuse radiation on vertical and inclined surfaces on clear days

There is not space to discuss in detail the relationships between vertical surface diffuse irradiation, and horizontal surface irradiation under clear sky conditions. Figure 10 which is derived from Parmelee's observations shows the importance of the precise orientation of the surface receiving the diffuse radiation relative to solar position. The ratio of the diffuse vertical surface irradiance to the horizontal surface diffuse irradiance is expressed in Figure 10 as a function of the cosine of the angle of incidence of the direct sun on the surface for different angles of the sun. The large variations are immediately apparent. This figure demonstrates forcibly that the isotropic approximation is very inaccurate for the estimation of incident diffuse cloudless sky radiation on vertical surfaces. Fuller discussion may be found in Page (12). However, these non isotropic features of the clear sky are modelled in our Sheffield clear sky computer programs.

Fig. 10

This diagram based on Parmelee's work demonstrates the large errors which may result from using the isotropic approximation for diffuse radiation

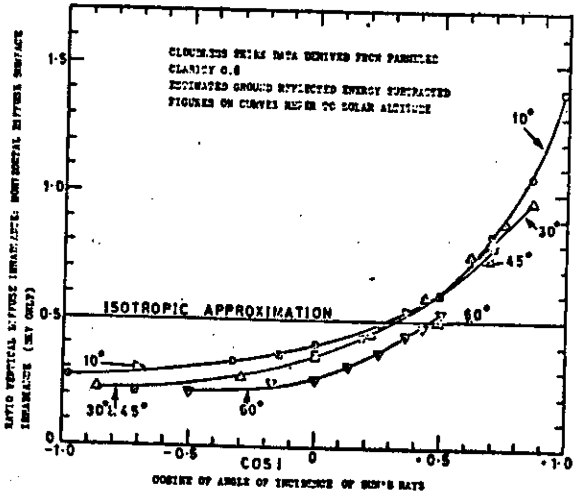
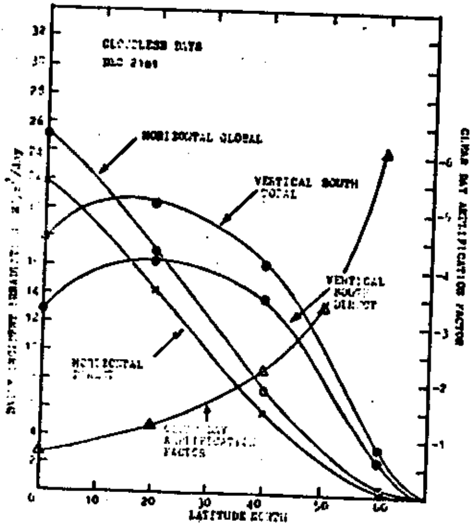


Figure 11 shows the effects of change of latitude on the cloudless irradiation of a horizontal surface and a vertical south surface calculated for a fixed turbidity of τ_a and ground albedo, using our program SUN3 for Dec 21st. It shows in December the most favoured latitudes for passive solar houses lie between 30 and 45°N. Further north a lot of the low sun's energy is lost in the atmosphere. The clear sky south vertical amplification factor however becomes quite large at high latitudes due to the favourable angle of incidence of the sun on the south wall, but the energy available close to the Arctic Circle on Dec 21st must necessarily be very low due to the long path length.

Fig. 11 Variations in the irradiation on a horizontal surface and on a vertical surface facing south with change of latitude $\tau_a = 0.150$, precipitable $H_2O = 5.0$mm, ground albedo = 0.25



The climatology of diffuse irradiation under average conditions

In cloudy climates diffuse irradiation dominates. The study of the climatology of diffuse radiation is therefore very important in solar building applications, especially at high latitudes and in the equatorial region where there is also a lot of cloud. Well over half the short wave energy income may be diffuse in such areas and it is important to have reasonably accurate methods for estimating the diffuse radiation available on building surfaces.

It is well known that the maximum amounts of diffuse radiation are received on days with partially clouded skies. Broken cumulus, in particular, can give very high values of diffuse radiation, and when the sun is shining through scattered broken cloud instantaneous values of global radiation can be recorded that are higher than the solar constant.

The basic problem is how, in the absence of local measurements, to separate the diffuse horizontal surface radiation, $\bar{H}_{dh}$, from the global radiation, $\bar{H}_h$. Page (13) found it was fortunately possible, using data from stations where both diffuse and direct irradiation are observed to set up reasonably reliable regression equations of the form:

$$\bar{H}_{dh}/\bar{H}_h = c + d(\bar{H}_h/\bar{H}_{oh}) \quad (3)$$

where $\bar{H}_{dh}$ = mean monthly values of daily diffuse irradiation on a horizontal plane,

$\bar{H}_h$ = mean monthly value of daily global irradiation on a horizontal plane,

$\bar{H}_{oh}$ = mean monthly daily irradiation on a horizontal plane in the absence of any atmosphere,

c & d are climatically determined regression constants which vary significantly from area to area in the world.

Liu and Jordan (14) in contrast put forward a single formula based on Blue Hill Observatory. Typical values of c and d for N. Europe and the US are given in Table 4, while Table 5 gives some values for the African continent calculated by the author. Corresponding data is available for Canada from Tuller (15)

The mean regression equation for the ten stations scattered across the world studied by the author in 1961 was found to be:

$$\bar{H}_{dh}/\bar{H}_h = 1.00 - 1.13\ \bar{H}_h/\bar{H}_{oh}$$

An important feature of this formula for estimating diffuse radiation is that it mathematically predicts the occurrence of a high level diffuse irradiation with relatively modest amounts of sunshine.

Rearranging equation 3, we get:

$$\bar{H}_{dh} = c\bar{H}_h + d(\bar{H}_h/\bar{H}_{oh})^2$$

This is a parabolic curve, and we may find the maximum value by simple differentiation, thus it is easy to show that:

$$\bar{H}_{dh(max)} = -c^2\bar{H}_{oh}/4d$$

and that this value occurs when $\bar{H}_h/\bar{H}_{oh} = -c/2d$

Observed relationships between daily irradiation and percentage possible sunshine for two stations close to the Equator in Africa are given in Figure 12. Both global and diffuse daily irradiation on a horizontal surface are plotted against percentage possible sunshine. In the equatorial climate of Kinshasa the maximum diffuse occurs with % possible sunshine is around 30%. Lubumbashi has a very sunny climate for part of the year. During this period the diffuse radiation is very low compared with Kinshasa at the same percentage possible sunshine where humid conditions prevail throughout the year. In the wet season at Lubumbashi the characteristics are similar to Kinshasa. Figure 12 shows that the diffuse radiation cannot be obtained by linear interpolation between clear and overcast day observations. Kasten (16) has comparable data for Hamburg given in terms of cloud cover and solar altitude for different seasons. The maximum diffuse typically occurs with cloud cover between 4 and 6 oktas when the diffuse irradiance is typically about 40% greater than the diffuse irradiance for cloudless sky conditions.

Table 4

REGRESSION EQUATIONS FOR $\bar{H}_{dh}/\bar{H}_h$ AGAINST $\bar{H}_h/\bar{H}_{oh}$ USING MONTHLY MEAN DAILY VALUES OF $\bar{H}_h$ AND $\bar{H}_{dh}$ OVER PERIOD, AND DIFFUSE MULTIPLIERS FROM KEW

Station		Values of c & d	Corr. Coeff.	$\frac{-c^2}{4d}$	Diffuse multiplier from Kew
London Weather Centre 51°31'N 1965-70	77m	c .990 d -1.103	0.98	.222	.949
Kew 51°28'N 1965-70	6m	c .980 d -1.026	0.97	.234	1.000
Bracknell 51°21'N 1965-70	73m	c .995 d -0.990	0.95	.250	1.068
Cambridge 52°12' 1965-70	13m	c .937 d -0.841	0.91	.261	1.115
Aberporth 52° 8' 1965-70	115m	c 1.064 d -1.140	0.97	.248	1.061
Lerwick 60°08' 1965-70	82m	c 1.078 d -1.14	0.96	.254	1.089
Hamburg 53°30' 1964-73		c 1.043 d -1.0386	.961	.262	1.119
Valentia 51°56' 1964-74	20m	c .958 d - .8508	.944	.270	1.153
Uccle 50°49' 1951-65	100m	c .9715 d - .9369	.968	.252	1.076
Blue Hill USA 42°12'N Nov 1945 - Oct 1949	205m	c .72 d - .67	.15	.193	.827

Table 5

VALUES OF CONSTANTS c & d IN REGRESSION EQUATION $\bar{H}_{dh}/\bar{H}_h = c + d\,(\bar{H}_h/\bar{H}_{oh})$ FOR STATIONS IN THE AFRICAN CONTINENT

STATION LATITUDE & HEIGHT (M)	VALUES OF c & d	CORR. COEFF.	RANGE OF MONTHLY MEAN VALUES $\bar{H}_h/\bar{H}_{oh}$	$\frac{-c^2}{4d}$	DIFFUSE MULTIPLIER	COMMENTS
KISANGANI 0°31'N 437 Sept 1952- Aug 1953	c 1.07 d -1.16	.93	39%-53%	.247	1.055	Hot humid climate
KINSHASA 4°22'S 450 Feb 1951-Dec 1952	c 1.08 d -1.21	.96	32%-52%	.241	1.032	Hot humid climate
WINDHOEK 22°34'S 1728 Aug 1951-Feb 1954	c 0.88 d -0.95	.95	57%-70%	.204	.871	Hot dry climate - high
PRETORIA 25°45'S 1369 Jan 1951-Feb 1954	c 0.98 d -1.16	.93	55%-69%	.207	.885	Hot dry climate - high
TANANARIVE 13°53'S 1310 Feb 1953-Feb 1954	c 1.20 d -1.39	.89	48%-65%	.259	1.107	Hot humid climate - high
DURBAN 29°50'S 5 July 1951-Feb 1954	c 1.10 d -1.43	.97	46%-61%	.212	.904	Hot humid climate
CAPETOWN 33°54'S 17 Sept 1951-Feb 1954	c 1.07 d -1.26	.93	56%-68%	.227	.971	Mediterranean type climate

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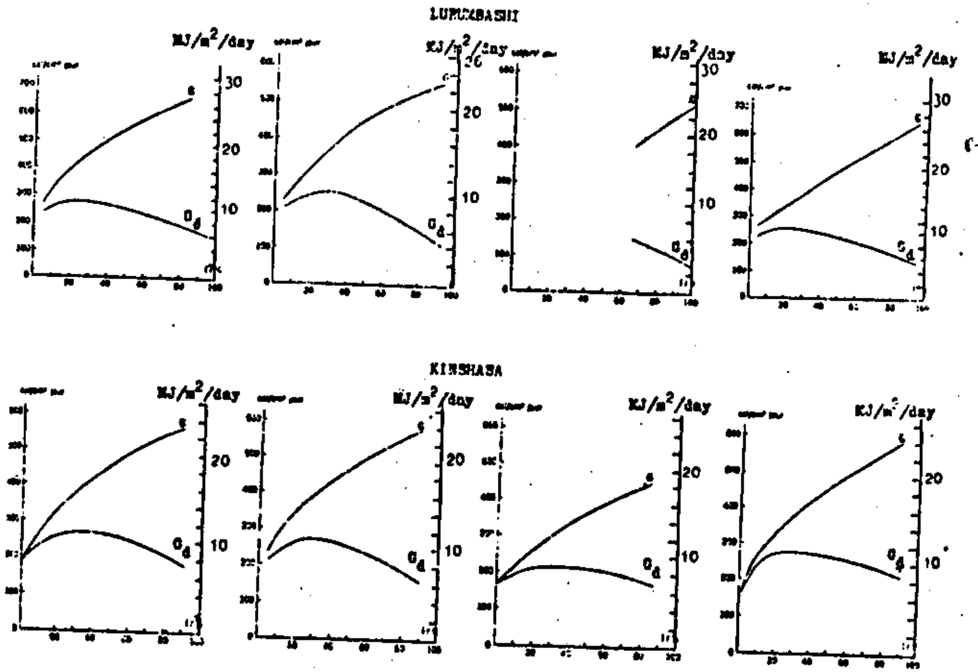
Fig. 12 Relationship between percentage possible sunshine and global and diffuse irradiance on a horizontal surface for two low latitude stations



Tables 4 and 5 imply the relative amount of diffuse energy for a given value of the monthly mean atmospheric transmission coefficient $\bar{H}_h/\bar{H}_{oh}$ varies from climate to climate. Some measure of the proportional variation from place to place may be obtained from values of $-c^2/4d$, which as I have shown define the maximum values of $\bar{H}_{dh}$ as a ratio to $\bar{H}_{oh}$. Values of $-c^2/4d$ are included in Tables 4 and 5. These values are also expressed as a ratio to the corresponding value of $-c^2/4d$ for Kew, England. We use this figure in our average day programs in Sheffield as a diffuse multiplier to correct our mean diffuse irradiance figures on the computer based on Kew to match actual observations at other stations more accurately. The multiplier may be greater than one, for example in clean high latitude relatively overcast climates, like Valentia, Ireland, or less than one for example in clear sunny climates like those found in the inland parts of Southern Africa. These corrections appear to hold over quite larger regions provided proper account is taken of local urban influences. The urban influence appears to depress the diffuse multiplier within a specific region by some 5 - 10%. Our experience in the UK is that the reduction in pollution which we are achieving in our cities has had a bigger impact on diffuse energy availability than on direct energy availability.

Hourly relationships for diffuse irradiance

We have additionally studied climatologically for several north western European stations the observed relationships between monthly mean hourly diffuse horizontal surface irradiance and the mean monthly solar altitudes in the middle of each observational hour recorded. We have found, provided long term means are taken, there is a very high correlation between monthly mean hourly diffuse horizontal surface irradiance and solar altitude for a number of stations in Western Europe. The relationship function is remarkably simple:

$$G_{dh} = a' + b'\alpha \qquad (4)$$

where G_{dh} is the monthly mean hourly diffuse irradiance for a particular hour when the altitude of the sun at the mid-point of that hour is α. This is the function we use in our average day computer model to predict diffuse radiation under average sky conditions in the first stage of the computation. Table 6 sets out some of the values of a' and b' we have recently determined. If the daily irradiation data are studied on a monthly annual basis for a particular station for a run of individual years, it is found that, as the average monthly global irradiation increases, the average diffuse irradiation also simultaneously increases in low sunshine climates. If however one is dealing with a very sunny climate the opposite is true. This observational result is, of course, implied by the parabolic nature of the relationship function already discussed:

$$\bar{H}_{dh} = c\bar{H}_h + d(\bar{H}^2_h/\bar{H}_{oh})$$

(This relationship is, of course, derived from the study of whole day data rather than from hourly values.) The rising or falling characteristic simply depends on whether $\bar{H}_h/\bar{H}_{oh}$ is above or below the peak value of $-c/2d$. By incorporating this additional relationship function into our computer program we are able to predict annual variations of annual monthly mean diffuse radiation from annual monthly mean sunshine data. We have not had time to study the monthly mean hourly diffuse relationship functions for the Southern Hemisphere in detail. The relationship discussed certainly holds approximately for the Australian data reported by Paltridge (17) and is more accurate than Paltridge's method of estimation in spite of its far greater simplicity. Nevertheless the relationship appears to hold somewhat less accurately than in the Northern Hemisphere and it is possible that the remarkably simple result found for temperate areas of the Northern Hemisphere depends on the fact that the influence of the summer increase in turbidity on diffuse irradiation coincides with and precisely balances the summer decrease due to changes in the mean solar distance, while just the opposite situation will exist in the Southern Hemisphere. Pending further studies equation 4 should be used with caution in the Southern Hemisphere.

Having explored the diffuse radiation problem in considerable detail, we can now consider the problem of predicting the actual irradiation on slopes under average conditions.

Table 6

CONSTANTS IN MONTHLY MEAN HOURLY DIFFUSE HORIZONTAL SURFACE IRRADIANCE FORMULA

$$G_{dh} = a' + b'\alpha \text{ watts/m}^2$$

WHERE α IS THE SOLAR ALTITUDE IN THE MIDDLE OF THE HOURLY PERIOD CONSIDERED

Station	Comment	a'	b'	Correlation Coefficient
DATA DERIVED FROM HOURLY OBSERVATIONS				
Kew 1959-68	Suburban London	2	4.532	0.996
Eskdalemuir 1959-68	Inland site in hills - possibly some pollution influence from Glasgow	2	4.798	0.997
Lerwick 1959-68	Northern exposed coastal position	2	5.068	0.997
Aberporth 1959-68	Coastal site West Wales	2	5.176	0.994
Hamburg 1964-73	Airport site	2	5.36	Fitted by eye. Preliminary figure based on four months - Jan, Mar, June, Sept.
Valentia 1964-74	Extreme westerly of coast Ireland Pollution levels v. low	2	5.60	Fitted by eye. Preliminary figure based on four months - Jan, Mar, June, Sept.
DATA DERIVED FROM DAILY OBSERVATIONS OF $\bar{H}_h$ & $\bar{H}_{dh}$				
Kew 1965-75	Suburban London with reduced pollution	2	4.804	Used computer radiation model to determine correction to 1959-68 period
Bracknell 1965-75	New town in countryside outside London	2	5.068	Used computer radiation model to determine correction to 1959-68 period

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Climatological variations in the mean irradiation of sloping surfaces

At high latitudes the levels of irradiation on horizontal surfaces even on cloudless days are very low in the winter half of the year. In summer the longer day compensates to a considerable extent for the lower mid-day sun. The low winter horizontal surface values are due partly to the unfavourable angles of incidence. Fortunately the solar energy density falling on a collector may be substantially increased by tilting the collector at an appropriate angle towards the Equator. Table 7 presents data on observed values of the mean irradiation incident on vertical surfaces at different stations as a ratio to the mean irradiation simultaneously incident on a horizontal surface. If the mornings are clearer than the afternoons an appropriate offset towards the easterly direction will give higher incident energy, and vice versa, if the afternoons are clearer. Figure 13 for Kinshasa shows in some climates very strong asymmetry may occur. The high humidities in the equatorial zone produce heavy cloud obstruction during the morning which lifts to some extent as the day progresses. Providing one can estimate the direct beam irradiance, which one can do if the hourly variations of turbidity and

Table 7

OBSERVED RATIOS OF MEAN MONTHLY VERTICAL SURFACE IRRADIATION TO MEAN MONTHLY HORIZONTAL SURFACE IRRADIATION

MONTH	VERT SOUTH KINSHASA 4°22'S 1954-60	VERT SOUTH BLUE HILL 42° 13' 1952-56	VERT SOUTH ODEILLO 42°29'N 1971-74	VERT SOUTH BRACKNELL* 51°21'N 1967-73	VERT SOUTH HAMBURG [illegible] 1952
J	0.46	1.80	1.76	1.38	1.40
F	0.37	1.38	1.33	1.26	1.[illegible]3
M	0.27	0.93	0.90	1.00	1.15
A	0.26	0.61	0.67	0.73	0.80
M	0.30	0.44	0.49	0.60	0.62
J	0.29	0.39	0.43	0.52	0.59
J	0.31	0.42	0.44	0.55	0.60
A	0.31	0.54	0.59	0.66	0.75
S	0.44	0.79	0.85	0.87	1.00
O	0.39	1.23	1.24	1.20	0.96
N	0.44	1.60	1.69	1.59	1.[illegible]0
D	0.49	1.94	2.09	1.65	1.[illegible]0

* Observations exclude ground reflections, observations adjusted to a ground albedo of 0.20.

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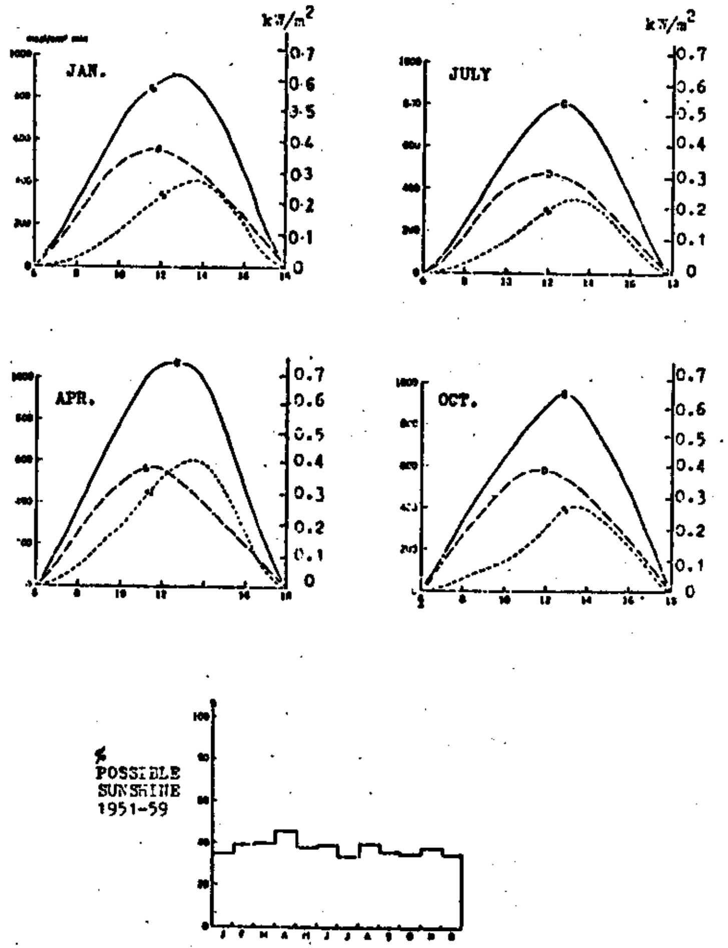
Fig. 13

Variations in mean global, direct and diffuse irradiance on a horizontal surface in a cloudy equatorial climate. Note a symmetry of direct irradiance about solar noon, Kinshasa 4°22'S, 15°15'E, 438m, 1954-1960.



sunshine are known, it is fairly easy to calculate the tilt which will collect the greatest amount of direct solar energy on clear and partially clouded days, using standard trignometrical methods.

However the estimation of the mean diffuse irradiation on slopes is more difficult because it is not isotropic. One must also consider the effects of ground albedo, which are greatest for the steepest slopes. Furthermore the ground albedo may vary strongly with the actual angle of incidence of the direct beam on that surface (18). The author presented a fairly simple approach for estimating the available energy on slopes to the Rome conference (13) and an updated version has been recently issued (12).

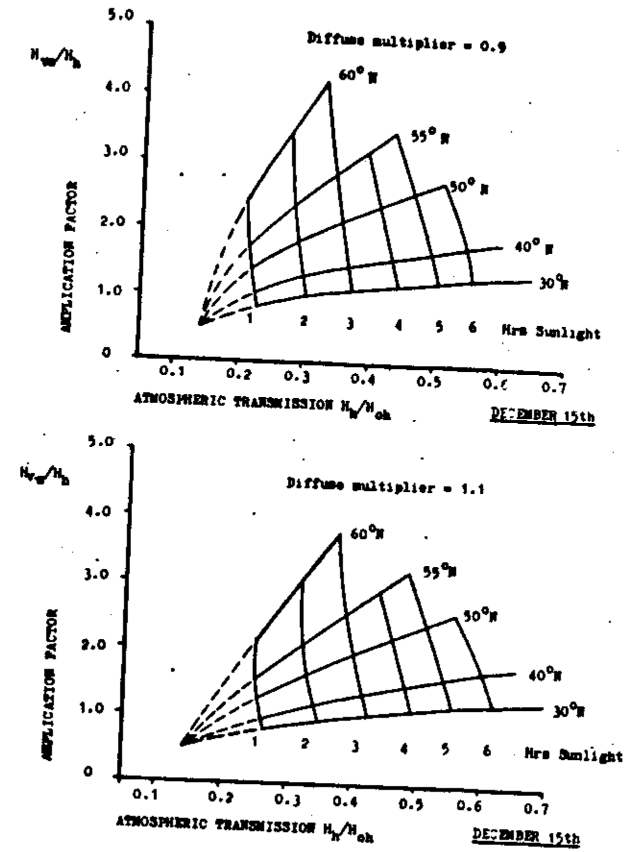
In Sheffield we now prefer to handle this problem in more detail on the digital computer and our average day solar radiation AVDY program generates hourly data for slopes of any inclination and any orientation from mean monthly values of the sunshine recorded. At present the accuracy is fully tested for the UK, but the program appears reliable between latitudes 40° and 60°N at this stage. Further checks are in progress. If appropriate values of the turbidity are available, it is certainly possible to estimate the mean slope irradiation ithin 10%. Our current climatological model considers the diffuse sky irradiation to be made up of two parts, one part coming from the clear blue sky and the other part from the overcast sky. The division of the diffuse into two parts is done on the basis of possible sunshine amount. The clear sky part is distributed in such a way that the area of high radiance around the sun is correctly allowed for as described by Rodgers et al (19). The radiance of diffuse overcast sky part is assumed to follow the Moon and Spencer distribution adopted by the CIE (20). The radiance of the overcast sky L_Θ at an angle Θ from the horizontal plane is related to the zenith radiance L_z by the relationship function:

$$L_\Theta = L_z(\frac{1}{3} + \frac{2}{3}\sin\Theta) \qquad (5)$$

This formula indicates the radiance at the zenith of the overcast sky is three times the radiance at the horizon. The diffuse sky irradiance on a vertical surface under overcast sky conditions is .3955 of the diffuse irradiance on a horizontal surface (21). As a horizontal surface receives the greatest overcast diffuse sky irradiation, so as the proportion of overcast diffuse radiation rises, the optimal tilt for maximum surface irradiation decreases. However, solar collectors are not linear systems, so it may be better to collect energy efficiently on the few clear days using a steeper tilt. The answer to such complex questions however can only be accurately determined by detailed simulation.

We have used our average day program to carry out a preliminary systematic study of the effects of sunshine amount, and diffuse multiplier on the irradiance multiplier for vertical south facing surfaces. Our preliminary results for Dec 15th are presented in Figure 14 for latitudes between 30°N and 60°N. It will be seen that as the sunshine and atmospheric transmission decrease, so the energy multiplier falls, and the benefits of southerly steep tilts are very small in situations where there is little sunlight. December, of course, is the most extreme month in radiation terms. Figure 14 brings out the enormous differences between sunny and cloudy climates and I must stress the dangers about being too optimistic about the actual amounts of solar energy available. Clear day analysis can lead to excessively optimistic estimates of solar energy prospects. Even in low latitudes considerable problems may be experienced in climates where there is a lot of cloud. Figure 15 compares the mean monthly variations in the vertical surface irradiation for the two low latitude

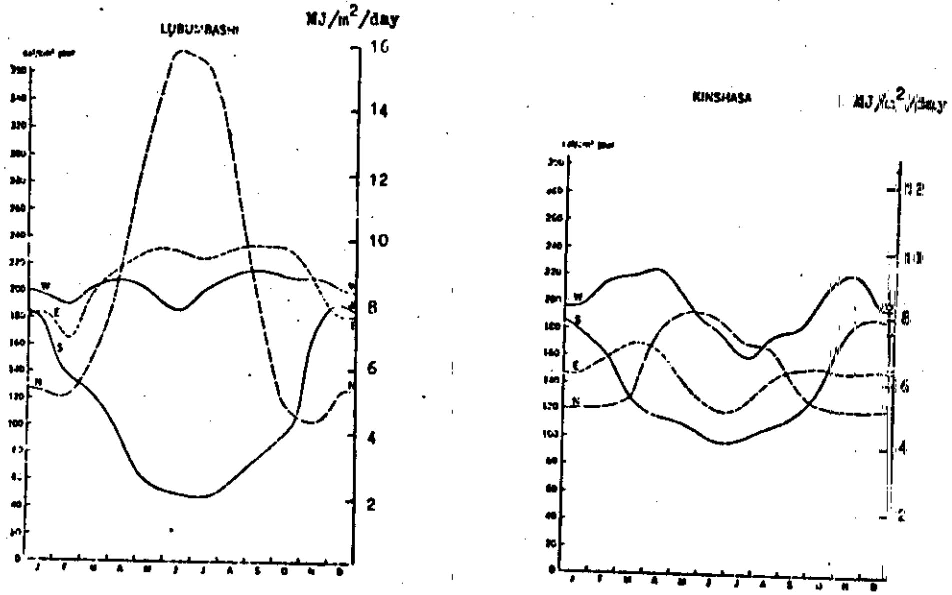
Fig. 14



African sites already discussed. The lower the latitude the less the advantages of using steeply tilted surfaces, as a comparison between Figure 15 and Figure 4 shows.

The broad climatological implications of tilt are clear. Tilting towards the Equator reduces the winter-summer energy density range, especially at high latitudes. Steep equatorial tilts increase winter energy availability at high latitudes and decrease summer energy availability. The optimum tilt depends on the purpose for which the solar energy is to be used. The corrections to horizontal surface data for increases in available energy density due to favourable tilt are greatest at high latitudes, and are least in equatorial regions. The more diffuse energy there is the shallower the tilt required for maximum incident energy. There may be big differences between mean insolation in the morning and the afternoon, which may make it desirable to twist the collector in the more favoured direction to take account of differences in cloudiness between morning and afternoon.

