Comfort and Passive Cooling

N. Baker
The Martin Centre - Department of Architecture - University of Cambridge UK

ABSTRACT. This paper is concerned with aspects of thermal comfort which are particularly relevant to passive cooling. A fundamental difference between cooling in a warm climate and heating in a cool climate is recognised due to the relationship between the physiological neutral temperature and ambient heat sinks. The need for a comfort performance assessment of a building design is established. The notion of *person cooling* as distinct from *space cooling* justifies the need for a behavioural comfort model as distinct from a fixed state model. Brief results from simulation and field studies are offered to support this view. This topic is identified as one needing further research. Other potential research topics include, psychological effects, airflow design for comfort, outdoor comfort, associated non-thermal comfort - glare and noise control.

1.0 INTRODUCTION

Much work has been done in the field of thermal comfort. However a review of the literature reveals that in most of the work relating to buildings there is a pre-occupation with thermal comfort in predominantly underheated climates. Where overheating is studied it tends to bein situations, well above the limits of the normal comfort zone, where there are physiological effects of serious heat stress. In this paper we are concerned with thermal comfort within the upper limits of the comfort zone.

Man in the natural unmodified environment would not survive for long. In a biological sense, the most important function of a building is to modify the environment in order to provide comfort. In this paper, we are concerned with the degree to which the building itself can accomplish that aim, or if energy consuming mechanical interventions are necessary, how the energy consumption can be minimised, fig 1.

Man's pursuit of comfort is, of course, essential to survival of the species- it is not just whimpishness! It is a basic drive comparable with hunger and sex. So successful is man in response to this drive, that he has occupied a wider range of climatic zones than any other species on earth - and all without the aid of modern technology. Only the ultimate harshness of Antarctica required 20th century technology to enable man to survive.

It is interesting to look at primitive shelters and to see what passive measures these illustrate. In fig 2 we see two simple shelters which are of geometrically similar form. One is to protect the nomadic herdsman of the Kalahari desert from the intense solar radiation, whilst the other protects the Indian of Tierra del Fuego, South America, from the deadly sub-zero winds. In both cases the shelter cannot be described as an envelope, it could not maintain an air temperature difference or protect from precipitation. But in each case the structure modifies a single climatic parameter, choosing the one which is most uncomfortable, and ultimately life-threatening.

As shelters become less primitive, so we see the range of environment functions increasing, and of course as pointed out by Rappaport (1) the influence of cultural and social factors, fig 3. But it can be argued that it was the growing sophistication of his shelter that moved man away from the edge of survival and released his energies for social and cultural development.

Today, buildings still carry out that primary function of providing comfort. In doing so they consume nearly half of the total energy used, and with the current awareness of the global environmental effects of this, clearly the provision of comfort is imposing a heavy cost. It is this balance between comfort and energy cost to which we are addressing ourselves today.

1.2 Heating and Cooling

It is a simple fact that a very small proportion of buildings in the world are actually cooled (in a thermo-dynamic sense), whereas a very large proportion of buildings are heated. Indeed, the non-passive provision of heat for comfort by combustion is almost as universal as shelter itself at primitive and traditional levels, fig 4, in all but the hottest climates. In contrast there are few traditional ways of providing cooling, (as distinct from the prevention of overheating).

Is there a fundamental difference then, in the case for heating and the case for cooling?

The mean monthly temperature in Athens, for July, is about 28° C. By accepted comfort theory, for a person at rest dressed in 0.3 Clo, the neutral temperature is also 28°C. We realise that discomfort will exist for a number of reasons - the actual temperature will vary about the daily and monthly mean, and in a building, the temperature may be elevated above prevailing ambient conditions due to gains from solar or other sources. However in almost all cases there will be ambient heat sinks available, and thus the discomfort problem reduces to one of the heat being in the wrong place at the wrong time, over a relatively short time scale.

This contrasts with the case for heating. The mean January temperature in Hamburg is 0°C. Even with a clothing level of 1.5 Clo a person at rest has a neutral temperature of about 19°C. Of ambient heat sources available, even the longest term, i.e. the ground, will be at about 9°C. No other passive thermal source is universaly available with the exception of solar energy, unless we turn to fossil sources.

Thus there does seem to be a basic difference, and this relates to the human temperatures for survival in relation to climatic temperatures - i.e. in most cases prevailing temperatures, at least on a daily average basis, are far further below our neutral temperatures than above. This seems like good news for passive solutions to cooling.

Another difference relates to magnitude of the comfort zone. Fig 5 shows the results of s study carried out by Humphreys (2). It shows clearly that for a given activity, the tolerance band is greater for people at a higher temperature and lower Clo value than vice versa.

However on the negative side, most human activities in buildings, including humans themselves, are heat producing. In an underheating situation these gains are assisting in providing comfort, whereas in an overheated situation they are adding to the problem. Casual "coolth" gains are extremely rare. Furthermore, the high grade energy of solar radiation can be controlled to give substantial useful gains in the heating situation, whereas in cooling it is more often a cause of the problem than a contribution to a solution.

1.3 The **prevention of overheating** and the **provision of cooling**

This brings us to this useful distinction. Where ambient conditions are such that in the absence of direct solar radiation, the upper comfort limit is not exceeded, our main concern is to prevent the building from providing an environment which is worse than that outside. We can show that for much of Europe this is the prevailing climatic condition, and even when it is exceeded, it is for a relatively short time. This assertion is supported by the traditional use of the outdoors for many domestic and social activities , in Southern Europe - and it is of course, the "holiday environment". It is only in modern working situations that conventions are forcing us indoors.

Thus the problem becomes one of **prevention of overheating,** ie the minimising of gains from solar radiation and from internal sources, rather than the provision of coolth sources. It suggests that this should be our first line of defence - e.g. we should be concerned with shading devices long before solar chimneys.

There are some cases where the climatic situation and the building use may demand that internal conditions are significantly cooler than ambient, or where internal gains are by necessity very high. Then the **provision of cooling** applies. Conventionally this is provided by mechanical refrigeration, and less commonly, but of special interest to us here, by passive cooling methods, fig 6.

I think that this distinction is important. It is analogous to the earlier days of solar heating where much confused thinking seemed to prevail about the relationship between conservation and solar heating. Arguments raged about solar fraction, solar contribution, absolute energy consumption etc. Now a more holistic view is taken and few would argue that to meet the objective of maximising comfort for a minimum energy consumption, conservation is the first step.

(For convenience, we shall still refer to both *prevention of overheating* and the *provision of cooling* by the inclusive term *passive cooling.*)

2.0 THE ASSESSMENT OF COMFORT PERFORMANCE

2.1 **Reduction** and **Avoidance**

We now have to approach the problem of how we assess passive cooling. First however we need to consider two possible outcomes of adopting passive measures - **avoidance** of mechanical cooling, and the **reduction** of cooling loads, fig 7.

If our passive measures, predominantly prevention of overheating, lead to a reduction of air-conditioning costs, then performance assessment is straight forward, being analogous to displaced auxiliary heating in a passive solar heated building. But supposing our objective is to avoid mechanical cooling altogether, then we do not have an energy consumption upon which to base our assessment.

Clearly the answer is a **comfort performance index.** We need a way of assessing a design proposal in such a way to show that the comfort criteria are met and thus the *avoidance* strategy can be pursued.

Before going on to discuss the nature of this comfort performance index I would like to stress the importance of the *avoidance* option. It is clear that without a mechanical cooling system, no cooling energy can be used. It is not so clear how much energy will be used if a mechanical cooling system is present. If we knew that it would only be used in extreme conditions, then provided the design used passive measures to reduce the cooling load, the energy consumption might be very small. But experience shows that once having accepted artificial conditioning, occupants will begin to adjust their expectations to require lower temperatures than they would accept in a non-air-conditioned building. Indeed they will begin to "dress for the environment" - in the case of the work place for example, it could be argued that in summer air-conditioning is provided in order that the male occupants can still comfortably wear the business suit!

Certainly our experience in the UK in winter, supports this view. It is common in both domestic and non-domestic buildings to find higher indoor temperatures in the winter when the heating systems are under automatic control, than in the summer, when it is common practice to switch off heating systems altogether. This reverse acclimatization is supported by the trend to wear very light clothing indoors in winter. There is also evidence that occupants of air-conditioned buildings where they have little control over their environment, are far more critical in their thermal requirements.

Thus if mechanical cooling were present in a building, and particularly it was indistinguishable from the system of heating, it seems likely that people would develop a demand for cooling to temperatures considerably below that which they would be happy in a passive building.

2.2 Comfort Performance Index

We have already established the need for a comfort performance assessment of a proposed building. Fig 8 shows schematically an approach where the comfort performance of a proposed building can be compared with a base case. The purpose of the base case is to establish reasonable expectations for performance in the particular climate and for the particular building type. This would allow any improvement (or worsening) of performance to be measured against a value and the feed back to be used to optimise the design. Once the comfort performance criterion is met, the air-con equivalent can be used for the purposes of economic assessment. Here, energy consumption values for typical buildings of the same use type and location will be used to establish the value of the energy saved by taking the *avoidance* option.

The *comfort performance index* must be based upon a subjective comfort index, as distinct from a single objective parameter such as air temperature. Comfort models which take account of the environmental parameters air temperature, radiant temperature, humidity and air movement, are well established as typified by the work of Fanger (3), and described in detail in the next paper. By considering heat loss to the environment by the four mechanisms of convection, radiation, evaporation and conduction, a single equivalent or operative temperature can be derived for any set of environmental parameters. When this prevailing temperature is compared with a neutral temperature, at which metabolic gains and environmental losses are in balance, the discrepancy can be related numerically to a subjective response. In the classic work by Fanger these responses, referred to as the Predicted Mean Vote (PMV) are ascribed a value viz -

+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

Whilst this predicts a subjective response to an environmental state, it does not indicate the subjects satisfaction with that state. Clearly if we applied this to our proposed index, we would only be able to say for example "that the building would be warm for 60% and hot for 20% of the time". Fanger extended the PMV to include a statistical indication of satisfaction, or rather dissatisfaction with the Percentage Persons Dissatisfied (PPD), which derived from a direct relationship with PMV as indicated in fig 9.

Thus we have at our disposal, a well proven comfort index. But there are problems. In fig 10 we can see that PPD values are not only dependent upon environmental parameters, but also the human parameters of activity level and clothing. What values of these will we assume in evaluating our building?. Furthermore, work of Humphries and others suggests that we should not be using a neutral temperature derived from heat balance, but rather one which reflects a degree of acclimatisation. There may also be psychological factors which influence the neutral temperature, or rather more subtly, the shape of the PPD curve as we move away from zero.

When applying such an analysis to a heated building, these uncertainties may result in uncertainty in where to set the thermostat. In the case of testing a building design where we are trying to decide between the passive and mechanical options for cooling, uncertainty will have more serious consequences.

2.3 Variation of Comfort with Space and Time

A greater uncertainty is due to the fact that comfort conditions are neither constant in space, nor in time. Of the four environmental parameters influencing comfort, air temperature, radiant temperature, air movement, and relative humidity, the first three of these are likely to vary significantly from room to room, and within a room. They will also vary with time, and it is unlikely that any passive building will experience steady conditions throughout the occupied period.

Fig 11 shows the results of simulations carried out by Newsham (4) at the Martin Centre in Cambridge. The simulation model divides the room into 27 cells and calculates radiant and convective exchanges between the room air and 54 surface nodes. Temperature gradients, vertical and horizontal, are predicted by a simplified model, but airflow itself is not modelled.

The results shown here give map out the variation in space and time of the PPD, calculated from radiant and air temperature alone, for the room in a predominantly overheated situation. The climatic data is for a day in July, in the UK, and the rather low ventilation rates have led to overheating. The non-uniformity in space and time is very evident.

One of the investigations of the study was to see if when an occupant moved around the room, seeking the most comfortable point, this would lead to a significant reduction in overheating (or underheating), as indicated by hours of PPD > 20%. Fig 12 shows the path taken by the "comfort seeking occupant". The results on the hours of discomfort were dramatic - the annual overheated hours were reduced from 570 hours to 130 hours.

We would not like to suggest that it is always desirable that occupants have to seek out a comfortable position. It is not always practicable -in a densely occupied office or classroom for example. However it is probably quite close to actual behaviour, especially in houses where the occupant ususally has a freer choice of position. In cool climates, the traditional approach to heating, i.e. the fireplace or stove, led to considerable temperature gradients (both air and radiant), and normal occupant behaviour would include moving around until comfortable. And indeed, the need for this may be regarded as a positive attribute of the room.

In a field study by Griffiths (5), PMV values calculated at a single point, show very poor correlation with actual subjective replies. The reasons for this are not quite clear from the study, but the fact that the correlation was best for the offices, where the was a greater probability of uniformity and less opportunity for occupant choice of position, suggests that spatial distribution may have had something to do with it. The results also showed that in a space tending to underheating, people are more tolerant of the recorded low temperatures, than expected, suggesting that the non-uniformity may have been used to provide local comfort.

It seems that a combination of common sense and the rather scant evidence above, suggests that a comfort performance index must take account of variation in time and space of predicted comfort conditions, and must take account of how the occupant is likely to behave. This behavioural aspect should also include clothing and activity level, and possibly other unspecified (so far) factors. It must also include the operation of building controls such as blinds and opening windows.

2.4 Behavioural Models

This all points to an interest approach differing from the conventional way of assessing building performance. Hitherto, passive building performance assessment has concentrated upon the energy performance in heating situations. For this purpose, the occupant model has been very, very crude - usually the occupant is modelled as an inert temperature sensor located in the middle of the room. Has this mattered, and if not, why not?