Fig. 15 Mean monthly irradiation falling on vertical surfaces facing two cardinal points at Lubumbashi and Kinshasa. Note roughly equal irradiation of all surfaces in the humid equatorial climate of Kinshasa, and the marked differences which appear in the sunny season at Lubumbashi with the sun standing north of the elevation



Climatological factors affecting heat losses from flat plate solar collection systems

The overall thermal efficiency of collection of solar energy depends on the balance between the energy gains and the thermal energy losses. If the collection system is properly insulated, most of the heat loss will occur from the front face. The long wave radiative losses will depend on the equivalent radiative temperature of the sky, which is strongly influenced by the amount of cloud cover.

Unsworth and Monteith (22) have shown that measurements of $\emptyset_t$, the long wave flux density on a horizontal surface under cloudless conditions in the Sudan and also at Sutton Bonington, UK is well represented by the straight line:

$$\emptyset_t \doteq c' + d' T_a^4 \qquad (6)$$

where T_a is the screen air temperature in degrees Kelvin

is Stefan Boltzman constant.

The constants c' and d' were found to have values of - 119 ± 16 Wm-2 and 1.06 ± 0.04 respectively. When the screen air temperature is expressed in °C the cloudless sky relationship reduced to:

$$\emptyset_t = 213 + 5.5\, t_a \quad W/m^2$$

The downward radiation is increased by the presence of cloud, and the flux of downward radiation below different types of cloud can be estimated from Kondratyev (23). The difference between the outgoing long wave radiation and the incoming short wave radiation is known as the net long wave radiation. It normally has a negative value. When the radiation temperature of the ground is equal to the screen air temperature, the ratio of the net long wave radiation under cloudy skies to the corresponding net flux under clear skies is equal to 1 - 0.84c, where c is the fraction of sky covered by cloud. Thus the net long wave radiation exchange under overcast conditions typically falls to 16% of the clear sky value. The long wave radiance of the sky is not uniform and Unsworth (24) has dealt in detail with the geometry of interception of long wave radiation by slopes. Long wave energy exchanges with the ground become increasingly important as the slope angle gets greater. We have used Unsworth's paper to prepare an interactive program for predicting long wave radiation exchanges and have used it to produce Figure 16. Figure 16 shows that steeply sloping collectors have a somewhat more favourable long wave energy balance than collectors with small tilts, especially in clear weather, and more account needs to be taken of this climatological factor in assessing collector performance.

The convection losses are influenced by external wind speeds and air temperatures. The wind speed, of course, increases substantially with height. The aerodynamic factors that influence the detailed flow over the collection surface are important, but are poorly considered at present, and there is considerable scope for further study of how to reduce the energy losses from collectors due to wind flow. Our own wind tunnel and full scale work on energy transfer in Sheffield has so far been confined to the study of the actual energy losses from the windows of a 19 storey building. Our experience to date indicates that the actual heat transfer coefficients are different from those used in conventional engineering calculations. Wind is, of course, particularly important in the case of unglazed collectors. Low mounting positions on sites well sheltered by low trees are likely to be best for solar collection when using unglazed collectors for swimming pools. Exposed sites on the tops of poles are favourable for the efficient operation of solar cells whose

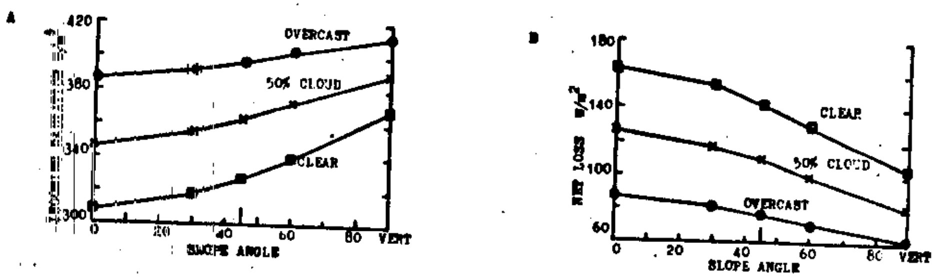


Fig. 16 Effect of slope angle and sky clarity on (A) total incoming long wave radiation (sky + ground + ground reflectance) (B) net long wave radiation loss from surface to sky and ground with air temp at 17°C, collector surface temp 30°C, collector surface emittance 0.95, ground emittance 0.90, and ground surface temperature 20°C.

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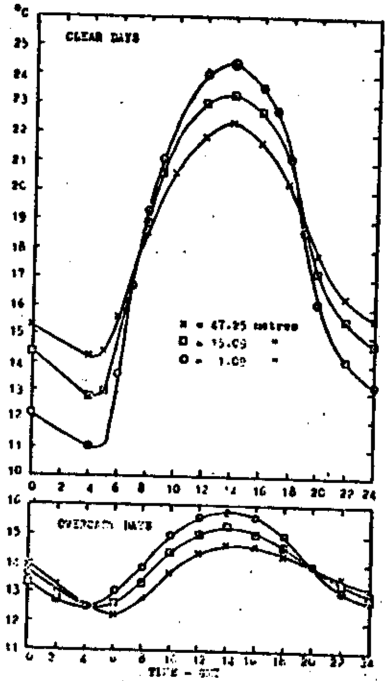
Fig. 17 Effect of height and insolation on air temperature regimes on sunny days and on overcast days - S.E. England summer.

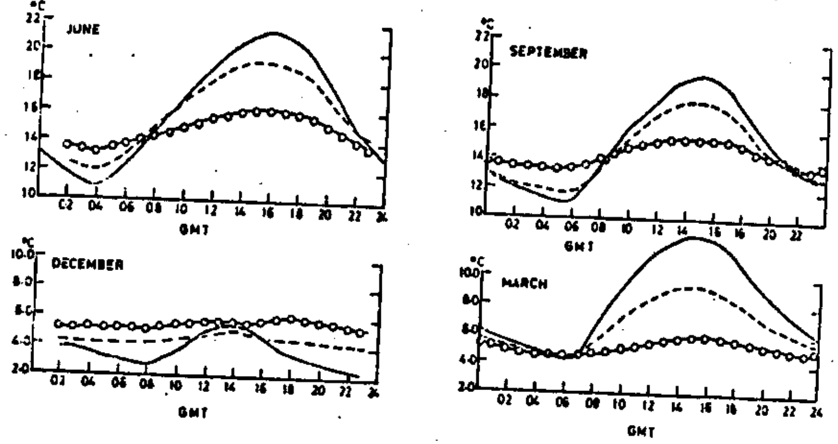


performance is adversely affected by significant rises of temperature. Increasing attention is being paid to micro-climatic factors in building design (for example for general review refer Page (25)), but so far little systematic attention seems to have been given to the importance of microclimatic considerations in the solar house design field. For example Figure 17 shows typical relationships found between air temperature and height in the UK for clear and overcast weather.

Climatological factors affecting space heating and space cooling demands

Finally in assessing the climatic feasibility of using solar energy for space heating and space cooling, it is obviously important to simultaneously study the impact of climate on the actual energy demands in buildings. In space cooling, especially in situations where the radiant heat load through the windows and/or the rest of the structure dominates over the latent heat load, the solar radiation supply will be closely linked to the energy demand patterns, and the problems of solar energy storage will be minimal. A few hours storage may suffice. In space heating, especially in very high latitudes, the opposite situation will often

Fig. 18 Diurnal variations in shade air temperature at Kew for three classes of daily irradiation, smooth curve - days of high radiation, dotted curve - average days, and smooth curve with circles - days of low irradiation, for the months of March, June, September and December.



prevail, and the solar supply will be six months out of phase with the heating energy demand.

The solar heat gain variables and the heat loss variables are, of course, statistically interlinked, and the temperature regimes on sunny days are quite different from overcast days. The nights may be much colder after sunny days than when the weather is overcast, as the clouds associated with overcast days substantially reduce the outgoing radiation and so stabilise the night-day temperature differences. Figure 18 illustrates the screen air temperature regimes found for days of different radiation classes at Kew, England. Statistically overcast days in winter are warmer throughout the twenty-four hours than clear days. In the UK it is normally windier on overcast days than on clear days. In other parts of the world this relationship could well be reversed as high insolation in dry desert areas tends to stir up the daytime surface winds due to strong vertical convection. In the humid tropics the wind speeds are often very low on overcast days and the weather may become very oppressive indeed.

Such complex climatological interactions can only be properly demonstrated by appropriate local meteorological studies and observations. I wish to stress the need for meteorological services to observe and prepare meteorological summaries for solar house design which respect a design logic that needs the simultaneous assessment of solar heat gains and collection heat losses. Guidance is also needed on the effects of height and of shelter.

In high latitudes economic solar energy utilisation may only become feasible when and if we can develop cheap long term solar energy stores to store summer energy. In mid-latitudes between 25° and 40°, there is usually a far better balance between winter energy supplies on south facing surfaces, and space heating demands. In such areas successful space

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heating solutions can be built in less stringent energy storage criteria. Some measure of the relative scale of the problems to be solved can be compiled by comparing the winter degree days (to some suitable base) with the available radiation on a favourably inclined surface (say tilt equal to the latitude, or the latitude + 10°). The centre of the US located around latitude 35° - 40°N is for example much colder in winter than the south west of the UK warmed by the Gulf Stream at latitude 51°N, but has a much better solar radiation climate. The length of the heating season in North Western Europe is very long and solar space heating can play an alternative role to full space heating by helping to keep buildings comfortable in spring, summer, and autumn, while the mid-winter load is met from fossil fuels, or possibly, in future, from wind and wave power which are in very plentiful supply at that time of year. UK experience indicates that with only short term storage available it is difficult to meet as much as 40% of the domestic space

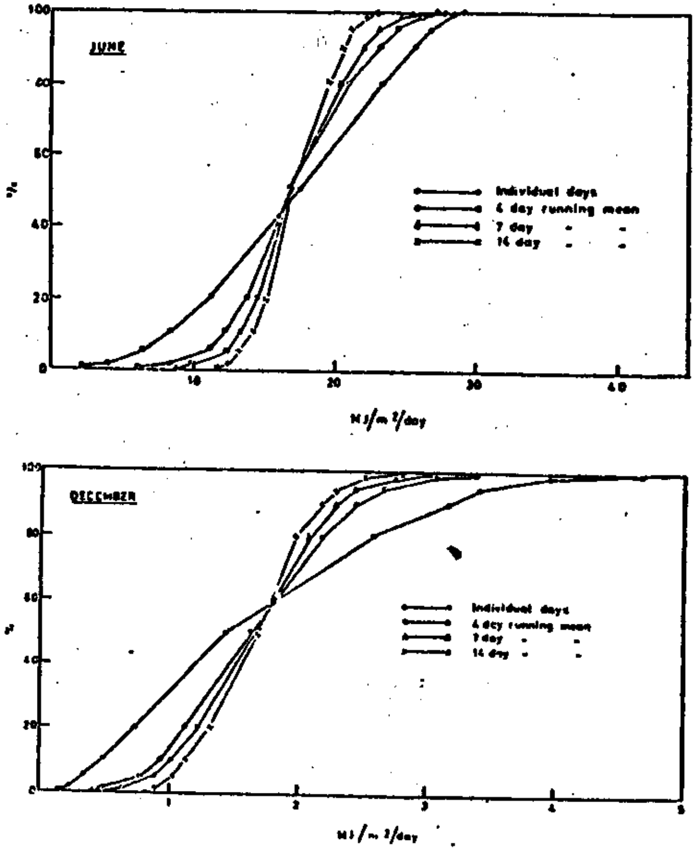

Fig. 19

Cumulative frequency distribution of average values of total daily global solar irradiation based on running means over different periods for a) June and b) December at Kew, 1951-1970.

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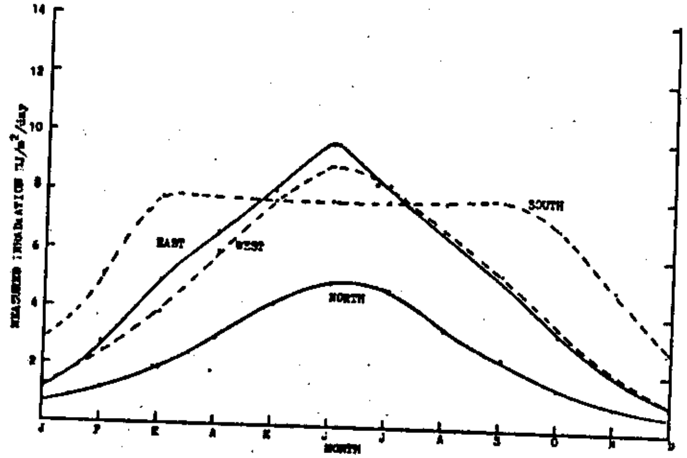
Fig. 20

Measured mean monthly daily irradiation on vertical surfaces facing south, north, east and west at Bracknell, England, latitude 51°21'N. Ground reflections are excluded. Period 1966-73.



heating load from the sun in our latitudes, and this contribution comes mainly in the period March to May, and in October.

The pattern of day to day weather is also important as it affects storage needs. There is no space to discuss here the best ways of describing the temporal patterns for design purposes. Simple statistical radiation data for the US may be found in Jordan and Liu's recent review (26). The UK Meteorological Office have compiled statistics on the variations in solar energy on a horizontal surface using running means for different periods from one day to fourteen days. Data presented from the UK-ISES Report (1) shown in Figure 19 demonstrates the very large variability in the irradiation for single days, especially in December. The variability is substantially reduced if a four day period is considered, but there is little further change for the fourteen day running means. If short term storage is to be used in such a climate, the benefits of fourteen day storage capacity will be modest compared with four day storage over one day storage. If really long term storage is available, as in the Danish Zero Energy House (27), then very long term running means over months can be considered, and the principles of storage design are fundamentally changed in nature.

Conclusion

Further collaboration between meteorologists, building scientists and architects will be needed to produce a sounder climatological foundation for solar house design. The computer can play an important role in assisting developments in this area because many of the calculations are relatively long and tedious to perform. Our computing approach in Sheffield enables appropriate design aids be rapidly produced for different centres but considerable further detailed meteorological study is still needed to make design forecasts more reliable in various parts of the world. More study for example is needed of the links between meteorological factors influencing the demands for energy, with the factors that influence the supply of solar energy. The microclimatological considerations need greater attention. As solar house design is a very difficult systems engineering problem, collaboration in systems analysis will be vital to success, and the will to achieve effective interdisciplinary communication essential. We must take pride in what we achieve as a team rather than simply in the professional activities through which we make our personal contribution to the wider human good.

Acknowledgements

The computer based research project on solar radiation estimation reported in this paper is partly financed by the Science Research Council. The help of my collaborators in this project, G.G. Rodgers and C.G. Souster, has been invaluable in the task of preparing the tables and diagrams. Figures 1,3,6, 18 and 19 have been drawn from the UK Section of the International Solar Energy Society's comprehensive report, "Solar Energy - a UK Assessment", and I am grateful to the Society for letting me reproduce them. Figures 5, 12, 13, and 15 have been taken from the excellent Atlas Climatique du Bassin Congolais which provides a fund of good information on how to present radiation and other meteorological data for a whole territory (28). Time unfortunately did not allow me to seek their formal permission, but I hope they will accept the need for the more experienced to help the less experienced in this vital field. At present few tropical countries can provide such excellent data.

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MAPPING IMPLICATIONS OF RURAL ENERGY SYSTEMS IN NIGERIA

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Introduction

Nigeria ranks as the sixth largest producer of oil in the world, and the second largest in Africa, following only Libya. Nigeria also has substantial reserves of natural gas and coal, and the gigantic Kainji Hydro-electric Dam Project recently completed at a cost of N 175.3 x 10^6. However, the rural areas hardly feel the impact of Nigeria's importance as a major energy producer; in fact energy is in short supply all over the country. We are now too accustomed to the long queues at gasoline stations and the notorious intermittent blackouts that have given the Nigerian Electric Power Authority (NEPA) all kinds of names, such as "No Electric Power Available" and "Not Enough Power Again," just to mention two. In addition, the constant threat that fossil fuels will inevitably be exhausted makes the development of a rural energy strategy a necessity in Nigeria. Part of the solution to our energy problems may be found in developing various energy alternatives for the rural areas so as to reduce our heavy dependence on hydro-electric power. This calls for a proper assessment of our current energy resources and intensive research into our potential energy resources in order to establish a sound rural energy strategy. The need to accord a special place to energy mapping will therefore continue to assume great importance in our national mapping programme. It is the objective of this paper to make a brief but general review of some energy-related maps and to discuss the potentials for rural energy resources and the role of photogrammetry as a mapping tool for energy-related studies.

Current Energy Resources

Hydro-electric power

Figure 4 shows among other things the location of major

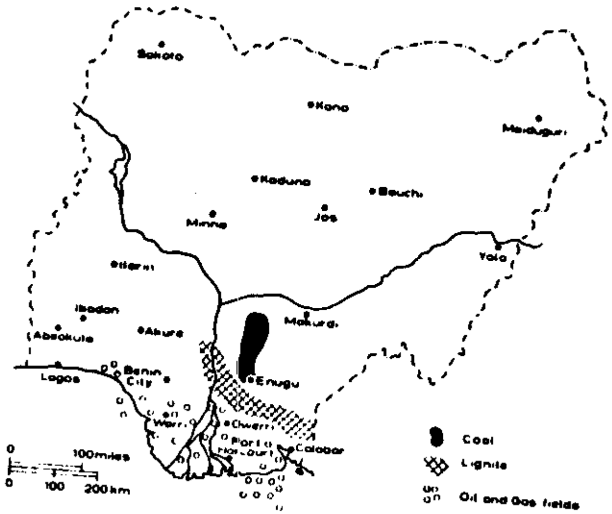

Fig. 1. Nigeria : Mineral Energy Resources

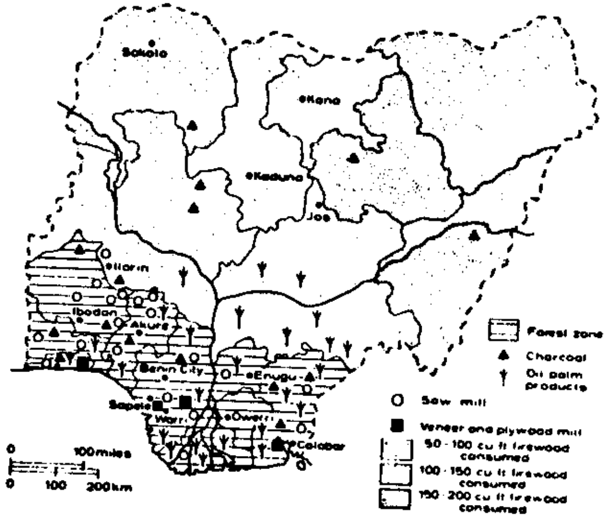

Fig. 2. Nigeria : Rural Energy Resources

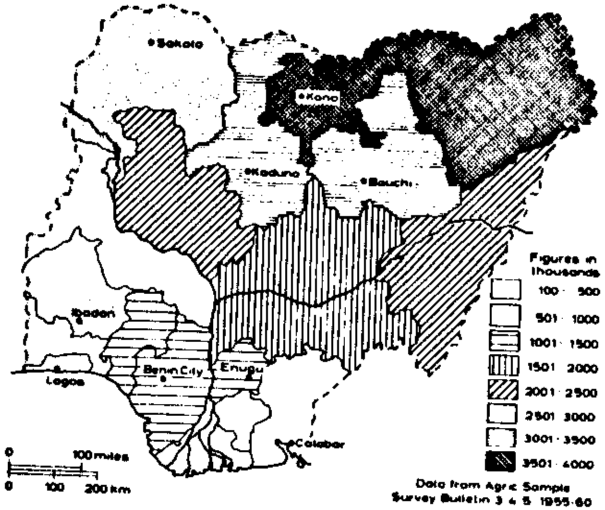

Fig. 3. Nigeria : Livestock Distribution (Data from Agric, Sample Survey Bulletin, 3, 4, 5, [1955–1960]

dam projects in Nigeria. The Kainji Dam project constitutes the major source (about 80 per cent) of our electric power supply. In the Third National Development Plan Period (1975-1980) NEPA's development programmes, at an estimated cost of N 837.5 x 10^6, include short- and long-range projects for the requirements of rural electrification (Nigerian Handbook 1977, p. 116).

Fossil fuels

The oil and gas producing areas and oil refineries are shown in Figure 1. The country's first refinery is located at Alesa near Port Harcourt. A second refinery was recently opened in Warri and the third is currently being built in Kaduna. The major by-products of crude oil used in the rural areas include gasoline, kerosene, paraffin, and butane gas.

Coal fields

Coal is Nigeria's third main source of power. Figure 1 also shows the major coal fields in Nigeria. Five economically important (sub-bituminous) coal seams occur at Enugu and Ezimo in Anambra State, at Orukpa in Benue State and at Okaba, and in the Ogboybya-Odokpona area in Kwara State. There are about 344.8 x 10^6 metric tons of workable sub-bituminous coal reserves (Swardt and Casey 1961, preface). The high ash content of Nigerian coal makes it primarily suitable as a domestic fuel in the rural areas or as a boiler fuel for industrial use and only of limited potential value as a source of hydrocarbons.

Since the Nigerian Railway Corporation replaced steam with diesel locomotives, local demand for coal has been drastically cut down. Coal therefore could be a valuable source of rural energy for heating and cooking apart from exporting the excess to newly-discovered markets such as Ghana and Egypt. Lignite, with an estimated reserve of about 71.1 x 10^6 metric tons, is found in Tertiary Sediments which extend from the Oborukpa and Ogwashi-Asaba areas in Bendel State to Orlu in Imo State.

Palm products

The oil palm is indigenous to tropical closed forest in Nigeria and its products include palm oil, palm oil sediment, palm kernels, kernel shells, and the pounded and squeezed dry pulp of palm nuts. These are all dependable sources of fuel in the rural areas of the Nigerian palm belt which stretches through the southern states (Figure 3).

Fuelwood and vegetable products

These include farm wastes (corn stalks, weeds, yam stalks, etc.) and saw-mill wastes (sawdust, slabs, and offcuts) as well as fuelwood cut from the forest and savannah. Figure 2

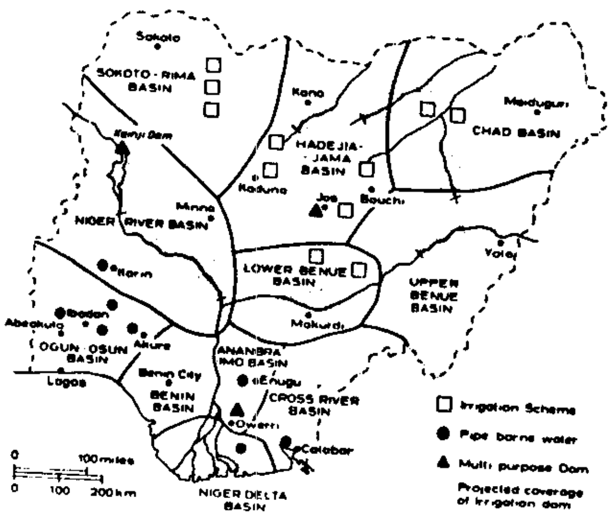

Fig. 4. Nigeria : Water Power Resources

shows the distribution of fuelwood consumption in the northern states (where reliable data are available), the location of saw-mills, and the extent of the forest zones where many of the tree species referred to by Afolabi Ojo (1978, p. 174) as capable of producing good quality charcoal are found. The forest area also has great potential for the development of fuel plantations.

Animal dung

Attention has been drawn to the importance of animal dung as a rural energy resource (Ojo 1978, p. 175) especially in the northern part of the country which has a large population of livestock (Figure 3). It has also been suggested that "the supply of animal dung can sustain the establishment of biogas plants on small-scale basis in the rural areas" (Ojo 1978, p. 175).

Potential Energy Resources

Nigeria has considerable potential energy resources, such as small-scale hydro-electric power dams, tidal power, geothermal energy, wind power, and solar energy.

Water power

According to Decrees No. 25 and 37 of 1976, the whole country is divided into 11 River Basin Authorities which operate under the Federal Ministry of Water Resources; they are the Sokoto-Rima, Hadejia-Jama, Chad, Niger, Upper Benue, Lower Benue, Cross River, Anambra-Imo, Ogun-Oshun, Benin, and the Niger Delta Development Authorities (see Figure 4). One of the main functions of these authorities should be to develop a rural electrification strategy in collaboration with NEPA by constructing multi-purpose dams for the generation of electricity.

Another important rural energy strategy in Nigeria is the conversion of numerous reservoirs for irrigation and "pipe-borne water" into dual-purpose schemes to include the generation of electricity, since these small-scale sources of water (Figure 4), in addition to serving their primary function, could also be used to operate low horse-power hydraulic turbines for the provision of electricity for small communities. There are a few examples of dual-purpose reservoirs in the country, including those on the Oji river at Siroko and at Jos. This type of strategy will not only ensure a wider provision of rural electricity but also a much more stable and reliable supply.

Tidal power

Tidal power is obtained from the "filling and emptying of a dam" (Hubbert 1971, p. 66), which are synchronized with the alternation of high and low tides so as to generate as much power as possible. A number of promising sites

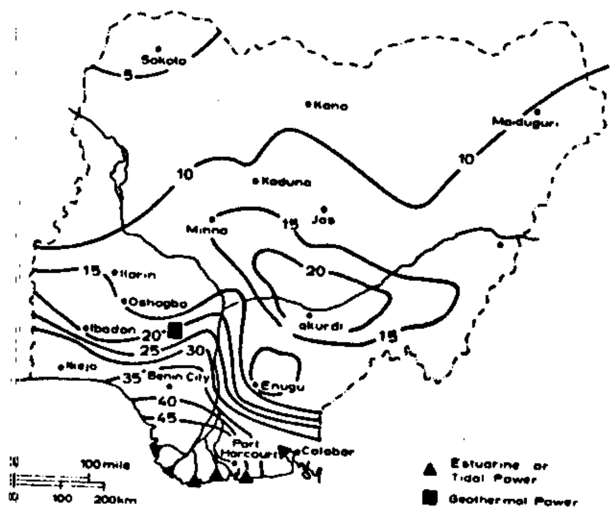

Fig. 5. Nigeria : Isoline Showing Percentage Occurrence of Calm Wind

for tidal power exist along the coastal area of Nigeria (Figure 5).

Geothermal power

Geothermal power can be tapped from the heat stored in the earth, for example by driving a well through the escape fissure of a hot spring. The only known area in the country which has a potential for such power is at Ikogosi (Figure 5), where steam wells could be dug to tap geothermal energy for generating electricity to serve the needs of the neighbouring communities.

Wind power

Wind as a source of power has two almost unique advantages: (i) it does not impose an extra heat burden on the environment, and (ii) it is ubiquitous. Wind is, however, unfortunately capricious. To harness it effectively, the various locations in the country where the occurrence of calm wind is rare must be determined. Table 1 shows the percentage occurrence of calm wind at 16 weather stations in Nigeria (see Figure 5). The areas around Port Harcourt and Benin City seem to be unlikely places for the development of wind power as an energy resource, and Figure 5 shows that the northern states have the greater potential for harnessing wind energy.

Solar power

Perhaps the greatest potential for rural energy supply in Nigeria lies in solar power. Solar-generated energy shares the two merits of wind power mentioned earlier. However, since solar radiation is intermittent at any one place, a large-scale storage device must be provided to smooth out the daily variation if it is to be used as a constant energy source. Figures 6-8, showing the distribution of mean daily hours of bright sunshine and the mean annual daylight distribution of net radiation, indicate that most of the northern states would be more suited to the use of solar energy than their southern counterparts.

Other potential energy sources are lightning power and atomic energy.