Probably it has not mattered too much, because the most significant error would be in heating energy input, and the same systematic error would be made when making comparisons. Validations of precision models almost always involve data from test cells or simulated occupancy houses, where these behavioural aspects do not appear. However, where we are testing a building to see if the avoidance of mechanical cooling is justified, it is crucial that the influence of behaviour on comfort performance, is taken into account.

Thus any assessment will require both a building model, to predict the effect of the building upon the climatic boundary conditions, and a behavioural model, to predict the response of the occupant.

There are precedents for behavioural models in building performance assessment. A good example is in light-switching algorithms. These predict the probable response of an occupant to ambient daylight levels in a room, in order to determine the saving of electrical energy. It is interesting to note too, that in some respects the human response has proved more energy efficient than an automatic "objective" response. For example, an automatic switch-on with a datum of 300 lux for an office building has proved to be pessimistic since often people will tolerate far lower levels at the beginning and end of the day, provided they associate it with daylight and not insufficient artificial lighting.

2.5 Design Tools

Any assessment model has the potential of becoming a design tool, provided it can respond to design parameters available early in the design development. The time and space dependency required in the behavioural model here, suggest that this would only be available from deep-analysis simulation. This requires much building data, apart from the so-far unknown spatial data required for the behavioural part of the model.

At the Martin Centre we are currently working on a behavioural model which aims to quantify an occupants exposure to daylight. This incorporates a statistical position occupancy model, which basically gives the probability that a person will be in a specific place at a specific time. Rather than a simulation model, which due to the complexity of movements and occupancy patterns of an actual building, we are trying to develop a parameterised model, using parameters such as depth from outside wall, distance from workstation, with special space-use weightings for circulation, rest rooms, toilets, etc.

If such parameterised simplified behavioural models appropriate to thermal comfort can be derived, then it might be possible to combine these with simplified thermal models and produce comfort performance design tools.

3.0

In the second part of the paper a number of other aspects of comfort which have particular bearing on passive cooling, are now discussed.

3.1 Interior Environment Design

The occupant centred comfort models discussed above, suggests that where conditioning of some kind, whether mechanical or passive, has to be provided, it would be most efficient to provide it on a local scale. This is already accepted, indeed preferred practice for lighting - i.e. task lighting, and as already discussed, until the concept of space heating was developed, was accepted (and perhaps preferred) practice for heating.

Thus we must develop the concept of "coolth emitters". An opening in the external wall which can modulate and direct the prevailing wind onto the occupant, could be considered to be a passive coolth emitter. An electrical fan, operating on the same environmental parameter, could be regarded as the auxiliary equivalent.

A cooled floor, cooled by a passive source such as a stream, or actively by chilled water, may also have advantages over the conventional convective volumetric cooling, fig 13. In this system, stratification and stability of the cooled lower layer of air provides an occupied zone, which in the case of the seated occupant is considerably less in volume than the whole room. Even furniture could be cooled, again passively or actively, and advantage taken of conductive losses from the body.

This brings us on to the whole area of interior design. Not only should this be directed to solving the environmental performance in an integrated way, i.e. the interaction between requirements of daylight, airflow, view, shading etc, but also the psychological aspects must be considered. The substantive research is yet to be done, but common experience hints to us that our physiological expectations may be influenced by visual and other physical cues.

I have long been interested in what I have called the "switched-off-escalator effect". We probably all have felt a curious sensation when walking down or up an immobilised escalator on the metro. Why is this feeling actually physical? We have only received visual cues to tell us that normally it is an escalator - we do not get the same feeling when we walk down an ordinary staircase.

If the visual cues that tell us that we are walking down an escalator, effect our muscles, posture and balance to such an extent, then maybe visual cues such as furnishing, finishes, view, planting etc can influence our expectations of thermal comfort. There has been some work in this area, mainly for the heating situation, and it did not show a positive effect. However this was investigating only the effect of colour. Maybe it is a "cocktail" of stimuli which have an effect - perhaps greater than the sum of the parts. If there is any validity in this suggestion, then it will promote a most exciting fusion of functional and aesthetic aspects of interior design.

3.2 Outdoor Thermal Comfort

The discussion above relates in part to the use of outdoor spaces in warm climates. The traditional precedent is very well established, but it tends to be limited to recreation and relaxation. The design of the outdoor space, shows evolutionary development in some cases, e.g. patios and courtyards, but is often ad hoc, e.g. the side of the street. The use of an "outdoor room" for office or institutional buildings is rarely in the brief of an architect. But outdoor architecture really could have something to offer as a means of passive cooling in the broadest sense.

Comfort analysis has been carried out on outdoor spaces in warm climates. Lauritano et al (6) produced Standard Effective Temperature predictions for Trapani, Italy, for shaded and unshaded situations. He concludes that there is a need to develop the model further to take account of the complex geometric geometry of the typical urban environment.

Fig 15 shows a section of the Faculty of Humanities of the University of Seville. In extreme conditions, in order to maintain cooler than ambient air at the base of the atrium, cross-ventilation through the library would have to be curtailed. But if the library were occupied, ventilation would have to take place. The answer was to design the outside space to the north of the library as an outside room or study area, still maintaining the necessary book security, and providing a pleasant natural working environment at no energy cost for lighting or cooling.

3.3 Non-thermal comfort

Finally, it must be noted that there are other aspects of comfort relating to passive cooling which are non-thermal, but may be interactive through psychological mechanisms with thermal comfort.

Glare is a good example. It appears from traditional solutions that glare may be more acceptable in cool climates, than in warm climates. This must be due to association with thermal discomfort. However it means that shading design should consider the brightness and positions of insolated surfaces which can be seen by the occupants, as well as considering the role of shading to prevent direct radiation from entering the room or actually falling on the occupants.

These constraints often conflict with the need to maintain sufficient daylighting levels, and make the design of shading devices no small problem.

Another non-thermal comfort problem, which may or may not interact psychologically, is that of noise control. Any naturally ventilated building is going to be more vulnerable to external noise, due to the openings required for ventilation. Also noise generated within buildings where rooms are interconnected to provide through routes for natural ventilation, may present problems. Undoubtedly, technology can find a solution to these problems.

4.0 RESEARCH TOPICS

To summarise, I have identified a number of topics in human comfort which are of special relevance to passive cooling, which I believe are in need of research. If I have omitted reference to work which already answers these questions, then I apologise to the authors, but it is clearly good news that the work has been done. However, even when in detail the research area has been covered, there may yet be the need to interpret and apply the findings to the specific context of passive cooling.