The Role of Photogrammetric Mapping in Energy-Related Matters

Photogrammetry is the technology that deals with the problem of extracting reliable information from all kinds of photographs—terrestrial, aerial, and from sapce, colour, black and white, infra-red, and so on. Two basic processes are involved—*measurement* and *interpretation*. *Measurement*, or quantitative photogrammetry, usually involves two conventional applications:

a. analogue photogrammetry for the derivation and produc-

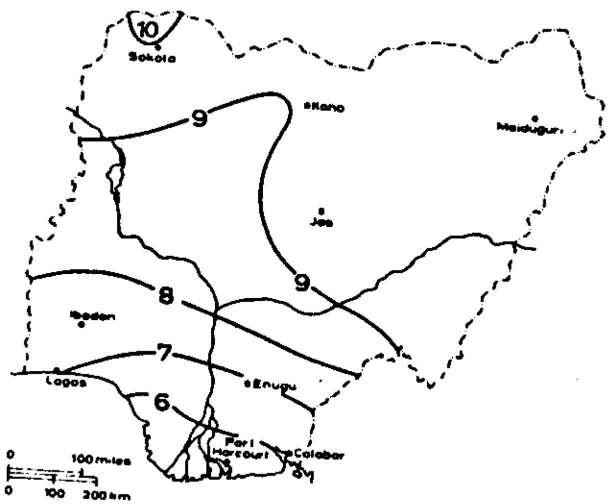

Fig. 6. Nigeria : Mean Daily Hours of Bright Sunshine (February)

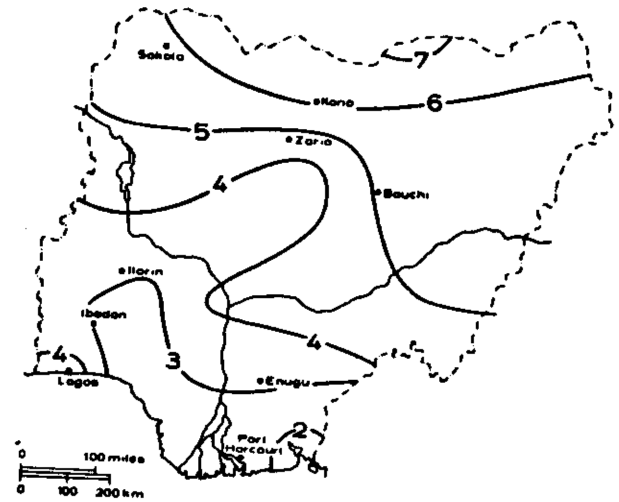

Fig. 7. Nigeria : Mean Daily Hours of Bright Sunshine (August)

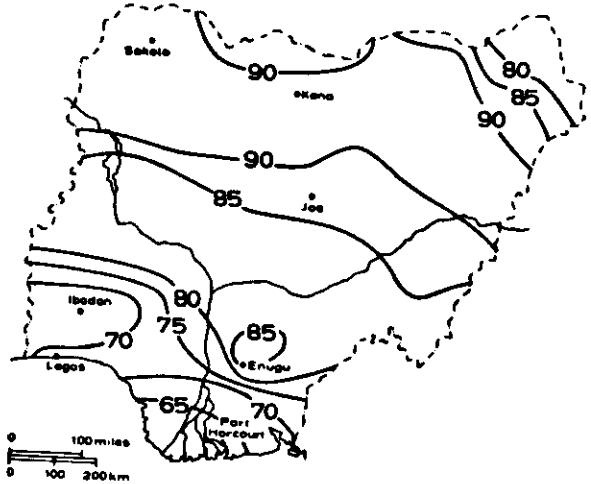

Fig. 8. Nigeria : Mean Annual Daylight Net Radiation (kcal/cm²)

tion of topographic maps, and

b. analytical photogrammetry for the determination of the space co-ordinates (X, Y, Z) of ground survey stations in a triangulation problem.

Analogue photogrammetry may be regarded as continuous mapping while analytical photogrammetry may be seen as discrete mapping.

Interpretation consists of the evaluation of photographic imagery, which may be acquired with special sensors or conventional cameras. Remote sensing may be correlated with quantitative photogrammetry for the production of conventional maps, thematic maps, and resource surveys (American Society of Photogrammetry 1977, p. 1463). The role of these two branches will now be discussed with particular reference to the exploration, evaluation, and exploitation of energy resources as a contribution towards developing a rural energy strategy.

Rural energy resource exploration

The application of photogrammetry to general reconnaissance study of surface geology is extremely valuable for inaccessible or densely populated areas where field-work is difficult or impossible, and photogrammetrically compiled topographic maps are invaluable for planning resource exploration.

An example of the application of remote sensing to resource exploration might be found in the detection of tree species which are suitable for charcoal. Rohde and Olson (1972) have reported a computer-oriented multispectral sensing for automatic recognition of forest tree species with an accuracy of 85 per cent, though better accuracy cannot be attained. Also the suitability of Nigeria's estuaries for tidal power might be determined by "a repetitive remotely sensed data coupled with a well-equipped concurrent surface data collection programme for providing extremely useful information for the complexity of estuarine flow" (Mairs and Clark 1973). Remote sensing combined with computer technology might also be used to explore the scope of the potential for geothermal energy in the vicinity of Ikogosi and elsewhere.

Rural energy resource evaluation

Quantitative photogrammetry is also an indispensable tool for the quantification and evaluation of energy resources after the exploration phase is completed. Photogrammetrically compiled topographic maps, and orthophoto maps, are suitable for the computation of areas and volumes associated with energy resources and their potential reserves (Richardus 1976). For example, digital photogrammetry could be used to determine the area and volume of water bodies contained in small-scale reservoirs which, as has been suggested earlier, could be used to operate a small hydraulic turbine for the supply of electricity for small communities. Quantitative remote sensing could also be used to evaluate the quality of fuelwood which could be derived from a fuelwood plantation. Another very different but important application of quantitative photogrammetry might be the precise calibration of the geometry of solar collectors, since imperfections in the manufacture of solar collectors affect the level of their efficiency. Thus, engineers who have experienced frustration in the template method of calibration because of gross inaccuracies have made use of photogrammetric techniques. An example of such a precise calibration has been reported by Ghosh (1966) who performed the calibration of a 44-foot parabolic solar collector.

TABLE 1. Percentage Occurrence of Calm Wind

	Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1.	Sokoto	1.4	0.9	0.1	0.8	0.6	0.8	0.8	0.9	1.6	3.2	2.1	0.8
2.	Kano	21.0	18.4	16.1	8.5	4.1	3.3	5.0	11.3	13.0	18.1	27.0	24.3
3.	Kaduna	2.9	3.1	5.1	5.4	5.3	5.9	9.0	10.9	13.7	14.4	8.7	4.4
4.	Minna	10.1	10.6	12.3	12.3	12.4	13.7	16.0	15.6	16.8	21.3	18.9	13.6
5.	Ilorin	4.9	6.4	4.7	8.5	9.1	10.4	5.0	6.3	12.0	9.8	8.5	10.1
6.	Oshogbo	12.3	8.4	7.1	10.3	9.9	9.7	7.5	5.5	11.5	16.3	16.1	14.7
7.	Ibadan	20.1	16.5	14.3	16.1	17.3	15.1	9.7	6.0	15.7	25.2	30.5	25.8
8.	Ikeja	26.3	21.8	24.1	27.3	26.9	25.3	20.7	20.7	25.6	32.5	31.2	29.0
9.	Benin City	38.3	30.7	28.4	30.5	30.5	31.2	30.1	29.2	32.3	36.0	39.5	43.6
10.	Enugu	11.9	7.6	5.6	7.8	13.1	14.4	0.3	9.9	9.2	10.0	16.0	13.4
11.	Port Harcourt	52.7	45.2	44.5	46.2	46.5	46.9	46.4	43.3	45.5	47.3	53.5	55.6
12.	Calabar	12.7	11.4	11.9	12.2	12.7	12.4	15.0	13.2	12.5	13.1	13.2	11.8
13.	Makurdi	35.8	26.5	15.4	17.7	25.5	25.0	17.7	20.3	30.5	35.5	41.6	43.7
14.	Jos	4.1	3.8	5.3	5.3	5.9	6.2	5.0	4.0	10.0	13.9	11.1	18.4
15.	Maiduguri	8.9	7.4	7.8	8.3	7.2	6.6	9.5	13.6	15.1	14.0	11.4	9.8
16.	Yola	10.5	8.0	7.2	6.3	8.2	12.9	14.9	15.5	16.6	23.3	19.7	12.0

Data Source : *The National Atlas of Nigeria*, 1977

Rural energy resource exploitation

Photogrammetric mapping is very important for the exploitation of rural energy resources. Large-scale topographic maps are extremely useful for the excavation of mineral energy, and such maps are also valuable for planning the transportation of rural energy resources from their source to the consuming centres. Another application of photogrammetry pertinent to the development of rural energy is the monitoring of the deformations and displacements of small-scale dams. Such dams may be subject to local displacement or deformation due to landslides and erosion, and people living in rural areas are very conscious of their safety. Indeed, safety may well be one of the most crucial factors to be considered in formulating rural energy developments of this kind. It is therefore necessary to perform periodic survey measurements on such dams as a check on their stability. The internal monitoring of stability exists in the form of the use of sophisticated instruments such as extensometers, strain gauges, indinometers, and rock noise listening devices. An external check on stability usually takes the form of conventional field survey measurements. Analytical photogrammetry offers many advantages over conventional methods, since the photography used in analytical photogrammetry is an instantaneous and complete record of the entire dam site at the time of exposure. All measurements of the dam site are therefore done simultaneously, a merit which is seriously lacking in ground survey methods, which can occupy several days during which possible deformation or displacement cannot be detected. Apart from their value for areas of the dam which are inaccessible photogrammetric methods have been found to be more economical than conventional field methods in which larger number of points are involved in the measurement (Brandenberger 1974). Furthermore, the photographs used for the photogrammetric work can also be used for other studies of the dam sites such as irrigation, agriculture, ecology, transportation, and settlement.

Conclusions and Recommendations

First, the emphasis in the formulation of a rural energy strategy has been on diversification of energy resources, and, based on current and potential resources, Nigeria may be divided into three rural energy zones, A, B, and C (Figure 9). Each zone is characterized by the predominant energy resources derivable from it, and the zones are created from the point of view of the suitability of the rural energy resources indicated; they are not mutually exclusive.

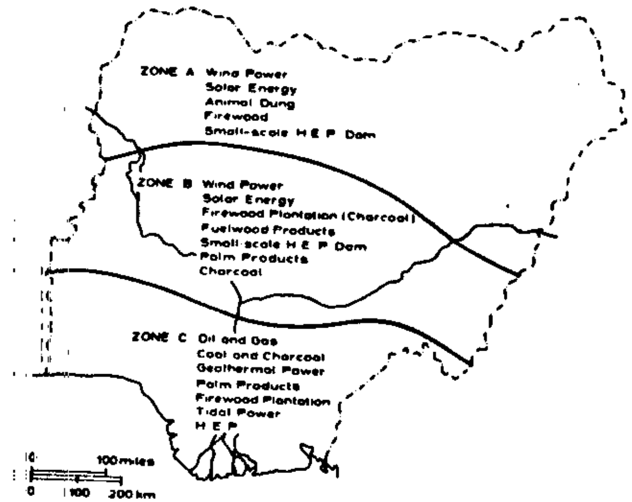

Fig. 9. Nigeria : Rural Energy Strategy Zones

Second, photogrammetry is an invaluable tool for the exploration, evaluation, and exploitation of rural energy resources.

Third, in order to allow for a workable research programme on rural energy systems, energy mapping should be given an important place in the national mapping programme. The importance of base maps (which are in short supply all over the country) cannot be over-emphasized: 1:50,000 maps are needed for exploration and 1:10,000 for evaluation and exploitation.

Fourth, the importance of digital terrain data for energy resource evaluation has been pointed out by Pausardien (1975). A digital terrain data bank is easily adaptable to computer handling for the automatic production of base maps such as slope, land use, geology, topography, and of orthophotos, all of which will expedite the successful implementation of a rural energy strategy in Nigeria.

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SUMMERTIME TEMPERATURES IN BUILDINGS WITHOUT AIR-CONDITIONING

A. G. Loudon

1. INTRODUCTION

Before the war the chief thermal problem in buildings was underheating in winter. Most buildings were 'heavy' - i.e. constructed of dense concrete or brickwork - and windows were fairly small. There was little trouble from overheating in summer in this type of building. A survey conducted in pre-war office buildings in 1948[1] indicated that only about 9% of the occupants were concerned about overheating.

However summer overheating is now a much more widespread problem than winter underheating, at least in non-domestic buildings such as offices, schools, hospitals and factories. This has been stressed in various publications. A House of Commons Estimates Committee on School Buildings[2] referred to excessive use of glass leading to cases of 'heat exhaustion' in school children. Manning[3, 4, 5] reported overheating in factories, offices and schools. He referred to cases where factory employees refused to work because of summer overheating, arising from solar gains through roofs. Langdon[6, 7] showed that as many as 40% of a sample of 2000 workers in modern London offices were sometimes too warm in summer. By contrast the proportion sometimes too cool in winter was only 23%. Stewart and Kibblewhite[8] showed that air temperatures in July-September 1964 in a group of naturally ventilated offices facing south of east-west were above 24°C (75°F) for some 30-35% of the time.

The chief reason for the recent increase in overheating is the change in styles of building and constructional methods. It is common to use large areas of glazing which can admit large solar heat gains, and also to use lightweight constructional materials which warm up quickly under the influence of solar gains. In some areas, windows have to be kept closed to exclude traffic noise, and buildings cannot be freely ventilated. This means that buildings which are warmer than outside cannot be cooled so effectively by ventilation.

Until recently there was no simple reliable means of predicting internal temperatures in hot weather as a function of building construction, glazing and sun-controls. Work at the Building Research Station has now provided a method. It is simple enough to use along with available methods of computing daylighting and other building requirements to achieve integrated building designs.

This paper sets out the method in some detail, shows how computed peak temperatures relate to user response, and applies the work to design. The essential features of the method are outlined in the main body of the paper, and Appendices give a fuller treatment as taught at recent Building Research Station post-graduate courses. The scheme of calculation forms the basis of a book now in preparation.

2. BASIS OF THE DESIGN METHOD

Maximum temperatures are calculated using:

(1) Data on external temperatures, and radiation intensities on vertical and inclined building surfaces, on days of full sunshine. Loads due to occupancy, lighting and other sources must also be determined.

(2) Data on the transmission, absorption and reflection of solar radiation by glass, sun-controls and other building surfaces.

(3) The method of calculating the thermal response of the building to solar heat gains and any other heat inputs, developed by Danter at BRS.[9]

The first two stages have been described elsewhere[10, 11] and are here briefly recapitulated. The calculation of resulting internal temperatures is set out in more detail.

2.1 Solar heat gains to buildings

Maximum internal temperatures in buildings occur during 'heat-waves' with a succession of warm cloudless sunny days. Such days are rare in Britain, averaging only about ten a year, but the intensities on cloudless days are needed for design calculations. Figure 1 shows how the internal temperature builds up on successive sunny days. The example is for a poorly ventilated room in a lightweight building with south-facing windows occupying 80% of the external wall, where temperatures are very high, and illustrates how buildings warm up. The radiation data and outside temperatures apply to sunny August days. The mean internal temperature slowly builds up to an equilibrium value and there is a diurnal swing about the mean. The maximum temperature occurs during 'steady cyclic' conditions when a regular regime of internal temperature has become established.

BRS research on radiation intensities on horizontal and vertical surfaces[10] has shown that it is convenient to include with direct radiation some of the 'circumsolar' diffuse radiation from near the sun, giving 'augmented direct' radiation.[10] The remaining 'background diffuse' radiation can be assumed to be uniform over the sky vault, and its value was determined. For most parts of Britain in the summer months it was found that 'augmented direct' intensities vary with solar altitude as proposed by P. Moon[12] for direct intensities. Data in Table 6.4 of the 1965 IHVE Guide[13] are a little higher than Moon's values, but are accurate enough for practical purposes. Petherbridge[14] has prepared sunpath diagrams and overlays for cloudless skies based on the BRS data; they enable direct and diffuse intensities to be found for surfaces with any orientation and inclination.

Design daily amounts of radiation on horizontal and vertical surfaces, assuming 20% ground reflectance, are plotted in Figure 2. The maximum daily amounts of radiation are seen to be similar on all vertical surfaces oriented south of east-west, viz. about 17 000 kJ/m² (1500 Btu/ft²) of surface, although orientation affects the time of year at which the maximum occurs; it is June on east and west faces, February and October on south faces. In August, when outside air temperatures are highest, all vertical surfaces south of east-west receive fairly large amounts of radiation. Horizontal surfaces receive more - as much as 28 000 kJ/m² (2500 Btu/ft²) in June. Buildings such as factories with large areas of unshaded rooflights, or poorly insulated roofs, are therefore particularly prone to overheating.

Peak intensities, plotted in Figure 3, are also similar in magnitude for all vertical surfaces oriented south of east-west - about 700 W/m² (220 Btu/ft²h) of surface. Orientation, however, affects both the time of year and the time of day at which the maximum occurs. The peak occurs in the morning on east-facing surfaces, at noon on south-facing surfaces and in the evening on west-facing surfaces. The times of year when maxima occur are the same as for daily amounts of radiation.

The transmission of radiation depends on the angle of the sun, and data for glass and louvre systems were set out in a CIE Conference paper.[11] The sunpath diagrams and overlays assembled by Petherbridge,[14] give the fractions of the incident radiation absorbed or transmitted at different times of year and different times of day. Another BRS paper[15] briefly describes different types of sun-controls and their properties.

3. THERMAL RESPONSE OF BUILDINGS TO SOLAR HEAT GAINS

The simplified method for calculating the thermal response of buildings to solar and other periodic heat gains[9] applies to steady cyclic conditions. Referring back to Figure 1, the problem is to calculate both the mean internal temperature $\bar{t}_i$ and the swing about the mean $(t_i - \bar{t}_i)$, here denoted $\tilde{t}_i$.*

For winter heating calculations, the rise in internal temperature above outside, $(t_i - t_o)$, is normally calculated from the rate of heat input q using the conventional steady-state heat balance equation:

$$q = (\Sigma AU + C_v)(t_i - t_o) \qquad (1)$$

* Symbols are listed in Appendix 5

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where A's and U's are areas and thermal transmittances of exposed panels (walls and windows, roofs and rooflights)

C_v is the ventilation heat loss per degree

t_i and t_o are inside and outside air temperatures.

This equation will not serve for calculating summertime temperatures:

(1) Because it is not strictly valid unless internal air and mean radiant temperatures are equal. Heat is transferred to the surfaces of exposed panels by longwave radiation from other room surfaces as well as by convection from air. The mean radiant temperature (MRT) is as important as the air temperature in determining heat losses;

(2) Because solar gains are frequently generated part-way through the structure. This applies, for instance, to the heat absorbed by glass, or by a blind between two sheets of glass. The fraction of the absorbed heat entering the building depends on where the heat is absorbed;

(3) Because solar heat gains are by no means uniform throughout the day. They reach a peak at noon on the south face, early morning on an east face and evening on a west face. Another factor causing internal temperature fluctuations is that in summer the outside air temperature varies diurnally by 8 - 10 deg C (10 - 15 deg F) about the mean. The diurnal variations in internal temperature $\tilde{t}_i$ can be as large as the rise in the mean above outside ($\bar{t}_i - \bar{t}_o$). (see Figure 1).

These points are now discussed in turn.

3.1 Internal environmental temperature

Equation (1) has to be modified to take account of the effect of the MRT on heat losses. Appendix 1 shows that this can be done by taking the internal temperature t_i, not as the air temperature t_{ai} but as the environmental temperature t_{ei}. This is a weighted mean between MRT and air temperature, given approximately by:

$$t_{ei} = 2/3\ t_{ri} + 1/3\ t_{ai} \qquad (2)$$

where t_{ri} is the mean radiant temperature.

The environmental temperature is a convenient temperature for calculating rates of heat flow, both for the steady state and for diurnal temperature swings. In addition to this, however, it is a better measure of the warmth of the environment than the air temperature since it is approximately equal to the 'equivalent temperature' used as an index of thermal comfort. At an air temperature of, say 21°C, a room with radiant heating and warm walls (or warm blinds heated by solar radiation) feels warmer than a room at 21°C with air heating and cool walls. If the environmental temperature is 21°C, however, both rooms will (to a close approximation) feel equally warm. Whether heated by air or radiation, Appendix I shows that for all internal environments, we can write:

$$\bar{q}_t = (\Sigma AU + C_v)(\bar{t}_{ei} - \bar{t}_o) \qquad (1a)$$

where $\bar{q}_t$ is the total equivalent heat input to the building arising from solar and other sources. The ventilation conductance has to be adjusted to allow for the fact that ventilation heat transfer depends on inside air temperature, not on inside environmental temperature. This equation holds only where the heat losses through internal room panels (flank and rear walls, floor and ceiling) are zero - for instance, in a room in a multi-storey block surrounded by other rooms at the same temperature. Other terms can be added when necessary to allow for heat transmission through internal panels. When ventilation rates are high, C_v has to be corrected as described in Appendix 3.

3.2 Heat generated part-way through the structure

Heat absorbed by a sheet of glass or a blind is partly retransmitted inwards and partly outwards. The 'equivalent heat input' to the room q_e due to solar gain is required for calculation. The mean value of q_e, $\bar{q}_e$, is equal in magnitude to the 'cooling

load' due to solar radiation, which is required to keep the mean internal temperature $\bar{t}_{ei}$ equal to the mean outside temperature t_o. Appendix 2 shows that q_e may be obtained by multiplying the heat absorbed by the glass or blind by a fraction f, the retransmission factor, given by:

$$f = \frac{\text{thermal resistance from outside air to sheet}}{\text{total thermal resistance of system}} \qquad (4)$$

Values of f for various combinations of glass and blind are listed in Table I.

Table I. Fractions of absorbed heat retransmitted to building

Component	Retransmission factor f
Single glazing, no solar control	0.3
Double sheet	
outer glass	0.15
inner glass, or internal blind separated by an unventilated airspace	0.65
Single glazing, internal venetian blind	
glass	0.3
venetian blind	0.8
Single glazing, external louver system	
glass	0.3
louver system	0.03
Double glazing, blind behind both panes	
outer glass	0.1
inner glass	0.6
internal blind	1.0
Double glazing, blind between panes	
outer glass	0.1
blind	0.4
inner glass	0.7
Double glazing, blind outside both panes	
external blind	0
outer glass	0.2
inner glass	0.7

Figure 4 illustrates the calculation of equivalent heat input due to solar gain for a window system consisting of two sheets, e.g. double glazing or single glazing with an internal blind enclosing an unventilated air space. Taking the incident radiation intensity as I_s, the proportions absorbed at outer and inner sheets as α_o and α_i (allowing for inter-reflections) and the proportion directly transmitted as τ, we have:

$$q_e = I_s\,(0.15\alpha_o + 0.65\alpha_i + \tau)$$

since the values of f for outer and inner sheets are 0.15 and 0.65;

and in general:

$$\bar{q}_e = S \times \bar{I}_s \qquad (5)$$

Equation (5) defines the 'solar gain factor' S for the window system, or for a wall or roof.

Solar gain factors, like radiation transmittances and absorptances, depend on the angle of the incident radiation. Moreover, allowance has to be made for inter-reflections between different surfaces in the window system. Average values for

August for orientations south of east-west have been calculated for a number of typical window systems, and are listed in Table 2. They can be applied without serious error throughout the summer months.

The term 'solar gain factor' was chosen as appropriate for both glass and blinds; these factors are equivalent to the 'shade factors' in the IHVE Guide.

There is also an effective heat input from solar heat absorbed at the outside surface of walls or roofs. It can be seen by reference to equation (4)that the 'retransmission factor' $f = R_{so} \times U$ since U is the reciprocal of the total thermal resistance. Effective heat inputs from solar gains through different windows, rooflights, walls or roofs, and heat inputs from occupants, lights or other sources have to be added to obtain $\bar{q}_t$. The mean temperature $\bar{t}_{ei}$ is then found from equation (1a).

3.3 Thermal response to periodic variations in heat input

Danter's procedure enables the swings in internal temperature to be calculated from the swings in effective heat input to the room and the properties of the building structure. The method is a very simple one and, although approximate, is sufficiently accurate for most practical purposes. Briefly, the actual heat exchanges in a room by convection between air and surfaces and by radiation between surfaces (Figure 5a) are replaced by exchanges between the point X (Figure 5b) and surfaces. The circuits are equivalent, and the temperature at X is the 'environmental temperature' t_{ei}. Heat exchanges between the X-point and the surroundings are calculated.
For a steady-state heat flow we consider only the heat flow rates by ventilation and by transmission through the exposed wall 1.

For periodic heat flow, however, we also consider the rates of heat flow into and out of the thermal capacity of internal walls, floors and ceilings. The heat flow paths to internal panels (walls, floors, or roofs) are through the surface resistances and resistance-capacity networks representing the half-thickness of the panels. (Only the half-thickness is considered when rooms are surrounded by similar rooms since the heat flow rates at the centres are zero.)

The heat flow rates to the partitions are determined by their areas and 'admittances' per unit area, Y. The 'admittance' of a building component is a measure of its ability to smooth out diurnal temperature swings in the building. Heat flow rates by ventilation and transmission through windows are determined by the'ventilation conductance' C_v and thermal transmittance U, as with steady-state flow. Admittances per unit area are listed for a number of constructions in Table 3.

TABLE 2. Solar gain factors

System	Solar gain factor S	Alternating solar gain factor S_a	
		heavy building	light building
Single glazing			
Clear sheet glass (24 oz or 32 oz)	0.77	0.43	0.54
Clear plate (¼ in.)	0.74	0.41	0.51
Heat absorbing (¼ in. Antisun)	0.51	0.35	0.41
Heat absorbing (¼ in. Calorex)	0.38	0.34	0.36
*Lacquer coated glass (Grey)	0.55	0.37	0.42
Double glazing (outer + inner panes)			
Clear sheet glass (24 oz + 24 oz or 32 oz + 32 oz)	0.67	0.40	0.49
Clear plate (¼ in. + ¼ in.)	0.61	0.39	0.47
Heat absorbing (¼ in. Antisun) + clear (32 oz)		0.30	0.35
Heat absorbing (¼ in. Antisun) + clear (¼ in. plate)	0.37	0.27	0.30
Heat absorbing (¼ in. Calorex) + clear (¼ in. plate)	0.23	0.19	0.20
Heat reflecting (¼ in. Stopray) + clear (¼ in. plate)	0.25	0.14	0.17
Internal sun controls + 32 oz. glass			
*Dark green woven plastics blind	0.64	0.57	0.62
*White venetian blind	0.46	0.43	0.46
*White cotton curtain	0.41	0.25	0.33
*Cream holland linen blind	0.29	0.26	0.29
Blinds between double glazing			
*White venetian blinds between two panes of clear glass (32 oz)	0.28	0.23	0.25
External suncontrols + 32 oz glass			
*Dark green woven plastics blind	0.20	0.13	0.18
*White louvered sun-breakers with blades at 45° (horizontal or vertical blades)	0.12	0.06	0.09
*Canvas roller blind	0.11	0.07	0.09
*Miniature louvered blind	0.10	0.05	0.06

* Typical value.

Data refers to British glass unless otherwise stated

TABLE 3. Admittances of building elements

Building element	Admittance Y W/m² deg C	(Btu/ft²h deg F)	Surface factor F
Walls and windows:			
Glass or blinds	same as U-value		same as retransmission factor f
Perfectly lightweight structures, Internal	0	(0)	1.0
External	same as U-value		$1 - U \times R_{si}$
Walls of the following densities, more than 0.075 m thick			
650 Kg/m³	3.0	(0.5)	0.8
1100	4.0	(0.7)	0.65
1750	5.0	(0.9)	0.5
2250	6.0	(1.1)	0.4
Heavy partition with lining of resistance 0.18 m² deg C/W (1.0 ft² h deg F/Btu)	3.0	(0.5)	[illegible]
Two 0.013 m fibreboard sheets separated by airspace	2.0	(0.3)	[illegible]
Floors:			
Concrete	6.0	(1.1)	0.5
Concrete and carpet or wood blocks, furniture	3.0	(0.5)	0.7
Suspended timber	2.0	(0.35)	0.8
Suspended timber and carpet	1.5	(0.25)	[illegible]
Ceilings:			
Plastered concrete	6.0	(1.1)	[illegible]
Cavity-plasterboard	3.0	(0.5)	[illegible]
Lath and plaster and timber	2.0	(0.3)	[illegible]

When temperatures and rates of heat input are changing slowly, no great error is introduced by directly adding heat flow rates by ventilation and conduction through windows to the heat flow rates into and out of internal panels, although the latter do in fact lag behind temperature changes by one hour or so. This leads to the simple equation relating the temperature swing $\tilde{t}_{ei}$ to the swing in effective heat input $\tilde{q}_t$:

$$\tilde{q}_t = (\Sigma AY + C_v)\ \tilde{t}_{ei} \qquad (6)$$

Though developed for sinusoidal heat inputs, studies with an electrical analogue have shown that equation (6) can be used without serious error when the heat input is non-sinusoidal; errors are greater when the heat input is 'peaky' (concentrated in a small part of the day) than when it is more nearly sinusoidal.

Effective alternating heat inputs $\tilde{q}_e$ have to be determined separately for the various heat sources, and then added to obtain $\tilde{q}_t$.

These effective heat inputs are equal in magnitude (and opposite in sign) to the rates at which heat would have to be abstracted or put in to hold the internal temperature constant. Alternating heat gains due to solar heat absorbed by glass and blinds have to be multiplied by retransmission factors f just as in steady-state calculations. However, alternating heat inputs due to radiation absorbed at the surfaces of panels (walls or floors) have to be treated differently from mean heat inputs. This is because these panels have a finite impedance to alternating heat inputs, as opposed to an infinite impedance to steady heat inputs. They therefore have to be multiplied by 'surface factors' F to obtain effective alternating heat inputs $\tilde{q}_e$:

$$\text{i.e. } \tilde{q}_e = F\,(q_e - \bar{q}_e)$$

Thus the alternating heat input at the surface of a concrete floor has to be multiplied by the factor F = 0.5 to obtain the effective heat input. Surface factors for some different building elements are listed in Table 3.