1.0 BEHAVIOURAL COMFORT PERFORMANCE MODELS

Sub-tasks

1.1 Occupant studies

(i) dress, posture, activity, use of building controls
(ii) psychological effect, comfort expectations, interior design

1.2 Building studies

(i) 3D room models, airflow and radiation
(ii) interior design, furnishings, layout etc
(iii) "coolth emitters" and controls

2.0 OUTDOOR COMFORT DESIGN

3.0 NON-THERMAL COMFORT

3.1 Glare
3.2 Noise

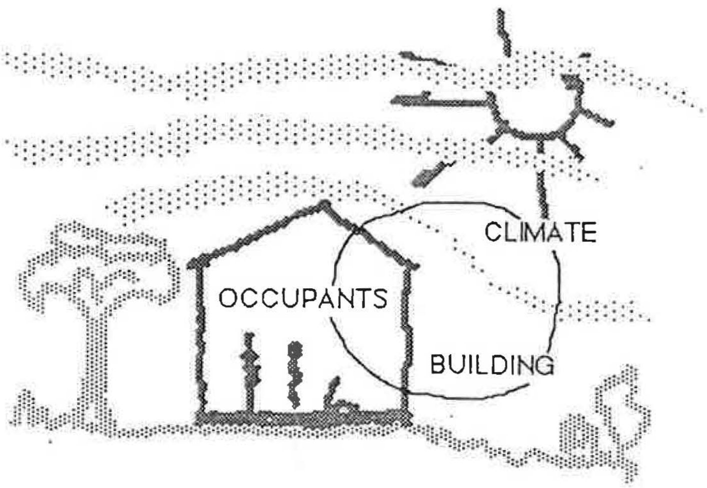
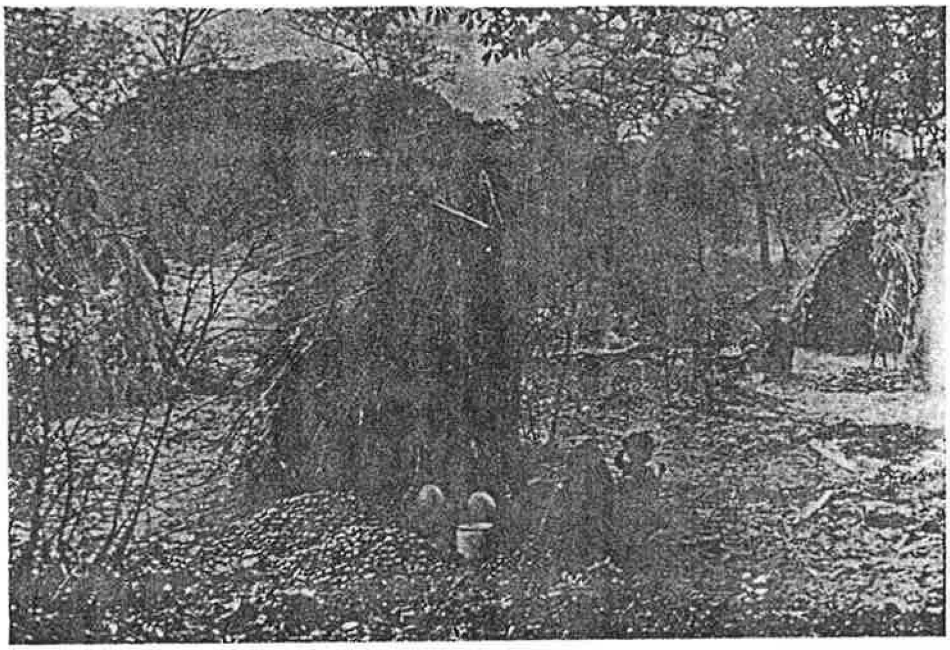


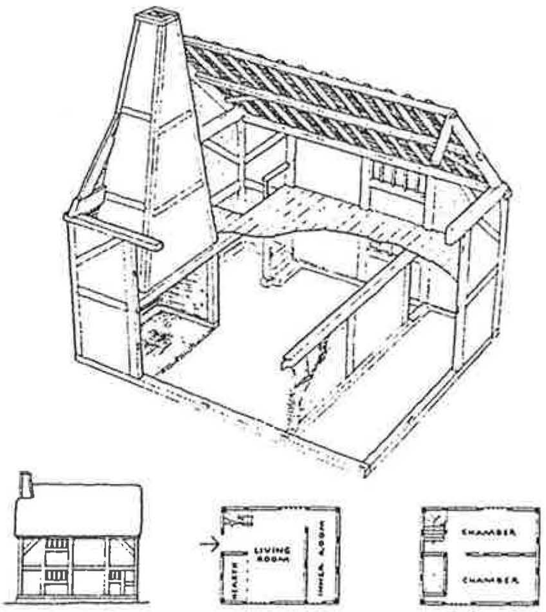
Fig 1 The building acts as a moderator between the biological needs of the occupant and the climate



Sunbreak of the Kalahari nomad, Africa

Windbreak in Tierra del Fuego, S America

Fig 2. Two similar forms, the sunbreak and the windbreak each protect against the most threatening environmental stress



Drawing of an early seventeenth-century cottage rebuilt by the Central Electricity Generating Board at Coleshill and now part of a Field and Local Studies Centre; an example of the transitional phase between a central open hearth and a closed chimney breast. The hearth occupies one half of a small end bay with a timber-frame wattle and daub 'chimney' or canopy above. In other houses similar in plan but perhaps rather earlier in date, the narrow end bay might have been a smoke bay without any canopy or chimney with the stairs to the upper floor within this open smoke bay.

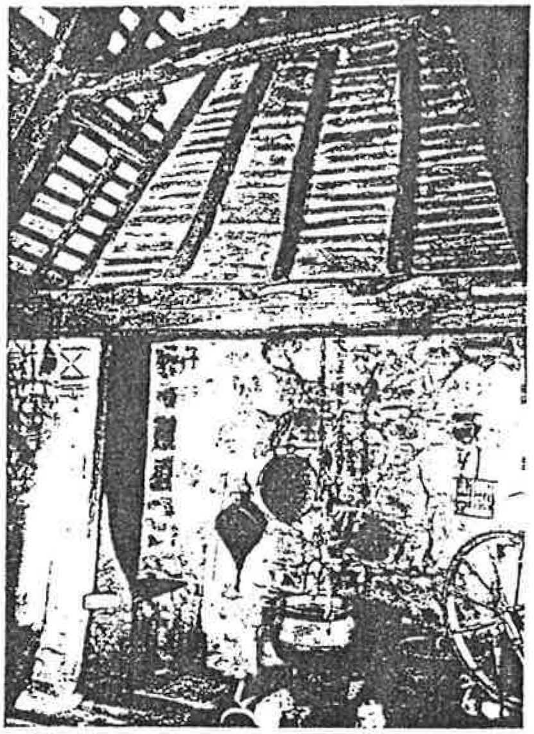
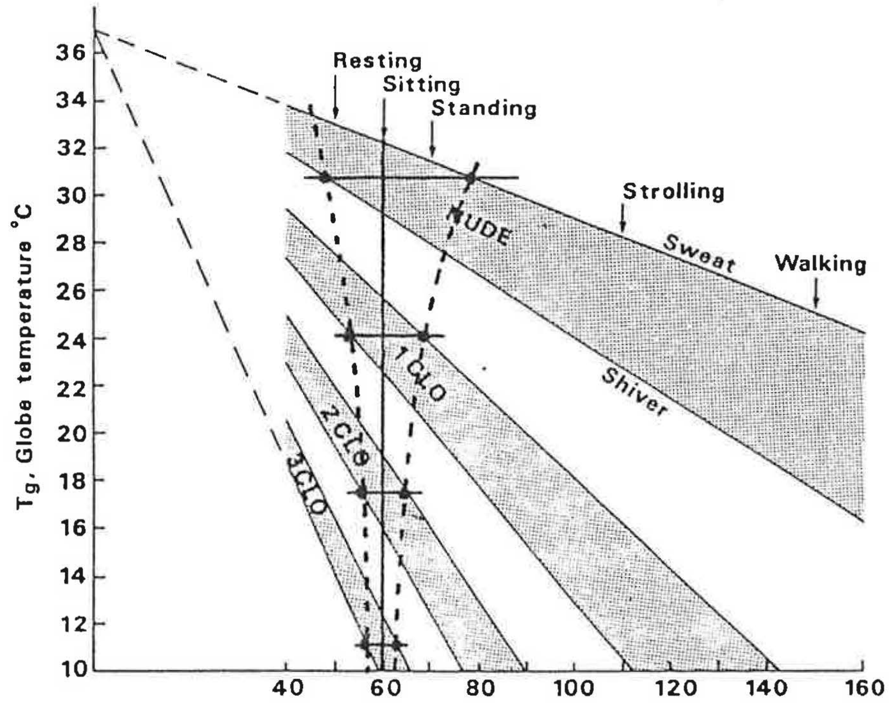