The effective alternating heat input due to solar gain can be written:

$$\tilde{q}_e = S_a \times \tilde{I}_s \qquad (7)$$

where S_a is the 'alternating solar gain factor' for the window system or wall or roof. S_a differs between 'heavy' and 'light' buildings because of differences in the surface factor F. In this context 'heavy' buildings have solid internal walls and partitions, and 'light' buildings have lightweight demountable partitioning with suspended ceilings; both are assumed to have concrete floors. Values of F of 0.5 and 0.8 have been assumed in the two cases. Average alternating solar gain factors for orientations south of east-west are listed in Table 2 for 'heavy' and 'light' buildings; these are not found in existing reference manuals. One point revealed by the Table is that internal blinds, particularly dark coloured blinds, are no better than unprotected glass in reducing temperature swings, although they can reduce the mean temperature rise.

3.4 Gains through walls and roofs

Solar heat gains through walls are usually negligible compared with solar gains through windows, but solar gains through poorly insulated roofs can cause overheating in factories and other single-storey buildings. A method developed by Danter(16) allows the resulting heat flow through the wall or roof to be calculated. This method can also be used to calculate the effect of temperature swings in one room on an adjacent room of dissimilar characteristics; in general, however, the diurnal swing due to transmission from an adjacent room is small.

3.5 Effect of outside air temperature variations

The effect of outside air temperature variations on internal temperature variations is allowed for as in other cases by calculating the heat which would have to be put into or extracted from the X_i-point to hold the internal temperature constant. This heat input is:

$$\tilde{q}_e = (\Sigma AU + C_v)\ \tilde{t}_o \qquad (8)$$

The heat gain from occupants, lighting and other internal sources can as an approximation be regarded as being generated at the X-point, i.e. the factor F for these heat inputs can be taken as unity.

The various components $\tilde{q}_e$ have to be added to find the total heat input swing $\tilde{q}_t$, and the swing in internal temperature $\tilde{t}_{ei}$ is found from equation (6).

The method can be extended to conditions which are not steady-cyclic ones by combining the 'Q/U' method of calculating the response of a room to changes in heat input or external temperature with the admittance procedure for calculating temperature swings. The diurnal swing $\tilde{t}_{ei}$ is then calculated in relation to a slowly varying quasi-mean temperature $\bar{t}_{ei}$. Temperatures have been successfully predicted during variable weather conditions using this technique.(19)

4 COMPARISONS WITH FIELD MEASUREMENTS

The procedure described has been used to calculate temperatures in a variety of buildings in which measurements have been made. As an example, Figure 6 gives comparisons of calculated and measured temperatures in a number of unoccupied and nominally unventilated offices during a Whitsun holiday period. Agreement is fairly good; it is difficult to get very close agreement in field studies because basic data, particularly on air infiltration rates, are not known accurately. It has not been possible to make such comparisons in occupied and naturally ventilated offices, because of the irregular use of blinds and ventilation openings.

Buildings in use have been investigated in a different way. Because of the difficulty of obtaining temperatures and ventilation records in occupied buildings during the rare periods when heat-waves occur, calculated peak temperatures have been compared directly with complaints of overheating obtained in user surveys. Data from the office survey mentioned in the Introduction[6, 7] were divided into sub-samples with different window aspects and window sizes, and offices in noisy and quiet areas were considered separately. This latter distinction was made because it was expected that there would be more overheating complaints in noisy than in quiet areas; this is because people could not open windows to ventilate buildings freely. Overheating complaints were related to calculated peak temperatures in offices of the type illustrated in Figure 7, where room dimensions are averages for the offices in the survey. These results have been reported elsewhere.(17, 18)

Calculated inside temperatures are based on the radiation intensities on sunny days, and on the corresponding daily-mean outside temperatures and temperature swings in Table 4. They are a few degrees higher than monthly-mean values. Of course there are occasions on which outside temperatures on sunny days are higher than those in Table 4, but it is very unusual to have a spell of sunny days during which both radiation intensities and outside air temperatures are simultaneously maintained at their highest values. Preliminary results suggest that the design data in Table 4 yield internal 'peak' temperatures which are exceeded on only about 10% of occupied hours.

TABLE 4 Daily-mean outside temperatures for sunny days (Garston, Herts)

Month	Temperature			
	Daily-mean on sunny days *		Mean diurnal swing on sunny days *	
	°C	°F	deg C	deg F
March	7 (6)	44 (43)	12 (9)	22 (16)
April	8 (8)	47 (47)	12 (10)	22 (18)
May	12 (12)	54 (53)	13 (11)	24 (19)
June	16 (15)	60 (59)	15 (11)	27 (19)
July	19 (17)	66 (62)	14 (9)	25 (17)
August	18 (16)	64 (61)	13 (10)	23 (18)
September	14 (14)	58 (57)	12 (9)	21 (16)

* Mean values for all days are given in brackets
Data are fairly typical for most of the populous areas in Britain

Figure 8 shows how calculated peak temperatures vary with window size in 'heavy' and 'light' buildings with low and high ventilation rates, (2 and 10 air changes/h). (As before, 'heavy' buildings have solid partitions, 'light' buildings have demountable partitions and suspended ceilings; both have concrete floors.) Figure 9 shows how peak temperatures calculated from outside temperature on sunny days relate to complaints of overheating in different categories of office. (A similar graph in earlier papers[17, 18] was based on 'sunny day' outside temperatures during the year preceding the survey.) Those 'sometimes too warm' and those 'definitely uncomfortable' are shown separately on the graph. A ventilation rate of 2 ach was assumed in noisy areas and 10 ach in quiet areas. There is a clear relationship between user comments and calculated peak temperatures.

This technique has been repeated in a survey of school buildings, and this will be reported later. Although the data have not yet been fully analysed, the preliminary results are interesting. As with offices, a considerable proportion of the occupants (teachers) were sometimes too hot in summer. Again, more discomfort was experienced in noisy than in quiet areas. Moreover, other things being equal, there was more discomfort when classrooms could be ventilated from only one side than when they had openings on more than one wall and could have cross-ventilation. Within each of these categories, discomfort was related to window size and orientation in the manner suggested by calculations of maximum temperature.

Figure 10 gives a preliminary comparison of overheating complaints and calculated temperatures, based on the outside temperatures in Table 4 and the assumed ventilation rates set out in Table 5. These rates were selected to bring the data on to the same curve.

TABLE 5 Assumed ventilation rates for heat-wave conditions

	Position of opening windows	Whether quiet or noisy area	Ventilation rate air changes/h
Offices	one side only	quiet	10
		noisy	2
Schools	one side only	quiet	10
		noisy	5
	more the one side	quiet	30
		noisy	10

In the earlier survey, the office workers were simply asked whether they were 'slightly' or 'definitely' uncomfortable because of overheating, and were not offered the choice of 'occasionally' or 'often' in their response. In the schools study a wider range of alternatives were offered. For the purposes of this paper, the scale, which ranged from comfort to definite discomfort, has been divided to produce two plots which represent these extremes. The upper points (filled symbols in Figure 10) show the proportions reporting any degree of discomfort except 'occasionally slightly uncomfortable'. The lower points (open symbols) show the proportions 'definitely uncomfortable' except those 'occasionally definitely uncomfortable'.

The proportions reporting thermal discomfort shown in Figure 10, like those in Figure 9, are clearly related to the calculated peak temperatures. Moreover, although there were differences in the assumptions made in the calculations and in the forms of the questions relating to offices and schools, the amounts of thermal discomfort at different calculated peak temperatures were similar.

The important point is that, if temperatures are calculated on the assumptions which have been set out, criteria can be set which enable one to decide in advance whether a given design of office or school is likely to be thermally comfortable. The setting of a criterion involves a value judgement on what is acceptable, but the graphs provide an essential link between such a judgement and computed temperatures. For instance, adopting the criterion that not more than 10% of the occupants would be definitely uncomfortable would lead to a design requirement of about 27°C (80°F) for both offices and schools.

5 DESIGN IMPLICATIONS

As a first point, heavy buildings screened from solar radiation do not rise more than a few degrees above the mean outside temperature unless there are appreciable heat gains from lighting, occupants or other heat sources. It is primarily the daily-mean temperature that has to be considered, rather than the maximum; diurnal temperature variations can be smoothed by the thermal capacity of the building. In heavy buildings, the outside temperature variations of 10 - 15 deg C that occur during the day cause internal variations of only 1 - 2 degrees. In this connection, Table 6 shows how frequently daily-mean temperatures of 20°C to 24°C are exceeded at Garston, Hertsland in London.

TABLE 6 Frequency with which given daily-mean temperatures are exceeded

Location	Average number of days per annum exceeding:				
	20°C	21°C	22°C	23°C	24°C
Garston	3.2	1.6	0.8	0.4	0.2
London Weather Centre	6.4	4.4	2.2	0.9	0.7

These data show that even in central London, which is warmer than the surrounding country, daily-mean external temperatures seldom exceed 22°C. Very few parts of Britain are much warmer than central London. Internal temperatures in heavy buildings need not therefore exceed 24°C on more than 1 or 2 days per annum unless solar gains are admitted or there are other appreciable internal heat gains.

It is clear, therefore, that the British climate does not in itself make air-conditioning essential, if buildings are heavy, screened from solar radiation and do not have appreciable internal heat gains. As an illustration of this point, Figure 11a shows that the measured temperature in an east-facing office of massive construction, shaded by trees, remained at 20.5°C (69°F) throughout a sunny spell when the outside temperature varied from 10 - 27°C (50 - 80°F). By contrast, the temperature in a neighbouring room with large south-facing windows reached 26°C (78°F) during the same period, and the occupants complained of overheating (Figure 11b). This room had a smaller admittance than the first, as it was carpeted and had a lightweight roof structure.

On the basis of this work, recommendations have been made[18] about maximum areas of unshaded clear glass that can be used in naturally ventilated offices without exceeding a calculated peak temperature of 24°C(75°F). The corresponding maximum window sizes were calculated for 'heavy' and 'light' buildings, defined as above, and for noisy and quiet areas, assuming ventilation rates of 2 and 10 ach. It would be reasonable to use the same criteria of discomfort when making similar calculations for different office types, and for buildings shaded by sun-controls. Appendix 4 sets out the recommended procedure for calculating peak temperatures in more detail, and gives an illustrative example.

Mean temperatures during the summer months vary by a few degrees over Britain, and local data could be used when additional accuracy is sought. As the variations are only a few degrees, however, the data in Table 4 may be adequate for design calculations in most of Britain.

Air-conditioning may provide the preferred solution for lightweight buildings, or deep buildings with large internal heat gains. It may be worth while in some cases to compare the cost of a heavy, shallow building which is naturally ventilated, with the cost of a lightweight or deep building with air-conditioning.

6. CONCLUSIONS

A technique for calculating peak internal temperatures is presented which agrees with experimental measurements and is related to user complaints of overheating in offices and schools. The method can be applied generally to different types of building, but it is difficult to make accurate estimates of ventilation rates in naturally ventilated buildings, and further cross-checks with user experience may be needed. Data are given on properties of building components (e.g. surface factors and admittances) to use in calculations.

It is shown that a single 'shading factor' is not sufficient to specify the effect of a sun-control on internal temperatures, and both 'solar gain factors' and 'alternating solar gain factors' are listed for different types of sun-control. These can be applied directly to calculate the rise in the mean internal temperature and the swing about the mean.

This technique of calculation should be helpful in designing comfortable buildings. Peak temperatures can be calculated and if excessive, the designer has the choice of reducing the window size, increasing the mass of structure, fitting sun-controls or installing air-conditioning. The final choice will depend on cost, amenity and other considerations, but the methods outlined should provide useful guidance on alternative methods of controlling peak temperatures. Application of this work to air-conditioning design is also being studied, and preliminary results are reported in another contribution to this symposium.

Acknowledgment

This work was made possible by research on the thermal response of buildings by Mr. E. Danter, who kindly made his results available. The author is also indebted to other colleagues, particularly Mr. P. Petherbridge and Miss P. J. Arnold, who made important contributions to other aspects of the work.

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Appendix 1. Inside environmental temperature

The conventional steady-state heat balance equation giving the average rate of heat flow through an exposed building element of area A and thermal transmittance U is:

$$q/A = U(t_i - t_o) \quad \text{(A1)}$$

$$\text{with} \quad U = 1/(R_{si} + R_1 + R_2 + \ldots + R_{so}) \quad \text{(A2)}$$

$$\text{and} \quad R_{si} = 1/(Eh_r + h_c) \quad \text{(A3)}$$

where the R's are thermal resistances of the components of the structure, R_{si} and R_{so} inside and outside surface resistances, E the longwave emissivity factor for the surface, and h_r and h_c the radiation and convection coefficients.

The temperatures t_i and t_o are normally taken as inside and outside air temperatures. However, a difficulty arises when the internal air and mean radiant temperatures differ, because heat is transferred to the surface of the exposed panel (wall, window, roof or rooflight) by longwave radiation from other surfaces, as well as by convection from room air. Equation (1) is not therefore universally valid if t_i is taken to represent the inside air temperature. However, a valid equation can be developed as follows.

The equation for the rate of heat flow to the inside surface is:

$$q/A = Eh_r\,(t'_{ri} - t_{si}) + h_c(t_{ai} - t_{si}) \quad \text{(A4)}$$

where t'_{ri} is the mean surface temperature seen by the inside surface of the exposed panel, whose temperature is t_{si}. At the inside surface of a wall, typical values of Eh_r and h_c are 5.1 and 2.8 W/m^2 deg C.

This equation involves t'_{ri}, the mean radiant temperature seen by the exposed wall. However, it is more convenient to express heat losses in terms of the area-weighted mean temperature of all room surfaces, including that of the exposed panel, t_{ri}. This is the mean radiant temperature at the centre of a cubical room; it can be imagined as the temperature of a small sphere at the centre of an air-free room. The temperature t'_{ri} is the area-weighted mean temperature of surfaces other than that of the exposed panel, at least for a cubical room. This is because for a cubical room the form factor (i.e. the fraction of the radiation from one surface which falls on another) is 0.2 for each surface. t_{ri} could thus be calculated by adding contributions of the temperatures of the surfaces, 1/5 for each. The area-weighted mean temperature is:

$$t_{ri} = 5/6\, t'_{ri} + 1/6\, t_{si} \quad \text{(A5)}$$

Hence $t'_{ri} = 6/5\, t_{ri} - 1/5\, t_{si}$. Substituting in equation (A4) we have:

$$q/A = 6/5\, Eh_r(t_{ri} - t_{si}) + h_c(t_{ai} - t_{si})$$

To obtain the conventional form of equation (A1), we write:

$$q/A = (6/5\, Eh_r + h_c)\,(t_{ei} - t_{si}) \quad \text{(A6)}$$

$$\text{where} \quad t_{ei} = (6/5\, Eh_r t_{ri} + h_c t_{ai})/(6/5\, Eh_r + h_c) \quad \text{(A7)}$$

The temperature t_{ei} is here called the inside environmental temperature and is an appropriate inside temperature for calculating heat losses. An an approximation, it is 2/3 MRT + 1/3 air temp. Equation (A6) can be written:

$$q/A = (1/R_{si})\,(t_{ei} - t_{si}) \quad \text{(A6a)}$$

$$\text{with} \quad R_{si} = 1/(6/5\, Eh_r + h_c) \quad \text{(A8)}$$

$$R_{si} = 0.11 \text{ if } Eh_r = 5.1, h_c = 2.8$$

Danter has shown that heat losses can be calculated within an accuracy of ± 5% for a wide range of buildings using this environmental temperature t_{ei}, but that errors of up to 40% are obtained if heat losses are calculated in terms of the air temperature t_{ai}. Moreover, t_{ei} is a convenient temperature when considering the effect of a periodically varying heat input, as discussed in Appendix 3. The conventional values for inside surface resistance (0.13 for walls, 0.11 for ceilings with upward heat flow, 0.14 for floors with downward heat flow) can be retained without serious loss of accuracy, in spite of the difference between equation (A3) and equation (A8).

Appendix 2. Effect of heat inputs generated part-way through the structure

Equations (A1) to (A3) apply when no heat is generated within the structure, e.g. by absorption of solar radiation, taking t_i as the inside environmental temperature t_{ei}, and R_{si} as defined by equation (A8). Equation (A7) can be combined with other equations representing heat flow through thermal resistances. The mean rate of heat flow through a wall or roof of thermal resistance R is given by:

$$q/A = (t_{si} - t_{so}) / R \qquad (A9)$$

The thermal resistance of the material is of course negligible for single glazing, but for double glazing R = 0.18 m^2 deg C/W, the resistance of the airspace.

If the outside air temperature and the external surroundings are at the same temperature t_o, and no solar radiation falls on the surface:

$$q/A = (t_{so} - t_o) / R_{so} \qquad (A10)$$

where

$$R_{so} = 1/(Eh_r + h_c)$$

Combining equations (A6a), (A9) and (A10), we have the conventional steady-state equation (A1).

When considering double glazing, or glass in combination with a blind, however, it is necessary to take account of solar radiation absorbed at the inner face. If solar radiation of intensity I_s is transmitted through an outer sheet and absorbed by an inner sheet, equation (A9) becomes:

$$q/A + \alpha_i I_s = (t_{si} - t_{so})/R \qquad (A9a)$$

where α_i is the fraction of the incident radiation absorbed by the inner sheet. If solar radiation of intensity I_s falls on the outside surface of a wall, window, roof or rooflight of solar absorptivity α_o, the rate of heat input to the surface from this source is $\alpha_o I_s$. There is heat loss by convection equal to $h_c(t_{so} - t_{ao})$, where t_{so} is the outside surface temperature, t_{ao} the outside air temperature.

There is also heat transfer by longwave radiation to the external surroundings, sky and ground. On cloudless days the sky temperature seen by a horizontal surface is some 20 deg C below air temperature. The mean of sky and ground temperatures seen by a vertical surface is, however, roughly equal to air temperature. This is because the ground is warmer than air during sunny spells and thus compensates for the cool sky.

The equation for the rate of heat flow at the outside surface is:

$$q/A = Eh_r(t_{so} - t_{ro}) - \alpha_o I_s + h_c(t_{so} - t_{ao}) \qquad (A10a)$$

where t_{ro} is the mean radiant temperature of the external surroundings. At the outside surface of a wall, a typical value of Eh_r is 4.1 W/m^2 deg C for an outside air temperature of 5°C (0.7 Btu/ft^2h deg F at 40°F), and for normal exposure to wind a typical value of h_c is 15.2 W/m^2 deg C (2.6 Btu/ft^2h deg F).

If we write:

$$EI_L = Eh_r(t_{ao} - t_{ro}) \qquad (A11)$$

equation (A10a) becomes:

$$q/A + (\alpha_o I_s - EI_L) = (Eh_r + h_c)(t_{so} - t_{ao})$$

$$= (1/R_{so})(t_{so} - t_{ao}) \qquad (A10b)$$

EI_L is the longwave radiation loss from unit area of a surface at air temperature to surroundings. For a horizontal surface, I_L may be taken as 95 W/m^2 (30 Btu/ft^2h) for a cloudless sky, 15 (5) for an overcast sky, and intermediate values proportional to the cloud amount for partially clouded skies. The outside surface resistance R_{so} (= $1/(Eh_r + h_c)$) is about 0.05 for walls and 0.04 m^2 deg C/W for roofs (0.3 and 0.25 ft^2h deg F/Btu) for normal exposure to wind. If heat is absorbed at the inner layer we have:

$$q/A + (\alpha_o I_s - EI_L) + \alpha_i I_s = 1/R_{so} \times (t_{so} - t_{ao}) \qquad (A14)$$

By combining equations (A6a), (A9) and (A10b) we obtain:

$$q/A = \frac{t_{ei} - t_{si}}{R_{si}} = \frac{t_{si} - t_{so}}{R} = \frac{t_{so} - t_{ao}}{R_{so}} - (\alpha_o I_s - EI_L)$$

i.e.

$$q/A = \frac{t_{ei} - t_{ao}}{R_{si} + R + R_{so}} - (\alpha_o I_s - EI_L) \times \frac{R_{so}}{R_{si} + R + R_{so}}$$

or

$$q/A + f(\alpha_o I_s - EI_L) = U(t_{ei} - t_{ao}) \qquad (A12)$$

where

$$f = R_{so} / (R_{si} + R + R_{so}) \qquad (A13)$$

$$= R_{so} \times U \qquad (A13a)$$

is the 'retransmission factor' giving the fraction of absorbed heat retransmitted inwards.

Thus the heat input $(\alpha_o I_s - EI_L)$ generated at the outside surface of a structure is equivalent in its effect on internal temperature to a heat input $f(\alpha_o I_s - EI_L)$ generated within the structure. As an example, a heat input $\alpha_o I_s$ absorbed by vertical single glazing with I_L = 0, and f = 0.3, is equivalent to a heat input to the building of 0.3 $\alpha_o I_s$ per unit area of glass. The value of f = 0.3 applies when R_{so} = 0.05, U = 5.7 (0.3, 1.0 in British units).

Similarly one can see that the heat absorbed at the inner layer of double glazing has to be multiplied by the retransmission factor f = $(R_{so} + R) / (R_{so} + R + R_{si})$ to obtain the equivalent heat input within the structure. If R_{so} = 0.05, R = 0.18, R_{si} = 0.13, f = 0.65; the equivalent heat input within the building is 0.65 $\alpha_i I_s$.

In general, therefore, heat inputs generated part-way through a structure have to be multiplied by a retransmission factor f, given by:

$$f = \frac{\text{thermal resistance from outside to point where heat is generated}}{\text{total thermal resistance of structure}}$$

Appendix 3. Comments on treatment of periodic variations

The heat interchanges in a room by longwave radiation between surfaces and by convection with the air are illustrated diagrammatically in Figure 5a which represents a cross-section through a room with one exposed surface (surface 1). Since rates of heat transfer by longwave radiation and convection are roughly proportional to temperature difference, we can regard the surfaces and air as being connected by thermal resistances. The 'delta network' of Figure 5a can this be replaced by the 'star network' of Figure 5b.

Analysis shows that for a cubical room the 'star point' X is at the 'environmental temperature'' t_{ei} given by equation (A7), and the inside surface resistances R_{si} are given by equation (A8). Although this analysis is strictly valid only for a cubical room, experiments with an electrical analogue have shown that these equations are reasonably accurate for a wide range of room sizes and shapes.

The effect of heat put in or abstracted (e.g. by ventilation) at the air-temperature t_{ai} (see Figure 5a) can be allowed for by introducing a hypothetical conductance h_a between the air-point and the star-point X (Figure 5d). The heat transfer to the walls of area A is given by:

$$q_a = h_a A(t_{ei} - t_{ai}) \qquad (A15)$$

and also

$$q_a = h_c A(t_{ri} - t_{ai}) \qquad (A16)$$

Substituting $t_{ei} = 2/3\, t_{ri} + 1/3\, t_{ai}$ in equation (A15) we have

$$q_a = 2/3\, A h_a (t_{ri} - t_{ai})$$

Hence from equation (A16) $h_a = 3/2\, h_c$.

In SI units with $h_c = 2.8$, $h_a = 4.2\ W/m^2 deg\ C$, (in British units $h_c = 0.5$, $h_a = 0.75$)

The ventilation conductance C_v can be found by combining in series the conductances Ah_a and sV (ventilation heat loss per degree); it is given by:

$$\frac{1}{C_v} = \frac{1}{Ah_a} + \frac{1}{sV} \qquad (A17)$$

When the ventilation rate is low, C_v is approximately equal to sV. For a room of 30 - 60 m^3 (1000 - 2000 cu ft) C_v is only about 5 or 10% less than sV when the ventilation rate is 2 air changes/h, but it can be as low as 50% of sV when the ventilation rate is 20 - 30 air changes/h.

Appendix 4. Procedure for calculating maximum temperatures

On the basis of this work, the following procedure may be used for calculating maximum internal temperatures. It is illustrated by an example in Figure 12 which is for a south-facing school classroom of heavy construction with 50% of the external wall glazed, occupied by 30 children for 4 hours. For simplicity, it is assumed that there is no heat exchange with adjoining rooms. Calculations are made for July, the hottest month during term-time.

(1) Select an appropriate temperature $\bar{t}_o$ for design calculations. It is suggested that the mean temperature for sunny days should be used; the highest external temperatures (Table 6) are very seldom obtained during a succession of days of full sunshine. Monthly mean temperatures are published for different areas; those for sunny days are about 2 deg C higher during July and August. Data for Garston, Herts, are shown in Table 4. In the example $\bar{t}_o$ was taken as 19°C, the mean for sunny days in July.

The highest internal temperatures generally occur in August, but there are exceptions - e.g. schools which are on holiday in August, and rooms with south-facing windows protected by projecting screens. Such rooms may be reasonably cool in August, but too warm in October when the sun enters the building below the projecting screen.

(2) Find daily-mean solar gains through windows by multiplying the daily-mean radiation intensity (160 W/m^2 for the south-facing surface in the example in Figure 12) by the appropriate solar gain factors and window areas. Some data are given in Table 2; where values are not given, they can be calculated by the methods set out in the text. Find mean heat gains from lighting from known wattage of lighting fittings, mean heat gains from occupants (data are given in IHVE Guide), mean solar gains through walls or roofs exposed to radiation, and any other heat inputs. Add the various heat inputs to find the resultant daily-mean heat input to the room $\bar{q}_t$. In Figure 12 the mean heat inputs are shown on the lefthand side of the diagram. It is often convenient to relate the heat input to unit area of external wall, or, as in Figure 12, to unit area of floor.

(3) Determine the U-values and areas of exposed panels, and ventilation heat loss per degree (C_v). If the ventilation rate is low, C_v can be taken as equal to sV, i.e. the product of the volumetric specific heat of air s ($1.2 \times 10^3\ J/m^3 deg\ C$) and the ventilation rate V (m^3/sec). If the ventilation rate is high, C_v should be corrected as discussed in Appendix 3.

When buildings are naturally ventilated it is difficult to obtain a realistic estimate of the ventilation rate. This is determined by the occupants' use of window and door openings as well as by wind and stack pressures. Comparisons of computed temperatures with survey findings indicate that the average values in Table 5 may be appropriate for design calculations. Where buildings are mechanically ventilated, the ventilation rate can be established with much greater certainty. If heat inputs are related to unit area of exposed wall or floor, it is of course necessary to do the same for heat losses.

(4) Calculate the daily-mean internal temperature $\bar{t}_{ei}$ from the steady-state heat balance equation:

$$\bar{q}_t = (\Sigma AU + C_v)(\bar{t}_{ei} - \bar{t}_o) \qquad (A18)$$

This equation applies where there is no heat exchange with adjoining rooms i.e. where each room is surrounded by similar rooms at the same temperature. Additional terms have to be added when necessary to allow for heat transfer to adjacent rooms; if rooms on opposite sides of a building are considered, it is necessary to put in a term for heat transfer between rooms and calculate the mean temperature on both sides of the building by solving two simultaneous equations.

(5) Where the entire curve of daily variation of internal temperature is required, plot out hourly values of the various effective heat inputs, relating to the basic area considered. Daily swings of radiation intensities should first be calculated relative to the daily-mean value. In a detailed calculation, swings about the mean should be calculated separately for absorbed and transmitted components, and multiplied by appropriate retransmission or surface factors. For a more approximate calculation as in the illustrative example (Figure 12), swings in radiation intensity may be multiplied by the alternating solar gain factor (S_a) in Table 2. This will give a good estimate of peak temperatures, but temperatures at say 9 a.m. may be overestimated. The swings in effective heat inputs should be added and the total swing $\tilde{q}_t$ found.

If only the maximum value of t_{ei} is required, it is only necessary to determine the various effective heat inputs for a few hours near the time when the maximum temperature is expected.

(6) Determine the areas and admittances of both external and internal room panels (Table 3), relate to basic area, and calculate the temperature swing from the equation:

$$\tilde{q}_t = (\Sigma AY + C_v)\,\tilde{t}_{ei} \qquad (A19)$$

The temperature swing $\tilde{t}_{ei}$ should then be added to $\bar{t}_{ei}$ to obtain the computed internal temperature. The illustrative example shows a maximum temperature of 28°C; this room would be expected to be excessively warm in summer, and some form of external shading would be needed to provide comfortable conditions.

Appendix 5. Symbols

A	area
C_v	ventilation conductance (ventilation heat loss per degree)
E	longwave emissivity factor
f	retransmission factor for components of solar control
F	surface factor for building element
h_a	hypothetical conductance between the air point in a delta network and the X-point in a star network of thermal resistances
h_c	convection transfer coefficient
h_r	radiation transfer coefficient
I_L	longwave radiation loss of surface at air temperature to surroundings
I_s	incident total solar radiation intensity
q	rate of heat input; q_e equivalent heat input;
q_t	total equivalent heat input; q_a rate of heat transfer from air to surfaces
Q	total thermal capacity of the structure
R	thermal resistance; R_{si} inside surface resistance;
R_{so}	outside surface resistance; R_1, R_2 thermal resistance of components of structure
R_v	thermal resistance of ventilating air
s	volumetric specific heat of air
S	solar gain factor of window system or building element; S_a alternating solar gain factor
t_o	outside temperature; t_{ao} outside air;
t_{ro}	mean of external surroundings; t_{so} of outside of building element;
t_i	internal temperature; t_{ai} inside air;
t_{ei}	inside 'environmental' temperature;
t_{ri}	area weighted mean temperature of all room surfaces;
t'_{ri}	mean radiant temperature seen by inside surface of exposed panel;
t_{si}	temperature of inside of exposed building element
U	thermal transmittance
V	ventilation rate
Y	admittance per unit area
α	absorptivity to solar radiation; α_o outer sheet of window system
α_i	inner sheet of window system
τ	transmittance of solar radiation by window system

Note: The symbols $\bar{}$ and $\sim$ indicate the mean, and the deviation from the mean.

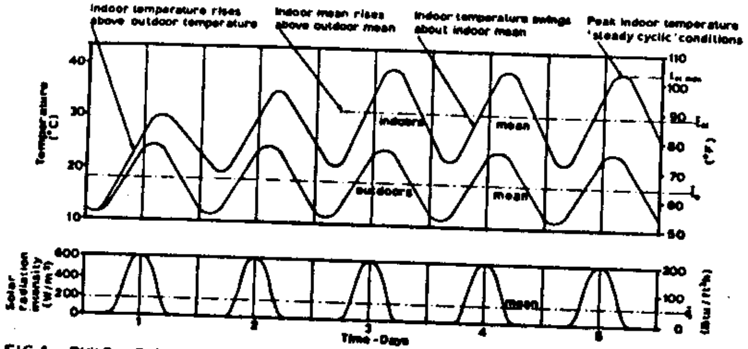


FIG 1 BUILD-UP OF INTERNAL TEMPERATURES DURING A HEAT-WAVE

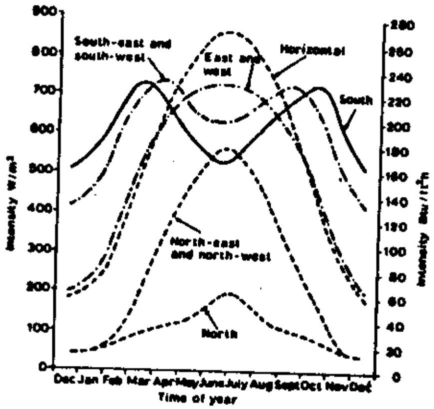


FIG 2 DESIGN PEAK SOLAR RADIATION INTENSITIES (DIRECT + SKY DIFFUSE + GROUND-REFLECTED) LAT 51,7° N

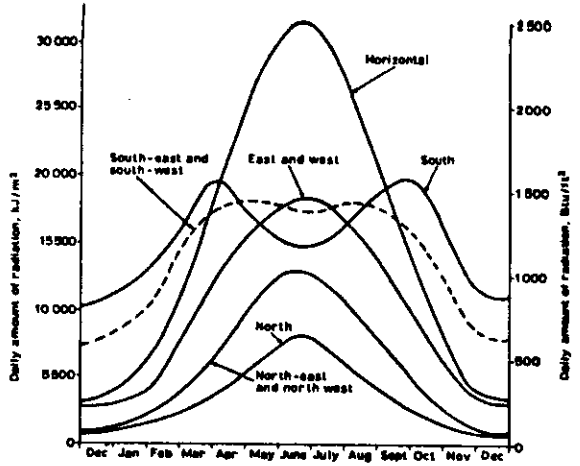


FIG 3 DESIGN DAILY AMOUNTS OF SOLAR RADIATION (DIRECT + SKY DIFFUSE + GROUND - REFLECTED RADIATION) LAT 51° 7' N

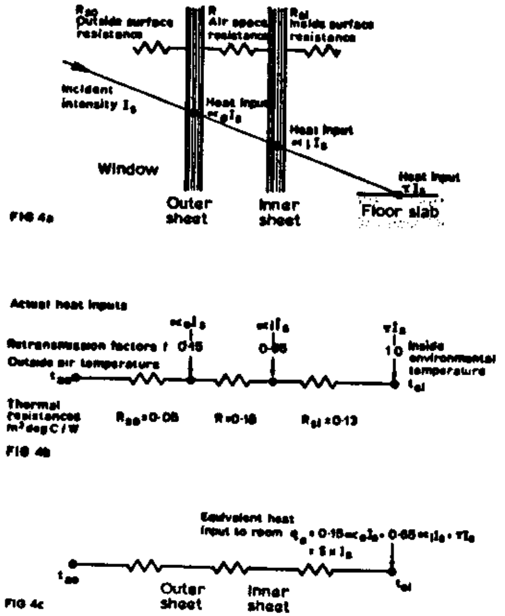


FIG 4 HEAT INTERCHANGES IN A WINDOW SYSTEM

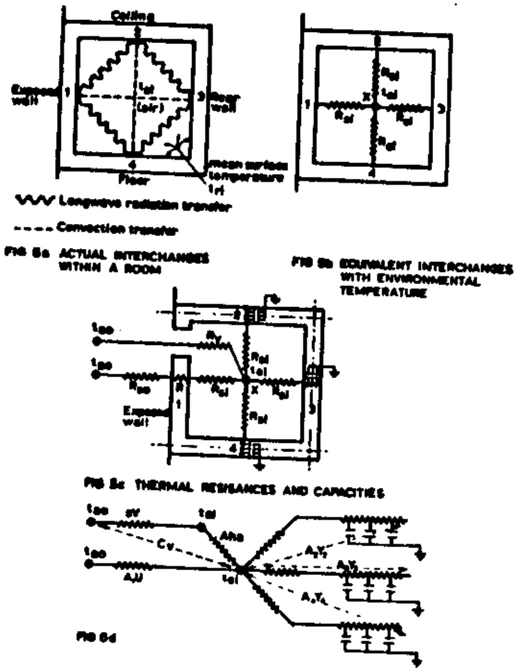


FIG 5 HEAT INTERCHANGES WITHIN A ROOM

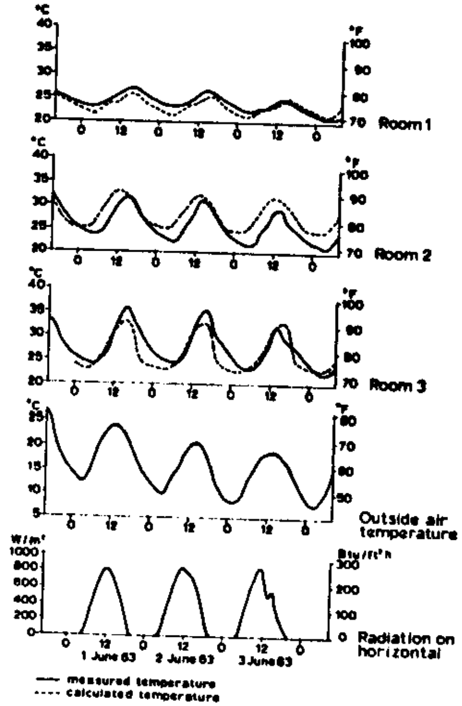


FIG 6 COMPARISON OF MEASURED AND CALCULATED TEMPERATURES IN OFFICES

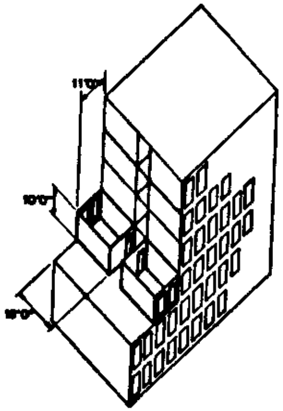


FIG 7 TYPE OF MULTISTORY BLOCK ASSUMED FOR DESIGN CALCULATIONS.

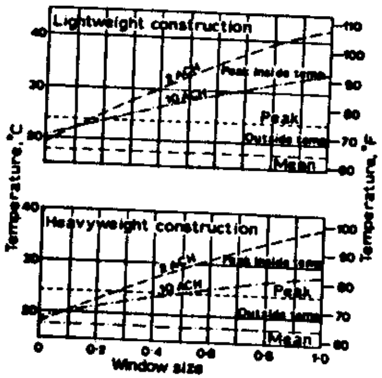
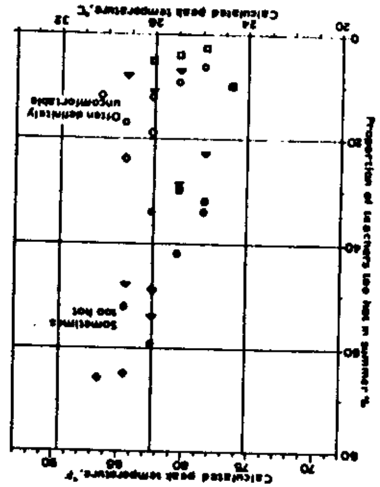
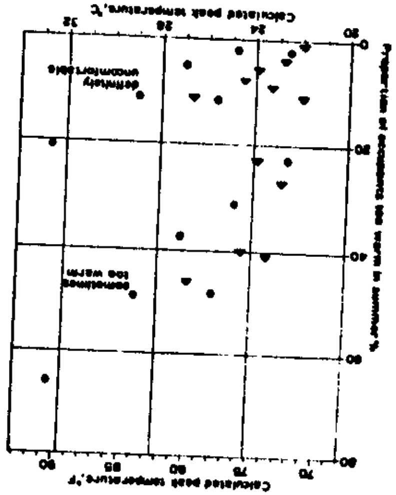


FIG 8 CALCULATED PEAK TEMPERATURE IN OFFICES VERSUS WINDOW SIZE.
(WINDOW SIZE IS GIVEN AS A FRACTION OF THE EXTERNAL WALL AREA)



KEY
● Ventilation through one wall, noisy (5 ach assumed)
○ Ventilation through one wall, quiet (10 ach assumed)
▼ Ventilation through two walls, noisy (10 ach assumed)
■ Ventilation through two walls, quiet (30 ach assumed)

FIG 10 RELATIONSHIP BETWEEN OVERHEATING COMPLAINTS AND CALCULATED PEAK TEMPERATURES IN SCHOOL CLASSROOMS.



KEY
● Noisy offices, (5 ach assumed)
▼ Quiet offices, (10 ach assumed)

FIG 9 RELATIONSHIP BETWEEN OVERHEATING COMPLAINTS AND CALCULATED PEAK TEMPERATURES IN OFFICES.

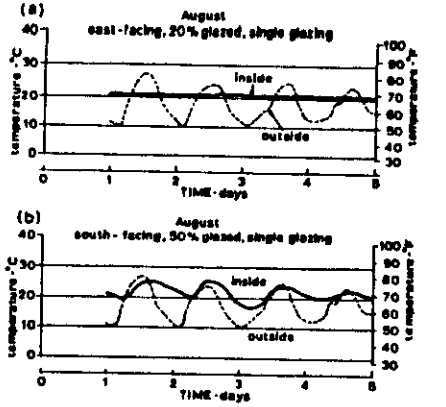


FIG 11 TEMPERATURE RECORDS DURING SUNNY SPELLS

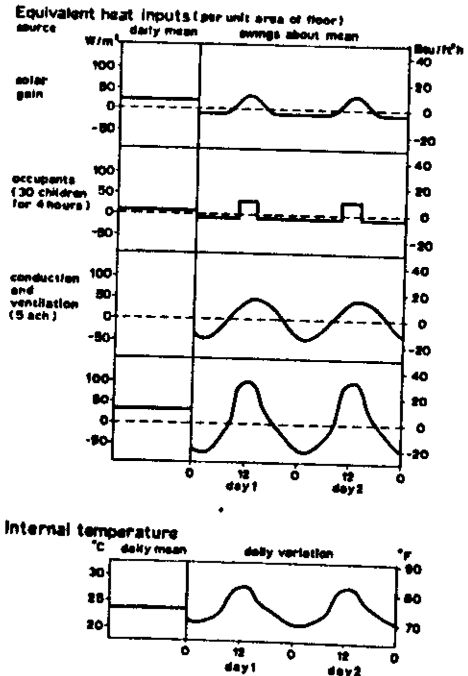


FIG 12 ILLUSTRATION OF PROCEDURE FOR CALCULATING PEAK TEMPERATURE

SCHOOL CLASSROOM 24' x 24' x 9' (7·3m x 7·3m x 2·7m)
HEAVY CONSTRUCTION 50% GLASS ON SOUTH FACE. JULY 15

Printed for Her Majesty's Stationery Office by Richardsons & Coppin Ltd., Grimsby. L7913 Dd 300307 2,000 7/68 ST

SECTION A8 SUMMERTIME TEMPERATURES IN BUILDINGS

Introduction

During warm sunny periods, buildings with windows facing in a southerly direction—any aspect from East to West through South—are subjected to daily cyclic heat gains from solar radiation: in addition, further gains arise from artificial lighting, occupants and other sources. In designing a building it is important to ensure that it will not become uncomfortably hot during sunny periods, i.e. that the maximum peak temperature should not frequently exceed, say, 27°C. This Section describes a technique[1] which enables the peak environmental temperature to be assessed for any proposed building design and also gives curves of peak temperature against window size for a simple design of multi-storey building. It should be noted that the data given do not include any allowance for the effect of sunshine falling directly on occupants whose discomfort would be further increased in such circumstances.

If the temperature is shown to be excessive and steps cannot be taken to overcome the problem by modification of the building design, the need for mechanical ventilation or, more probably, air-conditioning is self-evident.

ROUTINE CALCULATIONS

Application of the technique requires that the following be calculated in turn:

1. Mean heat gains from all sources.
2. Mean internal environmental temperature.
3. Swing (deviation), from mean-to-peak, in heat gains from all sources.
4. Swing (deviation), from mean-to-peak, in internal environmental temperature.
5. Hence, from (2) and (4), the peak internal environmental temperature.

Data required

In order that these steps may be followed, the following information is needed about the rooms concerned:

Areas of all structural elements of the enclosure, walls, floor, roof etc. and details of their construction. From these particulars, admittance values may be determined using Table A8.7. (See also Section A5.)

Area and aspect of all windows and details of blinds and/or shading. From these particulars, mean and alternating solar gains may be determined using Tables A8.1, A8.2 and A8.5 for the United Kingdom. (See also Section A6 for solar intensities at latitudes other than 51·7°N.)

Area, aspect and construction of external structural elements. From these particulars U values may be determined. (See Section A3.)

Any casual heat gains, constant or intermittent, from artificial lighting, occupants or other sources. (See Section A7.)

Details of the ventilation rate. In view of the difficulty in determining such particulars for naturally ventilated buildings, the empirical values listed in Table A8.4 may be used in the present context.

Peak and mean outdoor temperatures. For the United Kingdom it is proposed that, in the present context, the values listed in Table A8.3 which are typical of sunny days (i.e. 5% days of highest solar radiation) should be used.

Mean Heat Gains

Mean solar heat gain

The mean solar heat gain into a room is a function of the mean incident radiation intensity as read from Table A8.1 (for the United Kingdom), or from Tables A6.24 to A6.36 for other latitudes, the appropriate solar gain factor for the type of glass and solar protection as read from Table A8.2 and the sunlit area of the glazing. Thus:

$$Q'_s = S\,I'A_g \quad \ldots \quad \text{A8.1}$$

where:

Q'_s = mean solar gain .. W
I' = mean solar intensity .. W/m²
S = solar gain factor
A_g = sunlit area of glazing .. m²

For instances where the solar protection may vary throughout the 24 hours, by manipulation of blinds by occupants, some allowance should be made by bias of the solar gain factor. Any such allowance cannot be other than eclectic.

Mean casual heat gain

The mean heat gain from casual sources artificial lighting, occupants etc. is found by multiplying the individual items by their duration and averaging over the 24 hours whence:

$$Q'_c = \frac{(q_{c1} \times t_1) + (q_{c2} \times t_2)\ etc}{24} \quad \ldots \quad \text{A8.2}$$

where:

Q'_c = mean casual gain .. W
q_{c1} and q_{c2} = instantaneous casual gains .. W
t_1 and t_2 = duration of individual casual gains .. h

Total mean gain

The total mean heat gain is the sum of the mean solar and mean casual gains determined by equations A8.1 and A8.2 as:

$$Q'_t = Q'_s + Q'_c \quad \ldots \quad \text{A8.3}$$

Table A8.1. Total solar intensities on vertical surfaces (W/m²). **51·7°N**

Date	Orientation	Daily mean	Sun Time 0400	0500	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000
June 21	N	90	45	180	190	115	95	110	125	135	135	135	125	110	95	115	190	180	45
	NE	140	75	360	510	530	440	330	175	135	135	135	125	110	95	75	55	30	5
	E	190	60	340	560	680	605	630	505	335	135	135	125	110	95	75	55	30	5
	SE	185	15	140	315	475	580	625	615	545	420	260	125	110	95	75	55	30	5
	S	155	5	30	55	75	180	320	435	510	540	510	435	320	180	75	55	30	5
	SW	185	5	30	55	75	95	110	125	260	420	545	615	625	580	475	315	140	15
	W	190	5	30	55	75	95	110	125	135	135	335	505	630	605	680	560	340	60
	NW	140	5	30	55	75	95	110	125	135	135	135	175	330	460	530	510	360	75
July 23 and May 21	N	75		135	155	85	90	105	120	130	135	130	120	105	90	85	155	135	
	NE	125		280	465	605	435	310	150	130	135	130	120	105	90	70	45	20	
	E	180		275	525	665	695	630	505	330	135	130	120	105	90	70	45	20	
	SE	190		120	305	480	595	645	635	565	440	280	120	105	90	70	45	20	
	S	165		20	45	70	200	345	465	540	570	540	465	345	200	70	45	20	
	SW	190		20	45	70	90	105	120	280	440	565	635	645	595	480	305	120	
	W	180		20	45	70	90	105	120	130	135	330	505	630	695	665	525	275	
	NW	125		20	45	70	90	105	120	130	135	130	150	310	435	605	465	280	
August 24 and April 20	N	30		5	75	55	75	95	110	115	120	115	110	95	75	55	75	5	
	NE	90		15	305	405	365	240	110	115	120	115	110	95	75	55	30	0	
	E	150		15	370	585	640	615	495	320	120	115	110	95	75	55	30	0	
	SE	190		10	240	460	610	605	600	615	490	325	135	95	75	55	30	0	
	S	185		0	30	95	250	405	530	615	640	615	530	405	250	95	30	0	
	SW	190		0	30	55	75	95	135	325	490	615	600	605	610	460	240	10	
	W	150		0	30	55	75	95	110	115	120	320	495	615	640	585	370	15	
	NW	90		0	30	55	75	95	110	115	120	115	110	240	365	405	305	15	
September 22 and March 22	N	30				30	55	70	85	95	100	95	85	70	55	30			
	NE	50				215	240	145	85	95	100	95	85	70	55	30			
	E	110				365	535	645	450	290	100	95	85	70	55	30			
	SE	170				315	545	670	695	640	525	360	180	70	55	30			
	S	200				100	270	445	580	670	700	670	580	445	270	100			
	SW	170				30	55	70	180	360	525	640	695	670	545	315			
	W	110				30	55	70	85	95	100	290	450	645	535	365			
	NW	30				30	55	70	85	95	100	95	85	145	240	215			
October 23 and February 20	N	20				0	25	45	65	70	75	70	65	45	25	0			
	NE	25				10	110	60	65	70	75	70	65	50	25	0			
	E	70				25	315	430	370	240	75	70	65	50	25	0			
	SE	135				20	350	545	625	600	305	360	190	50	25	0			
	S	180				10	195	390	550	650	600	650	550	390	195	10			
	SW	135				0	25	50	190	360	505	600	625	545	350	20			
	W	70				0	25	50	65	70	75	240	370	410	315	25			
	NW	25				0	25	50	65	70	75	70	65	60	110	10			
November 21 and January 21	N	10					5	25	40	50	85	50	40	25	5				
	NE	10					10	25	40	50	85	50	40	25	5				
	E	35					50	235	255	180	55	50	40	25	5				
	SE	95					60	335	470	490	425	305	165	40	5				
	S	130					35	235	430	545	580	545	430	255	35				
	SW	95					5	40	165	305	425	490	470	335	60				
	W	35					5	25	40	50	55	180	255	235	50				
	NW	10					5	25	40	50	85	50	40	25	10				
December 22	N	10						15	30	40	45	40	30	15					
	NE	10						15	30	40	45	40	30	15					
	E	25						150	205	150	45	40	30	15					
	SE	75						225	385	425	375	270	140	30					
	S	105						175	360	475	515	475	360	175					
	SW	75						30	140	270	375	425	385	225					
	W	25						15	30	40	45	150	205	150					
	NW	10						15	30	40	45	40	30	15					

Basis for tabulated values:
1. Direct Radiation factor (sky clarity), k_c = 0·95
2. Cloudiness factor = 0
3. Ground Reflectance factor, k_r = 0·2
4. Altitude = 0 to 300 m (see Fig. A6.4 for correction factors).

Note: Bold figures are peak values for the orientation at each season.

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Mean internal environmental temperature

The mean internal environmental temperature may be determined from the equation:

$$Q'_t = (\Sigma A_g U_g + C_v)(t'_{ei} - t'_{ao}) + \Sigma A_f U_f (t'_{eo} - t'_{ao}) \quad \text{A8.4}$$

where:

ΣAU = sum of products of areas of exposed surfaces and the appropriate U values W/°C. The subscripts g and f refer to glass and opaque fabric respectively.

C_v = ventilation loss .. .. W/°C

t'_{ei} = mean internal environmental temperature .. .. °C

t'_{eo} = mean sol-air temperature (Tables A6.15 to 21). .. .. °C

t'_{ao} = mean outdoor air temperature .. °C (Table A8.3 for the United Kingdom)

For low rates of ventilation, equivalent to a ventilation loss of say 0·6 W/m³ °C (2 air changes per hour) or less,

$$C_v \approx 0{\cdot}33\, N v \quad .. \quad .. \quad .. \quad \text{A8.5}$$

where:

N = Rate of air interchange .. .. h^{-1}

v = room volume .. .. m^3

For higher rates of ventilation however it is necessary to make use of the conductance concept discussed in Section A5 where:

$$\frac{1}{C_v} = \frac{1}{0{\cdot}33\, N v} + \frac{1}{4{\cdot}8 \Sigma A} \quad .. \quad .. \quad .. \quad \text{A8.6}$$

where:

ΣA = total area of surfaces bounding the enclosure, whether internal or external m^2

The empirical values for ventilation rates listed in Table A8.4 may be used for naturally ventilated buildings in the United Kingdom.

Swing (deviation), mean-to-peak, in heat gain

The variations in heat input due to solar radiation, outside air temperature and casual gains have to be found and added to give the total swing in heat input. Solar heat gains are usually predominant, and an examination of the solar radiation intensities in Table A8.1 (for the United Kingdom), or Tables A6.24 to A6.36 for other latitudes, together with the outside air temperatures, will usually indicate when the peak indoor temperature will occur unless there are large casual heat gains within the room. For rooms with south or west facing external walls, the peak temperature will occur during early or late afternoon when high radiation intensities coincide with high outside air temperatures. In north-facing rooms with little solar radiation (which seldom suffer from overheating) the peak indoor temperature can be expected in the afternoon due to the warmth of the ventilating air. In east-facing rooms, the peak indoor temperatures can occur in the morning or afternoon, dependent on size of window, amount of natural ventilation and presence of casual gains.

In order to determine the swing (mean-to-peak) it is necessary to decide on the time of day when the peak indoor temperature is likely to occur, and compute the mean-to-peak effective heat inputs for this 'peak hour'. If there is a doubt about the choice of the peak hour, the same procedure must be followed for several times of day to ensure that the peak indoor temperature is found.

Swing in effective solar heat gain

From the solar radiation intensities listed in Table A8.1 (for the United Kingdom), or from Tables A6.24 to A6.36 for other latitudes, the difference between the intensity at the peak hour and the mean intensity may be found, in order to give the effective heat input due to solar radiation. A time lag of 1 hour should be assumed in heavyweight rooms to allow for the response of the *room surfaces* to the solar radiation, i.e. for a room

Table A8.2. Solar gain factors (S) for various types of glazing and shading (strictly accurate for U.K. only; approximately correct world wide).

Position of shading and type of sun protection		Solar gain factors* S for the following window types	
Shading	Type of sun protection	Single	Double
None	None	0·76	0·64
	Lightly heat absorbing glass	0·51	0·38
	Densely heat absorbing glass	0·39	0·25
	Lacquer coated glass, grey	0·56	—
	Heat reflecting glass, gold (sealed unit when double)	0·26	0·25
Internal	Dark green open weave plastic blind	0·62	0·56
	White venetian blind	0·46	0·46
	White cotton curtain	0·41	0·40
	Cream holland linen blind	0·30	0·33
Mid-pane	White venetian blind	—	0·28
External	Dark green open weave plastic blind	0·22	0·17
	Canvas roller blind	0·14	0·11
	White louvred sunbreaker, blades at 45°	0·14	0·11
	Dark green miniature louvred blind	0·13	0·10

Notes: *All glazing clear except where stated otherwise. Factors are typical values only and variations will occur due to density of blind weave, reflectivity and cleanliness of protection.

Table A8.3. Typical average outdoor air temperatures for 5% of days of highest solar radiation. (51·7°N latitude).

Month	Daily mean t_{ao} (°C)	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	Mean to peak swing $\tilde{t}_{ao}$ (°C)
		Typical temperatures, hour by hour (°C) — Sun time													
March	7·0	2·8	4·0	5·4	7·0	8·6	10·0	11·2	12·2	12·8	13·0	12·8	12·2	11·2	6·0
April	9·0	4·8	6·0	7·4	9·0	10·6	12·0	13·2	14·2	14·8	15·0	14·8	14·2	13·2	6·0
May	13·0	8·1	9·5	11·2	13·0	14·8	16·5	17·9	19·1	19·8	20·0	19·8	19·1	17·9	7·0
June	16·5	11·2	12·8	14·6	16·5	18·4	20·2	21·8	23·0	23·8	24·0	23·8	23·0	21·8	7·5
July	19·0	14·4	15·7	17·3	19·0	20·7	22·3	23·6	24·6	25·3	25·5	25·3	24·6	23·6	6·5
August	17·0	12·8	14·0	15·4	17·0	18·6	20·0	21·2	22·2	22·8	23·0	22·8	22·2	21·2	6·0
September	13·5	9·6	10·7	12·1	13·5	14·9	16·3	17·4	18·3	18·8	19·0	18·8	18·3	17·4	5·5

Notes: Peaks occur at 1500, means at 0900 and 2100, sinusoidal variations are assumed. Temperatures quoted are fairly typical of most populous areas in the United Kingdom. See Figures A2.13 and A2.14 for records at London (Heathrow).

Table A8.4. Ventilation rates for naturally ventilated buildings on sunny days.

Position of opening windows	Usage of windows: Day	Usage of windows: Night	Effective mean ventilation rate: Air changes (h^{-1})	Effective mean ventilation rate: Ventilation allowance (W/m² °C)
One side only	Closed	Closed	1	0·3
	Open	Closed	3	1·0
	Open	Open	10	3·3
More than one side	Closed	Closed	2	0·6
	Open	Closed	10	3·3
	Open	Open	30	10·0

Table A8.6. Building classification by weight.

Building classification	Construction	Average surface factor F (Table A8.7)
Heavyweight	Solid internal walls and partitions, solid floors and solid ceilings.	0·5
Lightweight	Lightweight demountable partitions with suspended ceilings. Floors *either* solid with carpet or wood block finish *or* suspended type.	0·8

Table A8.5. Alternating solar gain factors (S_a) for various types of glazing and shading and for heavyweight and lightweight buildings (strictly accurate for U.K. only; approximately correct world wide).