Fig 4. The use of fire to provide warmth is almost universal to man in cool climates.



Comfort zones for air velocity 1·0 m/s

Fig 5. Comfort is attained for a greater range of activity levels for low clothing values and high temperatures. Source Humphreys ( )

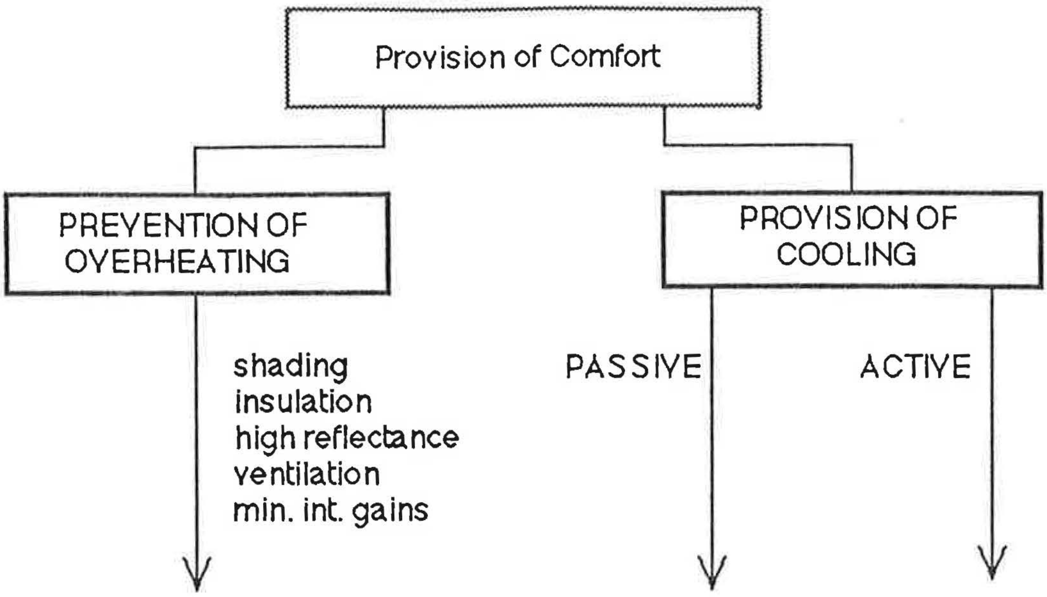


Fig 6. The provision of comfort - first strategy.

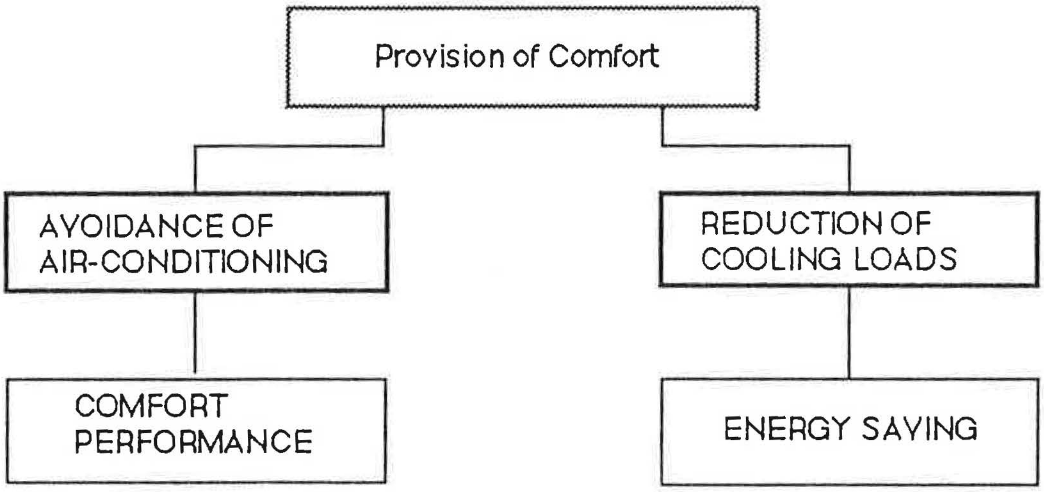


Fig 7 The provision of comfort - second strategy

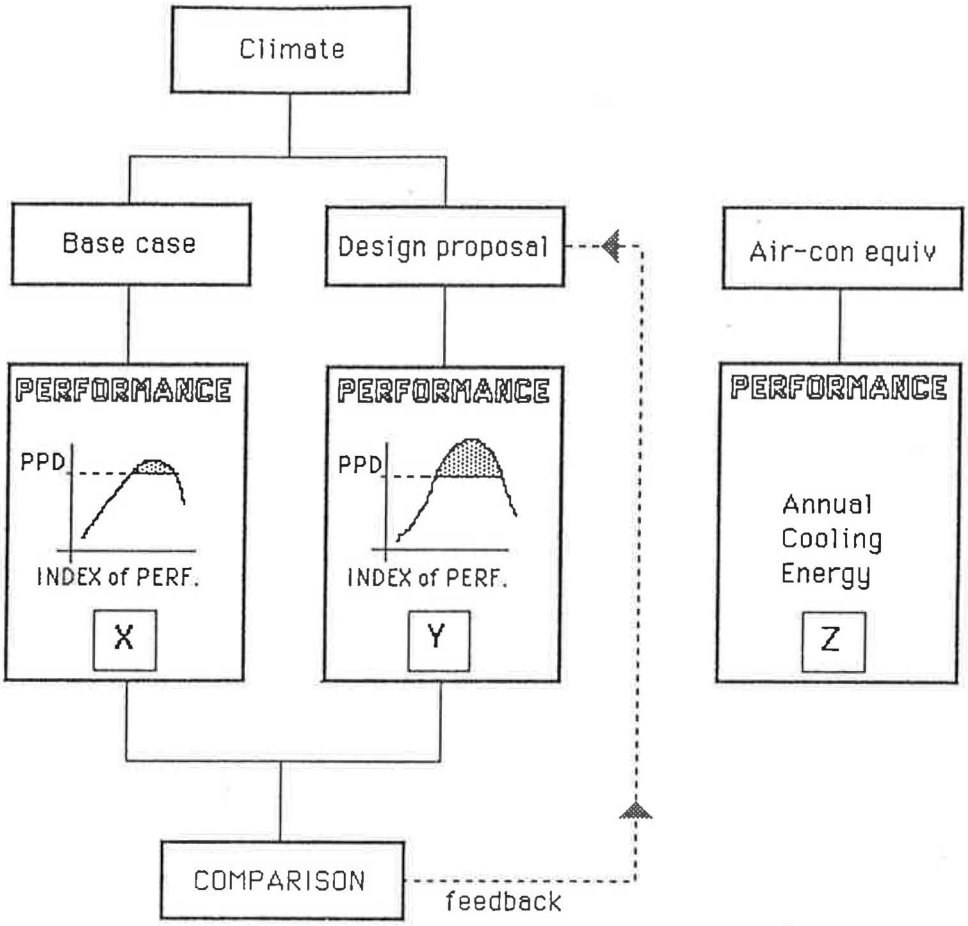


Fig 8. An approach to cooling performance assessment

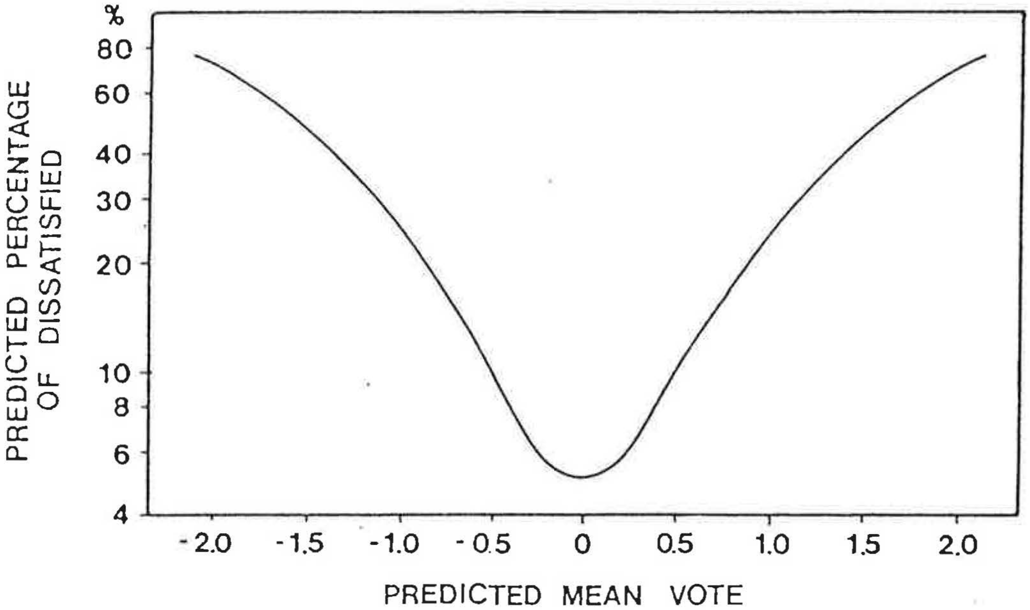


Fig 9. Relationship between PMV and PPD. Source - Fanger(3)