Position of shading and type of sun protection		Alternating solar gain factors* S_a for the following building and window types			
		Heavyweight building		Lightweight building	
Shading	Type of sun protection	Single	Double	Single	Double
None	None	0·42	0·39	0·65	0·56
	Lightly heat absorbing glass	0·36	0·27	0·47	0·35
	Densely heat absorbing glass	0·32	0·21	0·37	0·24
	Lacquer coated glass, grey	0·37	—	0·50	—
	Heat reflecting glass, gold (sealed unit when double)	0·21	0·14	0·25	0·20
Internal	Dark green open weave plastic blind	0·55	0·53	0·61	0·57
	White venetian blind	0·42	0·44	0·45	0·46
	White cotton curtain	0·27	0·31	0·35	0·37
	Cream holland linen blind	0·24	0·30	0·27	0·32
Mid-pane	White venetian blind	—	0·24	—	0·27
External	Dark green open weave plastic blind	0·16	0·13	0·22	0·17
	Canvas roller blind	0·10	0·08	0·13	0·10
	White louvred sunbreaker, blades at 45°	0·08	0·06	0·11	0·08
	Dark green miniature louvred blind	0·08	0·06	0·10	0·07

Notes: *All glazing clear except where stated otherwise. Factors are typical values only and variations will occur due to density of blind weave, reflectivity and cleanliness of protection.

of heavyweight construction, the radiation intensity incident on the surfaces at 1 hour earlier than the peak hour should be used. For a very lightweight construction, no allowance for time lag is necessary. This mean-to-peak difference must then be multiplied by the appropriate alternating solar gain factor, as read from Table A8.5, and by the area of the glazing, thus:

$$\tilde{Q}_s = S_a A_g (I_p - I') \quad \ldots \quad \text{A8.7}$$

where:

$\tilde{Q}_s$ = swing in effective heat gain due to solar radiation .. .. W

S_a = alternating solar gain factor

I_p = peak intensity of solar radiation .. W/m²

It will be noted that the magnitude of the alternating solar gain factor varies with the weight of the structure: the descriptions quoted in Table A8.6 give some guidance in this respect.

Swing in structural heat gain

The periodic heat flow through walls and roofs is discussed at length in Section A6, and the time lag data illustrated in Figs. A8.1 and A8.2 will give some indication as to whether this heat flow will contribute significantly to the peak load. In most instances in the United Kingdom this aspect may be neglected but the relevant equation is:

$$\tilde{Q}_f = f A U (t_{eo} - t'_{eo}) \quad \ldots \quad \text{A8.8}$$

where:

$\tilde{Q}_f$ = swing in the effective heat input due to structural gain .. .. W

ϕ = time lag (see Fig. A8.1) .. .. h

f = decrement factor dependent on the thickness of the wall or roof structure (see Fig. A8.2)

t_{eo} = sol-air temperature at time of peak hour less time lag .. .. .. °C

t'_{eo} = mean sol-air temperature .. .. °C

Swing in casual heat gain

From the examination of casual heat gains made to determine the mean, the value at the peak hour will have been revealed. The mean-to-peak swing may thence be determined from:

$$\tilde{Q}_c = Q_c - Q'_c \quad \ldots \quad \text{A8.9}$$

where:

$$Q_c = q_{c_1} + q_{c_2} + \text{etc} \quad \ldots \quad \text{W}$$

Swing in heat gain air-to-air

The difference between the outdoor air temperature at the peak hour and the mean outdoor air temperature must be found in order to give the variation in heat input due to the outside temperature swing. This temperature difference must be multiplied by the product of the area and U-value of the exposed glass and by the appropriate ventilation heat loss value, thus:

$$\tilde{Q}_a = (\Sigma A_g U_g + C_v)\, \tilde{t}_{ao} \quad \ldots \quad \text{A8.10}$$

where:

$\tilde{Q}_a$ = swing in effective heat input due to swing in outside temperature .. W

$\Sigma A_g U_g$ = sum of products of areas of exposed glazing and the appropriate U values .. .. W/°C

$\tilde{t}_{ao}$ = swing in outside air temperature °C (Table A8.3 for the United Kingdom)

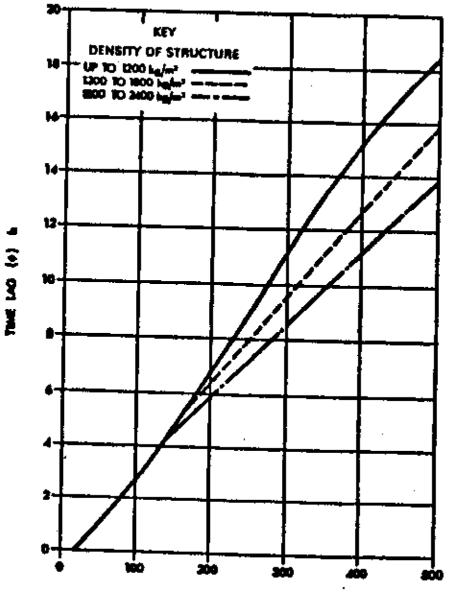

Fig. A8.1. Time lag ϕ

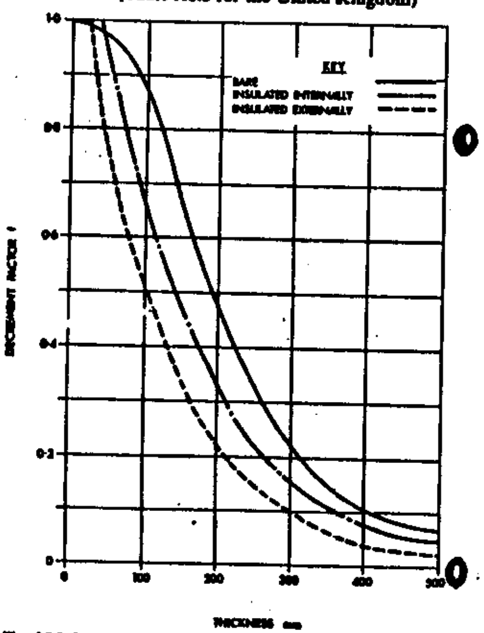

Fig. A8.2. Decrement factor

Total swing in heat gain

From the components listed, the total swing in effective heat input may be determined as:

$$\tilde{Q}_t = \tilde{Q}_s + \tilde{Q}_f + \tilde{Q}_c + \tilde{Q}_a \quad \ldots \quad \text{A8.11}$$

Swing (deviation), mean-to-peak, in internal environmental temperature

The magnitude of the mean-to-peak swing in internal environmental temperature may be determined by use of the admittance values listed in Table A8.7 and the following expression:

$$\tilde{Q}_t = (\Sigma A Y + C_v)\, \tilde{t}_{ei} \quad \ldots \quad \text{A8.12}$$

where:

$\Sigma A Y$ = sum of products of all room surface areas, internal and external and their appropriate admittance values .. W/°C

$\tilde{t}_{ei}$ = swing in internal environmental temperature .. .. °C

Peak internal environmental temperature

The peak internal environmental temperature is determined by adding the mean-to-peak swing to the mean, thus:

$$t''_{ei} = t'_{ei} + \tilde{t}_{ei} \quad \ldots \quad \text{A8.13}$$

where:

t''_{ei} = peak internal environmental temperature .. .. °C

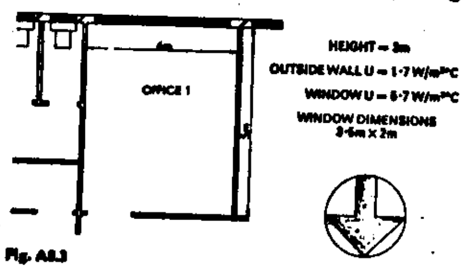

Fig. A8.3

Examples

The routine of such calculations is best illustrated by the following two examples.

Table A8.8. Characteristics of offices in Examples 1 and 2.

Item	Detail
Window	Single glazing, no shading or blinds
Floor	Linoleum on concrete, no carpet
Ceiling	Plastered concrete
Partitions	Plastered brickwork
Occupancy	4 persons for 8 hours (80 W each)
Lighting	30 W/m² of floor, 0700 to 0900 and 1700 to 1900
Classification	Heavyweight building

Table A8.7. Admittances and surface factors.

Structural element	Admittance Y (W/m² °C)	Surface factor F
Windows (typical)		
Single, unshaded	5·6	0·3
Single, internal blind	5·6	0·8
Double, unshaded	3·2	0·65
Double, mid-pane blind	3·2	0·7
Walls more than 0·075 m thick of following densities		
650 kg/m³	3·0	0·8
1100 kg/m³	4·0	0·65
1750 kg/m³	5·0	0·5
2250 kg/m³	6·0	0·4
Partitions		
Heavy with lining of resistance 0·18 m² °C/W	3·0	0·7
Two fibreboard sheets 0·013 m thick with air space	2·0	0·8
Floors		
Concrete	6·0	0·4
Concrete, carpet or woodblock ..	3·0	0·7
Suspended timber	2·0	0·8
Suspended timber and carpet ..	1·5	0·85
Ceilings		
Plastered concrete	6·0	0·4
Cavity plasterboard	3·0	0·7
Lath and plaster/timber	2·0	0·8

Example No. 1

An estimate is required of the peak internal environmental temperature likely to occur during a sunny period in August for office No. 1 in Fig. A8.3. The external wall faces a busy traffic route and the room is on an intermediate floor. Table A8.8 lists other particulars relating to the room and its occupancy etc.

Step a. Mean heat gains

Solar gain (equation A8.1, Tables A8.1 and A8.2)

$$Q'_s = 0{\cdot}76 \times 185(3{\cdot}5 \times 2) = 984\ \text{W}$$

Casual gain (equation A8.2)

$$Q'_c = \frac{(4 \times 80 \times 8) + (4 \times 5 \times 30 \times 4)}{24} = 207\ \text{W}$$

$$\text{Thus } Q'_t = 984 + 207 = 1191\ \text{W}$$

Step b. Mean internal environmental temperature

Ventilation loss (equation A8.5, Table A8.4 assuming the window to be closed day and night):

$$C_v = 0{\cdot}33\,(5 \times 4 \times 3) = 20\ \text{W/°C}$$

Fabric loss through window (Fig. A8.3)

$$U_g A_g = 5{\cdot}7\,(3{\cdot}5 \times 2) = 40\ \text{W/°C}$$

Fabric loss through outside wall (Fig. A8.3)

$$U_f A_f = 1{\cdot}7\,(12 - 7) = 8\ \text{W/°C}$$

Thus (equation A8.4 and Table A6.20)

$$1191 = (40 + 20)\,(t'_{ei} - 17) + 8(t'_{ei} - 25{\cdot}6)$$

and $t'_{ei} = 35{\cdot}5$°C.

Step c. Swing (mean-to-peak) in heat gain

Solar gain (equation A8.7, Tables A8.1 and A8.5) Peak hour is 1300 but allow for 1 hour time lag and take intensity at 1200.

$$\tilde{Q}_s = 0{\cdot}42(3{\cdot}5 \times 2)\,(640 - 185) = 1338\ \text{W}$$

Structural gain (equation A8.8, Fig. A8.1 and A8.2): Time lag is 7 hours and decrement factor 0·4: sol-air temperatures are listed in Table A6.20.

$\tilde{Q}_f = 0{\cdot}4 \times 1{\cdot}7(12-7)(13{\cdot}9-25{\cdot}6) = -40$ W

(i.e. this component could have been neglected)

Casual gain (equation A8.9).

$\tilde{Q}_c = (4 \times 80) - 207 = 113$ W

Gain air-to-air (equation A8.10 and Table A8.3).

$\tilde{Q}_a = [(3{\cdot}5 \times 2 \times 5{\cdot}7) + 20]\,(22{\cdot}2-17) = 312$ W

Thus:

$\tilde{Q}_t = 1338 - 40 + 113 + 312 = 1723$ W

Step d. Swing (mean-to-peak) in internal environmental temperature

Using Table A8.7

Floor	$AY = 20 \times 6$	= 120 W/°C
Ceiling	$AY = 20 \times 6$	= 120 W/°C
Window	$AY = 7 \times 5{\cdot}6$	= 39 W/°C
Outside Wall	$AY = 5 \times 5$	= 25 W/°C
Partitions	$AY = 42 \times 3$	= 126 W/°C

Thus (equation A8.12):

$1723 = (430 + 20)\,\tilde{t}_{ei}$ and $\tilde{t}_{ei} = 3{\cdot}8$°C

Step e. Peak internal environmental temperature

From equation A8.13

$\hat{t}'_{ei} = 35{\cdot}5 + 3{\cdot}8 = 39{\cdot}3$°C

Example No. 2

Taking the same room again, as for Example 1 but assuming the window to be open day and night (Ventilation loss of 3·3 W/m³°C, from Table A8.4) the calculation may be reworked as:

Step a

Q'_t (as before) = 1191W

Step b

From equation A8.6

$$\frac{1}{C_v} = \frac{1}{198} + \frac{1}{4{\cdot}8 \times 94} = 0{\cdot}0073\text{°C/W}$$

and $C_v = 138$ W/°C

Fabric loss through window (as before) = 40 W/°C
Fabric loss through outside wall (as before) = 8 W/°C
Thus (equation A8.4 and Table A6.20):

$1191 = (40 + 138)(\bar{t}'_{ei} - 17) + 8\,(\bar{t}'_{ei} - 25{\cdot}6)$

and $\bar{t}'_{ei} = 23{\cdot}8$°C

Step c

Gain air-to-air (equation A8.10 and Table A8.3)

$\tilde{Q}_a = [(3{\cdot}5 \times 2 \times 5{\cdot}7) + 138]\,(22{\cdot}2-17) = 926$ W

Thus:

$\tilde{Q}_t = 1338 - 40 + 113 + 926 = 2337$ W

Step d

From equation A8.12

$2337 = (430 + 138)\,\tilde{t}_{ei}$ and $\tilde{t}_{ei} = 4{\cdot}1$°C

Step e

From equation A8.13

$\hat{t}'_{ei} = 23{\cdot}8 + 4{\cdot}1 = 27{\cdot}9$°C

GENERALIZED SOLUTIONS

The method can easily be extended to cover the case where two sets of rooms on either side of a corridor receive different amounts of heat from solar radiation, so that there is transfer of heat across the corridor. Fig. A8.4 shows peak temperatures in rooms facing south or east-west, backed by similar rooms: there is very little difference in the calculated peak temperatures for different orientations within this range, although peaks occur at different times of day. The curves were calculated for two rates of ventilation loss, 0·6 and 3·3 W/m³ °C (2 and 10 air changes per hour) and for different sun-protection devices, heat absorbing glasses and blinds: it is clear that external blinds are the most effective. The curves, however, are theoretical in that they are based on the assumption that the blinds are drawn all day in sunny weather, whereas in practice it is questionable whether blinds are drawn until rooms are already too warm.

User studies suggest that internal venetian blinds have little effect on the thermal comfort in parts of the room which are not sunlit, although they are very effective in combating sun glare and overheating from direct sunshine falling on the occupants. The curves may therefore to some extent overestimate the practical effects of blinds in reducing internal temperatures.

REFERENCE

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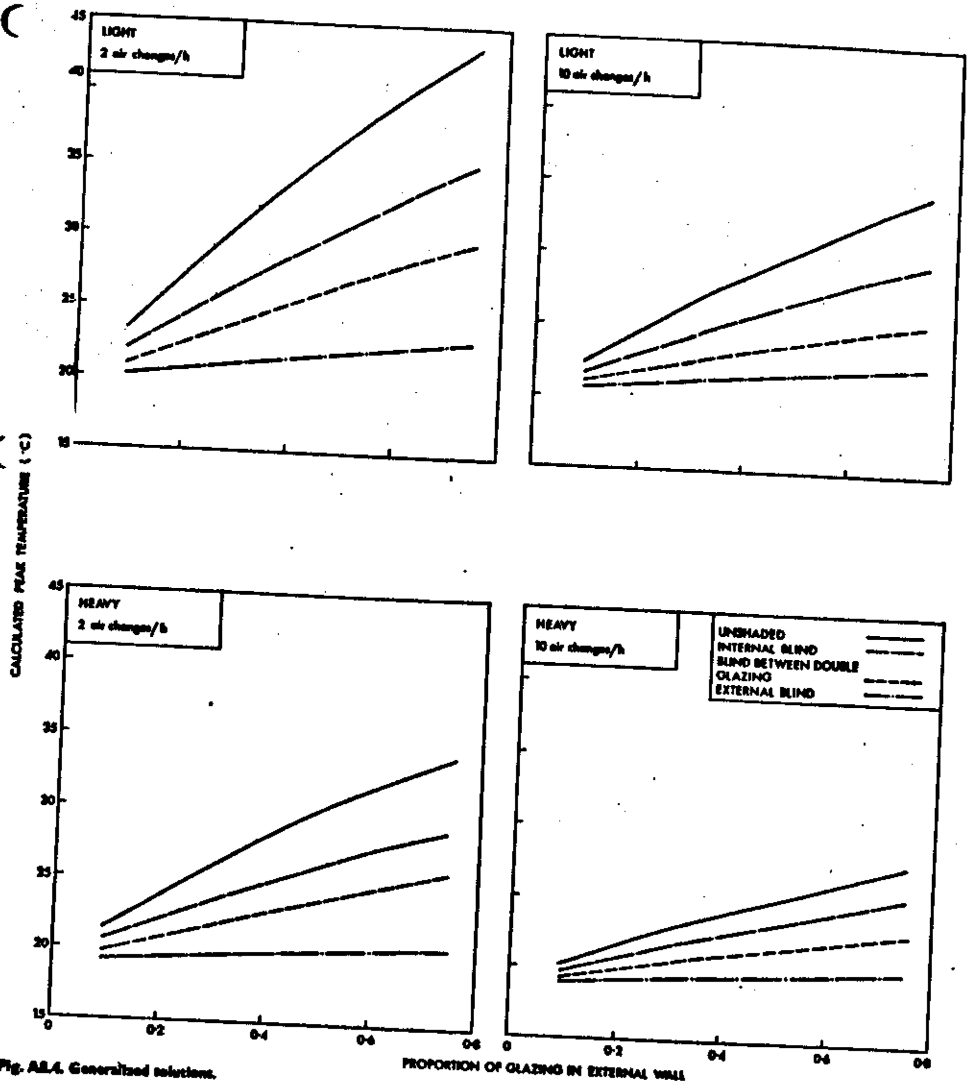

Fig. A8.4. Generalised solutions.

6.4

Feasibility of solar energy utilisation and research for buildings in developing countries

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Abstract

The rapid increase in oil price has highlighted the world's energy crisis. As we need energy in order to maintain and improve our standard of living, there is a need to explore alternative sources of energy. An attempt has been made in this paper to examine the world's energy problems and its effect on the developing countries.

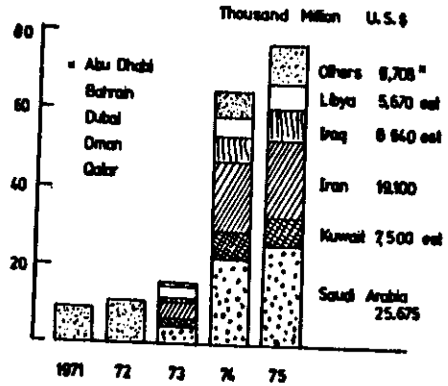
Without neglecting the fundamental thermal design problems of buildings in the developing countries, most of which lie within tropical climate, their possible utilisation of solar energy is discussed. There is a need for further research and co-operation between the developed and developing countries.

Introduction

The rapid increase in oil price has had a great effect on the world's energy crisis. According to Norton Belknap, vice president of planning for Exxon Corporation, the worlds biggest oil company, "The Arabian peninsular is the dumping ground of the worlds energy problems. After 1980 all the growth in OPEC output will come from the peninsular countries, yet the policies of these countries with regard to their oil reserves is impossible to predict. How the conflict between the world's demand for more oil and the Arab's possible reluctance to exhaust their supplies at the rate demanded by the West is resolved is one of the cosmic imponderables of the world today". OPEC – the Organisation of Petroleum Exporting Countries – an anachronism which remained mainly unknown to the world in general for the first 13 years of the organisations life, is now a household word. The true potential of this organisation as a politico-economic power and its strong influence on the world's energy needs became apparent in October 1973. After 13 years during which the price of a barrel of oil had changed from $1.80 (Jan. 1960) to only $2.90 (June 1973), the price was quadrupled to $11.65 a barrel in January 1974. The cathartic aftermath of this quadrupling has had a great impact on the West. Fig. 1 illustrates the magnitude of oil revenue for the main producing countries. As most of these e developing countries, their oil revenue are now being used to fund massive industrialisation plans aimed at producing a sophisicated economy no longer dependant on oil by the time the reserve of crude oil runs out. For example, Iraq has a five-year development plan costing an estimated $30 billion and Nigeria has committed itself to a $20 billions five-year plan. Due to the need for improved living conditions in these countries, substantial funds are usually allocated for housing and buildings.

Although at present we rely heavily on oil for our primary energy, it is evident that we can only do so for a few more decades (1) Apart from oil, other useful fossil fuels are coal and natural gas. At present over 98% of our energy comes from fossil fuels, but however large, its stock is finite. There are however other sources of energy available to mankind. As this paper relates to the developing countries, it is essential to mention that muscle power represents an important source of energy in most developing parts of the world. Nuclear energy has been developed, but is not universally welcomed as the construction of the plant is energy-intensive and the disposal of its long-lived active wastes still poses problems. Geothermal, solar, tidal, and wave energy are also significant where conditions are suitable.

Fig. 1 Oil revenue of the main producing countries (Source: The Economist Intelligence Unit Ltd)



It is a common practice to highlight capital sources when discussing future energy supplies. In assessing a possible energy source, it is essential to ascertain that it is of sufficient magnitude to satisfy our needs and that the means of its exploitation exists or can be developed. The economics of the exploitation and application of the system should be compared with other existing systems.

2.0 World Energy Demand.

It is a generally accepted view that the amount of energy used throughout the world is increasing quite rapidly. When compared with the rest of the world, a high per capita consumption has always been a way of life in America.

In order to assess the efficiency of our energy consumption, let us consider the American situation. About three hundred years ago, it was said that each American family required half an acre of woodland so as to obtain sufficient wood for fuel. Yet its per capita consumption of fuels has increased by only a factor of 2.3 in the last 150 years. This small increase in consumption in a century and a half can be attributed to the efficient conversion of fuel into usable energy. An example of this improved efficiency is found in generating electricity. In 1840 the thermal efficiency of power station was 4%, at present most power stations can attain an efficiency of 40%. By using oil instead of wood for home heating it is possible to obtain an improvement in efficiency from 8% to over 50%. However, it may not be possible to increase efficiencies infinitely as they are at present very close to theoretically established limits. It is therefore correct to assume that future improvements in the standard of living will depend on increased energy consumption. Examination of energy problem in the universe was carried out by Dyson (2). In his findings, he emphasized the preponderance of gravitational energy on a cosmological scale. As the second law of thermodynamics gives us a quantitative measure of disorder through the entropy, Dyson classified the forms of energy in accordance with their entropy per unit energy. This is illustrated in Fig. 2. Low values in this figure denote a high degree of order which will allow extensive abstraction of energy, whereas a high value for the entropy per unit energy signifies a state of disorder with comparatively low potential for useful energy conversion.

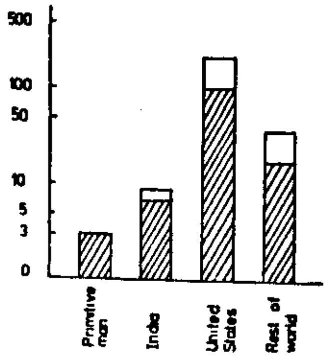
Energy consumption has changed in amount and distribution with time. This is illustrated in Figure 3 by comparing the per capita energy used in United States, India, the rest of the world in 1900 and 1970, and the primitive man. For the rest of the world, the per capita energy demand is lower than that of the United States by about a factor of 6, and in the case of India it is lower by a factor of 30. When compared with the primitive man, India uses only about three times per capita energy. This is the case with most developing countries of the world. As energy contributes to our standard of living, it is essential to increase the energy demand of all developing countries.

Fig. 2

Energy forms and their practically achievable utilization efficiencies.

Energy forms	Applications	Practically achievable efficiency, per cent	Fundamental limitation in utilization efficiency
energy released by relocation of material bodies	flywheels to produce translational motion	~100	energy conservation (first law of thermodynamics)
energy released by nuclear reactions	nuclear reactors to generate electricity	35 to 45	Carnot efficiency for the thermal cycles used
energy released by chemical reactions	fossil-fuel power plants to generate electricity	35 to 45	Carnot efficiency for thermal cycles used
	fuel cells to generate electricity	80 to 120 for the definition of efficiency used	energy conservation
solar radiation	photosynthesis	~1	energy conservation
	solar space and water heaters	5 to 20	Carnot efficiency for the thermal cycles used
	wind energy to generate electricity	10 to 60(?)	energy conservation
	hydroelectric power conversion	60 to 80	energy conservation
	photovoltaic cells	1 to 20	energy conservation
fusion energy	the goal is electricity generation	probably 35 to 45	Carnot efficiency for the thermal cycles used

Fig. 3



Growth of energy demand. (Shaded area, to 1900; unshaded area, 1900-70)

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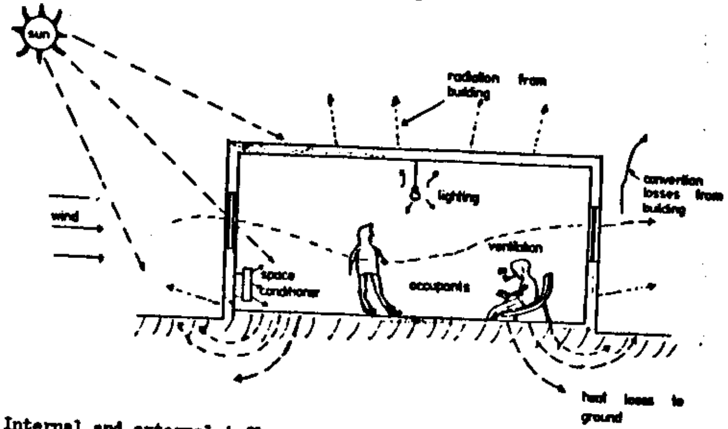
3.0 Fundamental climatic building design for the developing countries.

We have seen earlier in this paper that energy contributes to our standard of living. As far as building design is concerned, it is essential to attain a comfortable living condition and to achieve substantial functional performance. As an illustrative introduction, house's prehistoric precursor could be used to demonstrate mans energy need for comfort. Assuming that we lived in a cave located within a tropical climate, it is likely that the temperature would be stable and no energy may be required for space conditioning. On the other hand, if we are to live in a cave within a temperate climate, we may require heating all the year round as the ground temperature is usually about 13°C.

If we live above ground we are faced with diurnal and yearly temperature variations. Heat input from solar radiation, heat losses to the ground and to the atmosphere, as well as air movement will affect the thermal environment of buildings. Fig. 4 illustrates some internal and external environmental factors which influences thermal comfort in a building.

Fig. 4

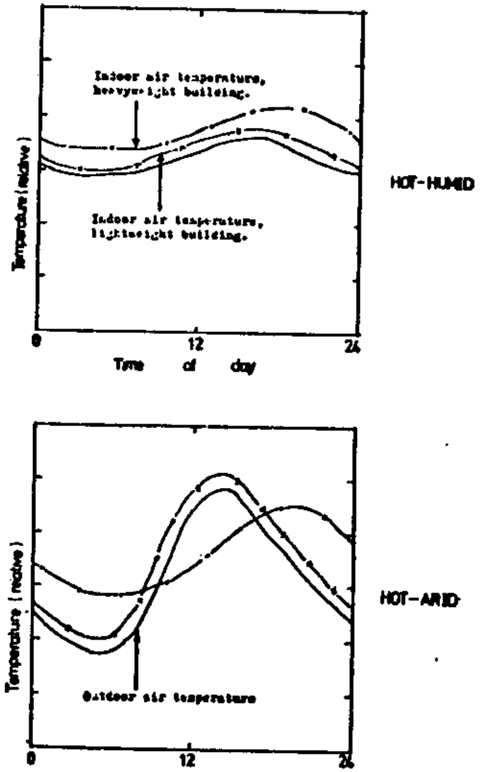


Internal and external influences on heat balance of building.

Generally speaking, almost all developing countries have tropical climates.(3) The design of tropical buildings differ in nature with those in temperate climates. In order to maintain suitable environmental comfort levels, a building envelope should act as a suitable modifier or filter of the external climate. Orientation, shape, form, materials, economic and social conditions are some of the important parameters (4) to be considered by anyone designing for the tropics. An understanding of the thermal performance of buildings in the tropics poses a difficult problem. This is due to the dearth of unco-ordinated research data and the complexity of the problem. Van Straaten (5) has shown that the main factors which determine the thermal response of a building under conditions of large diurnal variations are the thermal resistance and the heat storing potential of its various components. For heavy-weight and light-weight structures exposed to variations of external temperatures and solar radiation, the fundamental difference in their thermal response will depend on their heat storing capacity. For heavy-weight components, a good amount of heat can be absorbed without a significant rise to its temperature. However, light-weight materials will transmit heat almost directly to the interior of the building. The degree of heat gain or loss through light-weight components is therefore mainly dependant on their thermal resistances, but for heavy-weight components, it is dependant on both the influence of heat, storing capacity and thermal resistance. Fig. 5 shows a schematic representation of the differences in thermal response for both structures. From this it will be seen that for hot-humid climates, a light-weight construction has great advantages over heavy-weight one. The converse applies for hot-arid climates. However for hot-humid areas, a combination of light-weight and heavy-weight construction may prove satisfactory in certain cases. For instance, heavy-weight materials may be used in the east and west walls of a house when these walls cannot be shaded, while the shaded north and south walls could be of light-weight construction with sufficient openings for through ventilation. (6)

Fig. 5

Schematic representation of the variation of indoor air temperature for lightweight and heavyweight structures



It is practicable to attain a reasonable degree of control of internal room temperatures and air velocities by adjusting the details of design and materials to the prevailing climatic conditions. A summary of possible variations in indoor climate due to the influence of the external environment is given (7) in Fig. 6. The elimination of solar radiation from the interior of a building is the most important design factor. Various types of shading devices are now available for controlling heat transmission through window openings. To achieve a

Fig. 6
Range of variation in indoor climate

The climatic variable	Range of variation
Solar radiation absorbed in the walls	15 - 90% of incident radiation
Solar radiation penetrating through windows	10 - 90% of incident radiation
Indoor air temperature amplitude	10 - 150% of outdoor amplitude
Indoor maximum air temperature	-10 to + 10°C from outdoor maximum
Indoor minimum air temperature	0 to + 7°C from outdoor minimum
Indoor surface temperature	-8 to + 30°C from outdoor maximum
Average internal air speed, windows open	15 - 60% of outdoor wind speed
Actual air speeds at any point in room	10 - 120% of outdoor wind speed
Indoor vapour pressure	0 - 7 mmHg above outdoor level

satisfactory design of these devices, accurate solar angle prediction techniques should be used. The orientation and shaping of a building also provides a means of reducing solar heat gains.

In designing buildings for tropical climates it is essential to obtain adequate information on aspects of external climatic conditions which may affect the physical performance of the building and human comfort. Information such as sky conditions, the diurnal and annual temperature ranges, humidity, annual rainfall, radiation heat loss or gain, airflow characteristics, averages and extreme conditions and finally the microclimate of the location of the proposed building, will serve as essential design guide.

4.0 Solar Energy and Collectors.

Before considering the possible use of solar energy for buildings in developing countries, it is necessary to attempt a brief description of this natural energy source and its collection techniques. Although the sun is an enormous energy source, its energy density at the surface of the earth is relatively small. At the highest part of the atmosphere, the energy flux of the solar radiation is about 1.35 kW/m^2, with a spectral distribution resembling that of a black-body radiator at approximately 5800°K. Due to a variety of scattering and absorbing processes in the atmosphere, the maximum flux is reduced to about 1 kW/m^2 at the surface of the earth. A majority of the ultra violet radiation is taken away by absorption processes which is involved in the oxygen-ozone balance above 25 Km. There are also considerable fissures in the energy spectrum in the infra red radiation due to H_2O and CO_2 absorption. Although there is some scatter by atmospheric constituents and pollutants in clear conditions, the principal agencies for scattering are droplets of water in the clouds. Most of the scattered radiation reaches the ground, even in cloudy environments. Radiation is generally received at the surface of the earth in either direct or diffused form. Diffused radiation cannot be brought to a focus on a reflector.

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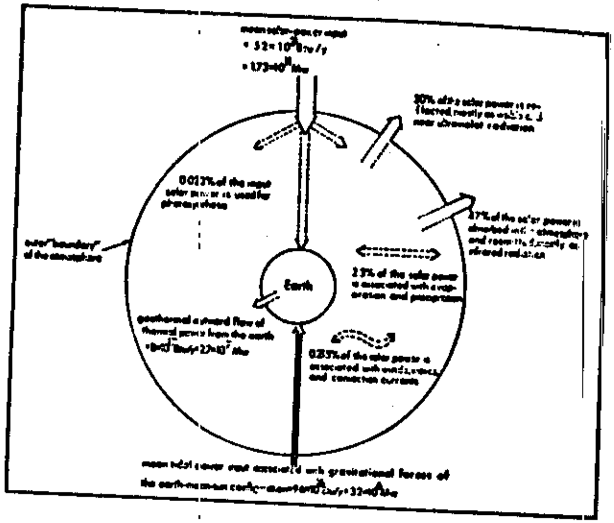
Fig. 7

Some aspects of energy flows (expressed as equivalent continuous power inputs) to and from the earth are shown. The solar power input is seen to be far greater than the tidal or geothermal power.



The wavelength of radiation determines its energy content, with shorter wavelengths representing higher grade energy. The intensity of solar radiation is less when the sun is at low altitude angle. Because of the inclination of the earth's axis to the plane of its orbit, the maximum altitude of the sun and the length of the day vary substantially with latitude and season. Fig. 7 shows the distribution (8) of the solar energy received by our planet, giving details of some energy flow to and from the earth.

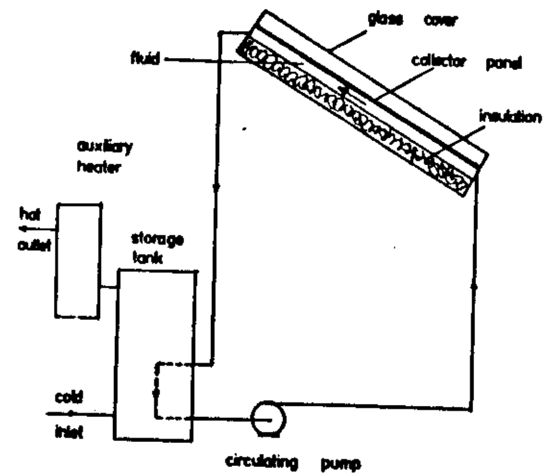
For building design, it is usually possible to obtain solar radiation data from meteorological stations. However in the absence of this data, it is possible to estimate (9) the daily total radiation if the duration of sunshine is recorded, viz:

$$Q = Q_{sc} \ (0.29 \times \cos \phi + 0.52 \ \frac{n}{N})$$

where Q = daily total radiation on horizontal plane (Wh/m^2 day)
Q_{sc} = solar constant per day.
ϕ = geographical latitude.
N = possible sunshine hours/day.
n = actual sunshine hours/day.
the value of Q_{sc} can be taken as 9830 Wh/m^2 day.

Devices for collecting solar energy usually consists of glass window and an absorbing surface with fluid underneath to transfer the collected heat. These surfaces could either be plane or concentric cyclinder. The choice of shape depends on whether direct solar radiation or radiation from a concentrating device such as a circular or parabolic cylinderical reflector, is to be collected. The flat-plate type shown in Fig. 8 is usually the simplest active collector. In this system, radiation goes through a transparent cover plate and is then absorbed by the collector panel. From this panel, heat is communicated to a fluid flowing in the

Fig. 8
Flat plate collector and water-heating system



enclosure in contact with the panel thereby energy is extracted from the system through the fluid for use elsewhere. Several factors will affect the efficiency of any device used. It is therefore essential to consider the efficiencies to be expected from solar collectors before chosing a system. Collector efficiency may be computed by the following formula:

$$E = 0.71 - 0.0054 \ \Delta T°C$$

where E is the daily collection efficiency and ΔT is the temperature rise above ambient.

5.0 Solar energy in buildings for developing countries.

The fundamental design requirements for buildings in the tropics which covers most of the developing countries have been described in section 3 of this paper. We shall now examine the feasibility of using solar energy for improving the living conditions of people in these countries.

The design of buildings for the tropics calls for adequate protection from solar radiation. So if we have to make use of this 'unwanted' natural energy it is essential that adequate precaution should be taken in order not to defeat our objectives. If we are to harness the sun's energy, effective insulation devices should be incorporated in the basic building design methodology. For example, if a system is to be adopted for room airconditioning, it will have a negative effectiveness if the system gives rise to increased heat gain into the building, with higher initial construction and running cost. Taking this case further, Fry and Drew (10) give examples of how reasonable comfort can be obtained in tropical buildings without having recourse to expensive air-conditioning plants. One of these examples illustrates the use of sunbreakers. With this in mind, it is essential to carry out a thorough cost effectiveness of any solar system to be adopted for tropical buildings. A suitable formula for computing this cost effectiveness is given in Appendix 1.

Assuming that cost effectiveness is satisfied, solar energy could be of practical value in tropical buildings for the following:

- Air conditioning and cooling.
- Water pumping.
- Water heating.
- Cooking.
- Water distillation.
- Electricity production.

The energy requirements for performing above tasks vary a great deal. As solar energy may be limited by the area of the building exposed to the sun and sky, the feasibility of attaining practical functional performance of any device should be considered carefully before adoption. For example, as the energy requirement for distillation is in the form of low grade heat, a system of this nature will be very suitable for application in developing countries in areas where fresh water supply is difficult to obtain. On the other hand, due to a high energy demand for air-conditioning, a room air-conditioned with solar energy needs a collector surface equal in area to the floor space of the room itself. Similarly, a lot of energy will be required to produce electricity.

For communal buildings in the rural areas of developing countries where power supply and other essential services are non-existent, solar energy could be adapted to meet with the villager's basic needs. A good example is the use of solar energy for water pumping in a remote desert school in Mauritania. (11) This project which was based on the work of Professor Masson of the University of Dakar consists of solar mechanical pumping installation using a cheap semi-concentrating aluminium roof trough system as collector. The system diagram of this installation is shown in Fig. 9. This system has a pumping height of 20m with a pumping rate of 8-10 m^3/h and operates 5-6 h/day.

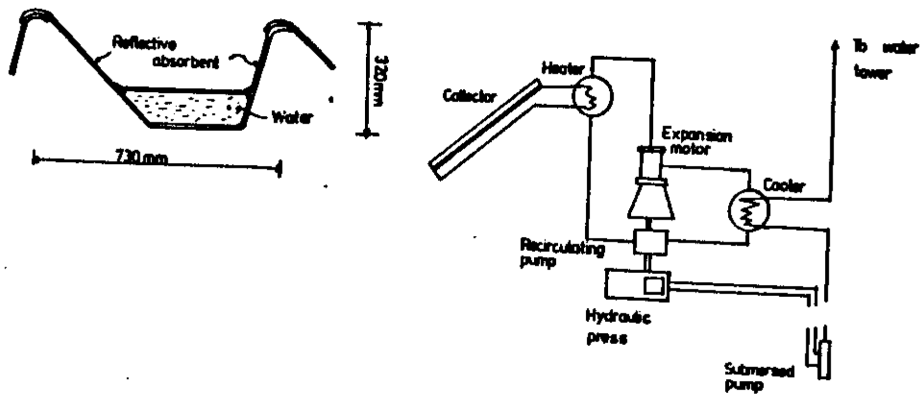


Fig. 9 Collector shape and system diagram for a solar-mechanical-pumping installation in Mauritania.

6.0 Solar energy research and building design.

Generally speaking, the fundamental design principles for buildings in the developing countries are well known by now. The thermal performance of buildings of given design and construction can be predicted with some accuracy by using either mathematical or physical models. Difficulties may however arise in the design and prediction of thermal performance of solar energy buildings in the tropics. This is mainly due to the fact that we now need to attract more solar radiation on buildings of this nature instead of aiming at offering protection against the sun. Further research is therefore needed in the following areas:

- Improving design methods and standards of non-solar energy buildings.
- Improving component insulation in areas of the building where collector surfaces are mounted.
- Cost effectiveness of solar systems.
- System efficiencies.
- Suitable solar energy systems for the developing countries.

7.0 Co-operation between the developed and the developing countries.

There is a need to increase the energy demand in the developing countries if the people in these countries are to achieve improved living conditions. The greater energy use by the developi ng world have a long term implication; such as increased drain on energy resources. In order to maintain the world's energy resources it has been suggested (12) that the developed countries should reduce their energy consumption per capita. These could be achieved in the following ways:

(1) Improvements in energy use efficiency.

(2) Energy conservation.

(3) Systematic replanning of our life style.

We also need to develop renewable energy sources, such as solar, wave and geothermal to augument the worlds energy needs.

So, apart from encouraging the developed world, such as the United States, to reduce their capita energy consumption, the developed world could assist and co-operate with the developing countries in research and development work in the energy field. The United Nations, UNESCO and other international bodies could establish joint research projects between institutions and research centres in both developed and developing countries. More research work should be carried out in the developing countries. Although it may be possible to monitor the conditions in the developing countries from the developed countries, differing cultural, social, climatic and economic conditions may constitute fundamental problems.

Appendix 1: Formulas for Computing Cost Effectiveness

The formula for computing cost effectiveness of a solar system for buildings is given below.

If an item is purchased and

> the initial capital cost per unit area is, c
> the expected lifetime is L (years),
> the interest rate is r (expressed as a fraction),

the payment per year for equal yearly payments over the lifetime L will be

$$P = \frac{(r+1)^L rc}{[(r+1)^L - 1]}$$

If f_o represents the initial fuel savings/unit area, and the expected average fuel inflation rate is α, then the average fuel savings/year-area, $\bar{f}$, over the lifetime L will be

$$\bar{f} = \frac{(1+\alpha)^L - 1}{L\alpha} f_o$$

For the capital improvement to be cost effective the average savings per year must exceed the average payment,

$$\bar{f} > P,$$

or

$$\frac{(1+\ )^L - 1}{L} f_o > \frac{(r+1)^L rc}{[(r+1)^L - 1]}$$

Alternatively, this can be reexpressed such that the ratio of the initial fuel savings/unit area, f_o, to the initial capital costs/unit area must be greater than

$$\frac{f_o}{c} > \frac{(r+1)^L \alpha r L}{[(1+\alpha)^L - 1]\,[(1+r)^L - 1]}$$

As an example, take $L = 20$ years, $r = 10\%$, $\alpha = 6\%$; then the ratio of the initial expected fuel savings to the initial capital costs must be greater than 0.064 to be cost effective.

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INTERNATIONAL CONFERENCE ON PASSIVE AND LOW ENERGY ARCHITECTURE

Regional Monograph for: NIGERIA

Prepared by: Professor Nelson I. Ngoka

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1. (a)

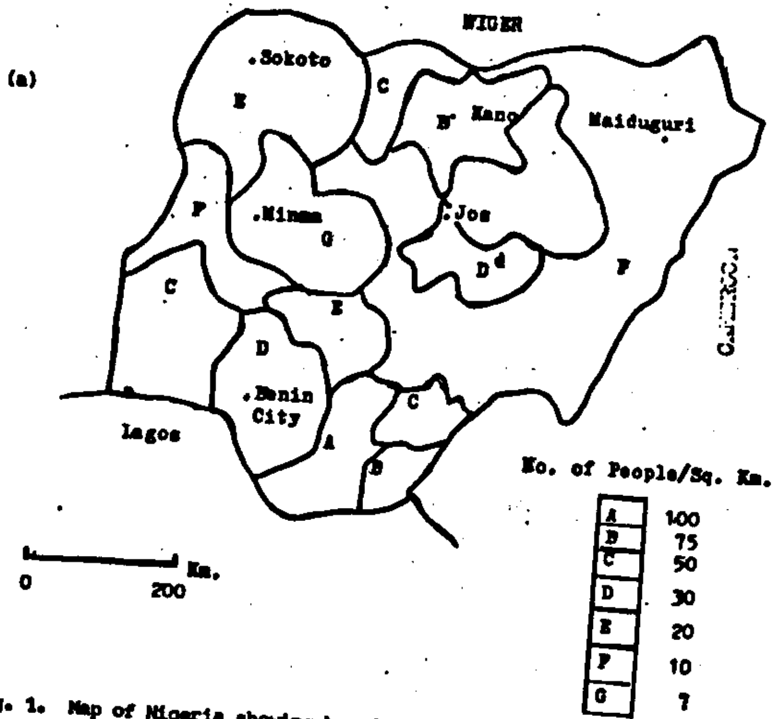

Fig. 1. Map of Nigeria showing boundaries and population destribution by density.

(b) Population projection for the year 2000.

	0-14 Years	15 - 44 Years	45 Years and above	Total
1963+	23,926	26,959	4,785	55,670
1970	28,510	32,120	5,701	66,331
1971	29,220	32,940	5,843	68,003
1972	29,970	33,770	5,992	69,732
1973	30,720	34,620	6,144	71,484
1974	31,510	35,500	6,298	73,308
1975	32,290	36,390	6,459	75,139
1976	33,120	37,410	6,622	77,152
1977	33,960	38,260	6,790	79,010
1978	34,810	39,220	6,961	80,991
1979	35,710	40,230	7,124	83,070
2000*	-	-	-	139,523

Table 1. Estimated Population of Nigeria by age group

Source: National Population Bureau.

Note: + 1963 Estimates are derived from the census taken at that date. Subsequent years figures are projections by the National Population Bureau.

* Projection from 1979 figures by author using 2.5% annual growth rate. Figures for age groups are omited

c. What is the projected regional population? This is 139,523,000 for the year 2,000.

2. (a) What quantity of climate data is available: There is a good amount of climatic data covering almost all geographical regions of the country.

(b) What is the quality and form of this data: Most upto date data are usually in crude form and generally reliable for building climatology work.

(c) Sources of climatic data: The Nigeria Meteorological Service, airports, Universities, and research institutions provide climate data for various parts of the country.

(d) Climatic data monitoring programs for Nigeria: Although climatic data are collected in various locations in Nigeria, most of these are for specific use and often cover only the microclimatic zone of the collector. The Nigerian Meteorological Service is however the only establishment which monitors climatic condition in most parts of the Federation. They provide information on rainfall, humidity, sunshine hours, various temperatures, and wind conditions. The instruments used at each synoptic stations are:

(i) Five-inch (127mm) diameter snowdon rainguage with apertures 18 inches (457mm) above the ground.

(ii) Hydrometers or Dry Bulb and Wet Bulb thermometers, and Maximum/Minimum thermometers, screened in a large Stevenson Screen painted white.

(iii) Cup Anemometers at a height of 7 feet (2.1 meters)

(iv) Campell - Stokes sunshine recorders.

Although data from all the Nigerian Meteorological Service stations are standardised, the case is not the same with the data collected from other establishments. There are often wide variations in the types of equipments used and modes of calibration and referencing.

(e) Near Term plans for data gathering to augument existing data: The Nigerian Building and Road Research Institute Lagos, has recently embarked on national data collection of solar insolation. More sophisticated equipments are being used for this project which aims at producing solar insolation maps of Nigeria. The author has also established a weather station at the Department of Building, University of Ife for monitoring solar radiation, wind speed and direction, temperature, and relative humidity.

(f) Description of Geographical region:
Nigeria with an area of about 923,769sq km is approximately four times the size of the United Kingdom or three times that of Ghana and Sierra Leone put together. Although only about 15% of the settled and productive area of West Africa is occupied by Nigeria, her population is well over half for the entire West African region. The longest distance from East to West is about 1,126 kilometers, and from North to South, about 1,046 kilometers. It is bounded on the South by the Gulf of Guinea, on the East by Cameroons Republic, on the North by Niger and Chad Republics, and on the West by the Republics of Dahomey and Niger.

There are varied physical conditions in the country. This is mainly due to the fact that the latitudinal length extends from about 4° to 14°N. Relief is like-wise varied with higher land than other West African countries. The South-Eastern boundary extends along the borders of the Cameroon and Bamenda Highlands, most of which average 1200-1500 metres. Majority of the land area of Jos Plateau lies at 1200-1800 metres.

(g) Climatic Information

Several climatic classifications of Nigeria have been provided by several authors 2,3,4,5.
Figure 2 shows the climatic map of Nigeria based on Papadakis(3) system. This information is considered adequate for passive building designs in Nigeria.

(h) Extent of Accomplishment of bioclimatic comfort analysis.

Some early work have been done by some investigators on West African region. The work of Peel(6), Ojikutu(7), and Ladell(8) are based on effective temperature index (ET).

More recent work on thermal comfort studies has been completed at the University of Ife(9). The results showed that thermal comfort was achieved at a globe temperature of 27.5°C when people were wearing light tropical clothing and doing sedentary work. Air movement was also found to be significant for the attainment of thermal comfort in the hot humid regions of Nigeria.

(i) Is this available to the public and professions

The work of the previous investigators are available in research libraries.
Results of the author's work(9) on thermal comfort will be made available to the public and the profession. It will be used extensively by the National Committee on "Thermal and Comfort standards in Nigeria Buildings" which has been set up by the Nigerian Standards Organisation under the Chairmanship of the author.

(j) Examples: The application of the E.T index to seven towns in Nigeria is given(8) in Table 2, Figs. 3 and 4 give some of the results of the thermal comfort studies carried out by the author(9).

Table 2 THE APPLICATION OF THE ET INDEX TO SEVEN STATIONS IN NIGERIA

Location	Month	Effective Temperature
Lagos	Jan.	Warm, approaching too warm
	March	Too warm at midday
	May	Warm
	July	Approaching warm
	Sept.	Warm at midday
	Nov.	Warm, approaching too warm
Kano	Jan.	Comfortable
	March	Warm, sometimes too warm at midday
	May	Too warm for most of day
	July	Warm for most of day, too warm at
	Sept.	midday
	Nov.	Comfortable
Enugu	Jan.	Comfortable
	March	Warm, approaching too warm at
	May	midday
	July	Warm at midday
	Nov.	Comfortable
Zaria	Jan.	Comfortable
	March	Comfortable
	May	Warm just at midday
	July	Approaching warm at midday
	Sept.	Comfortable
	Nov.	Comfortable
Jos	Jan.	Comfortable
	March	Comfortable
	May	Approaching warm at midday
	July	Comfortable
	Sept.	Comfortable
	Nov.	Comfortable

Table 2 (contd.)

Location	Month	Effective Temperature
Port Harcourt (bush)	Jan.	Warm.
	March	Comfortable
	May	Comfortable
	July	Just warm at midday
	Sept.	Approaching warm at midday
	Nov.	Warm
Port Harcourt (town)	Jan.	Warm
	March	Warm most of day too warm at midday
	May	Warm
	July	Just approaching warm at midday
	Sept.	Just warm at midday
	Nov.	Warm

(k) Climatic types and variables as applicable to building design and community and urban planning.

Microclimates of areas where buildings are to be constructed are useful guides for effective passive designs. Figures 5 and 6 give some useful information on monthly sunshine distribution; and graphs of sunshine hours, rainfall, vapour pressure, and temperature for selected locations in Nigeria.

3. (a) Most important heating, cooling and related ecotechniques needed for:

(i) Urban and rural housing applications: Essential cooling is needed in most parts of the country throughout the year except during the cold months in the Jos Plateau area. Although it has been suggested that some heating may be required during the cold months of the plateau region, this practice is limited to very few upper middle class families. What are essentially required in most dwellings include adequate ventilation, control of heat gain/loss into the buildings, control of relative humidity, adequate daylighting, and overall thermal comfort. Other applications are cooking, and water heating where solar techniques could be easily applied.

(ii) Commercial applications: As most commercial buildings are located in the congested areas of the city, it is often difficult to apply natural heating or cooling ecotechniques. However, where this is possible the requirements listed in (i) above will prevail too.

(iii) Commercial applications: As in (ii) above

(iv) Agricultural applications: Ecotechniques are needed for crop drying, seasoning of timber, water pumping, irrigation, and ventilation of animal buildings.

(v) Educational facilities and school buildings applications: In most educational buildings, the needs are for thermal comfort, and the use of solar electricity for running television sets in rural schools for educational programmes.

(vi) Transportation applications: Solar powered vehicles could be introduced in some parts of the country.

(b) Estimate of the amount of various forms of energy now being expended (both traditional and non-traditional).

We have not been able to carry out a detailed study of energy consumption in the country. As a result of this, information provided below are not as comprehensive as expected.
The index of primary commercial energy consumed increased from 1972 reference level of 100 to 449.2 in 1981. This is shown in Table 3 and Figure 7. It will be seen from Table 3 that at 17,990,068 tonnes of coal equivalent (tce), aggregate primary commercial energy increased by 13.4% between 1980 and 1981. Coal, hydro-power, gas and petroleum products contributed about 0.7, 6.4, 16.8 and 76.4 percent respectively in 1981 towards Nigeria's energy consumption. The trend in this consumption from 1974 to 1981 is shown in Figure 8. Electricity consumption have also increased rapidly (Table 4) over the years due to extensive use of airconditioners and other energy consumption devises (10).

TABLE 3

ENERGY CONSUMPTION

(Tonnes of coal equi)

Type	1979 (1)	Percentage share	1980 (2)	Percentage share	1981 (3)	Percentage share
Coal	148,703	1.1	124,629	0.8	127,937	0.7
Power (Hydro)	1,568,132	11.4	1,376,776	8.7	1,155,555	6.4
Gas	1,848,754	13.4	2,206,863	13.9	2,964,868	16.5
Petroleum .. products....	10,195,704	74.1	12,157,744	76.6	13,741,708	76.4
Total	13,761,293	100.7	15,866,042	100.0	17,990,068	100.0
Index of energy consumption (1972-100)	337.2		399.7		419.0	

Sources: Federal Ministry of Mines and power, Nigerian National Petroleum Corporation and National Electric Power Authority.

TABLE 4

ELECTRICITY CONSUMPTION (000KWH)

	1979 (1)	1980 (2)	1981 (3)	Percentage change b/w	
				(1) and (2)	(2) and (3)
Industrial	1,404,205	1,748,986	2,023,716	+24.6	+15.7
Commercial and street light ..	682,508	824,487	866,350	+20.8	+ 5.1
Residential	1,943,578	2,129,812	2,787,144	+ 9.6	+30.9
TOTAL	4,030,291	4,703,285	5,677,210	+16.7	+20.7

Source: National Electric Power Authority.

(c) Areas where passive systems and ecotechniques would have greatest impact on energy saving.

Figure 9 shows that there were gains in electrical energy consumption in the residential sector against losses in both industrial and commercial sector. This is mainly due to the changing pattern of lifestyle of Nigerians. Higher comfort standards are being adopted in most households. These are mainly due to increased use of hot water for bathing and washing, extensive cooling by airconditioning, use of freezers for food storage, and energy consumption by entertainment equipments such as video, television, and radio sets.

Passive systems and ecotechniques would therefore have greatest impact on energy conservation in residential buildings.

4. Building materials availability and use in Nigeria

Although local building materials such as mud, timber, raffia, and clay are readily available in the country, their use are mainly restricted to rural housing. In the rural areas mudwall construction is common. Although thatch roof is still widely used, most rural dwellers now prefer to use corrugated iron sheets due to their durability and ease of maintenance. Figure 10 illustrates the use of thatch roof and corrugated iron sheet in the hot-humid area of Nigeria.

Buildings in urban areas use imported building materials extensively. Although most of these materials are now being manufactured in the country, their high demands necessitates importation. For example, industrial and large commercial buildings use imported materials extensively for their construction.

5. Appropriate Construction methods employed in Nigeria

Application of appropriate construction methods are dictated by the geographical location of the building. As there are varied climatic conditions in Nigeria, the choice of construction methods are also varied.

Figure 11 shows the construction method adopted in the swampy warm-humid area of Nigeria. High ventilation rates which are needed in this region are achieved by the use of suspended thatch construction which permit free air movement around and inside the building.

Figure 12 shows a typical mudwall construction in the warm-humid area of the country. In this construction, ventilation is mainly through the windows and the mudwall provides thermal controls.

In the middle-belt region, a combination of thickwall and thatch roof construction are used. Window openings are generally small as high ventilation rates are not required. A typical building in this location is given in Fig. 13.

Further north, where semi-arid type of climate exist, appropriate buildings are constructed of mud. This is used for both wall and roof. Flat roof construction is generally used (Fig. 14).

6. Successful tradition and vernacular solutions for human comfort

The zone of optimum thermal comfort is the humidity, temperature and air movement range in which the majority of people feel neither too cold or too warm in a given environment. Traditional and vernacular buildings in Nigeria have shown that they are capable of meeting with above conditions. Buildings illustrated in Figs 11 to 14 are capable of providing required thermal comfort for their occupants.

7. Considering all the above questions as guidelines

(a) Suggest types of passive and low energy systems and ecotechniques which could be advantageously implemented, but which are not now used or adequately developed:

Cooling is required in most parts of Nigeria throughout the year. Due to variation in the climatic conditions, from coastal humid to inland arid areas, different passive and low energy systems and ecotechniques are required to suit each particular location. The following systems are suggested:

(i) Evaporative cooling
(ii) Open cycle cooling system
(iii) Storage type cooling system
(iv) Solar induced ventilation
(v) Radiant cooling
(vi) Geotecture. (earth integrated buildings)

(b) On the basis of climatological, thermal, luminous, aquous, vermin, structural, economic or aesthetic criteria, how would you evaluate new components and systems introduced in your region?

An overall cost benefit analysis will be carried out on the new components and systems.

(c) Which components and systems do you recommend?

For the hot-humid areas of Nigeria, the following components and systems are recommended:

i. Good thermal insulation of walls and roofs.
ii. Adequate ventilation of the rooms
iii. Solar water heaters
iv. Solar airconditioning.

The hot-arid zone of Nigeria should benefit from:

(i) Mass wall construction
(ii) Adequate thermal insulation of the building
(iii) Evaporative cooling
(iv) Solar water heating

(d) Which components and systems do you not recommend?

Any system that would not be suitable for the social, economic and climatic conditions of Nigeria.