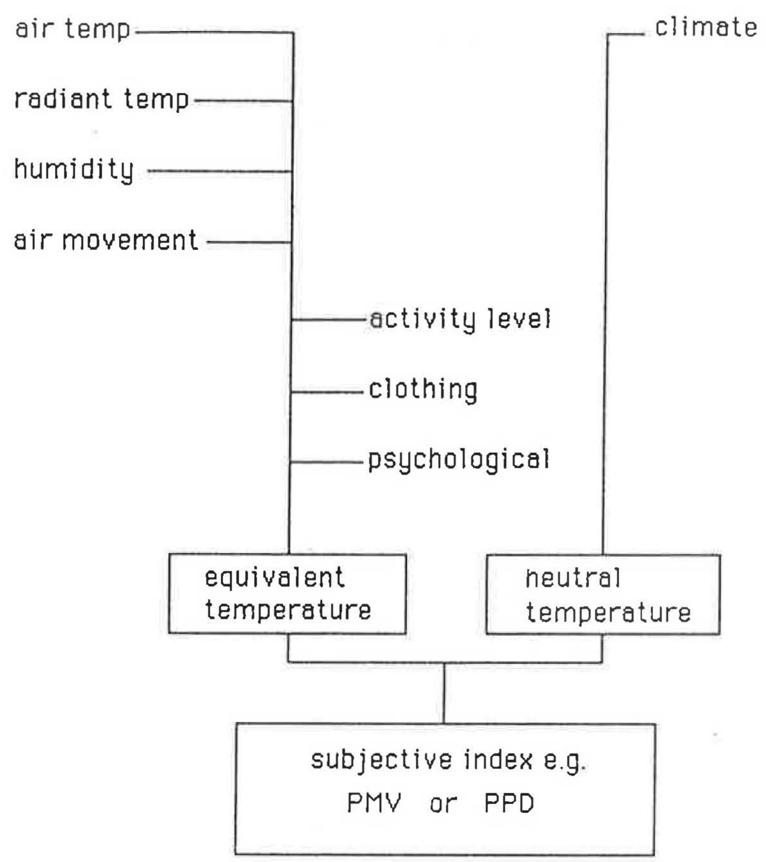


Fig 10. Environmental and human parameters of thermal comfort

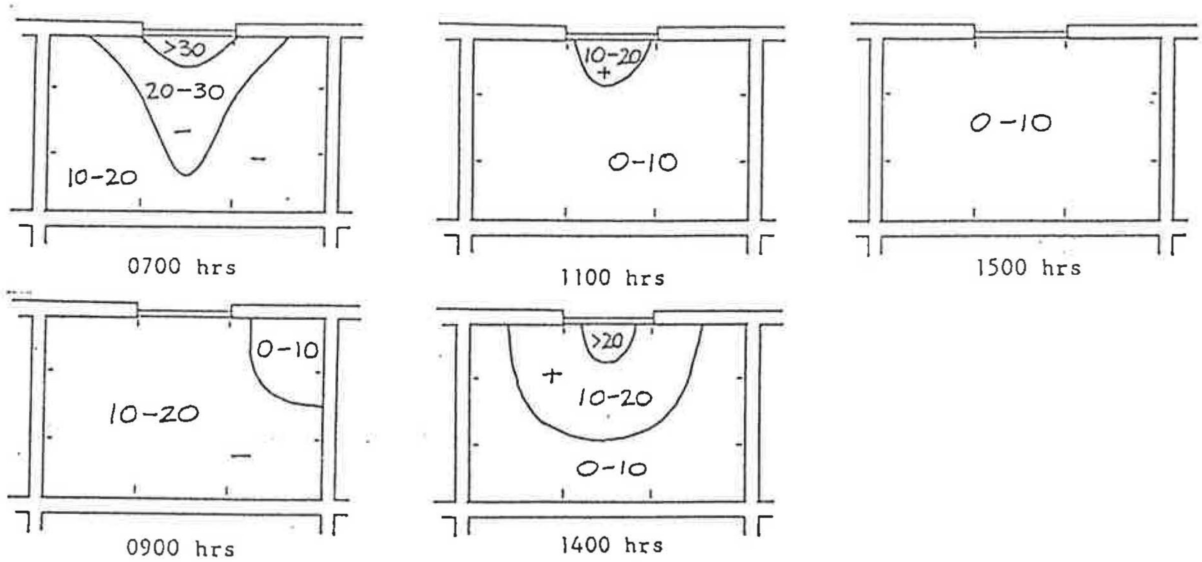
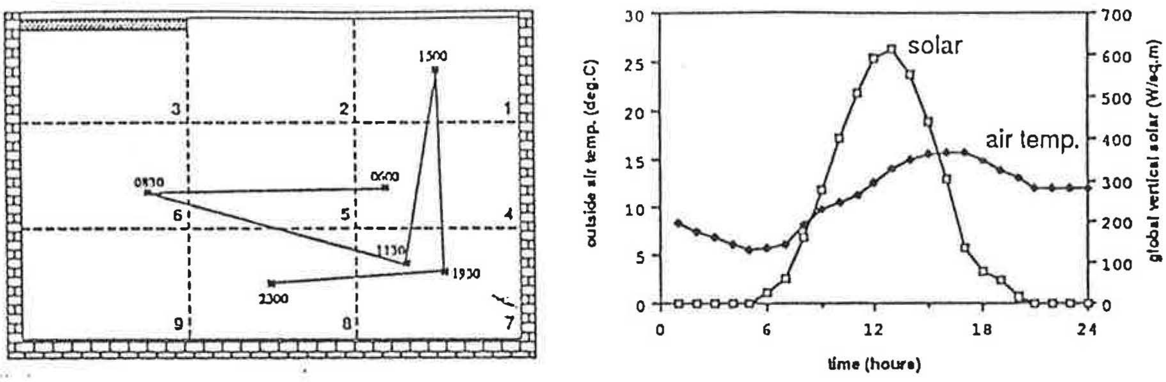


Fig 11. PPD contours for room predicted by simulation model FENESTRA



The most comfortable occupant position for various times of day (smaller figures indicate the hour at which that position is first occupied). The climate for that day (in April) is also shown.

Fig 12. Simulated path taken by "comfort seeking" occupant

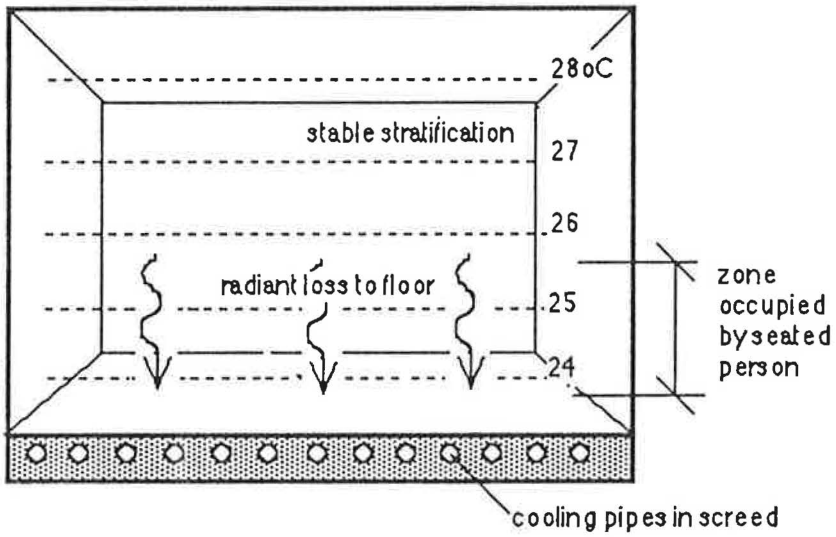


Fig 13. Thermal environment created by cooled floor

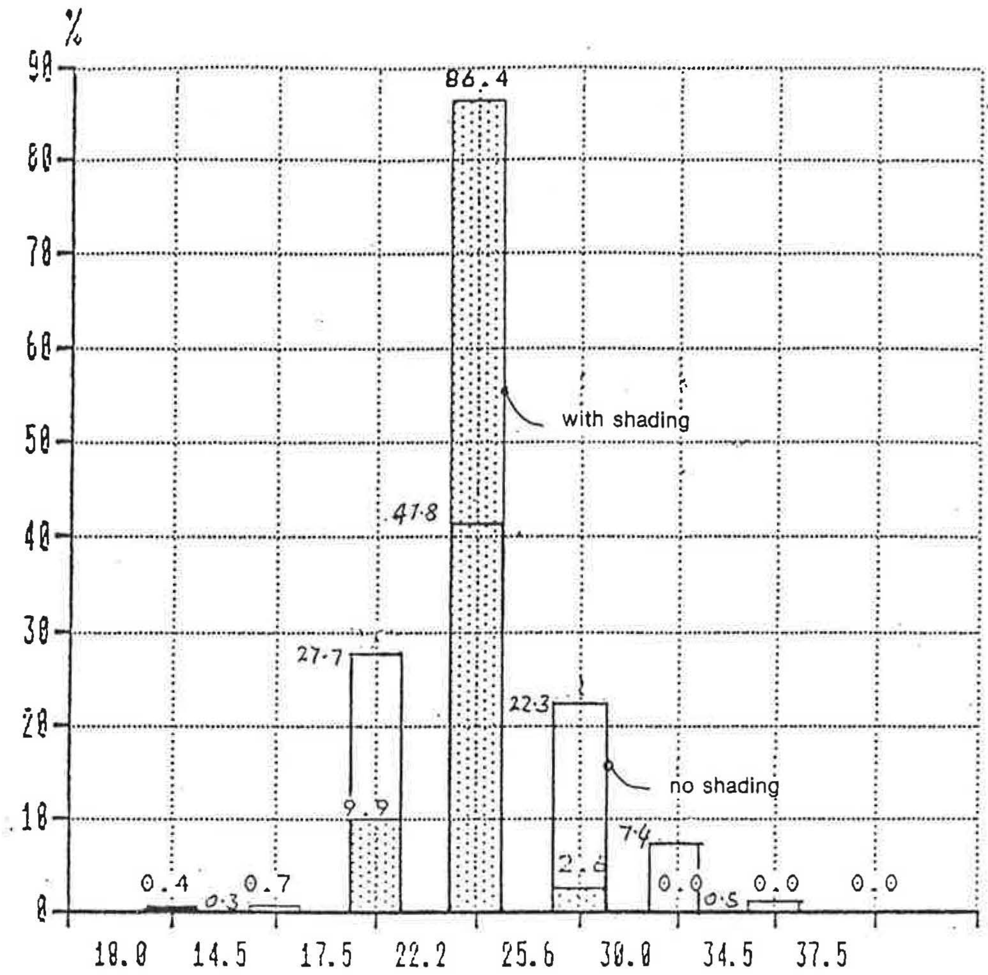


Fig 14. Predicted outdoor SET values for Trapani, Italy. Source - Lauratino

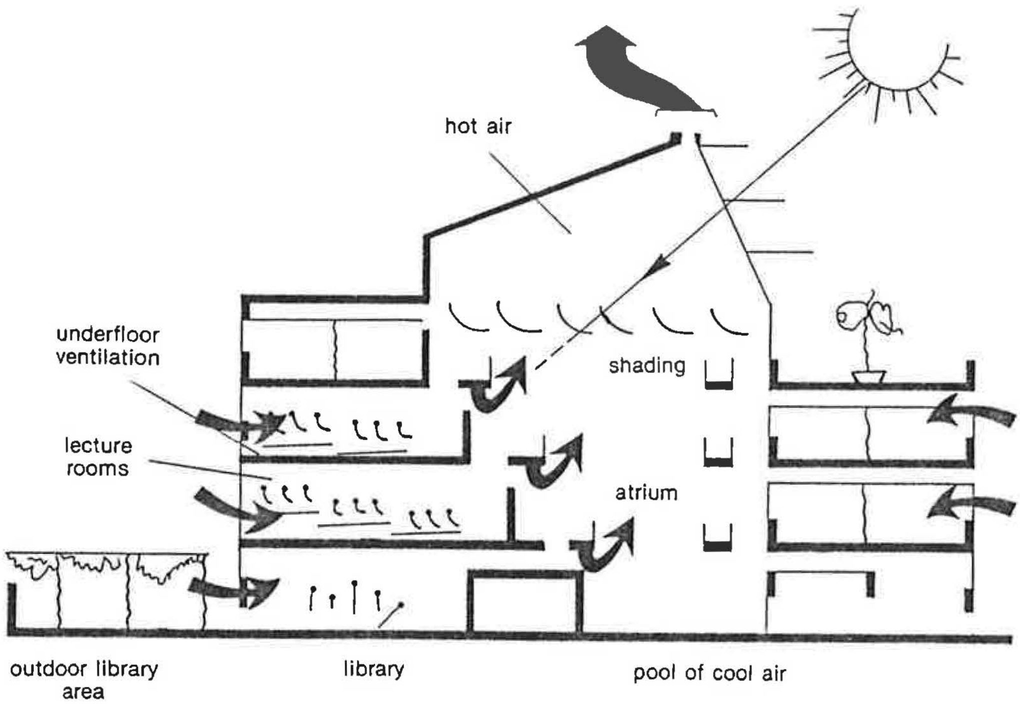


Fig 15. Section of projected Dept of Humanities, University of Seville, showing outdoor library area. Architect - J Lopez de Asiain

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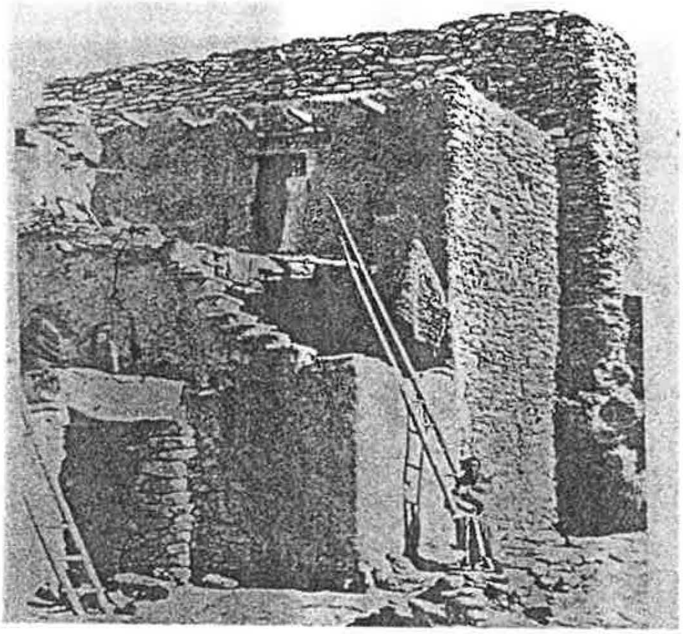
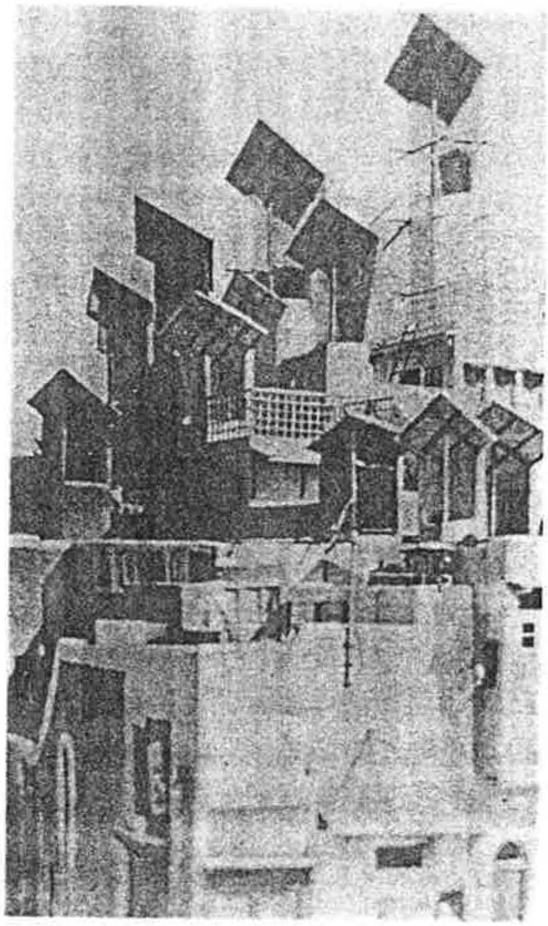


Pueblo Indian village, Central America

Indonesian house



Wind catchers of Hyderabad, Pakistan

Fig 3. Traditional solutions where more sophisticated environmental responses permit greater cultural influences