(e) Which components and systems would improve with adaptation.

Most of the systems listed in (c) above will improve with adaptation.

(f) On the basis of anticipated user acceptance, based on regional custom, which of the above components and systems are likely to be accepted by the public or commercial enterprises?

Solar induced cooling system, solar water heaters, evaporative coolers, and solar airconditioning.

8. Identify specific material, component or analytical improvement that will remove barriers or increase acceptance of new types of passive systems and ecotechniques.

(a) Meteorological data

More detailed meteorological data to cover a wider area of the country is needed. This should be made readily available in a suitable format to people involved in the design of passive systems and ecotechniques.

(b) Solar data

Reliable hourly solar radiation (this should cover both direct and diffused components) data for various parts of the country. There is also the need for solar maps drawn from actual field data instead of by mere approximations from data collected elsewhere.

(c) Bioclimatic data analysis and tools

There are reasonable amount of data for bioclimatic analysis but very little is known about the combined effect of all the climatic

variables, such as mean radiant temperature, air temperature, relative humidity, and air velocity.

(d) Energy responsive building design techniques.

There is a need for designers to acquire better knowledge of overall performance of solar control devises, means of provision of adequate ventilation, and relative humidity. Although various techniques are available, their successful application have so far been restricted to traditional buildings. Modern designers should integrate passive designs for new buildings and retrofits.

(e) Energy responsive community technique.

This is a very important area. The author has carried out some feasibility studies on ways and means of establishing an energy responsive planning for Abuja, the new Federal capital city of Nigeria.

A number of energy-related innovations can be introduced. For example, urban refuse can be used to produce usable energy; energy conservation techniques applied to buildings will reduce peak load demands on power plants; small scale industries and businesses could be established to provide the products and services for energy efficient construction.

(f) Techniques for development of indigenous raw materials for insulation

Straw is usually mixed with mud during the construction of the building. The ratio of straw/mud depends on the degree of insulation required. Fig. 15 shows the straw which was used in making-up the mudwall construction in Fig. 16.

(g) Adequate computer modelling of proposed components and systems, predictions and performance evaluation.

Computer models of the proposed components and systems are not yet available in Nigeria. Work is however in progress under the supervision of the author to produce suitable computer models for the analysis and design of various passive systems.

(h) Other ecotechniques

Solar access is essential for systems to be used in the urban area where buildings are often very close to each other. Solar access law is therefore an important factor to be taken into consideration.

9. Identify below any hand-held methods and computer systems developed or available in your region for predicting, modelling and performance evaluation of:

(a) Passive Heating Systems: None in Nigeria at present.

(b) Passive cooling system

The author has in co-operation with Cassella, London developed a hand-held Wet Bulb Globe Temperature (WBGT) heat stress monitor. This equipment assists in the assessment of performance of passive cooling.

(c) Passive dehumidification systems

None available.

(d) Active heating systems

None available

(e) Active cooling system

Some large firms may have either hand-held or computer system for the prediction modelling and performance evaluation of their airconditioning and mechanical fan cooling systems.

(f) Active dehumidification System

None to my knowledge

(g) Other ecotechniques.

None.

10. (a) What, if any, encouragement is given by central or local government in passive systems and ecotechniques research and development? In which form is this assistance rendered?

There has not been any governmental support.

(b) As above, but assistance from public or private corporations

None so far.

(c) To what extent is progress in passive systems and ecotechniques the result of individual interest and endeavor?

In Nigeria, progress in passive systems and ecotechniques has been due to the individual effort of the author. This has been through several publications, television appearances, exhibitions, and public lectures. The Solar Energy Society of Nigeria which the author co-founded in 1980 has recognised passive solar as an important aspect in the country's solar application.

11. Identify and describe the purpose of work of building and experimental stations in your regions, whether private government or agency sponsored.

Nigeria has only one establishment which carries out research on building. Although this Institute (The Nigeria Building and Road Research Institute) was set up in 1977 by the Federal Government, they have not been able to produce any meaningful results. This is attributed to lack of staff and adequate equipments.

12. Describe and illustrate to the extent possible, significant experiences in buildings, communities, and urban areas with application of passive and low energy ecotechniques.

Passive cooling systems include naturally ventilated traditional buildings in the humid south, and thick wall and roof pond systems in in the arid north.

The author has however developed a solar induced ventilation system for use in southern Nigeria. This building which is known as the Ngoka Solar House is capable of providing passive cooling throughout the day.

Effort is underway to get the Federal Government to incorporate this system in their national housing development schemes.

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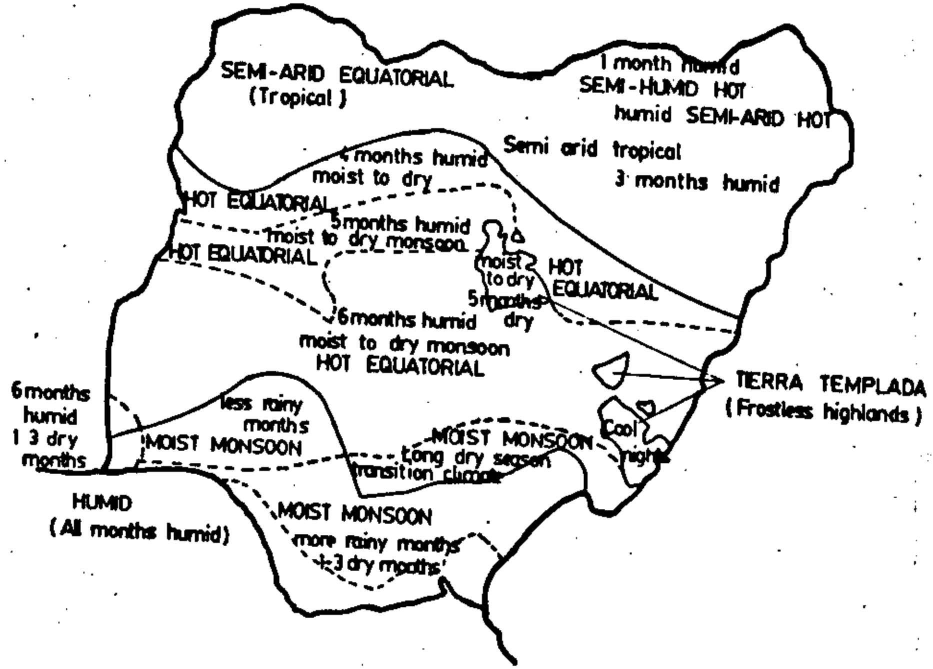

Fig 2 The climates of Nigeria (after Papadakis 1951)

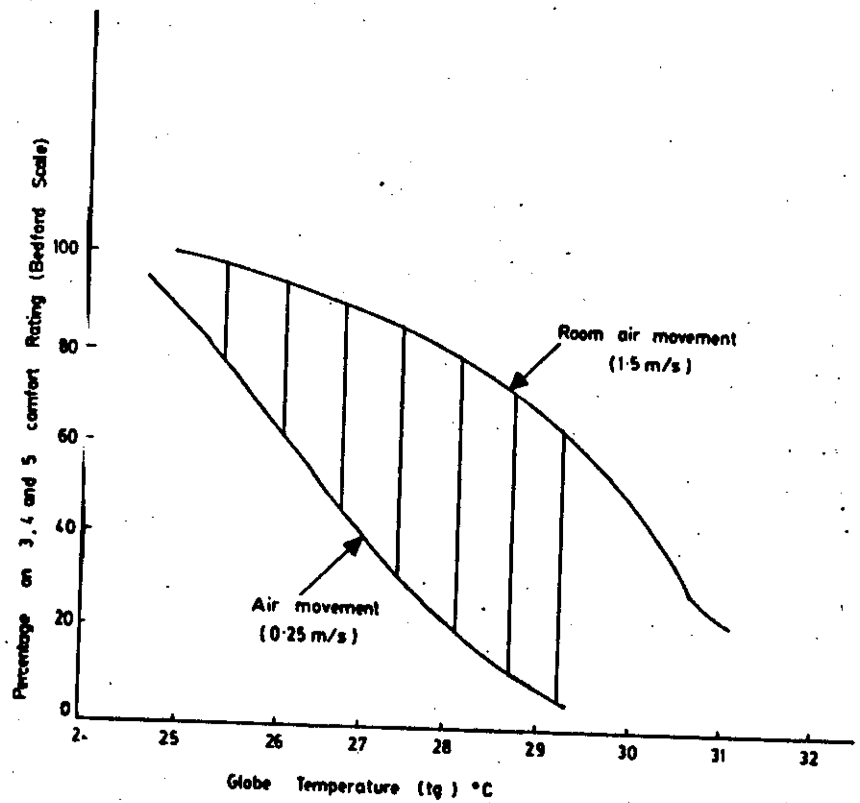

Fig 3 The influence of air movement on comfort level for semi nude students

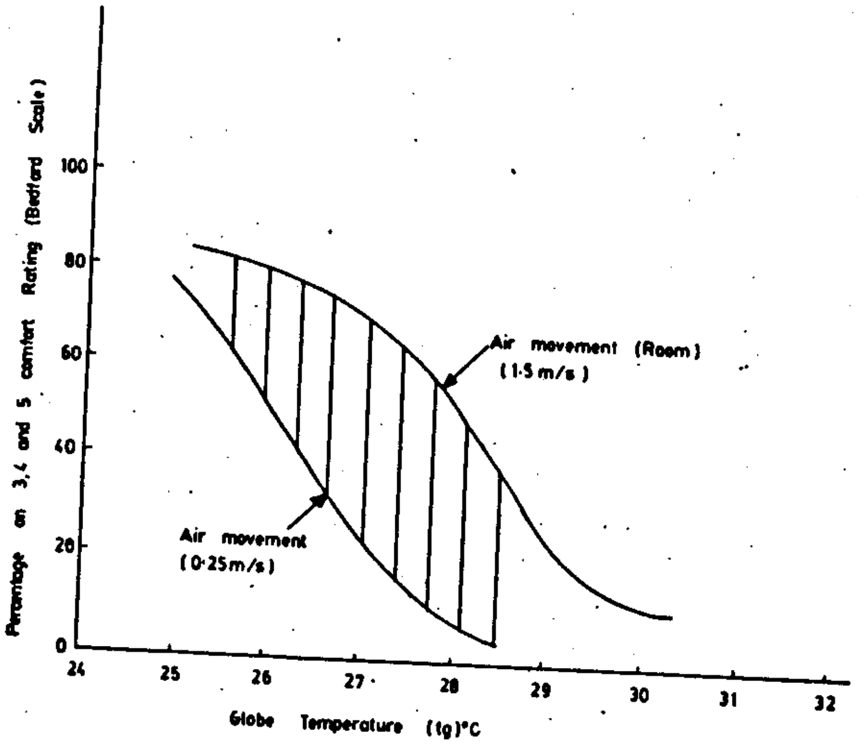

Fig 4 The influence of air movement on comfort level for students in tropical clothing

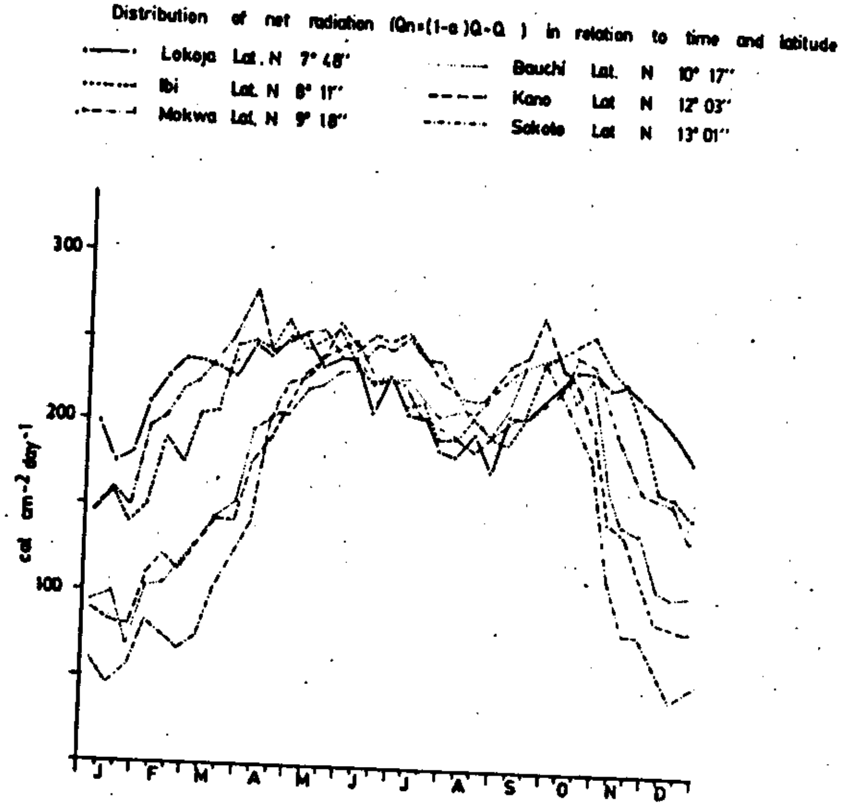

Fig 5 Distribution of net radiation for some Nigerian towns

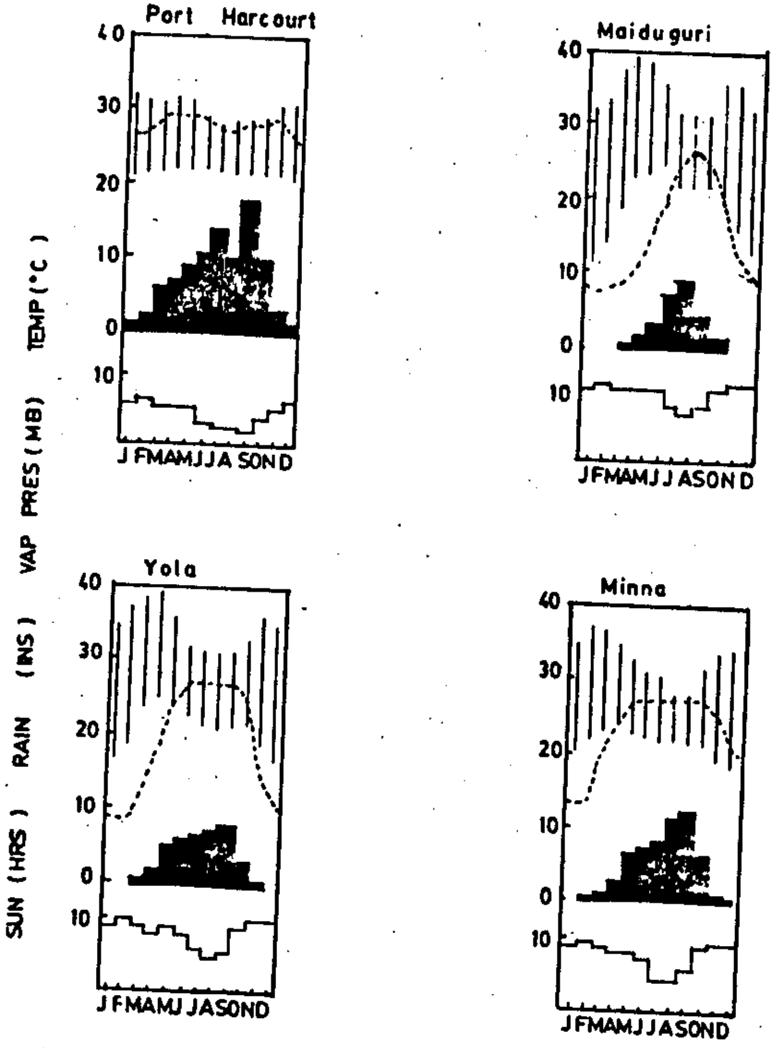

Fig 6 Graphs of climate of Nigeria

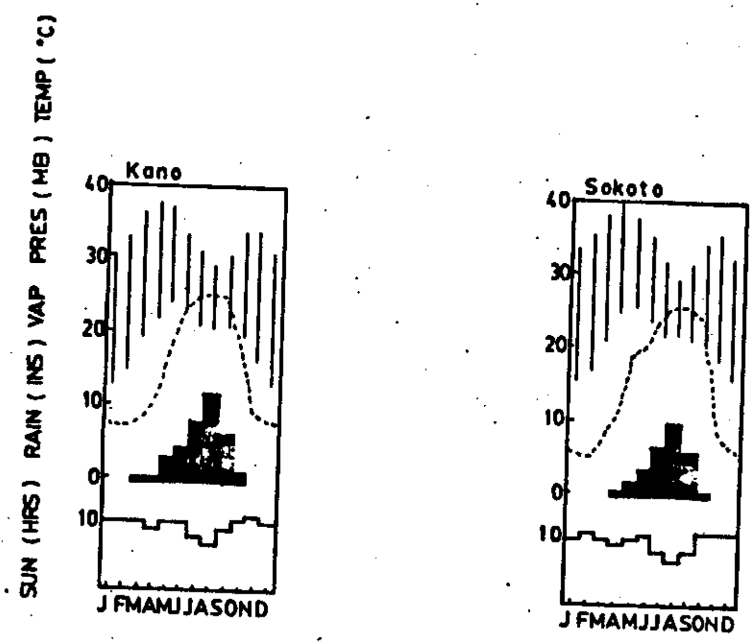

Fig 6 Graphs of climate of Nigeria

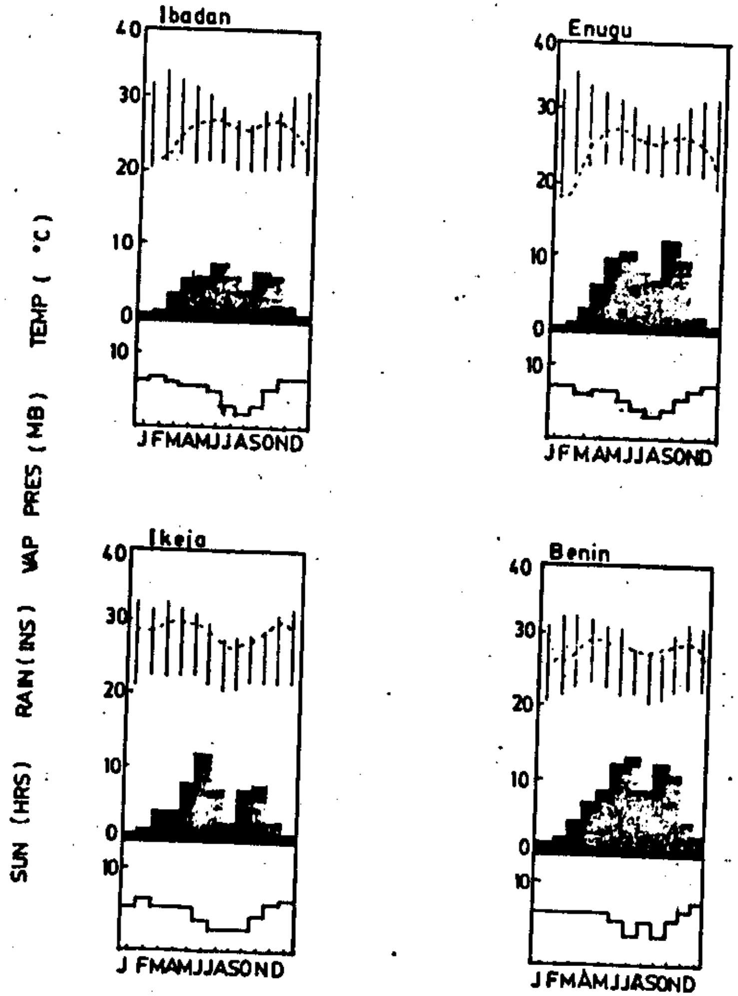

Fig 6 Graphs of climate of Nigeria

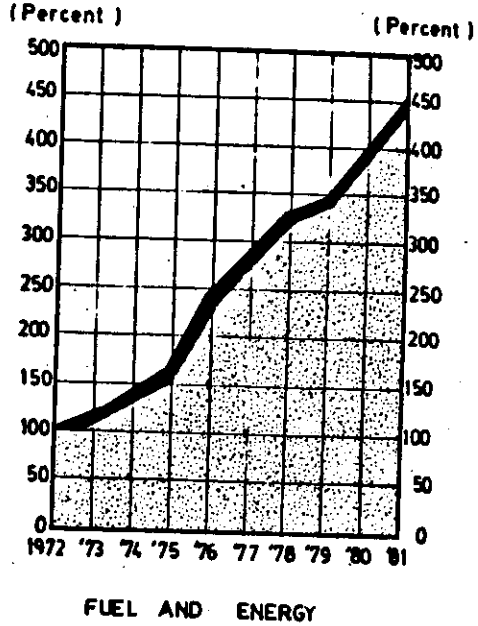

Fig 7 Index of Primary Commercial Energy Consumed 1972 – 1981

Fi

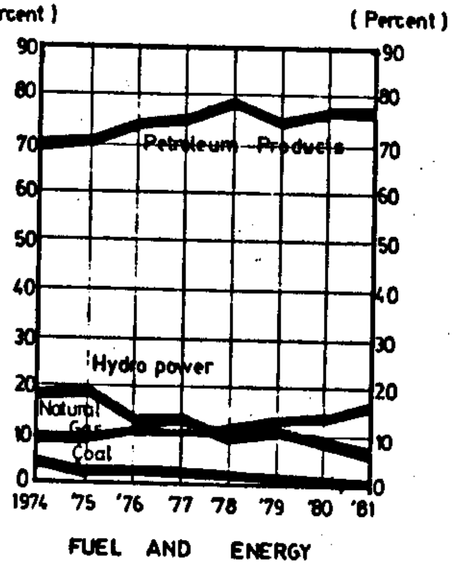

Fig 8 Percentage Share of Energy Consumption

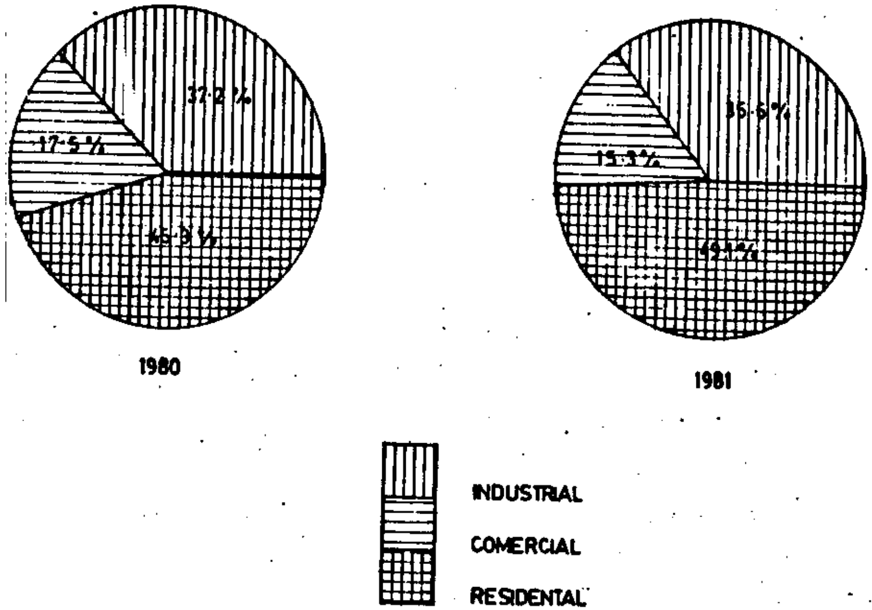

Fig 9 Electricity Consumption in Nigeria

FIG. 10. USE OF THATCH ROOF AND CORRUGATED IRON SHEET IN HOT-HUMID AREAS.

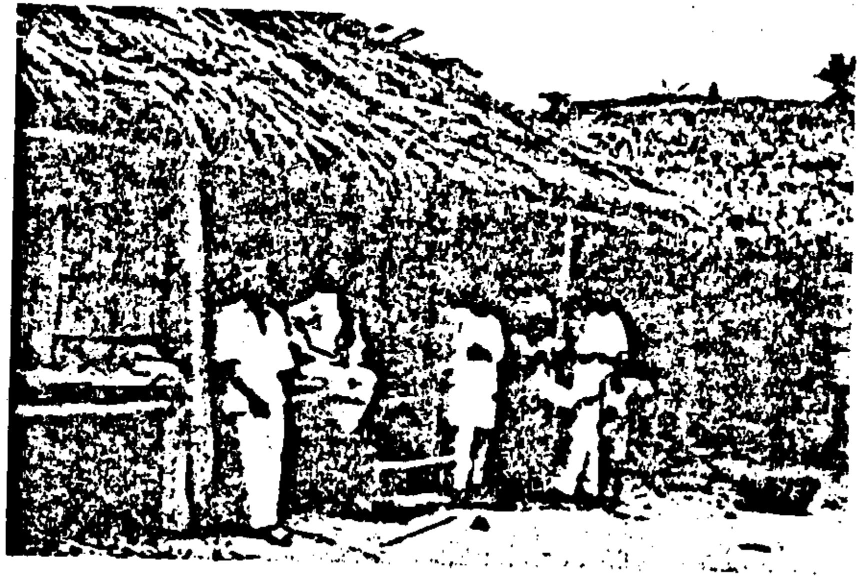

FIG. 11. CONSTRUCTION METHOD IN SWAMPY WARM-HUMID AREAS OF NIGERIA

FIG. 12. MUDWALL WITH CEMENT PLASTER AND CORRUGATED IRON SHEET ROOFING.

FIG. 13. A TYPICAL HUT IN THE MIDDLEBELT REGION

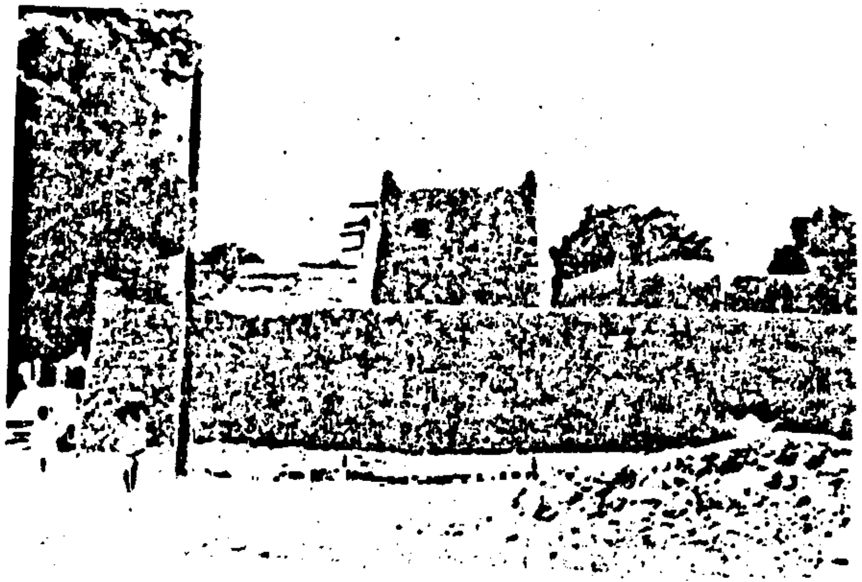

FIG. 14. USE OF MUD FOR ROOF AND WALL CONSTRUCTION IN THE SEMI-ARID ZONE.

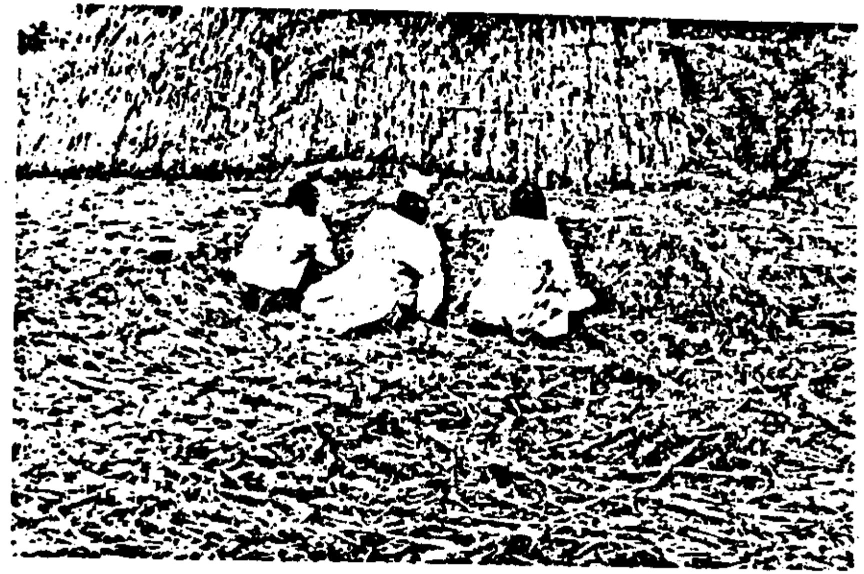

FIG. 15. STRAW USED FOR COMPOSITE MUDWALL CONSTRUCTION

FIG. 16. DETAILS OF COMPOSITE WALL CONSTRUCTION.